THE MATURITY OF CHEMICAL RECYCLING AND ITS RELEVANCE IN THE PLASTICS VALUE CHAIN

CASE HUHTAMAKI

Lappeenranta–Lahti University of Technology LUT

Master's Thesis in Industrial Engineering and Management

2024

Janita Behr

Examiners: Professor Ville Ojanen
Docent Nina Tura

ABSTRACT

Lappeenranta–Lahti University of Technology LUT

LUT School of Engineering Sciences

Industrial Engineering and Management

Janita Behr

The maturity of chemical recycling and its relevance in the plastics value chain: Case Huhtamaki

Master's thesis
2024
96 pages, 8 figures, 3 tables and 1 appendix
Examiners: Professor Ville Ojanen, Docent Nina Tura
Keywords: chemical recycling, advanced recycling, plastics value chain, plastic recycling, circular economy, pyrolysis, gasification, solvolysis, mass balance, mass balance method

The amount of plastic waste in our society increases constantly and a huge part of it ends up at landfills, incineration or even our environment. Recycling plastic is complex and various methods such as recycling targets are set to support it. Mechanical recycling has been dominant for a long time, but it still cannot recycle all kinds of plastic waste produced on our planet. Chemical recycling is a recycling method that uses chemical processes to convert plastic waste back into its building blocks, which can be further processed back into plastic products that have the same quality as products made out of virgin fossil resources. The aim of this thesis is to examine the maturity of chemical recycling and its relevance in the plastics value chain. The objective is to understand the maturity level of the technology, its challenges and benefits and to provide an understanding for the case company Huhtamaki about their internal and external possibilities to introduce chemical recycling in their value chain.

The thesis has been conducted as a qualitative study and it consists of a literature review and empirical part. The literature review focuses on the overall picture of the plastics value chain and chemical recycling. The literature review provides the base for the empirical part, in which data is collected from interviews. The empirical part examines the perspective of field professionals on the topic and explores the internal and external opportunities for Huhtamaki.

The study finds out that although chemical recycling is mature from a technological point of view, the industry faces many challenges including the lack of infrastructure and investment, and complex legislation. Chemical recycling is very relevant in the plastics value chain, as it reduces the amount of plastic waste with its ability to recycle materials, which mechanical recycling cannot. Chemically recycled raw materials are scarce on the market, but the industry is seeing growth in the near future. Huhtamaki has the opportunity to capture value from this growth by working with various stakeholders to ensure they have chemically recycled raw material for the future.

TIIVISTELMÄ

Lappeenrannan–Lahden teknillinen yliopisto LUT

LUTin insinööritieteiden tiedekunta

Tuotantotalous

Janita Behr

Kemiallisen kierrätyksen kypsyys ja sen merkityksellisyys muovin arvoketjussa: Case Huhtamäki

Tuotantotalouden diplomityö
2024
96 sivua, 8 kuvaa, 3 taulukkoa ja 1 liite
Tarkastaja: Professori Ville Ojanen, Dosentti Nina Tura
Avainsanat: kemiallinen kierrätys, muovin arvoketju, muovin kierrätys, kiertotalous, pyrolyysi, kaasutus, solvolyysi, massatase, massatasemenetelmä

Muovijätteen määrä yhteiskunnassamme vain yltyy, ja suuri osa joutuu kaatopaikalle, polttoon tai jopa luontoomme. Muovin kierrätys on monimutkainen prosessi, ja sitä yritetään parhaillaan tukea esimerkiksi erilaisilla kierrätystavoitteilla. Mekaaninen kierrätys on ollut jo pitkään dominoiva kierrätysmenetelmä, mutta sekään ei pysty kierrättämään kaikkea muovijätettä mitä maapallollamme kertyy. Kemiallinen kierrätys on kierrätysmenetelmä, jonka avulla muovijäte voidaan kemiallisin menetelmin kierrättää takaisin sen alkuperäisiin rakennusosiin, jotka voidaan jatkojalostaa takaisin samanlaatuisiksi muovituotteiksi mitä fossiilisella neitseellisellä raaka-aineella saataisiin tuotettua. Tämän diplomityön tavoitteena on tutkia kemiallisen kierrätyksen kypsyyttä sekä sen merkityksellisyyttä muovin arvoketjussa. Työn tavoite on ymmärtää teknologian valmiusastetta, haasteita ja hyötyjä, sekä tuottaa case yritys Huhtamäelle ymmärrys heidän ulkoisista ja sisäisistä mahdollisuuksista ottaa kemiallinen kierrätys käyttöön arvoketjuunsa.

Tutkimus on toteutettu laadullisena tutkimuksena ja se koostuu kirjallisuuskatsauksesta sekä empiriaosuudesta. Kirjallisuuskatsaus keskittyy muovin arvoketjun kokonaiskuvaan sekä kemialliseen kierrätykseen. Kirjallisuuskatsaus luo pohjan empiiriselle tutkimukselle, jonka aineisto on kerätty haastatteluiden avulla. Empiriaosuudessa tutkitaan alan ammattilaisten näkökulmaa aiheesta ja selvitetään mitkä ovat sisäiset ja ulkoiset mahdollisuudet Huhtamäelle.

Tutkimuksen tuloksena todetaan, että vaikka kemiallinen kierrätys on teknologian näkökulmasta kypsä, on toimialan kasvun esteenä paljon haasteita kuten puutteellinen infrastruktuuri, monimutkainen lainsäädäntö ja investointien vähäisyys. Kemiallinen kierrätys on hyvin merkillinen osa muovin arvoketjua, sillä se vähentää muovijätteen määrää sen kyvyllä kierrättää sellaista muovijätettä, mihin mekaaninen kierrätys ei kykene. Kemiallisesti kierrätettyä raaka-ainetta on niukasti markkinoilla, mutta alan nähdään kasvavan lähitulevaisuudessa. Huhtamäellä on mahdollisuus tarttua tähän kasvuun tekemällä yhteistyötä eri sidosryhmien kanssa varmistaen täten heille tarpeellisen määrän kemiallisesti kierrätettyä raaka-ainetta.

ACKNOWLEDGEMENTS

I would like to thank Paul Collins for supporting me in finding a thesis topic within the company and for always keeping up a good spirit. Thank you for believing in me and my abilities. I wish you the best and hope that we will meet each other in the future. I also hope to someday hear you playing the piano. Good luck with that.

Since my early university years, I have been deeply interested in the circular economy. My bachelor's thesis explored circularity within the clothing industry, solidifying my passion for the topic and inspiring me to dig even deeper in my master's studies. When Paul introduced me to the concept of chemical recycling as a potential thesis topic, I had never heard about it before. Initially, I hesitated, unsure if my lack of prior knowledge on the subject would make it a good fit. However, the concept intrigued me so much that I decided to take on the challenge—and I couldn't be happier with that decision. The topic is highly relevant to the plastic industry's transition toward a circular economy, and through this work, I have gained invaluable knowledge and insights into this critical area.

I want to thank my family and friends for their encouragement and support during my writing process. My family always had the proper words to urge me to keep going and finish this assignment without too much stress. Thank you so much for your encouragement and belief in me. Thanks to my friends who kept my sanity during this writing process by supporting and spending time with me after writing days. Special thanks to Jenni, who sat with me in the library so many times while we worked on our theses. Without her, I wouldn't have been in the library as many times as I was, and my most productive hours were spent there.

Writing this means that my studies at LUT University will soon come to an end. I've been living elsewhere for the past year, yet it still seems weird that I'll never return to Kiltis (Guild room) to hang out with friends during lecture, to Viipurisali (Viipuri hall) for a lecture or to Kellari (basement) for a sits-party. Or maybe I will… I appreciate every experience I gained during my six years of studies in Lappeenranta. That being said, I say goodbye to college life with a big warm smile and a group of people who have become lifelong friends. Thank you!

Helsinki 16.12.2024

Janita Behr

List of abbreviations

CO	Carbon monoxide
CO2	Carbon dioxide
CR	Chemical recycling
EoL	End-of-Life
ERP	Extended producer responsibility
FMCG	Fast-moving consumer goods
GHG	Greenhouse gas
H_2	Hydrogen
HDPE	High-density polyethylene
LCA	Life cycle assessment
MSW	Municipal solid waste
MR	Mechanical recycling
PA	Polyamide
PCPW	Post-consumer plastic waste
PCR	Post-consumer recycling
PE	Polyethylene
PET	Polyethylene terephthalate
PP	Polypropylene
PPWD	Packaging and Packaging Waste Directive
PPWR	Packaging and Packaging Waste Regulation
PS	Polystyrene
PU	Polyurethane
PVS	Polyvinyl chloride

Table of contents

Abstract

Acknowledgements

Abbreviations

1 Introduction 9
1.1 Background 9
1.2 Objectives, research questions and scope 10
1.3 Research methods and data collection 11
1.4 Structure of the report 12
2 The plastic value chain 14
2.1 Definition and background 14
2.2 Linear, recycling, and circular economies in the plastic value chain 16
2.3 Plastic waste generation and treatment 18
2.4 Current state of plastic recycling 20
2.5 Legislative landscape for plastic packaging 22
3 Chemical recycling 25
3.1 Definition and core techniques 25
3.1.1 Pyrolysis 28
3.1.2 Gasification 30
3.1.3 Solvolysis 31
3.2 Comparison of chemical and mechanical recycling 32
3.3 Mass balance 34
3.4 Technological maturity, gaps and challenges 39
4 Forecast of required resin for Huhtamaki 44
4.1 Introduction of the case company 44
4.2 Data collected from Huhtamaki 45
4.3 Analysis and forecast 46
5 Interview results 49
5.1 Background of the interviewees 49
5.2 Maturity of the technology and possibilities in scaling up the industry 49

5.3 The future of chemical recycling 56
5.4 Main challenges and benefits of chemical recycling 58
5.5 Legislative landscape 63
5.6 Possibilities for plastic packaging manufacturers 70
5.7 Insight into volumes 74
6 Discussion and conclusions 77
6.1 Answering research questions 78
6.2 Recommendations for Huhtamaki 84
6.3 Future research 85
References 86

Appendices

Appendix 1. Interview questions

LIST OF FIGURES

FIGURE 1. THE MAIN STAGES OF THE PLASTICS VALUE CHAIN (ADAPTED FROM SILTALOPPI & JÄHI, 2021) 16

FIGURE 2. ILLUSTRATION OF THE LINEAR, RECYCLING, AND CIRCULAR ECONOMIES (ADAPTED FROM COLLIAS ET AL., 2021) 17

FIGURE 3. DIFFERENT RECYCLING PROCESSES FOR PLASTICS, RECYCLING LOOPS AND FEEDSTOCKS IN EACH RECYCLING PROCESS (ADAPTED FROM COLLIAS ET AL., 2021) ... 21

FIGURE 4. THE PATH OF CHEMICAL RECYCLING AND OTHER PLASTIC WASTE MANAGEMENT METHODS (ADAPTED FROM RIZOS ET AL., 2023 & LIU ET AL., 2024) 27

FIGURE 5. SIMPLIFIED PRINCIPLE OF MASS BALANCE METHOD (ADAPTED FROM ZERO WASTE EUROPE, 2021 & ISCC, 2024) 36

FIGURE 6. MASS BALANCE ALLOCATION RULES EXPLAINED (ADAPTED FROM DAPHNE & AHMED, 2024) 37

FIGURE 7. FORECAST OF THE REQUIRED RESIN FOR HUHTAMAKI OPERATIONS IN EU BETWEEN 2024-2030 47

FIGURE 8. FORECAST AND SHARES OF RESIN SOURCES FOR HUHTAMAKI EU OPERATIONS IN 2024-2030 48

LIST OF TABLES

TABLE 1. CHARACTERISTICS OF MECHANICAL AND CHEMICAL RECYCLING TECHNOLOGIES (ADAPTED FROM BIESSEY ET AL., 2023) 28

TABLE 2. FORECAST OF RECYCLED RESIN SHARES FOR HUHTAMAKI EU OPERATIONS DURING 2024-2030 47

TABLE 3. SUMMARY OF MAIN CHALLENGES AND BENEFITS OF CR 59

1 Introduction

The first chapter contains the introduction to this thesis. The chapter provides background to the topic to clarify why this topic was chosen for this thesis. The chapter also includes the research questions and objectives of the research including the scope of study. The research methods and data collection are discussed, and the structure of the thesis is explained.

1.1 Background

In today's world, imagining life without plastics seems nearly impossible. From the moment our digital devices wake us up in the morning to the numerous uses throughout the day, from smartphones to medical supplies, plastics are a necessary part of modern living. (Szaky, 2019) This widespread use across various sectors, including transport, communications, and healthcare, has highlighted the dual nature of plastics. While plastics offer undeniable benefits due to their durability and functionality, these same characteristics contribute to their persistence in the environment, often leading to significant pollution on land and in the sea. (Payne & Jones, 2021; Eze et al., 2021)

The global challenge of managing plastic waste has become a key political issue, particularly within the European Union. The adoption of the EU's Single-Use Plastics Directive is an example of efforts and acts to mitigate plastic wastes environmental impact. Despite these initiatives, the journey toward a circular economy where waste does not exist (Ellen MacArthur Foundation, n.d.) for plastics is still full of obstacles and challenges. Without more rigorous policies promoting circularity, projections indicate that plastic waste generation could continue to rise (Rizos et al., 2023). Here is where chemical recycling, a technology that enables circularity by using different chemical processes to convert plastic waste into its original components (for example monomers or oligomers) comes in.

Chemical recycling is a game changer in the plastics industry, since it can convert plastic waste to components that can be used in reprocessing it back into some form of plastic. The core technologies identified and studied in this thesis are pyrolysis, gasification and solvolysis. Current research focuses mainly on the technicalities, benefits and chemical aspects of the technologies. This thesis aims to examine the maturity of the technology and

the relevance of it in the plastics value chain since this kind of combination has not been researched yet. The thesis topic originated from the expressed interest of the case company, Huhtamaki.

1.2 Objectives, research questions and scope

The aim of this thesis is to examine the maturity of chemical recycling and the relevance of it in the plastics value chain. To do that, a few objectives have been set to support that goal. One of the objectives of this research is to gain a clear understanding of the plastics value chain as a whole, to get an understanding of the area in which chemical recycling is operating. One of the objectives of this work is also to understand the legislation around plastics, which might affect the chemical recycling industry.

Another objective is to identify and study the core technologies of chemical recycling. In this thesis, by core technologies are meant the most discussed technologies in chemical recycling. This objective includes understanding how chemical recycling and these core technologies function in general and identify key benefits and challenges of them. The next objective is to understand the relevance of chemical recycling in the plastics value chain. This involves analyzing its role and relevance as part of the broader system and how it could contribute to improving circularity in the plastics value chain. This thesis also aims to examine the current maturity of the chemical recycling core technologies to provide insight into how developed these technologies are.

In addition, this thesis will evaluate the potential for Huhtamaki to introduce chemical recycling into its value chain. This includes investigating the availability of recycled materials, assessing the volumes required by the company, and forecasting how much of these volumes could come from both mechanical and chemical recycling. This analysis will help determine the feasibility and strategic value of introducing chemical recycling into Huhtamaki's operations.

This thesis has three main research questions. The questions are based on the objectives of this research and will guide the work. The research questions of this study are:

1. *How mature are the core technologies of chemical recycling in recycling plastics?*
2. *What is the relevance of chemical recycling in the plastics value chain?*

3. *What is the potential of introducing chemical recycling into Huhtamaki's operations?*

The scope of this work was based on the geographical location of the case company's operations and the materials it uses in the segment for which this thesis was written. The study focuses geographically only on Europe since the headquarters is in Europe in Finland, and a lot of operation is located there. The study focuses also only on plastic recycling and does not assess any other materials that can be chemically recycled. Also, only three technologies within the chemical recycling industry are examined. These three core technologies are identified to be the most discussed ones in recent research. The thesis mainly focuses on plastic packaging, as it aligns with one of the core businesses of the case company. However, due to research limitations, the study also includes information relevant to plastics in general.

1.3 Research methods and data collection

The research has been conducted as a qualitative study, focusing on qualitative data collection and analysis. The method was chosen, because the research questions cannot be answered by numerical data. To reach the objectives of this thesis, qualitative data must be collected. The theoretical part of the study is written as a literature review, which helps to outline the topic of the study and helps to frame the research. The literature review will be used in the research part to compare the research findings to existing theory and find possible conflicts or similarities.

The literature review of the study supports the formulation of the research questions. The literature review is based on key concepts of the research topic and provides a basis for new insights from the research part and conclusions. In the literature review a variety of sources including books, scientific articles, relevant organizations in the topic field and reliable statistical websites were used. The literature review has used AI to understand complex concepts and to search for information according to the guidelines of the LUT University (LUT, 2023)

In the qualitative research, data is collected through structured but conversational interviews. This method was applied for data collection in this thesis by conducting seven interviews with field professionals and experts. The interviewees were chosen based on internal

suggestions from Huhtamaki. The position of interviewees in their companies varies from CEO to Policy Officer, but all have significant knowledge about chemical recycling. The interviews were conducted via Teams meetings, and they lasted between 1h 9min and 1h 29min. All interviews were recorded, and transcripts were made of each interview. All interviewees had the same questions, and they were distributed to the interviewees before the formal interview to ensure better quality in answers. The main points of the interviews were collected on a Microsoft Excel sheet to support and assist the analysis. In the beginning there were thirteen questions, but the final analysis was made based on 11 questions that were relevant to answer the research questions and meet the objectives of the thesis. The questions can be found in Appendix 1.

Data of the case company Huhtamaki was also collected with an interview with two colleagues that have insights into the polymer volumes needed of the company. The interview was held in Teams, and it was recorded. No transcript was made, but notes about the discussed information were conducted. The purpose of the interview was to gain understanding about the ability of Huhtamaki to possible purchase chemically recycled raw material for their production and to meet the objective of understanding the ability of Huhtamaki to purchase the raw material in the future. The data is also used to forecast Huhtamaki's future demand for raw materials and to estimate the potential percentage that could be met through chemical or mechanical recycling.

1.4 Structure of the report

This thesis is structured in the following way. After the introduction chapter, the second chapter discusses the complexity and the different aspects of the plastic value chain, including the generation and treatment of plastic waste, plastics recycling and the different recycling economies. Also, the legislative landscape of plastic packaging and waste is being discussed and reviewed. In the third chapter the definition of chemical recycling and the core techniques are discussed. The current state and maturity of chemical recycling is also being discussed focusing on the core techniques. In addition, chemical and mechanical recycling methods are compared, and technology gaps and challenges are identified.

In the fourth chapter the case company Huhtamaki is introduced. Also, information about the company’s current material requirements is discussed. In the fifth chapter the research

results from conducted interviews with chemical recycling experts are being discussed and analyzed. In addition, the potential for Huhtamaki to introduce chemical recycling in its operations is being discussed and analyzed. The sixth chapter discusses the research findings and answers the research questions based on them and the theory gathered in the second and third chapter. Recommendations for Huhtamaki and for future research on the subject are also discussed at the end of the chapter.

2 The plastic value chain

This chapter discusses the complexity and the different aspects of the plastic value chain, including the generation and treatment of plastic waste, plastics recycling and the different recycling economies. Also, the legislative landscape of plastic packaging and waste is being discussed and reviewed.

2.1 Definition and background

In 1907 “the Father of the Plastic Industry” Leo H. Baekeland invented the world’s first synthetic, durable plastic called Bakelite that became fast the most favored material for products like telephones, radios, toys and later even for wartime equipment. By then the improvements in chemical technologies developed during World War I had merged with the progress in mass production achieved during World War II, laying the foundation for today's modern plastic economy. The versatility and low production costs of plastic have established it to become one of the most used materials of modern times. (Szaky, 2019; European Environment Agency, 2023)

Today, almost everyone comes into contact with plastics, plastic packaging being the most common form, accounting for around 36% of the total volume of plastic produced (Szaky, 2019; UNEP, 2023; Ciuffi et al., 2020). Even the COVID-19 pandemic could not have been addressed without protective equipment made from plastic (Eze et al., 2021). Plastic in general consists of a blend of different polymers, such as polyethylene terephthalate (PET), polyethylene (PE), polyvinyl chloride (PVC), polypropylene (PP), and polystyrene (PS) (Jiang et al., 2022). Plastics are essential in today's global economy and everyday life, yet their management often results in significant environmental damage, preventing the growth of a circular economy for plastics. The adverse impacts of plastic pollution have become increasingly apparent, particularly with the widespread dispersal of single-use plastics and the growing concern over microplastics contaminating ecosystems, affecting human health, and permeating the entire food chain. (Amadei et al., 2023)

Every year, humanity generates over 430 million tonnes of plastics, with around 66% consisting of short-lived goods that rapidly transition into waste, accumulating in oceans and

eventually entering the human food chain (UNEP, 2023). Factors such as product design, consumption habits, and the specific industries involved influence when plastic products reach their end-of-life stage. Once at this stage, the options for managing end-of-life (EoL) plastics include reuse, recycling, incineration, and landfilling. Trends are also showing a continuous increase in both the amount of plastics in use and the volumes of plastic waste globally (Rizos et al., 2023). Adopting a circular economy approach across the whole plastics value chain is crucial for fostering sustainable practices in production, design, usage, and the management of waste (Johansen et al., 2022). This value chain highlights the significance of a continuous cycle by extending from the early phases of oil refinement to the production, retail, consumption and at the end, recycling these resources back into the chain. (Siltaloppi & Jähi, 2021).

