Plastic circular economy in the EU:

Material Flow Analysis and Transition Analysis

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A thesis submitted in partial fulfilment

of the requirements for the degree of

Doctor of Philosophy

of

University College London

Institute for Sustainable Resources

Bartlett School of Environment, Energy and Resources

University College London

2023

Declaration

I, Wan-Ting Hsu, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Acknowledgements

I would like to sincerely thank everyone who has supported me during this PhD journey. This thesis would not have been possible without the support, guidance, and company from you all.

First of all, I would like to thank my supervisors, Dr Will McDowall and Dr Teresa Domenech, for their continuous support, supervision, care, encouragement, and inspiration, and for giving me helpful feedback on this thesis. I would also want to thank my upgrade panels, Prof Raimund Bleischwitz and Prof Julia Stegemann, for the discussions on structuring this thesis at the early stage.

I would like to express my heartfelt thanks to all interviewees for providing their valuable time and sharing their experiences and knowledge with me. I am deeply grateful to Adrian Whyle from Plastics Europe and Janis Winzer from Fraunhofer IZM and Anca David for their guidance on the potential interviewees. Moreover, I would like to thank Emile Van Eygen from TU Wien for sharing with me his vast experience in and knowledge of plastic material flow analysis. I wish to express my gratitude to Keith Freegard for his assistance in providing information on recycling losses for the material flow analysis. Thanks also to Yekatherina Bobrova, Seigo Robinson, Ke Zhou, Robert Lee and Krishna Mohan Thazhathu Valiyaveettil for discussing the causal loop diagrams with me.

My brilliant fellow PhD students and colleagues at UCL made this PhD journey fun and enjoyable. I would like to thank them for their company and insightful conversations, especially Arkaitz Usubiaga-Liaño, Stijn van Ewijk, Tony Carr, Alexandros Sfyridis, Theodoros Arvanitopoulos, Simon Damkjaer, Seigo Robinson, Chris Kim, Kentaro Mayr, Zein Khraizat, Diana Ramirez Soto, Haoning Liu, Miguel Casas-Arredondo, Ke Zhou, Xin Chen, Yuchen Yang, Ke-Ting Pan, and Shih-Che Hsu. I would like to express my deepest gratitude to Rob Liddiard who always incredibly supports me in countless ways.

I would also like to show my appreciation to my friends who I met at National Taiwan University, Kuang-Ly Cheng, and Yu-Jung Liu, for exchanging their PhD experiences and discussions on the circular economy issues. I would also want to thank Marc Anthony who is the independent Editor-at-Large at the Academic Writing Education Centre for the coaching on academic writing from the beginning of preparing this PhD application to the end of proofreading this thesis.

Pursuing this PhD has been a lonely and challenging journey, I am extremely grateful to those who support me in maintaining my mental health. Especially, my therapist, Stéphan Barette from The Association of Group and Individual Psychotherapy (AGIP), who listens to all my struggles and achievements, reminds me to be kind to myself, and gives me so much professional support, warmth and care. I would also like to thank all my friends from F45 Camden, F45 Nottingham Waterside and the UCL hiking club who give me so much positive energy and encouragement.

At the writing up stage, I am thankful to my line manager at the British Geological Survey, Dr Evi Petavratzi, showing her understanding and encouraging me to complete writing this PhD thesis, whilst also working as a full-time material flow research analyst. Thanks also go to Nadine Slater from Equality Focus – sponsored by UCL Student Support and Wellbeing team – for mentoring me in making plans for writing this thesis.

I also want to thank the readers who open this thesis and read it. You made my PhD work worth it. I hope you find some interesting and helpful information.

Finally, I would like to thank Mathew Hutton and Robert Lee who have always believed in me and incredibly supported me in many ways with their warm hearts. I must express my deep gratitude to my mother for her support to me in pursuing this PhD abroad.