A deep understanding of the plastics value chain is essential in today's complex industrial ecosystem. Therefore, significant modifications or perhaps complete development of the value chain of plastics is hard to realize by looking at only a single process, stage or actor. It demands to look at all activities happening in the multiple different steps of the plastics value chain. This value chain encompasses the extraction of raw materials, their transformation into plastic polymers, the production and distribution of plastic goods, and their eventual recycling into new raw materials. Such comprehensive knowledge allows stakeholders to better identify environmental impacts, enhance resource efficiency, and implement more sustainable practices across the board. (TraceX, 2023; Ritzén & Sandström, 2017; Paletta et al., 2019)

A detailed illustration can be seen in Figure 1, which provides a systematic and comprehensive overview of the plastic value chain, highlighting three critical stages: raw material refinement, manufacturing and distribution, and recycling. These stages represent the key transformations that materials undergo within the value chain, showcasing the flow from raw material to the final recycled product. (Siltaloppi & Jähi, 2021)

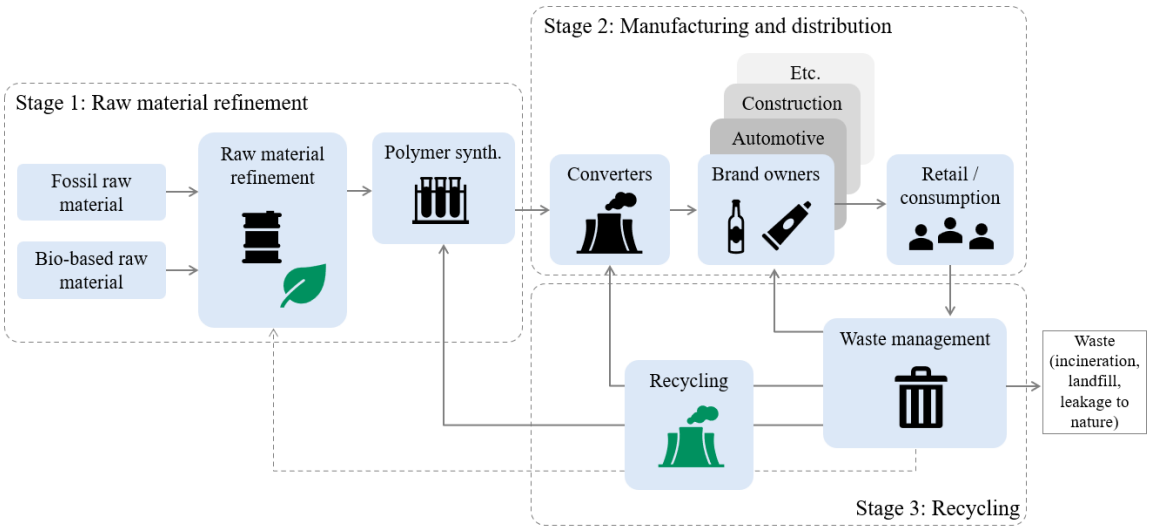


Figure 1. The main stages of the plastics value chain (Adapted from Siltaloppi & Jähi, 2021)

The production of plastics has many steps, and it begins with the extraction and cracking of natural gas and oil to produce monomers and feedstock. These monomers are then polymerized to form polymers, which are later blended with additives to create compounders. These compounders or pure polymers are produced into final goods through additional manufacturing and eventually turned into plastic waste, subjected to various waste management treatments such as mechanical and chemical recycling or unwanted options, such as incineration and landfilling. Depending on the recycling method, the recycled material can be sent back to the different stages of the value chain. The primary method of recycling plastics in Europe is currently mechanical recycling. The lifecycle of plastic involves multiple stakeholders, including manufacturers, retailers, distributors, consumers, brand owners, municipalities, waste management companies, recycling groups, petrochemical producers and converters. (Hsu et al., 2022; TraceX, 2023; Thiounn & Smith, 2020)

2.2 Linear, recycling, and circular economies in the plastic value chain

In the 17th century during the industrial revolution the linear economy (take – make – dispose) was developed. The four steps in the linear economy are 1) harvesting resources (raw material) from the earth, 2) utilizing energy to manufacture goods, 3) discarding goods after they are no longer needed and 4) purchasing new products (Figure 2). The second

economy model development was the recycling economy. In this model the raw materials are reused (for example wastepaper recycled to new paper) and after their second life, some of the materials are disposed away. The circular economy, which utilizes existing waste streams as potential sources for future secondary materials, is the third and most environmentally friendly model, managing resources differently. According to Ellen MacArthur Foundation (2013) the circular economy seeks to eliminate waste by designing and optimizing products for continuous reuse and disassembly. (Collias et al., 2021)

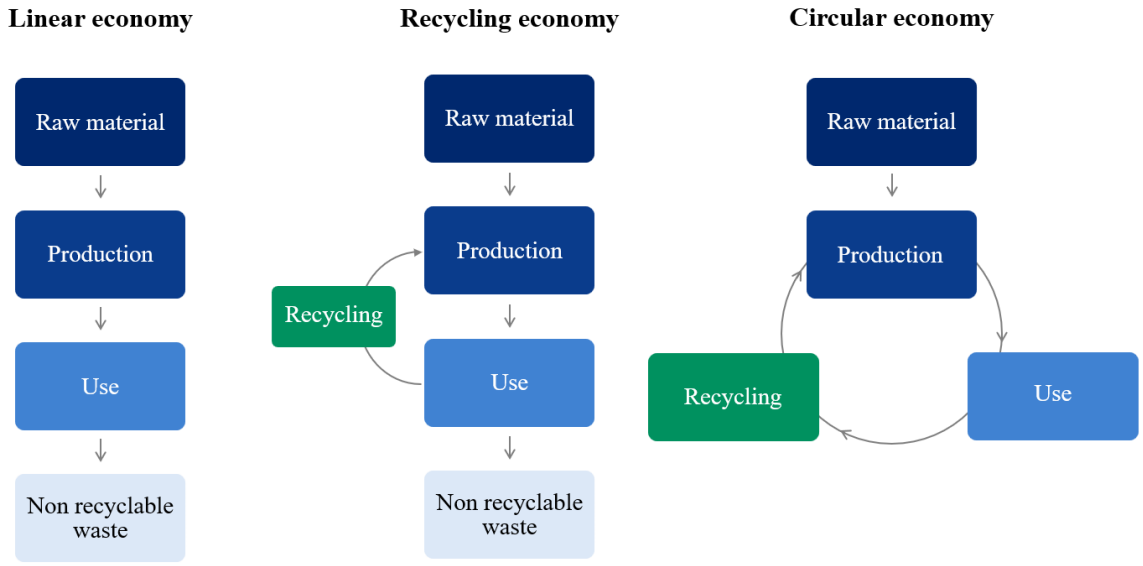


Figure 2. Illustration of the linear, recycling, and circular economies (Adapted from Collias et al., 2021)

The concept of the circular economy is applied to deal with challenging and very urgent issues such as climate change, depleting fossil raw materials and many environmental problems (Dominko et al., 2023). CO2 emissions and environmental contamination are major issues arising from the linear development of plastic through its value chain (Johansen et al., 2022). Taking into account the loss of added value due to sorting and reprocessing, only five percent of the value of single-use plastics is preserved for future use. (Collias et al., 2021)

A plastics circular economy is founded on the concepts of maximizing resource use, minimizing waste and pollution, and maintaining a minimal carbon footprint. The process begins by reducing the amount of packaging material used and implementing reusable packaging options when feasible. In cases where packaging cannot be reused, recycling is a

better alternative than discarding, burning, or allowing it to become litter. (The Consumer Goods Forum, 2022)

Companies and major brands are in the position to drive change in order to promote sustainability and enhance the circularity of the plastic value chain (Szaky, 2019). According to Johansen et al. (2022), minimizing waste and pollution from plastics requires exploring not only recycling methods but also the development of a circular value chain. The focus should be on creating a circular plastic economy to prevent plastic pollution, encompassing not only recycling but also design, usage, and regulatory measures. (Bucknall, 2020; Johansen et al., 2022). To ensure plastic waste is homogeneous and can be optimally recycled, it is essential not only to have the appropriate recycling facilities but also to design, use, produce and dispose of plastic materials in a way that enables closed-loop recycling. (Nielsen et al., 2020; Eriksen et al., 2020).

2.3 Plastic waste generation and treatment

Over the past several decades global plastics production and consumption have seen significant growth (Babayemi et al., 2019). Due to the Covid-19 pandemic plastic production saw a sharp drop in the first half of 2020 but production recovered fast already in the second half of the year (European Parliament, 2023). From the year 1950 to 2015, around 8,300 million tonnes of virgin plastic were produced worldwide, leading to the generation of around 6,300 million tonnes of plastic waste. (Babayemi et al., 2019) Out of this waste, approximately 9% was recycled, 12% was incinerated, and the rest 79% ended up in landfills. The mostly found polymers in plastic waste are PET, PP and PE (Thiounn & Smith, 2020). The amount of post-consumer plastic waste (PCPW) in the environment is consistently rising. It is estimated that global plastic production reaches approximately 300 million tons annually, with this figure continuing to grow each year (Li et al., 2016; Geyer et al., 2017; Eze et al., 2021).

According to Plastics Europe (2022) the EU generated approximately 30 million tonnes of post-consumer plastic waste in 2020. According to the EU waste hierarchy, landfilling, which is considered the least desirable method for managing end-of-life plastics, still sees approximately 23% of plastic waste being disposed of in this manner. Around 42% of plastic waste is incinerated to recover energy. Therefore, incineration is the most common method

for disposing of plastic waste. The third option in the EU waste hierarchy is recycling. It is described as having many environmental benefits over landfilling and incineration. (Plastics Europe 2022; Hamilton et al., 2019)

Approximately 36% of all produced plastics are utilized in packaging (UNEP, 2023; Maitlo et al., 2022). That amount includes single-use plastic beverages and food containers, from which around 85% are landfilled or end up as mismanaged waste. The main problem in plastic waste disposal is that plastic does not biodegrade like other materials and therefore its pollution can suffocate marine wildlife, damage soils and even poison or contaminate groundwater and thereby leading to very serious health impacts. The issue of plastic waste leakage into the environment is a significant concern for the EU and the whole world. Improperly managed plastic waste may enter rivers, wastewater systems, or be carried to the oceans by wind and tides. Furthermore, microplastics, which constitute about 33% of the 9.2 million tonnes of plastics lost every year to the environment, are tiny fragments that may escape into ecosystems during the use or wear and tear of plastic products. One problem occurring besides this is that the data of reused plastics is notably limited, as it is challenging to track the flow of plastic materials that are involved in second-hand trade or consumer exchange. (Rizos et al., 2023; Hsu et al., 2021)

Plastic packaging disposal also significantly impacts climate change due to the substantial greenhouse gas emissions that occur at every stage of the lifecycle, also the disposal of it. The disposal of plastic through landfilling, recycling, or incineration has different impacts on CO2 emissions. While landfilling emits the least GHGs in absolute terms, it poses long-term environmental risks. Recycling, while better in terms of emissions, is limited by technological and economic factors. Incineration, particularly without energy recovery, is the most emission-intensive disposal method, contributing significantly to global GHG emissions. The rising trend towards incineration is expected to exacerbate this impact, especially with the projected increase in plastic production and disposal. (Hamilton et al., 2019)

As the plastic industry plans a substantial increase in production, the associated emissions from this sector are poised to become an even more significant contributor to global greenhouse gas levels. Current projections suggest that by 2030, emissions from plastic production and disposal could equate to those from hundreds of coal-fired power plants. If unchecked, the cumulative emissions from plastics could consume a significant portion of

the global carbon budget, severely impacting efforts to limit global temperature rises under international climate goals. (Hamilton et al., 2019)

2.4 Current state of plastic recycling

In the European Waste Framework Directive, the definition of recycling is seen as any recovery process that reprocesses waste materials into products, materials, or substances for their original or different purposes (Kusenberg et al., 2022). Plastic waste poses a major challenge because of its high generation rate and the currently low rate of recycling (Gabisa et al., 2023) being approximately a third of all produced plastic in Europe (European Parliament, 2023). However, the recycling rate of plastic packaging, being almost 40%, is higher than the overall plastic recycling rate (Eurostat, 2023). Recycling is the second most common way after landfilling to dispose of plastic waste in Europe (European Parliament, 2023).

It has been estimated from Plastics Europe (2022) that in 2020, approximately 35% of all plastic waste was sent for recycling (member States level the number varies from 21% to 45%). According to Gabisa et al. (2023) recycling is one approach or strategy to achieve circularity in the plastics value chain. According to the same study, plastic recycling can substantially reduce resource depletion and lifecycle GHG emissions. Potential recycling methods depend on the quality and quantity of the collected waste, as well as the effectiveness of processes of sorting and separation (Kusenberg et al., 2022). It is desired for developed countries to replace landfilling with recycling, as landfilling causes secondary damage such as ecosystem destruction and groundwater pollution (Tsuchimoto & Kajikawa, 2022).

Around 50% of all plastic collected for recycling is being sent to countries outside the EU for processing and treatment (CDE, 2021). In 2023, the amount of exported plastic waste to countries not in the EU was 33 million tonnes (EU Monitor, 2023). The waste is usually exported because of insufficient local capacity, financial limitations, or technological resources for treating waste locally. Currently the problem of exporting the waste is, that some countries, such as China, are reducing EU exports and by that the share of plastic waste that is dumped in landfills or ended up in incineration in the EU increases. (European Parliament, 2023)

Plastics recycling can be accomplished via different methods based on the type of plastic and the capabilities of the recycling facility. Figure 3 illustrates the most common recycling processes for plastics. Enhancing collection systems and sorting technologies is crucial for increasing recycling rates. When plastics are collected separately, the recycling rates are up to 10 times greater compared to when they are collected in mixed systems. (Plastics Europe, 2024a) The recycling rate for post-consumer plastic for mechanical recycling stands at around 23% in Europe (Packaging Europe, 2022a), and only 0,2% for chemical recycling (EuRIC, 2023). Unfortunately, most of the collected plastics for recycling are lost in the sorting stage or not collected at all (Packaging Europe, 2022a).

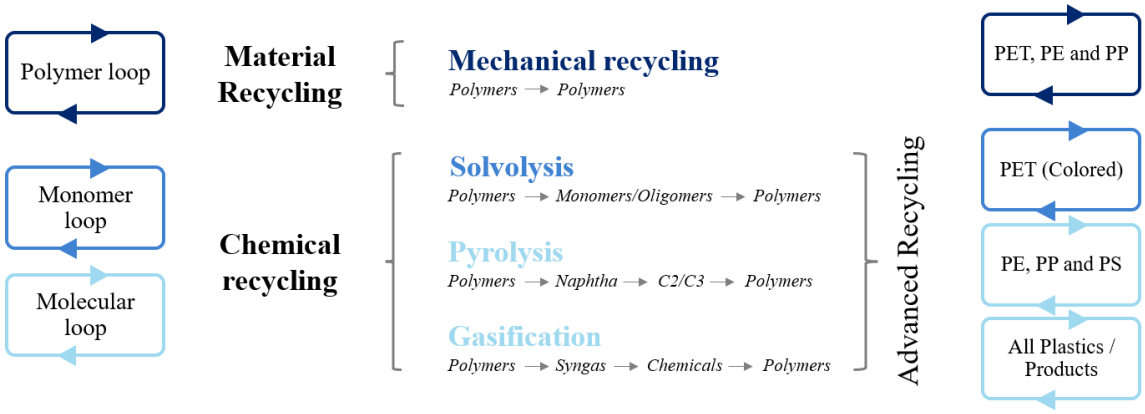


Figure 3. Different recycling processes for plastics, recycling loops and feedstocks in each recycling process (Adapted from Collias et al., 2021)

In Figure 3 different plastic recycling methods are introduced. Mechanical recycling currently is the primary method for recycling plastic waste, involving steps such as collection, sorting, shredding, grinding, washing and drying, and reprocessing (TWI, 2024; Delva et al., 2018). This technique has the advantage of requiring less energy and avoiding the use of hazardous chemicals. However, it often results in plastics with reduced tensile strength and inferior properties. (Maitlo et al., 2022; Dogu et al., 2021) Despite these drawbacks, mechanical recycling is favored for its ability to convert plastic waste into reusable plastics, although the recycled materials tend to be of lower quality and strength compared to new plastics (Tsuchimoto & Kajikawa, 2022). This method is particularly common for recycling plastics such as PET and high-density polyethylene (HDPE), which are used in products like soft drink bottles and containers and are relatively straightforward to recycle (Plastics Europe, 2024a).

Chemical recycling is an expanding method in the recycling industry, presenting significant potential for scalability. (Chemical recycling and its core technologies are explained more comprehensive in chapter 3.1 The process involves altering the chemical structure of polymeric waste, converting it back into raw materials suitable for manufacturing plastics or other products. Pyrolysis, gasification and solvolysis (other name for depolymerisation) are different technologies in the field of chemical recycling. (Plastics Europe, 2024a) Pyrolysis decomposes plastic waste into methane, hydrogen, carbon monoxide and hydrocarbons with high-quality usable as fuel (Maitlo et al., 2022), gasification involves treating polymers at high temperatures in a controlled oxygen environment breaking them down into hydrogen and carbon monoxide (known as syngas) (Kingsbury, 2022; Maitlo et al., 2022), and solvolysis produces monomers or oligomers that can after their purification be directly utilized in the process of polymerisation (Quicker et al., 2022).

The EU's low plastic recycling rate leads to major economic and environmental disadvantages. About 95% of the value of plastic packaging is wasted after a brief initial use. The primary challenges are that recycled plastics are of lower quality and more expensive than new materials. Plastics processors need large amounts of recycled plastic, meeting strict standards and competitively priced. The variety of discarded plastics complicates recycling, raising costs and reducing quality. Consequently, in 2018, recycled plastic only met 6% of Europe's plastic demand. (European Parliament, 2023)

2.5 Legislative landscape for plastic packaging

According to Ellen MacArthur Foundation & MacKinsey (2016) the ocean will have more plastic by mass than fish by 2050 if we do not act on the problem of plastic waste generation. Over the past decades The European Union has set targets, laws and different regulations for packaging, plastic packaging and plastic use in general. In 2015, the European Commission implemented an EU Action Plan that identifies plastic as a top priority and commits to preparing a strategy that tackles plastics' problems along their whole value chain by considering their whole life cycle. The Commission adopted in 2018 the Plastic Strategy that includes the goal of turning recycling profitable for businesses. (CMS, 2024)

The Packaging and Packaging Waste Directive (PPWD) is a piece of EU legislation designed to manage packaging and packaging waste. Its primary aims are to harmonize national

measures for packaging waste management, prevent packaging waste generation, and reduce its environmental impact. In order to support a circular economy, this directive also establishes goals for the recycling rates of different packaging materials and encourages package reuse and recycling. The directive covers all packaging introduced to the European market and all resulting packaging waste, regardless of the material or origin. (European Parliament & Council, 2018; European Commission, 2023)

The most burning topic currently for all packaging manufacturers is the Packaging and Packaging Waste Directive becoming a regulation, the Packaging and Packaging Waste Regulation (PPWR). The difference between a directive and regulation in the EU is that a directive sets out a goal for EU member countries to achieve and countries translate the directive into its own legislation making differences in implementations. The change from a directive to a regulation ensures that all the same rules apply for all the member countries, since a regulation must be applied all across the EU. The regulation sets standards for the entire lifecycle of packaging concerning environmental sustainability and labelling to permit market placement. It includes requirements for extended producer responsibility (EPR) and measures to prevent packaging waste, such as reducing unnecessary packaging and promoting the reuse or refill of packaging. Additionally, it outlines the necessary steps for the collection, treatment, and recycling of packaging waste. The PPWR will also restrict single-use plastic packaging in various sectors, such as grouped packaging at retail points, packaging for vegetables and fresh fruit weighing under 1.5 kg, and for food and beverages provided in restaurants, hotels, and catering services. (European Union, n.d..; European Parliament, 2024a; UPM, 2024)

In April 2024 the European Parliament approved the packaging and packaging waste regulation (European Parliament, 2024b). In June, following the EU elections, the elected new Parliament must accept the provisional agreement via a "corrigendum". The European Council will then formally adopt the regulation by the end of 2024, and it will take effect after 20 days from publishment in the EU’s Official Journal. The PPWR will be applicable 18 months after it becomes effective, indicating that all 27 EU Member States must enforce the new packaging regulations by summer 2026. (UPM, 2024) The PPWR binds all EU countries and imported packaging with its rules (Deutsche Recycling, 2024), and thus contributes to achieving climate neutrality by 2050 in the EU (European Parliament, 2024a).

The main goals of the PPWR are to reduce packaging waste, to ensure that all packaging available on the market is designed with specific requirements for recyclable packaging and requirements for the use of Post-Consumer Recycling (PCR) materials, and to encourage companies to manufacture more sustainable packaging solutions through eco-modulated EPR systems. The PPWR has specific deadlines to achieving its goals:

- By 2030, all packaging must be recyclable in the EU market
- By 2035, manufacturers must prove that their packaging products can be extensively recycled
- By 2035, most packaging should meet these requirements (Deutsche Recycling, 2024)

For packaging manufacturers one of the main requirements in the PPWR is that by 2030, a minimum of 10% of plastic in packaging must contain contact sensitive raw material and 35% non-contact sensitive raw material (European Parliament, 2024c). In addition to the PPWR, the EU has set new rules in 2024 for packaging that supports the reduce, reuse, and recycling of packaging. These rules consist of several targets and requirements aimed at reducing packaging waste. By 2030, packaging reduction targets are set at 5%, increasing to 10% by 2035, and 15% by 2040. EU countries must specifically reduce plastic packaging waste. To minimize excessive packaging, a maximum empty space ratio of 50% is required for transport, grouped, and e-commerce packaging. Additionally, from the beginning of 2030, certain types of single-use plastic packaging, such as those for fresh produce, café and restaurant consumables, individual portions, toiletry products, and very lightweight plastic bags, will be banned. (European Parliament, 2024d)

3 Chemical recycling

Under current European regulations, chemical recycling is currently the only method to recycle large quantities of flexible plastics packaging (The Consumer Goods Forum, 2022). In this chapter, the definition of chemical recycling and the core techniques are discussed. The current state and maturity of the technology is also being discussed. In addition, chemical and mechanical recycling methods are compared, and technology gaps are identified.

3.1 Definition and core techniques

The name of this recycling technology varies in academia. According to Luu (2023) and Rizos et al. (2023) chemical recycling encompasses a variety of technologies designed to recycle end-of-life (EoL) plastics and thus can be seen as an umbrella term. Chemical Recycling is also known as advanced recycling, molecular recycling (Luu, 2023) and feedstock recycling (Biessey et al., 2023) in some literature. In this report we continue by using only the term ‘chemical recycling’.

Because chemical recycling is a concept, there is no universally agreed definition for it in the EU legislation (Garcia-Gutierrez et al., 2023). According to John Sewell, Secretary General of Chemical Recycling Europe, who was interviewed by Nageler-Petritz (2023), chemical recycling is defined as any reprocessing method that modifies the composition of polymeric waste, converting it into chemical substances or products for either the original purpose or other uses, excluding energy recovery. According to the definition of recent academic and scientific publications (Collias et al., 2021; Delva et al., 2019; European Coalition for Chemical Recycling, 2024; Biessey et al., 2023), the technology is understood as a process where the polymer chain of the recycled plastic is chemically converted into its monomers, oligomers, polymers or hydrocarbon products (such as carbon monoxide, carbon dioxide, hydrogen and methane) using heat, solvent, enzymes or sound waves (Luu, 2023). With these technologies, the recycled feedstock can avoid being landfilled and instead re-enters the manufacturing supply chains. In comparison, mechanical or physical recycling

does not break the actual chemical structure of the recycled plastics such as chemical recycling does (Biessey et al., 2023).

As the mostly used term, chemical recycling is intensively discussed and used in different contexts (Quicker et al., 2022). If chemical recycling is used for producing new plastic products from plastic waste, a rigorous series of technical process steps must be taken into account. Key processes within this sequence include alternative thermal waste treatment methods such as gasification and pyrolysis. (Vollmer et al., 2020) Plastic fractions that are not suitable for mechanical recycling and unsorted mixed plastic waste of lower quality are primarily utilized for energy recovery. These fractions are anticipated to be transformed into virgin plastics or comparable high-quality chemical products through chemical recycling processes (Vogel et al., 2020). To achieve this, the waste undergoes conversion via chemical or thermo-chemical processes. The resulting products can be purified after and reused as petrochemical feedstock that can replace fossil feedstock in various chemical synthesis processes. (Tukker, 2002; Huang et al., 2022; Netsch et al., 2022). All chemical recycling technologies have the ability to produce high quality yield and thus no quality difference in end products occur compared to using virgin fossil feedstock as raw material (Cefic, n.d. a).

In current research the most discussed technologies of chemical recycling are pyrolysis, gasification and solvolysis also known as depolymerisation or chemolysis (Collias et al., 2021; Vogel et al., 2020; Quicker et al., 2022; Jiang et al., 2022; Garcia-Gutierrez et al., 2023; Zeller et al., 2021). In this report we will only use the term ‘solvolysis’. Additionally, based on the current research, these three technologies are identified as the core technologies of chemical recycling. Figure 4 illustrates the recycling paths of the core technologies of chemical recycling and the paths of reuse, mechanical recycling and physical recycling for comparison. The figure illustrates that the different technologies of chemical recycling form a loop that can be seen as starting with the recycling of plastic waste into hydrocarbons and monomers, which can then be produced into polymers and material products. Solvolysis has a monomer loop, where the recycled feedstock is converted into its constitutive monomers. Gasification and pyrolysis have molecular loops, since the feedstock is transformed first into small molecules or a group of molecules such as syngas and pyrolysis oil before being further reprocessed into monomers and polymers. At the EoL stage, the plastic product can be reintroduced into the chemical recycling loop, creating a circular economy for plastics. (Garcia-Gutierrez et al., 2023)

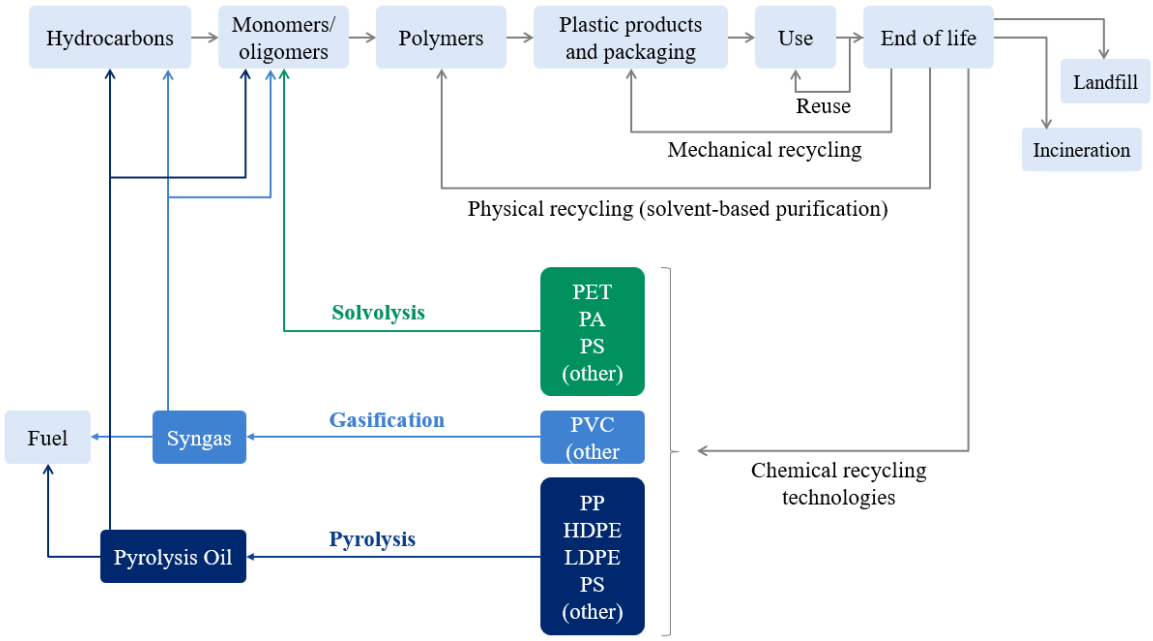


Figure 4. The path of chemical recycling and other plastic waste management methods (Adapted from Rizos et al., 2023 & Liu et al., 2024)

> *"Chemical recycling is a game-changer and a key building block of the circular economy"* (Steilemann, n.d.)

Chemical recycling offers significant advantages in addressing the plastic waste issue, particularly for plastics that are unsuitable for mechanical recycling due to their heterogeneous nature and the presence of multiple polymers (Matlo et al., 2022). Unlike traditional methods such as incineration, which process plastics collectively, chemical recycling can effectively manage mixed plastic waste streams, multi-layered products, and even contaminated material at the same time producing less emissions (European Coalition for Chemical Recycling, 2024; Dogu et al., 2021; Li et al., 2022).

Chemical recycling holds the promise at an industrial scale of recycling post-consumer flexible plastics efficiently. A big advantage of chemical recycling for the packaging industry is that the output of all the different technologies is food compliant and thus can be used for critical applications (Kinsbury, 2022). It has the potential to greatly increase packaging recycling rates, which would help meet recyclability goals and make it possible to convert flexible plastics into pure PP or PE, which are suitable for novel applications using food-grade plastic. (The Consumer Goods Forum, 2022). Methods like pyrolysis and gasification are particularly effective for converting plastic waste into valuable products,

while also being environmentally friendly and requiring minimal space for plant installation (Maitlo et al., 2022).

Before introducing the chemical recycling core technologies in more specific, Table 1 compares the key characteristics of mechanical recycling and the three discussed chemical recycling technologies; pyrolysis, gasification and solvolysis.

Table 1. Characteristics of mechanical and chemical recycling technologies (Adapted from Biessey et al., 2023)

	Mechanical processes	**Chemical Recycling technologies**		
		Pyrolysis	**Gasification**	**Solvolysis**
Working principle	Melting and regranulation polymers	Thermal and/or catalytic cracking of polymers in the absence of oxygen	Thermal reaction of plastic waste with gasification agent (air, oxygen or steam)	Breaking down specific bonds in polymers by using solvent or chemical agents (acids, alcohols or bases)
Target plastics	All plastic waste that is not contaminated and can be mechanically recycled	Polyolefins (PE, PP) and PS *(Peng et al., 2022; Kingsbury, 2022)*	PVC, all kinds of waste *(Kingsbury, 2022; Zeller et al., 2021)*	PET *(Li et al., 2022)*
(Typical) products	Purified polymers	Pyrolysis oil, gas, solids	Syngas	Monomers/oligomers

3.1.1 Pyrolysis

According to Liu et al. (2024) pyrolysis is categorized as a thermochemical recycling process, that has been employed for centuries, notably in charcoal production and the cooking of hard coal (Vogel et al., 2020). Pyrolysis involves feeding feedstock into a reactor where it is heated in an inert environment in the absence of oxygen (Dogu et al., 2021; Solis & Silveira, 2020). The process is breaking down organic materials into less complex molecules, resulting in the formation of key products like naphtha-like liquid oil (pyrolysis oil), waxes or gasses (depending on the temperature) and char. The liquid oil has a high quality that can be burned as feedstock and used for as many times as wanted in many

chemical processes, enabling a closed loop in the plastics value chain. (Eze et al., 2021; Vogel et al., 2020; Bridgwater, 2012; Dogu et al., 2021) The distribution of these products varies based on the feedstock, process conditions, and specific technology used (Zeller et al., 2021; Packaging Europe, 2022b).

The process of pyrolysis entails heating plastic waste to high temperatures, typically between 350°C and 700°C (Bridgwater, 2012; Zeller et al., 2021; Li et al., 2022). This can be done either with a catalyst (catalytic pyrolysis) or without one (thermal pyrolysis) (Bridgwater, 2012; Dogu et al., 2021), but most of the pyrolysis reactors involve a catalyst, since it helps in speeding up the reaction and deliver the wanted output (Kingsbury, 2022). The process of pyrolysis is quite simple since the parameters of the process can be changed and optimized to the product yield as preferred. The final products are influenced by various parameters including the pressure, temperature, residence time, heating rate and the use of catalysts. (Solis & Silveira, 2020)

Pyrolysis has gained significant attention as a chemical recycling method in Europe, driven by the increasing amounts of plastic waste and the decline in fossil energy resources. This method provides a means to convert complex plastic waste streams into high-value products that can be used for material or energy recovery. (Peng et al., 2022) Notably, liquid pyrolysis products can serve as substitutes for fossil hydrocarbon feedstocks, particularly in monomer production, although impurities and heteroatoms must be removed to ensure product quality (Zeller et al., 2021). Pyrolysis produces also far fewer emissions than incineration, which is where many plastics that cannot be mechanically recycled end up (Li et al., 2022).

The suitability of different plastics for pyrolysis varies. For example, PS is particularly suitable for catalytic pyrolysis due to its high liquid oil and aromatic yield. For thermal pyrolysis, target plastics are often PE and PP, that are also called polyolefins. PET and PVC are less favored for pyrolysis because PET consists of oxygen in its backbone and that is not favored in the pyrolysis process, and PVC has a low liquid yield and produces chlorinated hydrocarbons which can cause severe corrosion and release environmental toxins. (Peng et al., 2022; Kingsbury, 2022)

Pyrolysis technologies for chemical recycling have gained momentum, especially in Europe, with petrochemical companies integrating these technologies into their value chains and consumer brands committing to recycled content goals. Currently, pyrolysis is the only

method under European regulations that can process flexible plastic packaging and other mixed, degraded, or contaminated PE/PP streams at scale, converting them into pure PP or PE suitable for new food-grade plastic, thereby creating a circular system for high-quality materials. (The Consumer Goods Forum, 2022)

Pyrolysis presents a promising route for the chemical recycling of plastic circular economy if it is developed and used under credible, safe, ethical and environmentally sound conditions. Particularly as the industry seeks to address the dual challenges of increasing plastic waste and diminishing fossil fuel resources. (Quicker et al., 2022; The Consumer Goods Forum, 2022) Despite its promise, the use of mixed municipal waste in pyrolysis has not been widely accepted due to the heterogeneity of input materials, which can result in poor product quality. More homogeneous plastic fractions yield better recycling outcomes (Vogel et al., 2020). As such, the focus remains on improving the efficiency and scalability of pyrolysis for specific, less contaminated plastic waste streams.

3.1.2 Gasification

According to Liu et al. (2024) gasification is also categorized as a thermochemical recycling technology. Gasification transforms liquid or solid carbon-based feedstock into synthesis gas (syngas) with the main components being carbon monoxide [CO] and hydrogen [H_2] (Ciuffi et al., 2023; Zeller et al., 2021; Netsch et al., 2022; Liu et al., 2024). Gasification is usually performed in a high temperature and controlled environment with a gasification agent that can be pure oxygen, steam or air. Temperatures range from 700 to 1500 °C under atmospheric pressure. (Dogu et al., 2021; Kingsbury, 2022; Liu et al., 2024)

The gasification process was first introduced in the mid-1800s where important cities like London produced gas from coal to light up the streets. During World War II, gasification played a crucial role as it was utilized to produce syngas, which was then converted into synthetic gasoline through the Fischer-Tropsch process, a manufacturing method for clean synthetic liquid fuels. In the past few years, gasification has attracted significant attention as a thermochemical recycling method. This process can convert a wide range of biomass and waste materials, including plastic, wood, sewage sludge, municipal solid waste (MSW), crop residues, and various agricultural and industrial wastes to syngas. One of the main benefits of gasification is the ability to handle MSW and mixed and contaminated plastic waste with

minimal pre-treatment required (Ciuffi et al., 2020; Dogu et al., 2021; Li et al., 2022; Liu et al., 2024). Also, it is estimated that gasification could be more sustainable in an environmental and economical way (Li et al., 2022).

Syngas, the byproduct of gasification recycling technology, can be used to produce chemicals and fuels in the Fischer-Tropsch process, or it can be converted into methanol (Dogu et al, 2021; Kingsbury, 2022). The methanol value chain is normally resulting in products such as fertilizer, but it also has the potential to be converted back into polymers, thereby creating a circular process (Kingsbury, 2022). In addition, syngas can be utilized to generate thermal energy by directly burning the hydrogen and carbon monoxide it contains in heat generation equipment, like steam boilers, dryers, cement kilns, and for production of electricity.

Gasification offers a valuable opportunity for large-scale implementation of the circular economy by enabling the production of new polymers from recycled solid plastic waste (SPW) (Dogu et al., 2021). Its primary advantage lies in the minimal sorting required and the broad availability of feedstock since it is applicable to all types of waste. Since the process breaks down materials to base hydrogen and carbon monoxide, it is very adaptable. If there isn't enough plastic available, it can process food waste, wood, or almost any carbon-based material. (Kingsbury, 2022; Zeller et al., 2021) Gasification is also considered the most promising technology for heavily contaminated or unsorted plastic waste (Dogu et al., 2021).

3.1.3 Solvolysis

According to Rizos et al. (2023) solvolysis is categorized as a chemical depolymerization technology of chemical recycling. Solvolysis is a solvent-based process taking place in a liquid phase (Biessey et al., 2023) where plastic waste is broken down into its monomer or oligomer components using a solvent or chemical agents such as acids, alcohols or bases. The resulting monomers and oligomers can be purified and reused as secondary raw materials in processes to create new polymers and plastic products. The process temperature varies between 80-300 °C. (Kingsbury, 2022; Zeller et al., 2021; Maisels et al., 2022; Quicker et al., 2022; Cefic, n.d. a; Jiang et al., 2022) Solvolysis is the general term of different depolymerization processes using different solvents. Hydrolysis uses water,

alcoholysis alcohol, methanolysis methanol and ammonolysis ammonia etcetera. Deciding which method to use in which case is up to the wanted yield and the feedstock available. (Sunderland, 2011)

Unlike most pyrolysis and gasification facilities, industrial solvolysis plants are designed to handle specific types of plastic waste, primarily PET, polyamides (PAs) (Biessey et al., 2023) and polyurethanes (PUs). PE and PP are only recycled in hydrolysis plants using supercritical water (Maisels et al., 2022; Zeller et al., 2021). Currently, the main focus of solvolysis-based plastic recycling is on PET, which is commonly used in water and soda bottles, many disposable items, and clear plastic packaging (Li et al., 2022). Depending on the desired outcome for the recycled product, solvolysis may be preferred over other chemical recycling technologies for processing PET. (Kingsbury, 2022; Dogu et al., 2021)

3.2 Comparison of chemical and mechanical recycling

Mechanical recycling of plastics is often favored over some chemical recycling technologies, for example pyrolysis (for appropriate materials) because it requires less energy and incurs lower costs. However, it faces several challenges. Among these is the challenge of meeting the growing market demands for food-grade PP and PE as well as other premium recycled content grades. Additionally, there are issues with the loss of material properties and the accumulation of additives and potentially hazardous contaminants, which limit the number of times the material can be recycled before its quality degrades. The yield is also constrained by the degraded, mixed or contaminated nature of streams of plastic waste, leading to significant processing and sorting losses. Furthermore, the sorting, handling and processing of post-consumer flexible plastic packaging materials pose significant challenges, and the recycled polymers made from these sources have lower value end-markets. (The Consumer Goods Forum, 2022; Alassali et al., 2021; McKinsey & Company, 2022)

Although mechanical recycling has long been popular in plastic recycling, chemical recycling introduces efficient alternatives and solutions for recycling various types of plastics. One major advantage of chemical recycling over mechanical recycling is the high quality of the end products (Quicker et al., 2022), as chemical recycling produces chemically identical products compared to those being replaced. (Waste Management World, 2023) Mechanical recycling often cannot remove all impurities or unwanted additives, meaning

these impurities are likely to transfer into the recycled material, significantly reducing the quality of the resulting product (Quicker et al., 2022). With mechanical recycling, plastic waste can only be recycled to a certain extent, as its quality and strength degrade with each recycling cycle (Tsuchimoto & Kajikawa, 2022). However, an exception is seen in the recycling of PET, as plastic bottles, for example, consist solely of PET (Waste Management World, 2023). The collection of bottles in the EU through deposit return schemes contributes to PET's high recycling rate up to 54% for all PET and 72% for all PET bottles (Unesda, 2022; Statista, 2024).

The end-product made from raw materials derived from chemical recycling is completely identical in quality to the same product made from virgin raw materials, enabling the long-term retention of larger plastic flows in the plastic economy. In a perfect scenario, no virgin raw material would be needed for plastic production at all. (Payne & Jones, 2021; Rizos et al., 2023) Chemical recycling not only maintains high quality and keeps plastics in circulation longer, but it can also recycle materials that are difficult or impossible to recycle mechanically. These include multilayer packaging made of different polymer types, composite materials, films, flexible materials, and plastic waste that is simply too contaminated or otherwise unsuitable for mechanical recycling (Dogu et al., 2021; Waste Management World, 2023; Tsuchimoto & Kajikawa, 2022).

When comparing the economic viability of mechanical and chemical recycling, many different factors and stages must be considered. According to Dogu et al. (2021), chemical recycling technologies provide an economic advantage by requiring fewer preprocessing stages for raw materials, such as waste separation, which is often expensive. Additionally, the end products of chemical recycling typically include fuel products with high calorific value or other useful chemicals that can be easily marketed and sold potentially with profit (Dogu et al., 2021; Payne & Jones, 2021).

According to Maitlo et al. (2022), a combination of mechanical and chemical recycling for lightweight packaging would be a more economically advantageous option compared to solely relying on mechanical recycling. In the further processing of mechanically recycled plastics, it must also be considered that mechanical recycling requires significant effort and financial resources to be able to reuse plastic waste in new plastic products. Mechanical recycling is economically viable only if the plastic waste is neither contaminated nor complex, as this avoids the need for expensive separation processes. The market for recycled

products is also somewhat limited, which directly affects the strong price fluctuations, thereby complicating the creation of a profitable process (Ragaert et al., 2017). Therefore, the effort and costs of mechanical recycling must be weighed against the sales revenue from recycled materials (Maisels et al., 2022; Dogu et al., 2021).

Chemical recycling can very effectively complement mechanical recycling, but with the current technology and its maturity, it cannot fully replace mechanical recycling (Tsuchimoto & Kajikawa, 2022; Zeller et al., 2021). However, that is also unlikely to be a desirable goal. On a global scale, the infrastructure for mechanical recycling is much simpler than that required for chemical recycling technologies. Mechanical recycling techniques require relatively simple technology, making it a good starting point for plastic recycling worldwide (Dogu et al., 2021). In more developed regions, such as EU countries, there is a stronger economic and technological infrastructure, making it easier to consider the adoption of these technologies to enhance plastic recycling. Chemical recycling does not compete with mechanical recycling; rather, it can solve current issues with mechanical recycling and complement the existing infrastructure (Waste Management World, 2023).

3.3 Mass balance

The mass balance approach has been used for years as one of the most well-known chain of custody methods in sectors such as the furniture industry for sustainably sourced wood, the textile industry for organic cotton, and in the cocoa and chocolate industry for the use of sustainable raw materials. The method is critical for scaling up the chemical recycling industry, and it is being discussed currently in the European Commission. Mass balance can be used to track material flows throughout the entire value chain (Plastics Europe, 2020). However, in the chemical industry, applying mass balance to determine recycled content is a relatively new method. (Zero Waste Europe, 2021; Ellen MacArthur Foundation, n.d.; Plastics Europe, 2024b)

According to ISO 22095:2020 mass balance is defined as a "*chain of custody model in which materials or products with a set of specified characteristics are mixed according to defined criteria with materials or products without that set of characteristics*". According to the same standard a chain of custody is defined as a "*process by which inputs and outputs and associated information are transferred, monitored and controlled as they move through each*

step in the relevant supply chain". (ISO 22095:2020) The chain of custody process tracks and documents evidence throughout its entire lifecycle, from collection to safeguarding and analysis. This evidence is meticulously documented, specifying the individual handling each piece of evidence, the time/date of transfer or collection of the evidence, and the purpose of the collection or transfer of the evidence. The main idea of the chain of custody process is to demonstrate the lifecycle and movement of evidence in the supply chain and to ensure that there can be no claim of evidence tampering. The documentation must answer the following questions:

- Who collected the evidence? (for example, data media, devices, and related peripherals, etc.)
- How was the evidence collected, and where was it located at the time of collection?
- Who is responsible for the possession of the evidence?
- How has the evidence been stored and protected?
- Who took the evidence out of its current storage location and why?

All documented information regarding the movement of evidence must be kept in a secure location for current and future use. (Jansen & Ayers, 2004)

In practice, mass balance refers to an accounting principle designed to trace material flows in complex value chains. The method aims to track the inputs and outputs of the recycling and production process to determine the final recycled content of the outputs. (Ellen MacArthur Foundation, n.d.; Packaging Insights, 2023) When recycled materials are mixed with virgin fossil materials, it is practically and economically impossible to physically separate the recycled content (ISCC, n.d.; Plastics Europe, 2024b; Packaging Europe, 2023). Mass balance helps to allocate the recycled feedstock to specific final products produced from the material mix (Warringa et al., 2023). This accounting system allows for tracking and documenting the use of recycled materials and their incorporation into the final product (Warringa et al., 2023), thus enabling greater circularity in the process and transparency in global supply chains (ISCC, 2024). In order to show compliance, companies usually choose a third-party certification system, for example the most used ISCC Plus (International Sustainability and Carbon Certification) and REDcert, for certificating materials and end products. (ISCC, 2024; Plastics Europe, 2024b). Using a certification system adds credibility and proof for the use of recycled content (ISCC, 2024).

Figure 5 illustrates in a very simplified way how mass balancing works in practice. In this figure process losses are not taken into account to simplify the principle of mass balance method. A hypothetical amount of 400kg certified recycled feedstock and a hypothetical amount of 600kg fossil-based feedstock is sent to a processing unit, where the feedstocks are mixed to a total of 1000 kg mixed feedstock. Mass balance accounting and certifications enable that in the output product the 400 kg certified recycled feedstock is taken into account. For example, in 1000 kg of hypothetical products the manufacturer can claim either that 400 kg of product consists of 100% certified recycled materials or that 800 kg of product consist of 50% certified recycled materials, even if there actually is no certainty that the product in our hands physically contains that amount of certified recycled material (ISCC, 2024). This is only an example of how it could be counted, but there are various different methods.

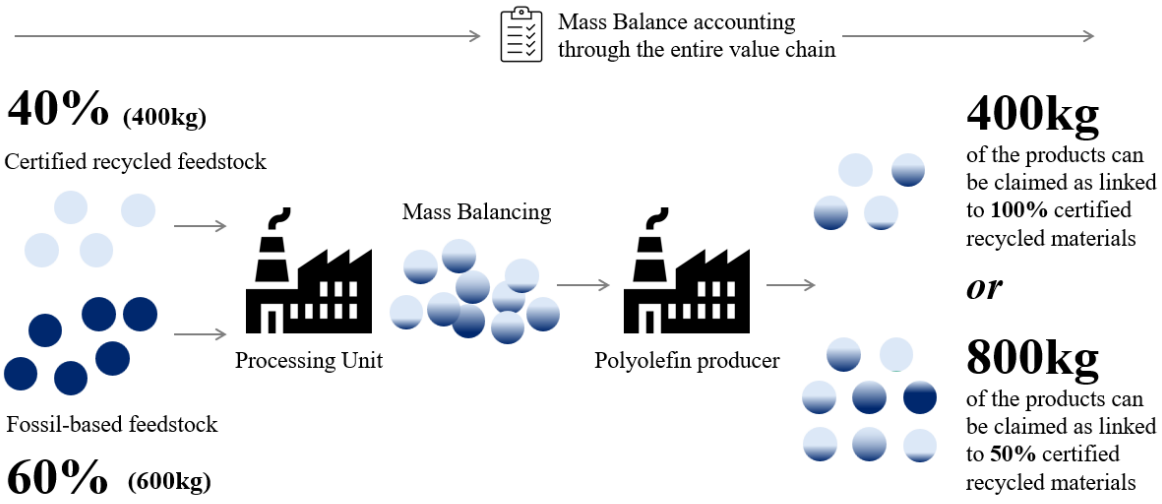


Figure 5. Simplified principle of mass balance method (Adapted from Zero Waste Europe, 2021 & ISCC, 2024)

One of the most important ways companies can transition to a circular economic approach is by increasing the proportion of recycled content in their products. (Ellen MacArthur Foundation, n.d.). The mass balance approach not only allows for the tracking of recycled materials but also provides the potential to quickly scale up chemical recycling capacity (Plastics Europe, 2024b; ISCC, 2024). This is because with mass balance, production facilities do not need to make large investments in building new production lines exclusively for recycled raw materials. Instead, recycled material can be mixed with virgin fossil raw materials, allowing chemically recycled feedstocks like pyrolysis oil to be blended with fossil-based naphtha, even in small amounts, without issues related to insufficient input

supply (Warringa et al., 2023). Therefore, mass balance not only increases the use of recycled materials but is also a very cost-effective and timely solution (Plastics Europe, 2024b).