'PhD life in plastic, it is fantastic!' My curiosity about the plastic circular economy started when some friends and I made Precious Plastic machines and organised an exhibition in Taiwan. My PhD research was driven by curiosity and determination for knowledge inspired by 2015 Conference of the International Society for Industrial Ecology, held in Surrey, UK. I believe the training and inspiration on this PhD journey at UCL have enhanced my passion for promoting a circular economy and sustainable resource management, and will continue in my future life journey.

Abstract

Plastic is valued for its versatility, but concerns have been raised over the environmental impacts of plastic waste. A more in-depth investigation of the plastic system is still needed to understand current flows and factors to close the plastic cycle.

This research applied a material flow analysis (MFA) and transition analysis (TA), using multilevel perspectives, to the plastic circular economy transition in the EU. The MFA covers over 400 categories of plastic-containing products with a detailed analysis of the final destination of waste. The TA identifies the interaction of barriers and drivers to use secondary plastics, with a focus on the regime level along the plastic value chain.

The MFA results indicate the EU produced over 66 million tonnes (Mt) of plastic polymers/fibres and an estimated consumption for plastic products of 73 Mt in 2016. Plastic waste increases amounted to over 37 Mt, and a significant amount of plastic waste was not recovered back into plastics in the EU. The uncertainty analysis of MFA highlights important data quality issues that need to be addressed.

To understand why using secondary plastics presents challenges, the TA mapped the factors across policies and standards, markets and business models, technology, and consumer preferences and behaviours that create a web of constraints and a web of drivers. TA results highlight that data-information-knowledge is the key gap as most of the aspects are cross-cutting. Different actors are involved in new business networks and play multiple roles in driving the co-evolutionary dynamic.

The thesis concludes that significant data gaps need MFA-based knowledge to inform policies that address the barriers and the potential socio-technical changes that can reshape plastic flows. The cases playing out across the whole value chain and four different application areas provide insights that are potentially more widely applicable to the circular economy transition processes in Europe.

Impact Statement

This PhD research project has applied material flow analysis (MFA), and transition analysis (TA) based on a multi-level perspective.

For the material flow analysis, this study applies a comprehensive MFA to quantify the plastic flows in the EU. It has two core areas of novelty: i) it is based on a more detailed product-by-product analysis than previous publications, and ii) it provides a detailed exploration of end-of-life destinations of plastic waste and estimation of losses. This part of the research has been published in the *Journal of Cleaner Environmental Systems* and identified as one of the articles having a wide impact on the field by the publisher. This has resulted in the establishment of new connections with researchers worldwide, including with those who have cited this paper, as well as a consultancy, a charity, and a recycling company to discuss material flow analysis methodology and plastic circular economy issues. At the point of publication of this thesis, the article has at least 37 citations. Of particular significance, this work has been cited in European Commission and European Environment Agency policy documents. The MFA dataset and results have also been used to further estimate plastic footprints in Europe by other research groups and further extend plastic MFA modelling by European Commission, Joint Research Centre.

In addition, the MFA results were referred to in a circular economy workshop and have been used as teaching materials for a UCL MSc module. Based on this MFA framework, I have also collaborated with UCL's Plastic Waste Innovation Hub to extend the plastic material flow analysis for another UK-based research project.

For the transition analysis, this study contributes to the multi-level perspective on transition studies by focusing on the empirical work in a new area of plastic circular economy, covering the entire value chain. The results of the transition analysis were presented at the International Conference on Resource Sustainability 2021 and was awarded 'Best Presentation' out of more than 220 presentations. Part of the results related to the role of data-information-knowledge in a plastic circular economy has been published in a special issue of *Journal of Sustainable Production and Consumption* and was on the list of 25 most downloaded papers from the journal. As a result of the paper being published, I was interviewed by Undark Magazine, with my experience and subsequent knowledge contributing to the content of an article entitled "*Your 'Recycled' Grocery Bag Might Not Have Been Recycled*."