Mass balance has various allocation rules that serve as guidelines for how the recycled material in the original input is correctly distributed to the final products. Currently, three different allocation rules (Figure 6) (proportional, non-proportional, fuel exempt) are being considered in potential legislation. (Warringa et al., 2023)

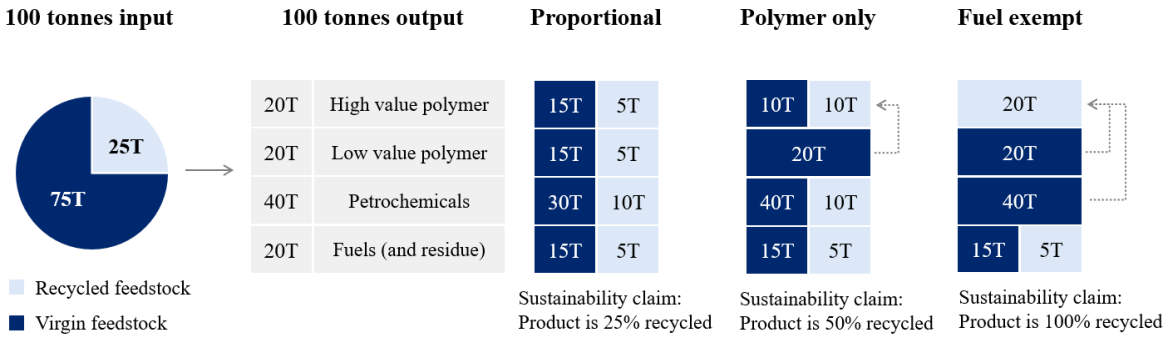


Figure 6. Mass balance allocation rules explained (Adapted from Daphne & Ahmed, 2024)

Proportional

In proportional allocation, the output is divided according to the proportions of the different inputs, meaning the distribution of outputs should directly reflect the percentage composition of the inputs. For example (Figure 6), if the input contains 25% recycled feedstock, then each output, such as high value polymer, low value polymer, petrochemicals, and fuels, should also contain 25% recycled material in the end. This is the most precise allocation rule but the least flexible, as reallocation between different outputs or production sites is prohibited. (Warringa et al., 2023; Daphne & Ahmed, 2024)

Non-proportional (polymer only)

This allocation rule allows for reallocation between polymers, unlike the proportional allocation rule. You could think of it as starting with the proportional allocation method for calculations, but then allowing transfers between polymers. For example, (Figure 6) when 25% recycled material is allocated to both high and low value polymers, the 25% (in this case, 5 tons) of recycled material allocated to the low value polymer can be reallocated to the high value polymer. This would mean that the sustainability claim for the high value polymer is that it contains 50% (10 tons) recycled material, while the low value polymer is

allocated an equal amount of virgin feedstock from the high value polymer. Therefore, the low value polymer would be labeled as using 100% virgin feedstock. (Warringa et al., 2023; Daphne & Ahmed, 2024)

Fuel exempt

The fuel exempt method allows reallocation between polymers and byproducts, excluding fuels from the calculations. No fuel used or sold can be reallocated to byproducts, and they are counted as losses. For example, (Figure 6) when 25% from both low value polymers (5 tonnes) and petrochemicals (10 tonnes) is reallocated to high value polymers, this allocation rule allows claiming that the high value polymer products contain 100% recycled content. The fuel exempt method permits all reallocations except from fuels. The purpose of this method is also to encourage companies to focus more on producing products that remain in the production chain rather than being used for energy. Some standards accept free allocation, where the reallocation of recycled content from any input is not restricted. This rule is not favored, as it may lead to greenwashing, despite offering the most market advantages and flexibility. (Warringa et al., 2023; Daphne & Ahmed, 2024)

In April 2023, 32 representatives of plastic product manufacturers, processors, and users sent a letter to the EU Member States, proposing that the European Commission and the Member States adopt the mass balance method as part of the EU's harmonized calculation rules for determining recycled content (Plastics Europe, 2024b). This letter specifically advocates for the adoption and establishment of the mass balance fuel-exempt method as a standardized approach for allocating recycled content in chemical recycling. The signatories include notable industry associations such as Plastics Europe, CEFIC, Chemical Recycling Europe, and The European Association for Packaging and the Environment. (Packaging Insight, 2023) The EU is currently developing standards to ensure that the recycled content of chemically recycled products can be certified using the mass balance method (Plastics Europe, 2024b). According to the signatories, the mass balance fuel-exempt method is crucial for the rapid expansion of chemical recycling capacity (Packaging Europe, 2023) and essential for accelerating investments in chemical recycling technologies (Plastics Europe, 2024b). The European Commission has not yet made a decision on the matter, but it is expected to do so during 2024.

The mass balance method can be used in long-loop chemical recycling technologies such as gasification and pyrolysis. Long-loop chemical recycling means the plastic is broken down

into smaller particles than monomers or polymers, and the end-product needs to be processed into plastic again from the very beginning. In short-loop processes, waste is broken down into polymers, oligomers or monomers, which are then used to produce a new plastic product in a few steps. In general, short-loop processes are implemented in factories that produce only plastic products and not, for example, other by-products such as fuels. Solvolysis is a short-loop process, so the recycled material produced by solvolysis does not need and cannot benefit from mass balance. In contrast, in long-loop chemical recycling, the output is, for example, pyrolysis oil, which due to its normally low capacity should be mixed with virgin fossil feedstock, making mass balance an important part of scaling up specifically long-loop chemical recycling technologies. (Warringa et al., 2023)

3.4 Technological maturity, gaps and challenges

Although not a complete solution, chemical recycling plays a critical part in creating a future that is waste-free for the most challenging plastics to recycle (Luu, 2023). It complements mechanical recycling and is a crucial component of a holistic approach to managing plastic waste that cannot be recycled by other recycling methods. The future of chemical recycling looks promising, and the technology is becoming one of the most important processes that can significantly reduce the amount of waste that ends up in landfills (Thiounn & Smith, 2020). In their study, Hsu et al. (2022) highlight the importance of communication and collaboration between stakeholders in the transition to a circular economy. The exchange of information and knowledge sharing as well as investments in technology development and innovation are key to the transition to a circular economy for plastics.

Current waste directives aim to ensure that by 2035 no more than 10% of municipal waste goes to landfill. The target is also to increase the recycling rate of plastic packaging to 50% by 2025 and 55% by 2030 (Plastics Europe, 2024c). In addition to the directives, consumers in developed countries have reported that they are willing to pay a premium for a product made from chemically recycled plastic because of its environmental value (Lu et al., 2024), so chemical recycling is in high demand for its ability to reduce plastic waste and promote the circular economy (Plastics Europe, 2024c). Commercialization has not yet been straightforward or rapidly developing due to challenges in the widespread application of

chemical recycling, such as quality and techno-economic issues (Lu et al., 2024; Hsu et al., 2022).

The technological readiness and maturity vary across the three processes under discussion (Cefic, n.d. b; Liu et al., 2024), and assessing their economic feasibility is challenging due to the limited number of comparators and thus data (Solis & Silveira, 2020). According to Zeller et al. (2021), there are no fully developed technologies for large-scale mixed plastic waste treatment. Yet, according to studies (Solis & Silveira, 2020; Dogu et al., 2021), pyrolysis and gasification are the most promising of chemical recycling technologies, but still according to studies (Lu et al., 2024; Liu et al., 2024; Solis & Silveira, 2020) the most mature, promising and profitable process of those two is pyrolysis. According to Solis & Silveira (2020), the technical readiness level for pyrolysis and gasification is 9/9. Solvolysis, which is not discussed in detail in many studies due to its challenges, has a technological readiness level of 4-7 (Biessey et al., 2023).

Although pyrolysis is considered a well-established process in the mature gas and oil sectors (Liu et al., 2024) and with centuries of experience in technical applications, it is a truly new technology for recycling plastic waste (Quicker et al., 2022). With existing infrastructure and expertise, and its suitability for mixed plastic waste treatment, the process is considered the most mature chemical recycling technology (Liu et al., 2024). Gasification, on the other hand, as the second most mature of the three technologies, is not widely used and there are currently only a few operational and available processes. Also, building a gasification plant requires much more capital expenditure than building a pyrolysis plant, for example, which may also account for the scarcity of gasification plants (Kingsbury, 2022; Biessey et al., 2023; Lu et al., 2024). The main problem with solvolysis is that its plant feedstock is limited to only one type of plastic, most commonly PET, which is not very cost-effective (Maisels et al., 2022). Also, the glycolysis of PET requires a higher reaction temperature and reaction time, which increases energy costs enormously (Jiang et al., 2022).

There is conflicting information in the research on qualitative problems. Some studies (Eze et al., 2021; Vogel et al., 2020; Bridgwater, 2012; Dogu et al., 2021; Payne & Jones, 2021; Rizos et al., 2023) state that chemically recycled feedstock is of high quality and even equivalent to virgin fossil feedstock. Some studies (Quicker et al., 2023; Lu et al., 2024; Rizos et al., 2023; Peng et al., 2022; Zeller et al., 2021) on the other hand, generally report that chemically recycled feedstock is of lower purity and quality than virgin feedstock. This

is due to factors such as the quality of the plastic waste used in the recycling process (product design solution including dyes, multilayer packaging, compounds, labels, adhesive residues, additives, etcetera), the quality and accuracy of the pre-processing, and materials that are incorrectly discarded. Contaminants in plastic waste can be generated in thermochemical processes, for example sulphur, nitrogen, phosphorus or tin, which can affect the recycling process and the quality of the final product.

Chemical recycling plants and activities already exist on an industrial scale, but only on a very small scale. Some are still under development, at demonstration level, on a smaller industrial scale or in the private sector (Liu et al., 2024; Cefic, n.d. b) This is partly due to the current lack of stakeholder and operator involvement and investment (Garcia-Gutierrez et al., 2023). There are other general problems in chemical recycling that hamper the expansion of the technology. One problem that points to a reluctance of major players in the plastics waste management and recycling sector to engage in chemical recycling is poor documentation compared to, for example, mechanical recycling or petrochemicals, where the challenges are well documented and there are clear solutions to the problems (Garcia-Gutierrez et al., 2023). Another more technological problem lies in reactors, which can often become clogged due to feed heterogeneity and hence constant changes in process parameters. This requires repeated cleaning operations, which means production downtime. (Peng et al., 2022)

Although some chemical recycling technologies are not yet economically viable (Liu et al., 2024) and are not yet commercially available (Quicker et al., 2022), there has been significant investment in the field by major companies such as Shell, Quantafuels and Plastic Energy (Lu et al., 2024). Yet, current investments are too low, and chemical recycling is experiencing economic challenges (Waste Management World, 2023). Most chemical recycling facilities have been created through partnerships between large and emerging small companies, where both have complementary technical expertise to develop processes and secure investment in the facilities. Increasingly, these technologies are being licensed as companies become more established, which is why the number of recycling plants is expected to grow further in the coming years. (Liu et al., 2024) There are currently three pyrolysis plants in Europe, owned by Plastic Energy and QuantaFuels. The first commercial QuantaFuels plant in Skive, Denmark, processes 20 kilo tonnes of recycled material per year. The other two plants are owned by Plastic Energy in Almeria, Spain, and in Seville, Spain,

where the plant processes 5 kilo tonnes per year (Lu et al., 2024). In addition to Plastic Energy and QuantaFuels, key players in the pyrolysis sector include BASF, Neste, Shell and Sabic (Liu et al., 2024).

Mechanical recycling is currently the dominant recycling route for plastics and is expected to remain so in the future. Mechanical recycling capacity is expected to be around 5.8 Mt in 2030 and up to 7.6 Mt in 2050. Chemical recycling capacity is also expected to increase from 100 000 tonnes in 2022 to almost 1.2 Mt by 2025 and 2.8 Mt by 2050 (Rizos et al., 2023; Waste Management World, 2023). According to Plastics Europe (2024mb), in the coming years its members plan to invest €2.6 billion by 2025 and €8 billion by 2030 into chemical recycling. Thirteen EU countries are currently planning 44 different projects that could produce 2.8 million tonnes of chemically recycled material per year by 2035. The increase in investment and thus capacity is likely to be influenced by the forthcoming European Commission decision on the introduction of the fuel exempt mass balance method, mentioned in the previous paragraph. If this is not adopted, it is possible that investment will be lower, making it difficult for chemical recycling to scale up. (Plastics Europe, 2024b)

The lack of infrastructure, for example in developing countries, makes chemical recycling more problematic, and plastic waste that cannot be mechanically recycled is incinerated or landfilled in these countries. In developing countries, where the chemical industry is much more developed, it should be possible to have all plastic waste chemically recycled that cannot be mechanically recycled. (Maisels et al., 2022) In addition to the lack of chemical industry development, collection, treatment and transport infrastructure are barriers in some regions. It is unclear which collection methods (such as source separation and centralized sorting) would be economically and environmentally feasible. A preliminary assessment of waste sorting policies, investments and transport system is essential to find the optimal solution to ensure a consistent and quality-controlled supply of plastic waste for chemical recycling processes. (Maitlo et al., 2022; Lu et al., 2024) Waste pre-treatment also plays a huge role in the performance of, for example, pyrolysis processes, as the presence of impurities (non-polymeric species) in waste streams can complicate pyrolysis processes, especially catalytic ones, as some additives can corrode equipment and deactivate catalysts (Peng et al., 2022).

Although chemical recycling has its own problems, it is also a prerequisite for the transition to a circular economy. According to the European Commission, the circular economy model

could save €600 billion and reduce 450 million tonnes of carbon dioxide emissions by 2030 (Liu et al., 2024). In addition, chemical and mechanical recycling could potentially together increase the plastic recycling rate up to 69% and reduce GHG emissions by 55% by the year 2050 (Plastics Europe, 2024b). As more and more plastic products, especially packaging, contain contaminating additives, it is likely that mechanical recycling will become more difficult and the need for chemical recycling will increase (Biessey et al, (Lu et al., 2024) In general, chemical recycling is therefore expected to increase significantly in the future, once the mass balance method is adopted by the European Commission.

4 Forecast of required resin for Huhtamaki

Packaging plays a significant role in today's world in ensuring safety and hygiene and in addition preventing food waste (Huhtamaki, 2024a). In this chapter the case company Huhtamaki is introduced. Additionally, a forecast of the required resins and shares of recycled content of Huhtamaki Flexible Packaging segment until 2030 is made based on data collected from the company.

4.1 Introduction of the case company

The case company Huhtamaki is a global sustainable packaging manufacturing company committed to making their packaging more circular and embed sustainability in everything they do. Huhtamaki's ambition is to become the first choice in sustainable packaging solutions. In 2023 the net sales of Huhtamaki were around EUR 4.2 billion with an EBIT of EUR 381 million (Huhtamaki, 2024b). The headquarters of the company is in Espoo, Finland, and its parent company Huhtamäki Oyj is listed on Nasdaq Helsinki Ltd. The company operates in 37 different countries and 107 locations with around 18 000 employees around the globe. (Huhtamaki, 2024a; Huhtamaki, 2024c)

Huhtamaki has a strong Nordic heritage and over 100 years of history (Huhtamaki, 2024a). The company name comes from the founder Mr. Heikki Huhtamäki who in 1920 established Huhtamäki Industries in Kokkola, Finland. The company began its journey by producing candy in addition with wooden boxes and containers for these delicacies. The first factory was opened in Savela, Finland in a stone barn. (Huhtamaki, 2024d)

Business Segments

Huhtamaki has three business segments: Fiber Foodservice EAO, North America and Flexible Packaging. Fiber Foodservice EAO business segment produces high-quality molded fiber packaging and paperboard to foodservice operators, coffee shops, fast food restaurants and fast-moving consumer goods (FMCG) companies. The North America business segment produces retail disposable branded tableware (e.g. Chinet®), private label products, foodservice packaging products and consumer goods packaging products (e.g. ice-

cream containers) serving local markets. Flexible Packaging business segment, that commissioned this thesis, offers innovative and light flexible plastic packaging materials, labels and pouches for food and beverages, pet food packaging, coffee packaging, barrier packaging, retort pouches and healthcare packaging products. The segment has 22 manufacturing units serving global markets in Europe, Africa, Middle East, South America and Asia. The net sales of Flexible Packaging segment in 2023 were EUR 1.342 billion. In April 2023 the segment launched their latest innovation, a new line of blueloop™ recyclable sustainable monomaterial products. The blueloop™ products are recyclable, reusable or compostable and have a lower carbon footprint than the products they are designed to replace. In addition, they are made from materials responsibly sourced. (Huhtamaki, 2024b; Huhtamaki, 2024e) According to Huhtamaki employee interview, the plastic in their products consists of 90% PE and 10% of PP.

4.2 Data collected from Huhtamaki

The purpose of this sub-section is to present data and information on the raw materials (resin) needed by Huhtamaki for their plastics production in order to develop a forecast of Huhtamaki's required resin volumes and the share of mechanical and chemical recycled resin over the period 2024-2030. The following information supporting the forecast has been collected by interviewing two employees of the company who are working in the Flexible Packaging segment in the procurement team and sales, marketing and innovation team. The following data was gathered about the required resin for the segment:

Total annual resin required in 2024: 150 000 tonnes

Expected resin required in 2030: 220 000 tonnes

The growth of the required resin in Flexibles can be calculated from that data, and it is around 46.7%. As the scope falls to Europe, only the data of the EU is used for making the forecast. In the forecast, it is assumed that the EU requirements for resin will also grow 46.7% by 2030. The following data gathered was data about the resin used in 2024 in the EU:

Total volume used to contact sensitive applications: 45 000 tonnes

Total volume used to non-contact sensitive applications: 39 000 tonnes

Total volume used in the EU in 2024: 84 000 tonnes (45 + 39 ktons)

Expected resin required in the EU in 2024 is calculated using the growth percentage of the total segment growth. By that, the expected resin required in 2030 is 123 228 tonnes.

As mentioned in chapter 2.2, according to the PPWR, by the year 2030, 10% of the total volume of the plastic in a packaging product must be contact sensitive sourced raw material (this can be thought to mean chemically recycled content) and 35% must be non-contact sensitive sourced raw material (this can be thought to mean mechanically recycled content). (European Parliament, 2024c) This information will be used to create the forecast about the shares of recycled content.

4.3 Analysis and forecast

As we have the data of resin used in 2024, and the data of Huhtamaki's own assumption on the required resin in 2030, we can create the forecast for the years in between with the following exponential growth equation (1):

$$P(t) = P_0 * (1 + r)^t \quad (1)$$

In this equation, the parameters mean the following:

P_t = *The end value (2030 resin)*

P_0 = *Initial value, the starting value (2024 resin)*

r = *Growth rate, expresses how much the quantity increases per time period (1 year)*

t = *Time that has passed since the initial value* (Kossovsky, 2019; Inigo et al., n.d.)

The parameter P_0 in this case is the base value of the year 2024 in the EU, which we know to be 84 000 tonnes. The parameter *t* is the time that passed since the initial value. This means every year has a different *t* value starting from 0 (2024), 1 (2025), 2 (2026) etcetera. The growth rate *r* can be calculated since the start and end values are known. The *r* value is calculated using the equation (2). In the equation (3) we can see the calculated *r* value to be 0,066.

$$r = \left(\frac{P(t)}{P_0}\right)^{\frac{1}{t}} - 1 \quad (2)$$

$$r = \left(\frac{123\ 228\ tonnes}{84\ 000\ tonnes}\right)^{\frac{1}{6}} - 1 \approx 0{,}066 \quad (3)$$

This equation of exponential growth was used because of the assumption that the quantity of required resin will grow much faster near 2030. With the data collected that is shown in the sub-section 4.2 and with the chosen exponential equation, the following forecast about required resin until 2030 was conducted (Figure 7):

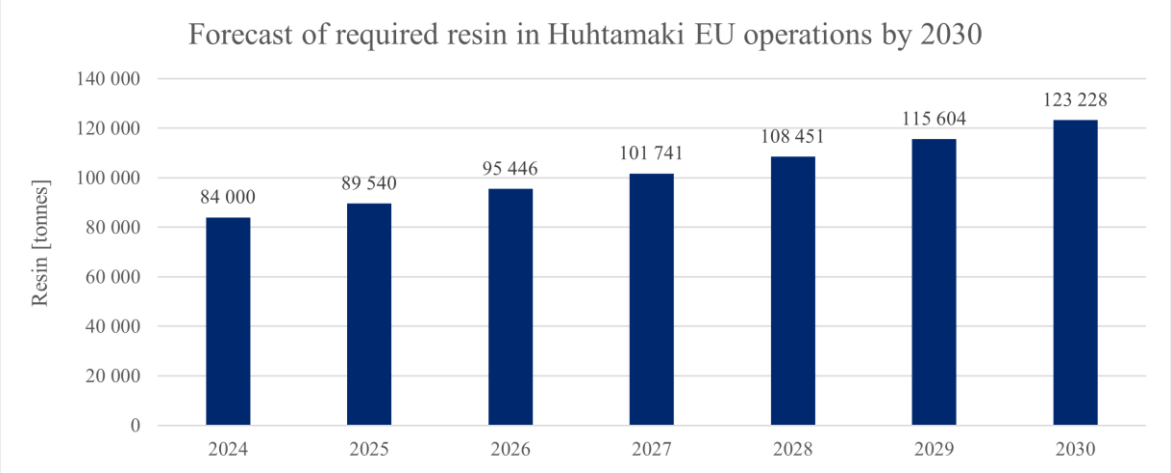


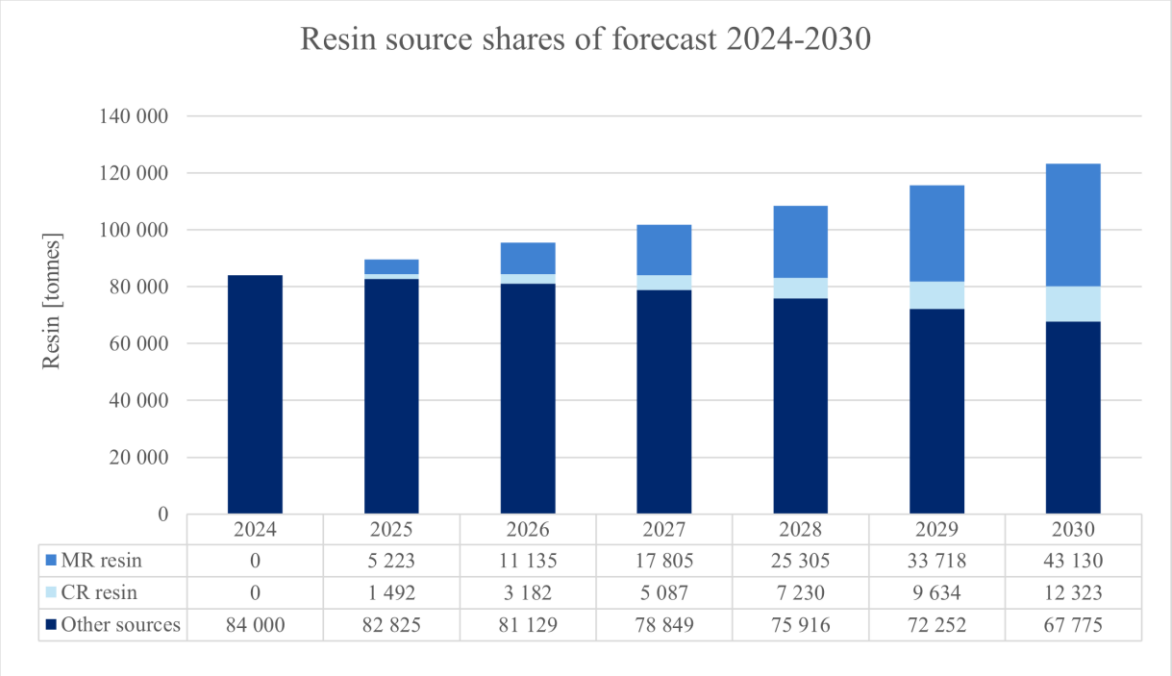
Figure 7. Forecast of the required resin for Huhtamaki operations in EU between 2024-2030

The forecast on how much of this total required resin could be chemically and mechanically recycled resin can be made with the assumption that in 2030 Huhtamaki will meet the PPWR target of 10% contact sensitive and 35% non-contact sensitive content. It is also assumed that in 2024 the amount of recycled content was 0%. Based on this information, we can create a similar forecast where every year the resin amount increases and eventually reaches the targets mentioned above. It is also assumed that all contact sensitive resin is chemically recycled and non-contact sensitive resin mechanically recycled. Table 2 illustrates the forecasted volumes.

Table 2. Forecast of recycled resin shares for Huhtamaki EU operations during 2024-2030

Year	Resin required [t]	CR-%	CR resin [tonnes]	MR-%	MR resin [t]
2024	84 000	0,00%	0	0,00%	0
2025	89 540	1,67%	1 492	5,83%	5 223
2026	95 446	3,33%	3 182	11,67%	11 135
2027	101 741	5,00%	5 087	17,50%	17 805
2028	108 451	6,67%	7 230	23,33%	25 305
2029	115 604	8,33%	9 634	29,17%	33 718
2030	123 228	10,00%	12 323	35,00%	43 130

In Table 2 the first column shows the forecast of required resin in Huhtamaki EU operations during the years 2024-2030. In the other columns the assumed cumulative growth percentages are shown, and next to them the volume of the chemically and mechanically recycled resin needs are calculated. If we assumed that Huhtamaki reaches the PPWR targets and the forecast of required resin is correct, in 2030 the required amount of chemically recycled (contact sensitive) resin is 12 323 tonnes and the required amount of mechanically recycled (non-contact sensitive) resin is 43 130 tonnes. The total amount and shares of resin sources from the forecast are illustrated also in Figure 8. With this change in the sources of resin, Huhtamaki can decrease their fossil-based resin use with around 19,3% by 2030.



	2024	2025	2026	2027	2028	2029	2030
MR resin	0	5 223	11 135	17 805	25 305	33 718	43 130
CR resin	0	1 492	3 182	5 087	7 230	9 634	12 323
Other sources	84 000	82 825	81 129	78 849	75 916	72 252	67 775

Figure 8. Forecast and shares of resin sources for Huhtamaki EU operations in 2024-2030

5 Interview results

In this chapter the interview results are discussed. The interview questions were divided into the following themes: background, maturity of the technology and possibilities in scaling up the industry, the future of chemical recycling, main challenges and benefits of chemical recycling, legislative landscape, possibilities for plastic packaging manufacturers and insight into volumes. In these sub-sections the main points of the interviewees are shown, compared and discussed.

5.1 Background of the interviewees

The interviewees were asked to tell something about their background and what their expertise is in the field of chemical recycling (CR). The interviewees all have very diverse backgrounds with different studies, different positions in different companies. They have worked with CR in different contexts ranging from 1 to 23 years. All interviewees have a broad understanding of the topic from different perspectives.

Some of the interviewees have more experience than others due to time spent being close to the CR industry or the differences in positions in the company. There are experts that are working in companies that do CR and companies that purify pyrolysis oil before it is converted into polymers through polymer manufacturers. Some of the interviewees have worked in CR related companies in their past, and some are in organizations related to waste management and plastic waste and thus have gained valuable knowledge around the topic. Six of the seven interviewees were also speakers in the Chemical Recycling Conference organized by Applied Market Information (AMI) in Brussels, Belgium on 4th-6th of June 2024.

5.2 Maturity of the technology and possibilities in scaling up the industry

This part of the research examines the maturity of chemical recycling focusing on the three core technologies: pyrolysis, gasification and solvolysis. This part also examines which of these three core technologies holds the most promise in scaling up the technology. The

interviewees were asked how mature these core technologies are and which of these technologies holds the most promise in scaling it up. The interviewees also provided a comprehensive justification for their answers.

The interviewees agreed that pyrolysis is the most mature of these three technologies among chemical recycling.

> *"Pyrolysis is the most mature of these technologies. Many projects are underway, but most are not yet operating commercially."* (Interviewee 1)
>
> *"The development is progressing rapidly, particularly in the field of pyrolysis in Europe."* (Interviewee 2)
>
> *"Pyrolysis appears to be the leading technology likely to reach commercial scale in Europe soon as is the most mature of these three technologies."* (Interviewee 3)

While many projects involving pyrolysis are currently under development, most are not yet operating at a commercial scale. This demonstrates that even while the technology is more developed than gasification and solvolysis, there is still work to be done before it can be widely used in industrial applications. The fast development of pyrolysis in Europe shows its leading position in the chemical recycling sector. Interviewees emphasized that Europe is at the forefront of developing this technology, with significant strides being made towards scaling up its use. This aligns with the view that pyrolysis is likely to be the first chemical recycling technology to reach commercial scale operations in Europe.

> *"Pyrolysis is a dominant since it has existed for many years, so it should be mature. Still in CR it is struggling with capacity."* (Interviewee 6)
>
> *"Pyrolysis has been around for a while, but the application around plastic is way younger. Due to the heterogeneity of plastic, it is hard to apply a process like pyrolysis on it."* (Interviewee 4)

It was also mentioned by a couple of interviewees that pyrolysis should be the most mature technology due to its long history in other applications, outside plastic. That has given a foundation of developed processes and operational experience. Its use in the context of plastic recycling is quite new and faces challenges with capacity and the heterogeneity of plastic.

> *"The forecast on where the install capacity is going into the future is made-up around 80% of pyrolysis. That is where most of the operational experience of the current companies lies in. With that comes the maturity of the technologies in pyrolysis.*

> *The demand for pyrolysis is the highest and triggers the industry to mature. That is how the market looks like."* (Interviewee 7)

Pyrolysis is expected to play a dominant role in the future of chemical recycling, with estimates indicating that this technology will account for around 80% of installed capacity in the next years. This strong focus is largely due to the significant experience companies have already gained with pyrolysis, which has helped to establish its position as a relatively mature and reliable option.

Moreover, the high demand for pyrolysis within the market has become a driving force behind its ongoing development. This demand not only supports further innovation but also encourages the industry to scale the technology more effectively. As a result, pyrolysis continues to stand out as the leading chemical recycling technology, both in terms of its current progress and its potential for future growth.

Interviewees had a few opinions on gasification and the challenges of its maturity.

> *"Currently, there are no commercial gasification plants for plastics in Europe. The technology is still emerging, and while there are promising projects, commercial deployment is not yet widespread."* (Interviewee 3)

> *"Gasification can handle almost any feedstock, but it needs to be done at a large scale to be profitable, and processing the resulting syngas back into plastic is complex, involving many steps."* (Interviewee 1)

> *"The input requirements for gasification are way lower than for pyrolysis, but the process itself is harder to manage."* (Interviewee 5)

> *"Gasification can handle large scales, but sourcing enough affordable feedstock is often difficult. Building large facilities without sufficient feedstock is risky."* (Interviewee 4)

According to interviewees gasification is still a developing technology in chemical recycling and currently has no commercially operating plants in Europe. There are some promising projects ongoing, but it is still emerging in the industry. One of the main advantages of gasification is that it can handle almost any feedstock making the process for plastic waste flexible. The problem is that the process is complex and needs to be done at large scale to be affordable, and currently there isn't enough affordable feedstock for it to be scaled up. This means it is currently very hard to make the recycling of plastic profitable.

> *"Gasification has some market space for* MSW*, but the issue is that it needs much more energy to operate."* (Interviewee 6)

It was also mentioned that although gasification would have some market place for MSW, additionally to the feedstock issue the energy efficiency is not that good as in the other chemical recycling technologies making the process much more expensive increasing emissions at the same time.

Interviewees agreed also on solvolysis being the least mature of these technologies even the fact that it is more efficient than gasification for plastic waste recycling.

> *"Solvolysis is probably the least mature of these technologies. From what I know, there are some small pilot and demo plants, but most of the technology is still in the 'demo phase.' A challenge with solvolysis is that it can only process single-materials like PET."* (Interviewee 1)
>
> *"Solvolysis is a highly efficient niche solution for more sorted material streams."* (Interviewee 2)
>
> *"Solvolysis has a lower environmental footprint but then you need typically a much more homogeneous input material."* (Interviewee 3)

It was mentioned that like gasification plants, also solvolysis plants are mainly operating as pilot or demo plants and not commercially. One benefit of the technology is the low environmental footprint compared to the other technologies. However, it faces some challenges that are limiting the possibility to scale it up. Interviewees mentioned that the main challenge of solvolysis is the feedstock requirements. The process requires homogeneous single materials like PET to be efficient and faces challenges with getting enough of the sufficient feedstock.

> *"Solvolysis is proven that it can work. But can it work at scale? Maybe. Can it work at scale with economic feedstock? And is that feedstock available? Highly questionable."* (Interviewee 4)
>
> *"Solvolysis uses less energy, making it better for the environment and easier to operate. However, we need to consider what materials it requires and how well it recycles. Recent studies show that it often needs government funding to be profitable. While funding might help early growth, if solvolysis isn't profitable in the long run, investing in it might not make sense."* (Interviewee 5)

Interviews revealed that solvolysis has been demonstrated to be an effective chemical recycling method for plastic in controlled conditions, but there are significant questions if it can be scaled up successfully. According to recent studies the technology often requires government funding to be able to run profitably. While such funding could help it scale up, it is questionable if it can remain financially sustainable without it. One interviewee

mentions that if profitability cannot be achieved in the long run, investing heavily in this technology might not make sense.

> *"All these technologies have maturity challenges, and the coming years will be critical to see how the plants currently being built will succeed and how capacity will develop."* (Interviewee 1)

> *"These technologies are well-established but face significant scaling challenges."* (Interviewee 4)

Although pyrolysis was mentioned to be the most mature one, it was also mentioned that all of the technologies face several challenges in their maturity and those need to be addressed if chemical recycling is to grow in the future. Interviewees were interested in seeing how the current projects of chemical recycling plants will succeed and how the capacity of them will develop.

In the second question, the interviewees were asked to point out the technology they think holds the most promise to be scaled up. The results were clear by indicating that pyrolysis is the one that is holding the most promise from these three technologies.

> *"Pyrolysis, there is no question about it, that is what is dominant in the market."* (Interviewee 6)

> *"Pyrolysis because it is highly efficient, converting about 70% of plastic waste into secondary raw materials. It's also self-sustaining, as it uses waste to generate nearly all the energy it needs, reducing energy consumption."* (Interviewee 2)

> *"Pyrolysis is the frontrunner, but it's uncertain which other technologies will succeed. We might end up with a few key technologies or a wide variety, each suited to specific polymers."* (Interviewee 3)

Interviewees agreed strongly that pyrolysis is with no question the frontrunner. One of the reasonings was that pyrolysis is currently dominant in the market due to its maturity. Another argument for it was the efficiency of the technology and the ability to use the energy generated by waste to its own processes, reducing the overall energy consumption of it. However, there is still uncertainty about which other technologies could succeed with pyrolysis, since it will probably not be the only one due to its feedstock limitations. It is possible that the industry could develop a few dominant technologies or a broader range of methods each specialized for specific types of polymers.

> *"It depends on the type of plastic. For example, PET plastic works well with solvolysis but not with pyrolysis. Statistics show that over 60% of all used plastic are polyolefins*

> *(PE, PP), which are best suited for pyrolysis. Gasification's strength is its flexibility with feedstock, but its economic viability is currently weak."* (Interviewee 1)
>
> *"Pyrolysis and solvolysis can work, while gasification may need way larger scales to be viable."* (Interviewee 4)

These responses suggest that the potential for scaling up chemical recycling technologies largely depends on the type of plastic being processed. Pyrolysis appears to hold the most promise due to its suitability for polyolefins which make up over 60% of all plastic waste While solvolysis is effective it is more suitable for single material plastics like PET, which are not compatible with pyrolysis. Like mentioned previously, gasification is highly flexible with feedstock but faces significant challenges with economic viability and requires large scales to become affordable. That is why pyrolysis and solvolysis are seen as more promising for scaling up, while gasification lags due to its current economic challenges.

The results indicate that the infrastructure for chemical recycling is a big challenge in scaling it up. The following was said:

> *"An important point is the synergy with existing infrastructure, which affects scalability. A recycling plant can't operate alone; we also need to consider how to use and transport its end products. This impacts the total cost of ownership, depending on how much new infrastructure needs to be built along the value chain."* (Interviewee 1)
>
> *"A key advantage of pyrolysis is the ability to build decentralized plants, cutting transport distances for plastic waste by about half, making the process more efficient and lowering transportation emissions. In contrast, gasification plants are centralized, requiring large-scale transport of plastic waste over long distances, which can lead to logistical challenges and higher environmental impact."* (Interviewee 2)
>
> *"Much depends on waste logistics, like EPR schemes and how well polymers are sorted at the source. Better separation increases the economic feasibility of polymer-specific methods, like solvolysis."* (Interviewee 3)

The scalability of chemical recycling technologies depends on their integration with existing infrastructure and logistics of waste. Interviewees highlighted that the success of a chemical recycling plant not only depends on the technology itself, but also on the infrastructure required to handle and transport its end products. The key advantage of pyrolysis, the identified most mature and promise holding technology, is the ability to build decentralized plants. By processing plastic waste closer to its source, transportation distances are reduced by about half, which improves efficiency and lower emissions. In contrast, gasification relies on distances. This creates logistical challenges and increases both costs and environmental impact, making the scalability more difficult. In addition, waste logistics such as extended

producer responsibility (ERP) schemes and the sorting of polymers at the source play a crucial role in the feasibility of scaling up chemical recycling. These factors underline the importance of considering the entire value chain when evaluating the scalability of the chemical recycling technology.

> *"The industry is overly focused on scaling up, but we should remember that large-scale systems take time to develop. For example, steam crackers started at around 50,000 tons decades ago and now operate at 1.2 to 1.5 million tons. CR will need a similar learning curve. Instead of aiming for massive scales, we should focus on matching available, affordable feedstock."* (Interviewee 4)
>
> *"The best approach is designing products for recycling from the start, rather than relying only on end-of-life solutions such as recycling. The EU's packaging regulation supports this by introducing design for recycling and recyclability criteria. Simplifying products and reducing contaminants early on will make recycling, both mechanical and chemical, more effective."* (Interviewee 5)
>
> *"As we can see from current volumes, CR will face a significant supply-demand gap in the future. It [the industry] needs more investments and scaling of recycling infrastructure to meet future needs."* (Interviewee 7)

While industry is heavily focused on achieving large-scale systems, some interviewees emphasized that scaling up should follow a gradual learning curve, much like the development of steam crackers, which evolved decades before they could handle the current capacities of million tons today. We must remember that it takes time to develop such technologies, and chemical recycling is not an exception in that. Instead of targeting massive capacities immediately, it was suggested that efforts should prioritize aligning operations with the availability and affordability of feedstock.

Another critical aspect highlighted was the importance of designing products with recycling in mind from the outset. For example, the EU's packaging regulations, which promote design-for-recycling and recyclability criteria, encourage simplifying products and reducing contaminants during production. This specific interviewee highlighting this was convinced, that if all plastic products would be designed in the first place to be recyclable or reusable, the plastic waste problem would be met. Because chemical recycling co-existing with mechanical recycling could get more feedstock to process, meaning that the industry could possibly grow, and waste amounts would reduce at the same time.

5.3 The future of chemical recycling

This part of the interviews focuses on the future of chemical recycling. The interviewees were asked to explain how they see the future of chemical recycling in the plastics value chain over the next five to ten years. The analysis resulted in a comprehensive understanding of what the drivers for chemical recycling in the plastics value chain are for the future.

The interviewees agreed that the future of chemical recycling in the plastics value chain over the next 5 to 10 years seems optimistic for now:

> *"I see a bright future. EU legislation is strongly moving toward supporting maximum recycling."* (Interviewee 1)
>
> *"We anticipate improvements in efficiency over the next 10 years, allowing for even higher conversion rates."* (Interviewee 2)
>
> *"We have seen already in the past a significant uptake. Couple of years ago we had very little capacity in Europe. But we see that the overall capacity is growing."* (Interviewee 3)

One of the drivers they mentioned is the EU legislation, which is heavily focused on maximizing recycling efforts in its member states. These kinds of regulatory pushes are expected to play a crucial role in growing demand for chemical recycling. The interviewees mentioned that advancements in technology are expected to lead to higher conversion rates over the next decade. These improvements could help address some of the current challenges, such as scalability and variation of feedstock, while enhancing the overall performance of recycling processes. Interviewees also pointed out the significant uptake in chemical recycling capacity in Europe during recent years. The capacity was quite small only a few years ago, but it has significantly increased since then. This indicates rising investments and interest in the technology and means that chemical recycling is gaining attraction and is likely to become a more visible part of the plastics value chain in the near future.

With significant market interest, aggressive ambitions, and a definite drive for capacity expansion, chemical recycling is emerging as a key component of the plastics industry's sustainability objectives:

> *"Individual companies like SABIC have set goals, such as recycling 1 million tons by 2030. And I can say for a fact that about two-thirds of this will come from CR. This highlights the growing importance of CR in reaching recycling targets."* (Interviewee 6)

> *"We're in talks with various petrochemical and other companies exploring chemical recycling, giving us a strong market overview and a solid pipeline of projects. It's clear that all companies are looking into CR."* (Interviewee 6)

> *"There are quite a lot of projects announced industry wide in Europe on pyrolysis, we do see a clear case for scale up there. We have this demand already created in the market and we have quite a lot of different companies who have projects under construction."* (Interviewee 7)

The Interviewees highlighted the growing role of chemical recycling in meeting recycling targets over the next decade. One example is SABIC, the world's largest petrochemical company (SABIC, 2024). They have set a big goal to recycle 1 million tons by 2030, with about two-thirds of this coming from chemical recycling. This shows that chemical recycling is becoming very important for meeting recycling goals. It was also mentioned that many petrochemical and other companies are actively exploring chemical recycling. These ongoing discussions and partnerships give a strong indication that the market is highly interested in the technology, with a solid pipeline of projects already in progress. The existing demand in the market and the number of projects currently under construction show that many companies are committed to expanding CR capacity and making it a larger part of the plastics recycling process.

The limitations of mechanical recycling also have an impact on the growth of chemical recycling:

> *"MR has limits, especially as its end products aren't suitable for food contact, so other methods are needed to meet the EU's ambitious goals. For CR, this means it needs to scale up."* (Interviewee 1)

> *"CR is essential because MR alone can't handle all types of plastic, and simply reducing plastic types isn't realistic."* (Interviewee 4)

The interviewees agreed that mechanical recycling has several limitations with certain types of plastic waste. It cannot process mixed plastic waste, and materials it produces cannot be used in food contact applications such as food packaging. The gap can be filled with chemical recycling, and thus the need for the technology is expected to grow in the future. Interviewees emphasized that the reduction of plastic types is not realistic, and thus chemical recycling will play a crucial role in the plastic waste issue.

Discussion around regulatory developments affecting the future of chemical recycling was also discussed with a few interviewees:

> *"We expect that now with the latest regulatory developments, there's going to be a push towards 2030 and then also beyond."* (Interviewee 3)

> *"For real change, governments and regulators need a more holistic and aggressive approach. Achieving a circular economy requires CR, MR, and product replacements where feasible—all with a focus on minimizing climate impact."* (Interviewee 4)

The interviewees highlighted the importance of upcoming regulatory changes in driving the future of recycling. One noted that recent developments in regulations are likely to create momentum toward achieving significant recycling progress by 2030 and continuing well beyond that. Another interviewee stressed that meaningful change requires governments and regulators to take a more comprehensive and bold approach. A circular economy cannot rely on one solution alone but must combine chemical recycling, mechanical recycling, and, where possible, the replacement of certain products. All of these efforts need to be aligned with minimizing the overall climate impact to create a truly sustainable system.

> *"Many brand owners also set pressure on plastic producers since they tend to favor recycled over renewable plastics."* (Interviewee 1)

> *"I have been in the CR field for around ten years now and have witnessed how slow the development of it is. But I can say that big packaging companies do not want to be associated with plastic waste, and want to solve the plastic waste issue, and CR will play a big role in it."* (Interviewee 6)

Some interviewees agreed on the fact that brand owners are pushing the industry to grow, since they are putting pressure on plastic producers by showing a clear preference for recycled plastic over renewable ones. This shift highlights the growing demand for more sustainable materials in the industry. One interviewee with over ten years of experience in the chemical recycling industry pointed out that the development of the industry is very slow. However, he mentioned that big packaging companies do not want to get associated with plastic waste and this drives them also to support the growth of chemical recycling, which can address this issue.

5.4 Main challenges and benefits of chemical recycling

This part of the interview results showcases the main challenges and benefits of chemical recycling focusing on the three core technologies. Also, general challenges and benefit of the industry were discussed. The interviewees were asked to identify the main challenges

and gaps of chemical recycling, and the following question asked about the benefits of it. The aim of the questions is to get a comprehensive overview of the factors that drive or slow down the growth of chemical recycling. Before delving into the details, Table 3 below provides an overview of the main challenges, gaps, and benefits of chemical recycling, as identified through the interview results.

Table 3. Summary of main challenges and benefits of CR

Main challenges and gaps	Main benefits
• Lack of infrastructure • Capacity issues • Lack of high-quality feedstock • Lack of investments and funding • Legislative landscape not supporting CR	• Ability to complement the gaps of MR • Increases recycling rates • Reduces plastic waste • Reduces dependencies on fossil resources by offering high-quality raw materials that replaces them

First the challenges and gaps of chemical recycling were discussed. The interviewees all agreed that the main problem lies in the current infrastructure and the capacity of plastic waste and thus the feedstock used in the process.

> *"One challenge is building capacity, which requires major investments. Since these technologies are relatively new, securing funding and permits isn't guaranteed. From an infrastructure perspective, there are also big geographical differences. To recycle plastic waste, it first needs to be collected, and in the EU, collection and recycling are well-established—sometimes too much so, as there's a push to mechanically recycle materials that don't really belong there."* (Interviewee 1)

> *"Improvements are needed not only in post-processing but also in pre-sorting and logistics to enhance the overall efficiency and purity of outputs."* (Interviewee 3)

> *"My hope is that pyrolysis companies succeed in getting their technology up and running stably, as this is the main challenge for growth right now. Building infrastructure takes time, and companies need to get their capacity scaled otherwise it will be very costly. Overcoming these challenges is essential."* (Interviewee 6)

> *"One important factor is that the industry needs to mature in sense of innovating around the processes. For example, lowering the carbon footprint, maximizing the yields and lowering contamination"* (Interviewee 7)

One big challenge is building more capacity, which needs a lot of investment. Since these technologies are still new, it can be hard to get enough funding and permits. There are also big differences in recycling infrastructure between regions. For example, in the EU, plastic

collection and recycling systems are well-developed, but sometimes materials are put into mechanical recycling when they don't belong there, which lowers efficiency.

Another issue is the need to improve pre-sorting and logistics. Better sorting and transportation would make the process more efficient and help produce cleaner recycled materials. Post-processing also needs to get better to maximize results. For pyrolysis companies, the main challenge is getting their technology to run reliably and consistently. Building the needed infrastructure takes time, and if companies don't scale up properly, it could become very expensive. Solving these problems is important for the industry to grow. The industry also needs to improve its processes overall. Innovations are needed to lower the carbon footprint, increase the amount of material recycled, and reduce contamination.

The interviewees highlighted the quality of chemical recycling products as one of the key challenges facing the industry:

> *"Scaling up CR faces several challenges, including advancing technology to produce high-quality, consistent pyrolysis oil for chemical feedstock. Improving efficiency is essential to maximize the conversion of plastic waste into valuable materials."* (Interviewee 2)

> *"As CR grows, it is crucial to ensure the output is suitable for further processing, especially with methods like pyrolysis, which requires refining to produce purer pyrolysis oil."* (Interviewee 3)

> *"Two key issues stand out. First is securing the right feedstock for CR without diverting material from MR. While some claim CR can handle any plastic, in reality, it often requires clean, quality material—putting it in competition with MR, which is more cost-effective. CR should focus on materials that can't be mechanically recycled to equivalent quality, like food-grade plastics. Second is post-conversion treatment. Chemical plants are highly sensitive to impurities, so ensuring the oil produced from recycled plastic is pure enough for these systems is crucial for effective recycling."* (Interviewee 4)

The interviewees agreed that one big issue is developing chemical recycling to produce high-quality pyrolysis oil that can eventually be used as a chemical feedstock. To make chemical recycling more effective, efficiency must be improved so that more plastic waste can be converted into valuable materials. It is also important to ensure that the output products, especially from methods like pyrolysis, are good enough for further processing. Pyrolysis oil, for example, often needs refining to make it purer and suitable for chemical plants like steam crackers to be converted into monomers and polymers.

Two main issues were highlighted regarding feedstock and post-conversion treatment. First, chemical recycling must secure the right types of plastic without competing with mechanical recycling, which is cheaper and better suited for certain materials. While chemical recycling is sometimes said to work with any plastic, it often needs clean, high-quality feedstock. Chemical recycling should focus on plastics that mechanical recycling cannot handle well or recycle to the same quality as chemical recycling can. Second, post-conversion treatment is critical because chemical plants are sensitive to impurities. The oil produced from recycled plastic must be clean enough for these systems, or the recycling process won't work effectively. Addressing these issues is key to making chemical recycling a reliable and scalable solution.

The interviewees pointed out that a strong regulatory framework is crucial for the development of chemical recycling:

> *"A strong regulatory framework, including mass balance, is essential for CR. Public acceptance is also a challenge, as many people don't fully understand the process."* (Interviewee 3)

> *"Another important factor is having some clarity on the status of CR as part of the legislative framework, which is not quite complicated and broad since it has been historically constructed with MR in mind. The CR industry meets difficulties in scaling up due to gaps in policy. The complicity of the regulatory framework is also not attracting private investors, that are crucial to scale up the industry in long term."* (Interviewee 7)

The interviewees mentioned that having clear rules, including mass balance methods, is essential to support the growth of chemical recycling. However, public acceptance is also a challenge, as many people don't fully understand how the process works, which can slow down progress and acceptance of change. One interviewee emphasized the need for more clarity in how chemical recycling fits within existing legislation. The current framework was largely created with mechanical recycling in mind, making it complicated and not fully suited for chemical recycling. This lack of clear policies creates challenges for the industry to scale up. Additionally, the complexity of the regulations can discourage private investors, whose support is essential for the long-term growth of chemical recycling. Addressing these policy gaps and simplifying the regulatory framework will be key to helping the industry scale up.

After discussing the challenges and gaps in recycling technologies, the interviewees identified several key benefits of chemical recycling.

> *"MR can't handle mixed or contaminated plastics, which CR can—this is a clear advantage."* (Interviewee 1)
>
> *"CR processes plastic waste that cannot be recycled mechanically due to technological, economic, or ecological constraints. While sorted single-stream plastics are best suited for MR, CR is ideal for mixed post-consumer plastics like PE, PP, and PS, where further sorting is costly."* (Interviewee 2)
>
> *"The main benefit is a truly circular economy, focusing on materials unsuitable for MR."* (Interviewee 4)
>
> *"The benefit is that we can recycle a wider range of plastics and improve decontamination, addressing some of the gaps in MR."* (Interviewee 5)
>
> *"MR is very limited in producing food grade recycled content especially in polyolefins (PE, PP). This is where chemical recyling can help a lot. It should be about acknowledging the limitations and gaps of MR and maximizing it with the use of CR technologies."* (Interviewee 7)

All agreed that the main advantage of chemical recycling is the already multiple times argued fact that it can handle the waste mechanical recycling cannot handle. This includes mixed or contaminated plastics, which are a major limitation for mechanical recycling. While sorted, single-stream plastics are better suited for mechanical recycling, chemical recycling works well with mixed post-consumer plastics such as PE, PP, and PS, where further sorting is costly and inefficient. Chemical recycling is particularly valuable for producing food-grade recycled content that mechanical recycling cannot do. By focusing on materials that mechanical recycling cannot process, it helps ensure that a broader range of plastic waste is recycled rather than ending up in landfills or incineration, contributing to a truly circular economy.

> *"This approach complements existing methods, helping to increase overall plastic recycling rates."* (Interviewee 2)
>
> *"CR enables returning materials to their original form, boosting overall recycling rates when co-existing with MR."* (Interviewee 4)

Interviewees also mentioned that one benefit of chemical recycling is that it contributes to increasing recycling rates. This is, as discussed before, due to its ability to recycle a broader range of plastic types than other recycling methods.

The interviewees highlighted another significant benefit of chemical recycling: its ability to produce high-quality recycled plastic and reduce dependence on fossil resources.

"CR produces plastic of virgin quality that can be used without restrictions in basically any application." (Interviewee 1)

"The feedstock from pyrolysis (pyrolysis oil) can be processed in petrochemical plants as a secondary raw material to substitute fossil resources." (Interviewee 2)

"CR reduces the requirement of fossil feed." (Interviewee 6)

"CR provides diversified feedstock for the petrochemical companies that can basically replace currently used fossil derived feedstocks. CR plays thus a very important role in decarbonizing the feedstock of the petrochemical industry." (Interviewee 7)

"Another benefit is reducing the use of virgin fossil resources by keeping above-ground carbon in circulation. This also lowers greenhouse gas emissions, as plastic incineration releases carbon into the atmosphere." (Interviewee 1)

Interviewees highlighted that chemical recycling can decrease the need for virgin fossil feedstock in plastic manufacturing plants, since the technology can produce high-quality raw material that substitute fossil resources. It was seen as a major benefit, since it also contributes to the circular economy and is one of the drivers to change the plastic value chain into more sustainable. This makes it an important part of the transition to more sustainable and resource-efficient industrial processes.

Interviewees also mentioned that chemical recycling has been proven to be a better solution than incineration. This means that the amount of waste going to incineration could be reduced in the future if the chemical recycling industry can be scaled up. As has been mentioned several times before, here again the interviewees mentioned its ability to solve the waste problem as a benefit.

"Several life cycle studies comparing CR with alternatives conclude that CR is generally a better option than incineration." (Interviewee 3)

"CR contributes to solving the plastic waste problem." (Interviewee 6)

5.5 Legislative landscape

This part of the interview examines the legislative landscape around chemical recycling and examines also more specifically the mass balance method, which is currently discussed in the European Commission. Mass balance and legislation renewal seems to be a critical part of scaling up the industry. The interviewees were asked about any specific regulations that they believe are particularly effective or problematic for the industry, and the second

question asked if they see a connection between mass balance method and scaling up the industry. Also, other complications around the legislative landscape of chemical recycling were discussed.

The interviewees discussed how waste management legislation can either support or undermine the chemical recycling sector:

> *"It would be helpful to clarify a clear definition of what counts as recycling and recycled content. In waste management, the EU promotes the free movement of goods, but waste isn't included. If waste is your raw material, how can small EU countries establish CR facilities? Should or can materials be transported across borders? When does it achieve product status? This requires a lot of bureaucracy. Waste and product legislation aren't aligned, causing challenges in the industry."* (Interviewee 1)

> *"Another area where I see the legislation being helpful and unhelpful is the whole area of waste management. People are paid to take stuff to landfill, so why on earth wouldn't they do that when they get more money for it than recovering the material? Or some countries, for example, are pushing towards waste to energy so they burn the material and get paid for that. And then mechanical recyclers want to fight against anything that could impact upon their feed of waste plastic."* (Interviewee 4)

The absence of clear definitions for what counts as recycling and recycled content was mentioned as one issue in the current legislation. According to one interviewee the principle of free movement of goods in the European Union does not apply for waste, which makes it complicated for chemical recyclers since their raw material is waste. Questions arise about whether and how materials can be transported across borders and when does waste stop being classified as waste and comes a product? There is a clear misalignment between waste and product legislation, and it creates significant problems in bureaucracy and a headache for the chemical recycling industry.

Another interviewee highlighted additional challenges related to waste management regulations. There are cases where people are paid to dispose of materials in landfills or burn it to produce energy. These practices are promoted in some countries making incineration and landfilling more profitable for waste handlers. The interviewee makes a great point of asking "…*why on earth wouldn't they do that when they get more money for it than recovering the material?"*. On top of this, mechanical recyclers often resist anything that might compete with or reduce their supply of plastic waste, adding another layer of complexity for the chemical recycling industry. These examples show that clearer and more aligned waste management regulations are needed to address these challenges. Better

definitions, harmonized rules across borders, and incentives that favor recycling over landfilling or incineration would help support the growth of chemical recycling in Europe.

The interviewees discussed how recycling targets influence the role of chemical recycling in waste management:

> *"Legislation will determine CR's role in waste management. The EU views it as contributing to recycling targets, but member states interpret this individually. For example, Germany does not yet recognize CR toward its plastic recycling targets."* (Interviewee 2)

> *"From a European perspective, requirement supporting recycled content enhances circularity and recycling."* (Interviewee 5)

> *"Two main requirements for meeting recycling targets are setting recycled material targets (not necessarily specific to CR) and ensuring mass balance. These are critical, especially in the transition phase, and are the most effective and feasible incentives given the current maturity of the technology. Other incentives can be considered later."* (Interviewee 3)

One key point was the variability of how different EU member states interpret recycling targets. For instance, while the EU views chemical recycling as contributing to its overall recycling goals, some countries, like Germany, do not yet count chemical recycling toward their plastic recycling targets. This inconsistency creates challenges for the industry in aligning its efforts with national policies. Another interviewee emphasized that setting clear requirements for recycled content plays an important role in promoting circularity and recycling. Such requirements encourage the use of recycled materials and support a broader transition to a circular economy.

Meeting recycling targets was seen as dependent on two key factors: setting clear recycled material goals and implementing systems to track progress, such as mass balance. These steps are especially important during the transition phase, given the current state of chemical recycling technology. As one interviewee noted, these are the most practical and effective tools for supporting the industry at its current maturity level, with other incentives to be explored as the technology evolves further. Mass balance and its importance was highlighted by many interviewees the following way:

> *"The mass balance is an important point. If it is not accepted, most of the plastic that cannot be mechanically recycled will end up in landfills or incinerated."* (Interviewee 4)

> *"There's a whole industry who has prepared to get started and they are ready to do it but the apparent thing is that they're lacking some crucial legislation from EU to get this*

> *rolling. One of the things that are specifically lacking is a lack of regulations what kind of mass balance you can use."* (Interviewee 6)

> *"Clear mass balance regulations are critical for scaling the CR industry, as they provide a standardized method to measure outputs like pyrolysis products. Without these standards, it's challenging for the industry to expand effectively, making this regulatory clarity a top priority."* (Interviewee 7)

Mass balance was seen as one of the key legislations that enable the scaling up of chemical recycling, specifically pyrolysis. It was emphasized that without mass balance, a large portion of plastic waste that cannot be mechanically recycled would end up in landfills or incineration. It was also mentioned that while the industry is ready to start scaling up chemical recycling, it is being held back by a lack of clear mass balance regulations from the EU. This lack of regulation creates uncertainty and slows down progress for companies that are otherwise prepared to move forward. Mass balance was seen as essential for the growth of the industry, and it will likely be the key in unlocking the potential of it.

> *"The Industrial Emission Directive (IED) is also interesting, as it helps monitor plant emissions, promoting transparency and favoring plants with the best environmental practices."* (Interviewee 5)

> *"The PPWR sets specific goals for food-contact polyolefins that only pyrolysis can currently address."* (Interviewee 7)

Interviewees also mentioned some specific regulations that impact on the chemical recycling industry. One that was mentioned was the Industrial Emission Directive (IED), which plays an important role in monitoring emissions from recycling plants. The directive encourages transparency and rewards plants that adopt the best environmental practices. This regulation is seen as a positive influence, pushing the industry toward cleaner and more sustainable operations. Another regulation that was pointed out was the relevance of the Packaging and Packaging Waste Regulation (PPWR). This regulation sets specific targets for food-contact polyolefins, such as PE and PP. These requirements currently align well with pyrolysis, as it is the only chemical recycling technology capable of meeting these strict standards. This makes the PPWR a key driver for the development and adoption of pyrolysis in particular. These examples show how regulations can both guide and support the chemical recycling industry by promoting environmental accountability and encouraging the use of advanced technologies to meet specific goals.

The interviewees were asked more specifically to talk about mass balance and the role of it in scaling up the industry. The interviewees highlighted the strong connection between the mass balance method and scaling up chemical recycling:

> *"As long as we rely on existing infrastructure in the plastic value chain, mass balance is essential to scale up CR. The current capacity of chemically recycled material isn't enough to supply a steam cracker, so it must be mixed with virgin fossil feedstock. To precisely allocate this recycled material in end products, mass balance is required."* (Interviewee 1)

> *"It is essential for scaling up CR by integrating recycled feedstocks like pyrolysis oil with fossil feedstocks in existing large chemical facilities."* (Interviewee 2)

> *"Mass balance is essential; without it, the industry won't survive. It's a straightforward question—do we want to give this industry a chance?"* (Interviewee 4)

> *"Definitely. It is a crucial thing, since investors won't invest in a technology where they don't know what the rules are."* (Interviewee 6)

One interviewee explained that as the industry relies heavily on existing infrastructure within the plastic value chain, mass balance becomes essential. Since the current capacity of chemically recycled materials is not enough to fully supply large facilities like steam crackers, these recycled materials must be mixed with virgin fossil feedstocks. Mass balance provides a solution for this by tracking and allocating the recycled content fed to the steam cracker, ensuring transparency and accountability. This integration between recycled content and fossil feedstock is key to scaling up chemical recycling and making it compatible with the established infrastructure.

The importance of mass balance was further emphasized by another interviewee, who stated that the chemical recycling industry cannot survive without it. They framed it as a simple but critical question: does society want to give this industry a real chance to grow and succeed? Without mass balance, this will not be possible. Mass balance is not just important for operations but also for attracting investments. Clear mass balance guidelines were seen as a crucial factor in securing the financial backing needed to scale up the industry, since investors do not invest in technologies which have a complex and unclear legislative landscape.

Interviewees agreed that mass balance will be essential for the transitional phase of chemical recycling, but it might not be always necessary:

> *"Eventually, when the industry can fill an entire steam cracker with pyrolysis oil, mass balance won't be needed, but it's crucial for the transition."* (Interviewee 1)

> *"We need mass balance, at least for the transitional period. Ideally, with increased recycling volumes, it may eventually become unnecessary, though it's hard to predict how long that transition will take."* (Interviewee 3)

In the future, hopefully, the industry can supply, for example enough pyrolysis oil to fully feed a steam cracker and mixing it with fossil feedstock won't be necessary. Until the chemical recycling volumes are reached, it remains critical for ensuring recycled content is properly tracked and allocated to the end products. One interviewee noted that it is difficult to predict how long the transitional phase will take since it depends on the technological development and the ability of the industry to scale up production. While mass balance may eventually become less important, its role during the transition period is considered necessary.

The role of mass balance in the chemical recycling industry was also discussed further:

> *"CR with mass balance complements MR, raises recycling rates, and allows companies to offer sustainable product options, passing on environmental benefits to customers."* (Interviewee 2)

> *"Mass balance legislation is essential for tracking recycled content across the supply chain, ensuring transparency and verifying recycled percentages for downstream users. Recognized in other industries, this methodology could drive CR to the higher volumes needed in Europe by enabling effective scaling and market integration."* (Interviewee 7)

The interviewees emphasized that as mass balance helps chemical recycling co-exist and complement mechanical recycling, it also plays a significant role in increasing the overall recycling rates. Mass balance plays a key role in allowing companies to track and allocate recycled content to their products, thus helping them offer more sustainable options to customers. This, in turn, provides clear environmental benefits for the end-users. It was also mentioned that mass balance is essential for ensuring transparency throughout the supply chain. By tracking recycled content and verifying the percentages used, mass balance creates trust and accountability for downstream users of recycled materials. This method is already recognized in other industries and could help chemical recycling achieve the higher volumes needed in Europe. It enables the industry to scale effectively and integrate recycled materials into existing markets, making it a crucial tool for future growth.

One interviewee had an interesting point of view on mass balance:

> *"There's a lack of pragmatism here—while debating fuel exemption method of mass balance, we're still drilling for oil, producing more plastic, and ultimately burning, burying, or leaking it into the ocean. It doesn't make sense. We urgently need to scale and develop sustainable industry solutions, which requires some level of pragmatic support."* (Interviewee 4)

The interviewee expressed frustration at the lack of pragmatism in the ongoing debates about mass balance in the European Commission. They emphasize the need to focus on scaling and supporting the industry, urging for more practical approach, like accepting mass balance, to drive progress. In practice, this means that the interviewee sees the bigger picture and the good that chemical recycling could achieve, while at the same time some fight against mass balance by arguing that it is greenwashing. The discussion around mass balance reveals differences in perspectives as one interviewee highlighted the point of greenwashing and had the only opinion against mass balance:

> *"The industry is pushing for mass balance as a transition method, but we see this as problematic. It allows marketing claims about recycled content that aren't accurate by weight, which raises concerns about greenwashing and what is truly being sold to consumers.*
>
> *Mass balance is questionable because it's essential to make the technology economically viable; without it, there's no clear business case. Even with mass balance, profitability is uncertain, raising long-term questions about whether this is the investment we need to make."* (Interviewee 5)

While other interviewees see mass balance as a necessary tool for scaling up chemical recycling and addressing the urgent need to reduce plastic waste, others question its long-term viability and transparency. The perspective of all other interviewees was challenged by one interviewee who raised concerns about greenwashing. The interviewee argued that mass balance allows companies to make marketing claims about recycled content that does not accurately define the physical composition of products. This apparently risks misleading consumers and undermining trust in recycled materials. In addition, the interviewee pointed out that although mass balance is critical for making chemical recycling economically viable, its profitability remains uncertain, even with the adoption of mass balance. This raises larger questions about whether recycling of chemicals in its current form is the best investment to achieve the sustainable development goals.

These opposing views highlight the complexity of the mass balance debate. On the other hand, interviewees see it as a necessary step for the sector to move and achieve scale. On the

other hand, others are concerned about possible misleading claims and question whether chemical recycling can deliver the long-term economic and environmental benefits it promises. Resolving this tension requires us to balance the urgency of expanding chemical recycling with the need for transparency and consumer confidence.

5.6 Possibilities for plastic packaging manufacturers

This part of the interview examines the possibilities for plastic packaging manufacturers in the context of introducing chemical recycling in their value chain. The interviewees were asked how plastic packaging manufacturers could introduce chemical recycling in their value chain. They were also asked to tell their opinion on if chemical recycling would be the best option for plastic packaging manufacturers like the case company Huhtamaki in the context of moving toward circularity.

A common theme was the importance of actively engaging with suppliers, polymer producers, and brand owners to drive demand and establish access to chemically recycled materials.

> *"It's worth actively discussing about CR with customers and brand owners to push for demand. For a company like Huhtamaki, the risk of using CR plastic is low since the quality doesn't differ from fossil-based plastic. Starting by directly asking your existing suppliers if they can provide chemically recycled material is the first step you can do. Many polymer producers are already involved in CR to some extent."* (Interviewee 1)
>
> *"Even a conversation with a polymer producer expressing interest can make a lot."* (Interviewee 3)
>
> *"You need to buy let's say certified ethylene or propylene from a petrochemical company. So I would assume this is the way forward."* (Interviewee 6)
>
> *"To access chemically recycled raw materials, you'd need to coordinate with your polymer supplier."* (Interviewee 7)

One interviewee suggested that manufacturers should begin by having direct discussions with their existing polymer suppliers to inquire about the availability of chemically recycled materials. Many polymer producers are already involved in chemical recycling to some degree, making this a logical first step. Even expressing interest in these materials to suppliers can help signal demand and encourage further development in the field. Another point that was highlighted was that for companies like Huhtamaki, trying out chemically

recycled raw materials is not risky since the quality of it is comparable to that of virgin fossil-based plastic. The interviewees also emphasized that a company like Huhtamaki could begin by coordinating with polymer suppliers and petrochemical producers. Even initiating conversations with these partners can make a significant impact, as it provides valuable insights into market demand and helps suppliers understand the specific materials their customers, such as Huhtamaki, are seeking.

The interviewees emphasized the importance of working closely with the plastics value chain to successfully integrate chemical recycling into operations and drive progress:

> *"There are many options: you can simply buy what's available, or work with the value chain to drive progress. Enhanced producer responsibility can help get purer inputs, and that will facilitate the whole process."* (Interviewee 3)

> *"You can either pay for materials and try to create value through your product and size it through green premium, or you can drive the change yourself. The challenge is that if you're only a small part of the value chain, capturing significant value is tough. The key is to disrupt—leveraging tools as a plastic packaging manufacturer, differentiating, and influencing regulators. The question is whether you'll lead or follow; leaders are more likely to capture value and set standards."* (Interviewee 4)

> *"Collaboration across the plastics supply chain is essential, both for securing chemically recycled materials and for helping policymakers understand industry needs and opportunities."* (Interviewee 7)

One interviewee pointed out that companies have different approaches to choose from: they can either purchase what is already available on the market or actively collaborate across the value chain to influence improvements. EPR schemes were mentioned as a tool for achieving purer input materials, which would simplify the chemical recycling process and make it more efficient. Another interviewee highlighted that companies have two main strategies. They can either pay for materials and try to create value through their product—possibly charging a green premium—or take a more active role in driving change. However, smaller players in the value chain may struggle to capture significant value unless they find ways to differentiate themselves.

The key to success, they explained, is disruption: using the tools available as a packaging manufacturer to innovate, influence regulations, and stand out in the market. Taking a leadership role not only allows companies to shape industry standards but also increases their chances of capturing value in the long term. Collaboration across the entire plastics supply chain was identified as essential by the interviewees. One interviewee explained that

this is necessary not only for securing access to chemically recycled materials but also for ensuring that policymakers fully understand the industry's needs and opportunities. Engaging with other stakeholders in the value chain can help align goals and create a more favorable environment for chemical recycling.

The interviewees were then asked to express their opinion on if chemical recycling would be the best option for plastic packaging manufacturers like Huhtamaki. They agreed that it is a promising option, especially when it comes to meeting food safety standards:

> *"Yes, especially since many of your products are for food contact. CR not only addresses the fossil resource issue but also helps solve the waste problem. In the long term, it's definitely worth staying actively informed."* (Interviewee 1)

> *"Absolutely. As a food packaging manufacturer, Huhtamaki's commitment to circularity aligns well with the sustainability benefits of CR. Unlike MR, CR effectively removes contaminants, making it suitable for contact-sensitive packaging and ensuring food safety."* (Interviewee 2)

> *"CR plays a very important role for packaging manufacturers, especially for securing specific recycled materials like food-contact polyolefins with pyrolysis and PET with solvolysis."* (Interviewee 7)

Interviewees emphasized that chemical recycling has a clear advantage for food packaging manufacturers. Chemical recycling can remove contaminants, making the resulting materials safe for food-contact application. This makes a strong case in favor to chemical recycling especially for companies like Huhtamaki, which requite high-quality materials that meet strict safety standards. It was also mentioned that the technology is particularly important for securing specific types of recycled materials. For example, food-contact polyolefins can be produced through pyrolysis, while solvolysis is effective for recycling PET.

Interviewees agreed that chemical recycling will probably not be the only solution for the plastics industry but rather a part of a broader toolkit. They emphasized that the industry needs different technologies to meet different needs:

> *"The future of CR is uncertain, but it's likely to play an important role. Not every company will need to be involved, just as not every car maker produces all vehicle types. Some companies may find CR essential to their strategy, while others may choose not to engage. There's no one solution that fits all."* (Interviewee 3)

> *"It is an option and should be part of the toolkit, but no single technology should dominate. As the industry evolves, multiple technologies will be essential. For high-value products, like food or pharma-grade materials, CR is critical to achieving virgin-quality material without the need of drilling new oil."* (Interviewee 4)

One interviewee pointed out that not every company will rely on chemical recycling, as strategies will vary depending on specific business goals, like car manufacturers producing different types of vehicles. Another interviewee mentioned that no single technology should dominate the market, and it will be essential that multiple approaches meet different demands. For high-value applications, such as food or pharmaceutical-grade materials, chemical recycling is critical for producing virgin-quality plastics without relying on new fossil resources, but it will be part of a broader toolkit rather than the only solution.

Interviewees shortly discussed the environmental impact of chemical recycling:

> *"Difficult to answer, but it will definitely be a significant part of circularity. But we also need to consider what is meant by sustainability. In CR we compete against using fossil feedstock, but at the same time do we have evaluations about the carbon intensity of our CR process? How much water do we use for example? These are important questions also."* (Interviewee 6)

> *"Systematically, chemical recycling reduces greenhouse gas emissions significantly compared to the current system where virgin fossil raw materials are being burned. In addition, a LCA was carried out, including an assessment of abiotic depletion potential (ADP), which measures the use of fossil raw materials. In this area, the reduction is even greater than in greenhouse gas emissions."* (Interviewee 1)

One interviewee pointed out that even though chemical recycling competes with fossil raw materials, it is important to take into account the carbon intensity of the process and other environmental factors such as the water use of the whole process. These are major issues when assessing the true sustainability of chemical recycling and there are no clear facts about it. Another interviewee mentioned that chemical recycling systematically achieves significant reductions in greenhouse gas emissions when compared to the current system, where virgin fossil feedstocks are ultimately burned. Furthermore, they highlighted that a life cycle assessment (LCA) revealed even greater reductions in abiotic depletion, which measures the consumption of fossil resources.

One important point about the principle of designing for circularity was highlighted in the following way:

> *"I would say the best way is to move towards reusable packaging by designing for circularity and prevent waste at the first point. Most of the end-of-life emissions could be avoided by a proper design for recycling. According to the European Commission, proper design for recycling could reduce end-of-life emission by 75%."* (Interviewee 5)

This interviewee emphasized the importance of first focusing on product design in order to reduce waste in the first place. They also stated that 75% of all end-of-life emissions could be reduced if a proper design for recycling and circularity would have been applied. This point takes into account the whole value chain of plastic and the importance of product design, rather than just thinking about how to recycle the product that has become waste.

5.7 Insight into volumes

The final part of the interviews explored the current volumes of chemically recycled raw material in Europe, as this information was limited to existing literature. The interviewees were asked if they had insight into the volumes. The results indicated that this is a complex question, and the information of those volumes is very limited also within the industries. The reasons for this and the possible future prospects for volume increasement were discussed.

> *"A few years ago, Europe had minimal capacity for CR. Tracking capacity remains challenging due to new plants frequently coming online, some for research and others commercial, with some shutting down. Many plants are still in pilot phases focused on research, making it hard to assess actual production capacity and utilization."* (Interviewee 3)

One interviewee explained that only a few years ago, Europe did not have that much capacity for chemical recycling. The situation has improved now but tracking the actual capacity remains very difficult. This is partly because new plants are constantly being established (some for research and others for commercial purposes) while some existing plants shut down. Additionally, many of the current facilities are still in pilot phases, focusing on testing and development rather than full-scale production. This uncertainty reflects the early stage of the chemical recycling industry in Europe, where the technology is still evolving and trying to scale up. Despite this, the potential for significant growth was acknowledged as the industry develops further and more plants transition from pilot to commercial operations.

> *"I cannot say specifically the current volumes. I believe that the volumes are still low because of regulatory uncertainty and therefore the lack of implemented investment projects."* (Interviewee 2)

> *"Extremely limited. There are very few active plants. It takes a long time for companies to capture those volumes."* (Interviewee 4)

> *"According to Plastic Europe's yearly report, the production of chemically recycled plastic is about 0,1% of European plastic."* (Interviewee 5)

> *"There is some pyrosis oil available on the European market already. Currently, quantities are limited."* (Interviewee 7)

The interviewees agreed that the current volumes of chemically recycled raw materials in Europe remain very low, reflecting both the early stage of the industry and ongoing challenges in scaling up. One interviewee pointed to regulatory uncertainty as a key barrier, explaining that the lack of clear rules has discouraged investments in large-scale projects, which has kept production volumes minimal. Another interviewee described the situation as "extremely limited," noting that only a few active plants are currently operating and that building capacity to capture significant volumes takes considerable time.

Specific figures were difficult to provide, but one interviewee referenced a report from Plastics Europe, estimating that chemically recycled plastic makes up just 0.1% of total plastic production in Europe. This highlights how small the chemical recycling sector is compared to the overall plastics industry. Another interviewee mentioned that while some pyrolysis oil is already available on the European market, the quantities are still very limited.

These responses align with earlier points about the challenges of tracking production capacity due to the mix of research-focused pilot plants and commercial facilities. They also reinforce the idea that increasing chemically recycled volumes will require clearer regulations, greater investment, and more time for the industry to mature.

> *"Overall, capacity is growing, especially with recent regulatory support pushing towards 2030. That is when we expect capacity to ramp up significantly."* (Interviewee 3)

> *"Capacity is growing, with many investment projects underway, but statistics can be misleading due to the significant gap between built and operational capacity. Since this is new technology, many facilities face startup challenges and operate below capacity for years after beginning operations."* (Interviewee 1)

> *"Availability is expected to improve in the coming years."* (Interviewee 7)

The interviewees noted that while the current volumes of chemically recycled materials in Europe are low, capacity is steadily growing, supported by recent developments in regulations. One interviewee highlighted that regulatory support is expected to drive significant increases in capacity by 2030, marking a turning point for the industry. Another

interviewee agreed with this optimism, pointing to numerous investment projects currently underway as evidence of progress.

The interviewees also emphasized that capacity growth comes with challenges. One interviewee explained that statistics on capacity can be misleading, as there is often a large gap between built and operational capacity. Many facilities face technical and operational challenges as they scale up, meaning they may operate below capacity for years after becoming operational. Despite this, another interviewee expressed confidence that availability of chemically recycled materials will improve in the coming years as the industry overcomes these initial hurdles.

These insights suggest that while the path to scaling chemical recycling is complex, the combination of growing investment and regulatory support is setting the stage for significant advancements in capacity and availability.

6 Discussion and conclusions

In this chapter, the research results are summarized by answering the research questions. In addition, recommendations for Huhtamaki and for future research are presented based on the results.

The aim of this master's thesis was to examine the maturity of chemical recycling and its relevance in the plastics value chain. The objectives of the thesis were to understand the concept of the plastics value chain and the relevant parts of it regarding chemical recycling, to understand the concept of chemical recycling, to identify the core technologies in the field, and to analyze the benefits and challenges of them. The aim of this was to get a comprehensive overview of the topic to understand what current research is saying and to interview field experts to gain more knowledge and understanding to reach the objectives. The goal was to get relevant information for the case company Huhtamaki for them to understand their possibilities and capabilities to introduce chemical recycling in their value chain. A forecast was conducted for the company to understand their resin volume needs in the future and the possible shares of chemically and mechanically recycled resin. The research supported the understanding of the current volumes and possibilities in the market now and in the future.

The literature review of the study revealed that plastic waste is a major issue for society and the planet. To solve this problem, more innovative and effective solutions than the current recycling methods are needed. Current research reveals that chemical recycling is a crucial part of the solution to reduce plastic waste and to enhance the circular economy of plastics especially when talking about food safety. However, current research also reveals that the technology is not operating at a scale yet due to several issues including the current infrastructure of waste management, feedstock availability and lack of investments.

The qualitative research found that field experts believe in this technology and want to see it grow. They mentioned that chemical recycling is crucial for the plastic industry and a necessity for circularity in the value chain of plastics. Chemical recycling was seen quite mature with its technology, but the complex legislative landscape was seen as the main barrier for getting enough investments and the clarity of material allocation by using mass

balance method. Other challenges, which were in line with the ones found in the literature review, also occurred during interviews.

6.1 Answering research questions

The first research question of the thesis was:

1. *How mature are the core technologies of chemical recycling in recycling plastics?*

The literature review supported the identification of the three core technologies of chemical recycling, which are pyrolysis, gasification and solvolysis (Collias et al., 2021; Vogel et al., 2020; Quicker et al., 2022; Jiang et al., 2022; Garcia-Gutierrez et al., 2023; Zeller et al., 2021). Although mechanical recycling is currently the primary method in Europe (Hsu et al., 2022) it has gained attraction and interest in the plastics value chain. According to this research, all these technologies face several challenges, and the technological readiness and maturity vary between them (Liu et al., 2024).

The current research indicates that pyrolysis is the most promising chemical recycling technology (Lu et al., 2024; Liu et al., 2024; Solis & Silveira, 2020) followed by gasification (Dogu et al., 2021). They both have a technical readiness level of 9/9 (Solis & Silveira, 2020). This study revealed that solvolysis was seen as the least mature technology with a technical readiness level of 4-7 (Biessey et al., 2023), although it is in fact more efficient than gasification for plastic waste. The arguments for this were that solvolysis requires government funding to be able to run profitably and it can process only limited types of monomaterial plastics such as PET, which is not cost effective (Maisels et al., 2022). Additionally, solvolysis plants are mainly not operating commercially.

Current research (Quicker et al., 2022) and the interviews indicated that pyrolysis has been around for centuries but is quite new in recycling plastic. Although the technology is mature and well-established (Liu et al., 2024), there are quite a few plants operating commercially. This study indicates that pyrolysis is likely to be the first chemical recycling technology to reach commercial scale in Europe, since the estimates are that pyrolysis will account for around 80% of installed capacity in the upcoming years. The interviews revealed that the maturity of pyrolysis comes also from the fact that it can use the energy generated by waste to its own process, making the process more efficient than others. In addition, they revealed

that there is high demand in the market for pyrolysis, which drives the industry to develop and mature even more. In addition, 60% of all plastic waste consists of polyolefins, which pyrolysis can recycle. This acts also as a driver for prioritizing the development of pyrolysis.

Gasification stays in second place due to the economic challenges it faces with needing much more capital expenditure than building a pyrolysis plant (Kingsbury, 2022; Biessey et al., 2023; Lu et al., 2024). The interviews revealed the same problem and added the issue of the lack of affordable feedstock. Additionally, it was mentioned that the energy efficiency is not great, and the technology is still developing with no commercial operation in Europe. Although the process is considered promising for heavily contaminated and unsorted plastic waste (Dogu et al., 2021) and is very flexible with feedstock, it faces too many challenges to be seen as the most mature technology.

When looking at the chemical recycling industry, the issue of commercialization comes up. According to current research commercial plants do exist, but on a very small scale (Liu et al., 2024; Cefic, n.d. b) due to quality and techno-economic issues (Lu et al., 2024; Hsu et al., 2022). The positive side is, there have been significant investments in the industry (Lu et al., 2024), and there are even more significant investments coming up (Plastics Europe, 2024b). Based on that, the industry is expected to grow rapidly in the upcoming years. The interviews revealed that the capacity in Europe has seen a significant increase, and many petrochemical and other companies are exploring chemical recycling. However, it was also mentioned that the investments are too low, and it is hard to get enough funding.

The main challenges for the maturity of chemical recycling are infrastructure, quality, capacity and policy issues. Infrastructure in collection, treatment and transport was seen as a barrier in some regions in current research (Maitlo et al., 2022; Lu et al., 2024). The interview results were in line with current research but added that pyrolysis has the advantage of building decentralized plants and thus the ability to process plastic waste closer to its source, improving efficiency and emissions reduction. Building a working infrastructure for chemical recycling takes time, and solving these will be important for the industry to grow and mature. According to current research (Peng et al., 2022) and the interviews, chemical plants are sensitive to impurities and thus chemical recycling struggles to produce high-quality end products that can be fed to post-processing facilities without any problems. Interviews revealed that pyrolysis oil often needs refining to make it purer for plants like a steam cracker.

The current research (Plastics Europe, 2024b) and interviews both mentioned a big challenge in getting enough investments for the industry due to the complexity of the current legislative landscape. It is crucial for maturing to get more clarity to some legislation such as the definition of what counts as recycling, what counts as a product or waste, and how the movement of goods in the EU works. There is a misalignment between waste and product legislation which creates problems for the industry. In addition, it was seen that the existing legislation is created mechanical recycling in mind, and chemical recycling does not fully fit in with it. However, regulatory pushes such as the EU legislation focusing on maximizing recycling efforts are seen as a driver for the industry. One specific regulation that was seen effective and as a driver for the industry is the PPWR as it sets targets for food-contact polyolefins, which aligns well with pyrolysis.

One specific part of the legislative landscape, mass balance, was seen in current research (Plastics Europe, 2020; Plastics Europe, 2024b; ISCC, 2024) and in the interview results as a crucial chain of custody method that enables the scaling up of the chemical recycling industry. It was also seen as essential for accelerating investments. The results of this study indicated that without mass balance, specifically the fuel-exempt method, the industry is not able to scale up and lots of plastic waste that cannot be mechanically recycled will end up in landfills or incineration. The main opinion across interviewees was that mass balance is needed especially in this transition phase of the industry, and after it has been able to scale up, mass balance is not needed anymore.

In conclusion, chemical recycling is technical wise mature, but faces a lot of other challenges in the plastics value chain that work as barriers for it to scale up. Pyrolysis is the most mature technology, followed by gasification with their technical maturity level. Although, they both face issues in scale and affordability. The industry is gaining attraction but remains in early stages, with limited commercialization and significant challenges in infrastructure, capacity, quality and policy. Investments are increasing, and regulatory pushes like EU recycling targets are driving growth in the industry, but unclear legislation, investment and funding difficulties hinder the progress. Mass balance is critical for scaling up and preventing plastic waste from going to landfills or incineration. Addressing these barriers is essential for the industry’s future growth.

The second research question of the thesis was:

2. *What is the relevance of chemical recycling in the plastics value chain?*

According to current research (The Consumer Goods Forum, 2022) chemical recycling is the only method currently to recycle large quantities of flexible plastics packaging. The interviews indicated that the industry will grow and be a visible part of the plastics value chain in the near future due to the capacity growth and attraction of it in the recent years. For several reasons mentioned below, chemical recycling is a key building block of the circular economy (Steilemann, n.d.) and the research part of this thesis aligned with that fact. Multiple different sources (Plastics Europe 2022; Hamilton et al., 2019; The Consumer Goods Forum, 2022; Biessey et al., 2023) and the research part indicated that chemical recycling is a better option for treating plastic waste than landfilling or incineration due to their high environmental impact. This is one of the reasons if the current attractiveness and demand for it. In addition, when comparing to mechanical recycling, chemical recycling can preserve almost the entire value of plastic waste, while mechanical recycling degrades the quality and strength, and thus preserving only 5% of it for future use (Collias et al., 2021; Tsuchimoto & Kajikawa, 2022).

When exploring mechanical recycling in more depth, it is clear what the limits of it are. It cannot handle contaminated or mixed plastic waste, and its products cannot be used in food-contact applications. Chemical recycling fills this gap since it can handle all that (European Coalition for Chemical Recycling, 2024; Dogu et al., 2021; Li et al, 2021; Kingsbury, 2022). Interviews were fully aligned with that, and the fact that it cannot fully replace mechanical recycling and must co-exist with it (Tsuchimoto & Kajikawa, 2022; Zeller et al., 2021; Dogu et al., 2021) in order to ensure a broader range of plastic waste is recycled in total.

The interviews were aligned with current research (The Consumer Goods Forum, 2022; Tukker, 2002; Huang et al., 2022; Netsch et al., 2022; Matlo et al., 2022) about the following facts. Because chemical recycling can handle the plastic waste mechanical recycling cannot, it ensures the potential to increase recycling rates of plastics. Another factor that contributes to the circular economy and sustainability in the plastics value chain is that since chemical recycling produces high-quality raw materials for plastic production, it can substitute fossil resources in various chemical synthesis processes. Additionally, chemical recycling contributes to the waste issue of plastics since its ability to recycle complex contaminated

plastics. Current research (Rizos et al., 2023; Hsu et al., 2021) also mentions that the plastic waste leakage into the environment is a significant concern, and chemical recycling helps with that.

One driver for the industry to grow is that brand owners are putting pressure on plastic producers by preferencing recycled plastics over renewable ones. This pushes the industry to grow in the near future. Another driver found is the fact that most polymers in plastic waste found are PP, PE and PET, which are suitable for pyrolysis and solvolysis technologies (Thiounn & Smith, 2020). In current research (Dogu et al., 2021; Payne & Jones, 2021) chemical recycling technologies also provide an economic advantage for the plastic value chain by requiring fewer preprocessing stages, which can be very expensive. The end products of chemical recycling typically include fuel products with high calorific value that can be sold with profit.

In conclusion, chemical recycling plays a crucial role in the plastics value chain, because it can recycle materials which mechanical recycling cannot such as contaminated and mixed plastics. Additionally, it can produce high-quality products that are suitable for food-contact applications in which mechanically recycled plastics cannot be utilized. It therefore plays a key role in increasing recycling rates and decreasing plastic waste amounts and their possible toxic leakage to the environment. The industry is expected to grow, because demand is rising, capacity increasing and brand owners are pushing to prioritize recycled plastics. In addition, chemical recycling provides economic advantages by minimizing preprocessing expenses and producing valuable products, which will drive further uptake and development.

The third research question of the thesis was:

3. *What is the potential of introducing chemical recycling into Huhtamaki's operations?*

The results from the interviews indicated that chemical recycling has a clear advantage for food packaging manufacturers since it produces products suitable for food-contact applications. This makes a strong case in favor to chemical recycling especially for companies like Huhtamaki, which requite high-quality materials that meet strict safety standards. It was also stated that companies do not want to get associated with plastic waste, and chemical recycling could be a great fit for those companies to be introduced in their value chain. Hsu et al. (2022) and the interviews highlighted the importance of communication and collaboration between stakeholders in the plastics value chain. It was

seen essential in order to not only secure access to chemically recycled materials but also for ensuring that policymakers understand the needs and opportunities of the industry. Collaboration and engagement in the value chain helps align goals and create a better environment for chemical recycling.

Huhtamaki can start the introduction of chemical recycling in their value chain by having discussions with their existing polymer suppliers and other petrochemical producers about available materials in the market. Many polymer producers are already involved in chemical recycling, which makes it easy to start there. Expressing interest in the materials to suppliers can help signal demand and encourage further development in the field. It also provides valuable insights into market demand and helps suppliers understand the specific materials Huhtamaki is seeking. It was also mentioned that if Huhtamaki wants to drive change and differentiate themselves from other, they need to be innovating and seeking for bigger opportunities in the field of chemical recycling.

Another good point in current research (Ellen MacArthur Foundation, 2013, Johansen et al., 2022; Nielsen et al., 2020; Eriksen et al., 2020) and from the qualitative research of this study was that companies like Huhtamaki should start from developing their product design. Design for circularity and recycling supports the whole industry by having more feedstock to be recycled, and by preventing plastic waste from getting landfilled or incinerated, or even leaked to the environment. 75% of all EoL emissions could be reduced if a proper design for recycling and circularity is applied to plastic products. This takes the whole plastics value chain into account rather than just thinking about how to recycle the product that has become waste.

The PPWR is a hot topic, and it requires packaging manufacturers like Huhtamaki to make changes in their product's raw materials. By 2030, a minimum of 10% of plastic in packaging must contain contact sensitive raw material and 35% non-contact sensitive raw material (European Parliament, 2024c). This pushes also Huhtamaki to act toward the world of chemical recycling, since their products contain approximately 90% of PE and 10% of PP, which are the main feedstock for the most mature chemical recycling technology pyrolysis.

In the forecast (Table 2) for Huhtamaki, it was calculated that if Huhtamaki wants to reach the PPWR targets of contact-sensitive and non-contact sensitive resin shares in their EU operations in 2030, they will need to procure 12 323 tonnes of chemically recycled resin and

43 130 tonnes mechanically recycled resin. The interviews highlighted the complexity of tracking the current chemically recycled volumes of raw material, since only a few active plants are currently operating and that building capacity to capture significant volumes takes time due to the challenges faced in the industry. No confirmation about volume amounts was received, but the volumes were described as ‘extremely limited’ and ‘very low’. Numerous investments and projects are currently underway as evidence of progress. For example, thirteen EU countries are currently planning 44 different projects that could potentially produce 2.8 million tonnes of chemically recycled material per year by 2030 (Plastics Europe, 2024b). Regulatory support, especially mass balance, is expected to drive significant increases in the capacities by 2030, which seems very promising for Huhtamaki.

In conclusion, chemical recycling offers Huhtamaki a clear advantage since it can provide food-grade materials which meet the company’s needs. Collaboration with suppliers and stakeholders in the plastics value chain is important in order to ensure the availability of these materials and influence the development of the industry. Engaging with polymer suppliers already involved in chemical recycling can help Huhtamaki to communicate their demand and gain insight into the market. Additionally, designing products for recycling and circularity supports growth of the chemical recycling industry and helps reduce waste and emissions at the same time. Achieving regulatory targets such as the PPWR will also drive Huhtamaki toward adopting chemically recycled materials, even if current volumes are limited. Promising investments and capacity expansions point to future opportunities for the company.

6.2 Recommendations for Huhtamaki

Based on the results of this research, the following actions are recommended for Huhtamaki as next steps:

- Indicate discussions with existing polymer suppliers and petrochemical producers already involved in chemical recycling to secure a steady supply of recycled materials and signal your demand for further development
- Promote the design for circularity and adopt the principle by enhancing products that has not been designed in that way

- Stress to innovation and product development teams the importance of designing for circularity to ensure the development of new products are aligned to the principle
- Track ongoing investments and capacity expansions in chemical recycling across Europe. Position the company to benefit from the projected increases in availability by 2030.
- Strategically plan to meet the PPWR's resin composition targets by 2030 by establishing strategic sourcing agreements with suppliers capable of providing chemically and mechanically recycled polymers
- Collaborate with chemical recycling technology providers and industry consortia to work together toward a common goal: the growth of chemical recycling volumes. Engage also with policymakers to promote regulations and incentives that support chemical recycling. Advocacy can accelerate the development of a robust infrastructure and reduce operational barriers of the industry.

6.3 Future research

Future research should explore the current chemical recycling volumes in depth, specifically for pyrolysis. The interviewees were asked about current volumes, but they did not have specific numerical insight into that. The study focused more on the technology itself, and thus future research could examine specific numbers of volumes by interviewing polymer producers.

Other chemical recycling technologies could be assessed in future research, since this thesis focused only on pyrolysis, gasification and solvolysis. Although, these were the mostly discussed and developed ones, so that might not make that much sense. It would still be worth to have a look into other techniques as well if any niche option is needed.

Future research could also examine the environmental effects of chemical recycling technologies in more specific. That could be in a form of a Lifecycle Assessment (LCA) including greenhouse gas emission, energy use, water use and resource efficiency.

References

Alassali, A., Picuno, C., Chong, Z. K., Guo, J., Maletz, R. & Kuchta, K. 2021. Towards Higher Quality of Recycled Plastics: Limitations from the Material's Perspective. Vol. 13, no. 23, p. 13266-13266.

Amadei, A. M., Rigamonti, L. & Sala, S. 2023. Exploring the EU plastic value chain: A material flow analysis. *Resources, conservation and recycling*. Vol. 197, p. 107105-.

Babayemi, J. O., Nnorom, I. C., Osibanjo, O. & Weber, R. 2019. Ensuring sustainability in plastics use in Africa: consumption, waste generation, and projections. Environmental sciences Europe. Vol. 31 no. 1, p. 1–20.

Biessey, P., Vogel, J., Seitz, M. & Quicker, P. 2023. Plastic Waste Utilization via Chemical Recycling: Approaches, Limitations, and the Challenges Ahead. Chemie ingenieur technik. Vol. 95, no. 8, p. 1199–1214.

Bridgwater, A. V. 2012. Review of fast pyrolysis of biomass and product upgrading. Biomass & bioenergy. Vol. 38, p. 68–94.

Bucknall, D. G. 2020. Plastics as a materials system in a circular economy. Plastics in the Circular Economy. Vol. 378, no. 2176.

CDE. 2021. Plastic waste and recycling in the EU: facts and figures. [Referred: 27.5.2024]. Available: https://www.cde.ual.es/en/plastic-waste-and-recycling-in-the-eu-facts-and-figures/

Cefic. No date a. Depolymerisation: Breaking it down to basic building blocks. [Referred: 6.8.2024]. Available: https://cefic.org/a-solution-provider-for-sustainability/chemical-recycling-making-plastics-circular/chemical-recycling-via-depolymerisation-to-monomer/

Cefic. No date b. Top Questions About Chemical Recycling. [Referred: 11.9.2024]. Available: https://cefic.org/a-solution-provider-for-sustainability/chemical-recycling-making-plastics-circular/top-questions-about-chemical-recycling/

Ciuffi, B., Chiaramonti, D., Rizzo, A. M., Frediani, M. & Rosi, L. 2020. A Critical Review of SCWG in the Context of Available Gasification Technologies for Plastic Waste. Vol. 10, no. 18, p. 6307-.

Collias, D. I., James, M. I., & Layman, J. M. 2021. Introduction – Circular Economy of Polymers and Recycling Technologies. In Circular Economy of Polymers: Topics in Recycling Technologies. ACS Symposium Series; American Chemical Society: Washington, DC. P. 1-21.

Daphne, T. & Ahmed, N. 2024. Mass balance for plastics: Different methods that advance chemical recycling [Referred: 6.9.2024]. Available: https://www.circularise.com/blogs/mass-balance-for-plastics-different-methods-that-advance-chemical-recycling

Delva, L., Van Kets, K., Kuzmanovic, M., Demets, R., Hubo, S., Mys, N., De Meester, S. & Ragaert, K. 2019. Mechanical Recycling of Polymers for Dummies. Capture - Plastics to Resource.

Delva, L., Hubo, S., Cardon, L. & Ragaert, K. 2018. On the role of flame retardants in mechanical recycling of solid plastic waste. *Waste management (Elmsford)*. Vol. 82, p. 198–206.

Deutsche Recycling. 2024. PPWR: A closer look at the EU Packaging Regulation. [Referred: 4.6.2024]. Available: https://deutsche-recycling.com/blog/ppwr-explained/

Dogu, O., Pelucchi, M., Van de Vijver, R., Van Steenberge, P. H. M., D'hooge, D. R., Cuoci, A., Mehl, M., Frassoldati, A., Faravelli, T. & Van Geem, K. M. 2021. The chemistry of chemical recycling of solid plastic waste via pyrolysis and gasification: State-of-the-art, challenges, and future directions. Progress in energy and combustion science. Vol. 84, p. 100901-.

Dominko, M., Primc, K., Slabe-Erker, R. & Kalar, B. 2023. A bibliometric analysis of circular economy in the fields of business and economics: towards more action-oriented research. Environment, development and sustainability. Vol. 25, no.7, p. 5797–5830.

Ellen MacArthur Foundation. 2013. Towards The Circular Economy. Vol. 1: Economic and business rationale for an accelerated transition.

Ellen MacArthur Foundation. No date. Enabling a circular economy for chemicals with the mass balance approach. A white paper from co.project mass balance.

Ellen MacArthur Foundation & McKinsey. 2016. The New Plastics Economy: Rethinking the future of plastics. World Economic Forum.

Eriksen, M.K., Pivnenko, K., Faraca, G., Boldrin, A. & Astrup, T.F. 2020. Dynamic material flow analysis of PET, PE, and PP flows. In Europe: evaluation of the potential for circular economy. Environ. Sci. Technol. Vol. 54, no. 24, p. 16166–16175.

EU Monitor. 2023. Waste management in the EU: infographic with facts and figures. [Referred: 27.5.2024]. Available: https://www.eumonitor.eu/9353000/1/j9vvik7m1c3gyxp/vknekgghpfwm?ctx=vg9pjk198axu

EuRIC. 2023. European recyclers' stance on chemical recycling, mass balance, and the true essentials to fuel the EU circular economy. EuRIC Position paper. European Recycling Industries' Confederation

European Coalition for Chemical Recycling. 2024. Chemical Recycling. [Referred: 8.7.2024]. Available: https://www.coalition-chemical-recycling.eu/#chemicalrecycling

European Commission. 2023. Packaging Waste. [Referred: 3.6.2024]. Available: https://environment.ec.europa.eu/topics/waste-and-recycling/packaging-waste_en

European Environment Agency. 2023. Plastics. [Referred: 15.4.2024]. Available: https://www.eea.europa.eu/en/topics/in-depth/plastics?activeAccordion=

European Parliament. 2024a. No title. [Referred: 3.6.2024]. Available: https://www.europarl.europa.eu/doceo/document/TA-9-2024-0318_EN.html#title2

European Parliament. 2024b. No title. [Referred: 4.6.2024]. Available: https://www.europarl.europa.eu/doceo/document/PV-9-2024-04-24-ITM-007-05_EN.html

European Parliament. 2024c. European Parliament resolution of 24 October 2024 on the proposal for a regulation of the European Parliament and of the Council on packaging and packaging waste (PPWR) (TA-9-2024-0318). [Referred: 25.11.2024] Available: https://www.europarl.europa.eu/doceo/document/TA-9-2024-0318_EN.html

European Parliament. 2024d. New EU rules to reduce, reuse and recycle packaging. [Referred: 3.6.2024]. Available: https://www.europarl.europa.eu/news/en/press-room/20240419IPR20589/new-eu-rules-to-reduce-reuse-and-recycle-packaging

European Parliament. 2023. Plastic waste and recycling in the EU: facts and figures. [Referred: 13.5.2024]. Available: https://www.europarl.europa.eu/topics/nl/article/20181212STO21610/plastic-afval-en-recycling-in-de-eu-feiten-en-cijfers

European Parliament & Council. 2018. Directive (EU) 2018/852 of the European Parliament and of the Council of 30 May 2018 amending Directive 94/62/EC on packaging and packaging waste. Official Journal of the European Union.

European Union. No date. Types of legislation. [Referred: 4.6.2024]. Available: https://european-union.europa.eu/institutions-law-budget/law/types-legislation_en

Eurostat. 2023. EU packaging waste generation with record increase. [Referred: 27.5.2024]. Available: https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20231019-1

Eze, W. U., Umunakwe, R., Obasi, H. C., Ugbaja, M. I., Uche, C. C. & Madufor, I. C. 2021. Plastics waste management: A review of pyrolysis technology. Clean Technologies and Recyling. Vol. 1, no. 1, p. 50-69.

Gabisa, E.W., Ratanatamskul, C. & Gheewala, S. H. 2023. Recycling of Plastics as a Strategy to Reduce Life Cycle GHG Emission, Microplastics and Resource Depletion. Sustainability. Vol. 15, p. 11529-.

Garcia-Gutierrez, P., Amadei, A. M., Klenert, D., Nessi, S., Tonini, D., Tosches, D., Ardente, F. & Saveyn, H. 2023. Environmental and economic assessment of plastic waste recycling, EUR 31423 EN, Publications Office of the European Union, Luxembourg.

Geyer, R., Jambeck, J. R. & Law, K. L. 2017. Production, use, and fate of all plastics ever made. Sci Adv. Vol. 3, no. 7.

Hamilton, L. A., Feit, S., Muffet, C., Kelso, M., Rubright, S. M., Bernhardt, C., Schaeffer E., Moon, D., Morris, J. & Labbé-Bellas, R. 2019. Plastic & Climate, The Hidden Costs of a Plastics Planet. Geneva: Center for International Environmental Law (CIEL).

Hsu, W.-T., Domenech, T. & McDowall, W. 2022. Closing the loop on plastics in Europe: The role of data, information and knowledge. Sustainable production and consumption. Vol. 33, p.942–951.

Hsu, W.-T., Domenech, T. & McDowall, W. 2021. How circular are plastics in the EU?: MFA of plastics in the EU and pathways to circularity. Cleaner Environmental Systems Vol. 2, p. 100004-.

Huang, J., Veksha, A., Chan, W. P., Giannis, A. & Lisak, G. 2022. Chemical Recycling of Plastic Waste for Sustainable Material Management: A Prospective Review on Catalysts and Processes. Renewable & sustainable energy reviews. Vol. 154, p. 111866-.

Huhtamaki. 2024a. Huhtamaki in brief. [Referred: 13.6.2024]. Available: https://www.huhtamaki.com/en/about/

Huhtamaki. 2024b. Annual Report 2023. Huhtamaki. [Referred: 13.6.2024]. Available: https://ml-eu.globenewswire.com/Resource/Download/3bb153f6-b92b-4746-af92-7511e7e59fad

Huhtamaki. 2024c. Values and direction. [Referred: 13.6.2024]. Available: https://www.huhtamaki.com/en/about/values-and-direction/

Huhtamaki. 2024d. Our history. [Referred: 13.6.2024]. Available: https://www.huhtamaki.com/en/about/our-history/

Huhtamaki. 2024e. Innovations for a circular world - 2023 highlights. [Referred: 13.6.2024]. Available: https://www.huhtamaki.com/en/highlights/sustainability/innovations-for-a-circular-world-2023-highlights/

Inigo, M., Jameson, J., Kozak, K., Lanzetta, M. & Sonier, K. No date. Exponential growth. In College mathematics for everyday life. [Referred: 25.11.2024]. Available: https://math.libretexts.org/Bookshelves/Applied_Mathematics/Book%3A_College_Mathematics_for_Everyday_Life_(Inigo_et_al)/04%3A_Growth/4.02%3A_Exponential_Growth

ISCC. 2024. Mass Balance Explained. [Referred: 5.9.2024]. Available: https://www.iscc-system.org/news/mass-balance-explained/

ISCC. No date. ISCC Certified Materials are Tracked Along the Supply Chain. [Referred: 6.9.2024]. Available: https://www.iscc-system.org/certification/chain-of-custody/mass-balance/

ISO 22095:2020 Chain of Custody standard. Switzerland: International Organization for Standardization.

Jiang, J., Shi, K., Zhang, X., Yu, K., Zhang, H., He, J., Ju, Y. & Liu, J. 2022. From plastic waste to wealth using chemical recycling: A review. Journal of environmental chemical engineering. Vol. 10, no.1, p. 106867-.

Johansen, M. R., Christensen, T. B., Ramos, T. M. & Syberg, K. 2022. A review of the plastic value chain from a circular economy perspective. Journal of environmental management. Vol. 302 (Pt A), p. 113975–113975.

Kingsbury, T. 2022. Chemical Recycling Types: Advantages and Disadvantages. GLG Betwork Member and former Director of Sustainability. Energy and Industrials. [Referred: 24.5.2024]. Available: https://glginsights.com/articles/chemical-recycling-types-advantages-and-disadvantages/

Kossovsky, A. E. 2019. Exponential Growth Series and Benford's Law. *arXiv.org*.

Kusenberg, M., Eschenbacher, A., Delva, L., De Meester, S., Delikonstantis, E., Stefanidis, G. D., Ragaert, K. & Van Geem, K. M. 2022. Towards high-quality petrochemical feedstocks from mixed plastic packaging waste via advanced recycling: The past, present and future. Fuel processing technology. Vol. 238, p. 107474-.

Li, H. et al. 2022. Expanding plastics recycling technologies: chemical aspects, technology status and challenges. Green Chemistry: An International Journal and Green Chemistry Resource : GC, Vol. 24, no. 23, p. 8899–92.

Li, W. C., Tse H. F., Fok, L. 2016. Plastic waste in the marine environment: A review of sources, occurrence and effects. Science of the Total Environment. Vol. 566-567, p. 333-349.

Liu, Q., Martinez-Villarreal, S., Wang, S., Ngoc Thanh Tien, N., Kammoun, M., De Roover, Q., Len, C. & Richel, A. 2024. The role of plastic chemical recycling processes in a circular

economy context. *Chemical Engineering Journal (Lausanne, Switzerland : 1996)*. Vol. 498, p. 155227-.

Lu, J., Wang, P., Gao, X., Han, M., Li, G., & Chen, W.-Q. 2024. Challenges in chemical recycling of plastics amid global plastic treaty. *Resources, Conservation and Recycling*. Vol. 205, p. 107569-.

LUT. 2023. AI-based tools policies. Guidance for students on using AI applications in their studies at LUT University. [Referred: 14.11.2024]. Available: https://elut.lut.fi/en/completing-studies/rules-and-regulations/ai-based-tools-policies

Luu, P. 2023. What is chemical recycling, why does it have so many different names, and why does it matter? Closed Loop Partners. [Referred: 4.6.2024]. Available: https://www.closedlooppartners.com/what-is-chemical-recycling-why-does-it-have-so-many-different-names-and-why-does-it-matter/

Maisels, A., Hiller, A., & Simon, F. 2022. Chemical Recycling for Plastic Waste: Status and Perspectives. ChemBioEng reviews. Vol. 9, no. 6, p. 541–555.

Maitlo, G., Ali, I., Maitlo, H. A., Ali, S., Unar, I. N., Ahmad, M. B., Bhutto, D. K., Karmani, R. K., Naich, S.u.R., Sajjad, R. U., et al. 2022. Plastic Waste Recycling, Applications, and Future Prospects for a Sustainable Environment. Sustainability. Vol, 14, 11637.

McKinsey & Company. 2022. Addressing the challenges of plastic waste: Circularity and leakage. [Referred: 18.4.2024]. Available: https://www.mckinsey.com/industries/chemicals/our-insights/addressing-the-challenges-of-plastic-waste-circularity-and-leakage

Nageler-Petritz, H. 2023. “Chemical recycling is one part of the overall solution to the problem of plastic waste”. Waste Management World. [Referred: 8.7.2024] Available: https://waste-management-world.com/resource-use/chemical-recycling-is-one-part-of-the-overall-solution-to-the-problem-of-plastic-waste/

Netsch, N., Simons, M., Feil, A., Leibold, H., Richter, F., Slama, J., Yogish, S. P., Greiff, K. & Stapf, D. 2022. Recycling of polystyrene-based external thermal insulation composite systems – Application of combined mechanical and chemical recycling. Waste management (Elmsford). Vol. 150, p.141–150.

Nielsen, T.D., Hasselbalch, J., Holmberg, K. & Stripple, J. 2020. Politics and the Plastic Crisis: A Review throughout the Plastic Life Cycle. In: Wiley Interdisciplinary Reviews: Energy and Environment. Vol. 9, no. 1.

Jansen, W. & Ayers, R. 2004. Guidelines on PDA Forensics. Recommendations of the National Institute of Standards and Technology. National Institute of Standards and Technology. Special Publication 800-72.

Packaging Europe. 2023. Mass balance fuel-use exempt necessary to scale up chemical recycling, says plastics supply chain. [Referred: 5.9.2024]. Available: https://packagingeurope.com/news/mass-balance-fuel-use-exempt-necessary-to-scale-up-chemical-recycling-says-plastics-supply-chain/10471.article

Packaging Europe. 2022a. European plastic mechanical recycling rate at 23%, says AMI. [Referred: 23.5.2024]. Available: https://packagingeurope.com/news/european-plastic-mechanical-recycling-rate-at-23-says-ami/7933.article

Packaging Europe. 2022b. Pyrolysis: clearing the air around chemical recycling. [Referred: 18.7.2024]. Available: https://packagingeurope.com/comment/pyrolysis-clearing-the-air-around-chemical-recycling/8846.article

Packaging Insights. 2023. EU urged to adopt mass balance fuel-use exempt method to boost chemical recycling. [Referred: 6.9.2024]. Available: https://www.packaginginsights.com/news/eu-urged-to-adopt-mass-balance-fuel-use-exempt-method-to-boost-chemical-recycling.html

Paletta, A. et al. 2019. Barriers and challenges to plastics valorisation in the context of a circular economy: Case studies from Italy. Journal of cleaner production. Vol. 241, p. 118149-.

Payne, J. & Jones, M. D. 2021. The Chemical Recycling of Polyesters for a Circular Plastics Economy: Challenges and Emerging Opportunities. ChemSusChem. Vol. 14, no. 19, p. 4041–4070.

Peng, Y., Wang, Y., Ke, L., Dai, L., Wu, Q., Cobb, K., Zeng, Y., Zou, R., Liu, Y. & Ruan, R. 2022. A review on catalytic pyrolysis of plastic wastes to high-value products. Energy conversion and management. Vol. 254, p. 115243-.

Plastics Europe. 2024a. Recycling. [Referred: 21.5.2024]. Available: https://plasticseurope.org/sustainability/circularity/recycling/

Plastics Europe. 2024b. Chemical Recycling and Mass Balance explained. [Referred: 5.9.2024]. Available: https://plasticseurope.org/knowledge-hub/chemical-recycling-mass-balance-explained/

Plastics Europe. 2024c. Chemical Recycling. [Referred: 6.7.2024]. Available: https://plasticseurope.org/sustainability/circularity/recycling/chemical-recycling/

Plastics Europe. 2022. The facts – 2022. Brussels: Plastics Europe.

Plastics Europe. 2020. MASS BALANCE APPROACH TO ACCELERATE THE USE OF RENEWABLE FEEDSTOCKS IN CHEMICAL PROCESSES. [Referred: 5.9.2024]. Available: https://plasticseurope.org/knowledge-hub/mass-balance-approach-to-accelerate-the-use-of-renewable-feedstocks-in-chemical-processes/

Quicker, P., Seitz, M. & Vogel, J. 2022. Chemical recycling: A critical assessment of potential process approaches. Waste Management & Research. Vol. 40, no. 10, p. 1494–1504.

Ragaert, K., Delva, L. & Van Geem, K. 2017. Mechanical and chemical recycling of solid plastic waste. Waste management (Elmsford). Vol. 69, p. 24–58.

Ritzén, S. & Sandström, G. O. 2017. Barriers to the circular economy: Integration of perspectives and domains. Procedia CIRP. Vol. 64, p. 7–12.

Rizos, V., Urban, P., Righetti, E. & Kassab, A. 2023. Chemical recycling of plastics. Technologies, trends and policy implications. CEPS in-depth analysis. Brussels.

SABIC. 2024. About. [Referred: 19.11.2024]. Available: https://www.sabic.com/en/about

Siltaloppi, J. & Jähi, M. 2021. Toward a sustainable plastics value chain: Core conundrums and emerging solution mechanisms for a systemic transition. Journal of cleaner production. Vol. 315, p. 128113-.

Solis, M. & Silveira, S. 2020. Technologies for chemical recycling of household plastics – A technical review and TRL assessment. Waste management (Elmsford). Vol. 105, p. 128–138.

Statista. 2024. Sorting for recycling rates of polyethylene terephthalate (PET) in Europe in 2022, by type. [Referred: 19.8.2024]. Available: https://www.statista.com/statistics/1316826/recycling-rate-of-pet-products-europe/

Steilemann, M. No date. Former Plastics Europe President and CEO of Covestro. Published in Plastics Europe. [Referred: 4.6.2024]. Available: https://plasticseurope.org/sustainability/circularity/recycling/chemical-recycling/

Sunderland, P. 2011 'Polymer Matrix Composites, Recycling of', in Encyclopedia of Materials: Science and Technology. Elsevier Ltd. pp. 7396–7399.

Szaky, T. 2019. The future of packaging: from linear to circular. First edition. Oakland, Calif: Berrett-Koehler Publishers, Inc. P. 9-21

The Consumer Goods Forum. 2022. Chemical Recycling in a Circular Economy for Plastics. A Vision and Principles Paper.

Thiounn, T. & Smith, R. C. 2020. Advances and approaches for chemical recycling of plastic waste. *Journal of polymer science (2020)*. Vol. 58, no. 10, p. 1347–1364.

TraceX. 2023. Understanding the Plastic Value Chain. [Referred: 23.4.2024]. Available: https://www.tracextech.com/understanding-plastic-value-chain/

Tsuchimoto, I. & Kajikawa, Y. 2022. Recycling of Plastic Waste: A Systematic Review Using Bibliometric Analysis. Sustainability. Vol. 14, no. 24, 16340.

Tukker, A. 2002. Plastics waste feedstock recycling, chemical recycling and incineration. Shawbury, U.K: Rapra Technology Ltd.

TWI. 2024. What is mechanical recycling? [Referred: 15.8.2024]. Available: https://www.twi-global.com/technical-knowledge/faqs/what-is-mechanical-recycling#WhataretheStepsofMechanicalRecycling

UNEP. 2023. Everything you need to know about plastic pollution. UN Environment Programme. [Referred: 15.4.2024]. Available: https://www.unep.org/news-and-stories/story/everything-you-need-know-about-plastic-pollution

Unesda. 2022. PET collection rates across Europe. [Referred: 19.8.2024]. Available: https://www.unesda.eu/pet-collection-rates/

UPM. 2024. New EU packaging rules are almost here. [Referred: 4.6.2024]. Available: https://www.upm.com/articles/public-affairs/24/new-eu-packaging-rules-are-almost-here/

Vogel, J., Krueger, F. & Fabian, M. 2020. Chemical Recycling. German Environment Agency. [Referred: 7.6.2024]. Available: https://www.umweltbundesamt.de/sites/default/files/medien/5750/publikationen/hgp_chemischesrecycling_englisch_bf.pdf

Vollmer, I., Jenks, M. J. F., Roelands, M. C. P., White, R. J. Harmelen, T., Wild, P. G. P. Meier, F., Keurentjes, J. T. F. & Weckhuysen, B. M. 2020. Beyond Mechanical Recycling: Giving New Life to Plastic Waste. Angewandte Chemie (International ed.). Vol. 59, no. 36, 15402–15423.

Warringa, G., Bergsma, G., Bouwman, P. & Broeren, M. Impacts of allocation rules on chemical recycling. Consequences on the environment and maximum circularity of plastics.

Zeller, M., Netsch, N., Richter, F., Leinold, H. & Stapf, D. 2021. Chemical Recycling of Mixed Plastic Wastes by Pyrolysis – Pilot Scale Investigations. Chemie ingenieur technik. Vol. 93, no. 11, p. 1763–1770.

Zero Waste Europe. 2021. Recycled content in plastics – the mass balance approach. [Referred: 5.9.2024]. Available: https://zerowasteeurope.eu/library/recycled-content-in-plastics-the-mass-balance-approach/

Appendix 1. Interview questions

1. What is your expertise in the chemical recycling environment?
2. How mature are the core technologies (pyrolysis, gasification, solvolysis) of chemical recycling in your point of view?
3. What do you see as the future of chemical recycling in the plastics value chain over the next 5-10 years?
4. Which technique do you think holds the most promise for scaling up, and why?
5. Can you point out the main gaps/challenges of chemical recycling technologies that need to be addressed for it to be scaled up?
6. What about the benefits of the technologies?
7. Are there any specific regulations that you believe are particularly effective or problematic for the chemical recycling industry?
8. Do you see a connection between mass balance method and scaling up chemical recycling? What is the role of mass balance?
9. How could plastic packaging manufacturers introduce chemical recycling in their value chain? What are the opportunities for manufacturers in the chemical recycling field?
10. In your opinion, would chemical recycling be the best option for plastic packaging manufacturers like Huhtamaki in the context of moving toward circularity?
11. Do you have insights on the current volumes of chemically recycled raw materials in Europe? What volumes could for example a plastic packaging manufacturer like Huhtamaki potentially buy for its own production?