MFA and multi-level perspective (MLP) studies in this thesis have contributed to both industrial ecology and transition studies. Several strategies were proposed to move towards more circular pathways with discussions on the potential socio-technical changes that would reshape the flows by combining a range of policy instruments as well as behavioural and techno-economic interventions. The findings allow for systemic understanding of transformation processes, which interconnect the material flows, actors, data-information-knowledge, and other factors, such as policies and standards, markets and business models, technologies, consumer preferences and behaviours, in a sociotechnical transition.

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https://doi.org/10.1016/j.spc.2022.08.019

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Sustainable production and consumption

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Wan-Ting Hsu

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16/04/2023

Supervisor/ Senior Author

Will McDowall

Date

19/04/2023

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Abbreviations and Acronyms

Abbreviation/Acronym	Description
ABS	Acrylonitrile butadiene styrene
Bio-PA	Bio-polyamides
Bio-PBS	Bio-polybutylene succinate
Bio-PC	Bio-polycarbonate
Bio-PE	Bio-polyethylene
Bio-PET	Bio-polyethylene terephthalate
Bio-PEF	Bio- polyethylene furanoate
Bio-PP	Bio-polypropylene
Bio-PTT	Bio-polytrimethylene terephthalate
CE	Circular economy
DRS	Deposit return scheme
ECTFE	Ethylene chlorotrifluoroethylene
ELV	End-of-life vehicle
EMF	Ellen Macarthur Foundation
EPR	Extended producer responsibility
EVOH	Ethylene vinyl alcohol
FEP	Fluorinated ethylene propylene
MFA	Material flow analysis
MLP	Multilevel perspective
MRF	Materials recovery facility
OECD	Organisation for Economic Co-operation and Development
PA	Polyamide
PAI	Polyamide-imide
PBAT	Polybutylene adipate terephthalate
PBT	Polybutylene terephthalate
PBI	Polybenzimidazole
PBS	Polybutylene succinate
PBST	Polybutylene succinate-co-terephthalate
PC	Polycarbonate
PCL	Polycaprolactone
PCTFE	Polychlorotrifluoroethylene
PDLA	Poly-D-lactic acid
PDLLA	Poly-DL-lactic acid
PE	Polyethylene
PEA	Polyesteramide
PEEK	Polyetheretherketone
PET-G	Polyethylene terephthalate glycol
PET-P	Polyethylene terephthalate
PESU	Polyethersulfone
PFA	Perfluoroalkoxy alkanes
PHAs	Polyhydroxyalkanoates
PLA	Polylactic acid
PLLA	Poly L-lactic acid
PMMA	Polymethyl methacrylate
POM	Polyoxymethylene
PP	Polypropylene
PPO	Polyphenylene oxide
PPS	Polyphenylene sulfide

PPSU	Polyphenylsulfone
PS	Polystyrene
PSU	Polysulfone
PTFE	Polytetrafluoroethylene
PTMAT	Polymethylene adipate /terephthalate
PVC	Polyvinyl chloride
PVDF	Polyvinylidene fluoride
PVOH	Polyvinyl alcohol
RVM	Reverse vending machines
SAN	Styrene acrylonitrile
TA	Transition analysis
TPU	Thermoplastic polyurethane
UHMWPE	Ultra-high molecular weight polyethylene
UNEP	United Nations Environment Programme
WEEE	Waste electrical and electronic equipment

1 Introduction

1.1 Background information on the problem with plastic

Plastic is an important and ubiquitous material in modern society due to its affordability, light weight and durable features. Plastic has contributed important benefits to society such as extending the shelf life of food through packaging (Andrady and Neal, 2009). Worldwide plastic production increased twentyfold between 1964 and 2014, reaching 311 million tonnes (Mt) in 2014 (Ellen MacArthur Foundation, 2016). Geyer et al. (2017) estimate that overall 8300 Mt of plastics have been produced to date. As the second largest producer following China, the EU plays an important role in the global plastic value chain, accounting for around 19% of world plastic material production and 12% of its consumption (Plastics Europe, 2017). A recent study predicted that plastics demand is likely to continue to grow until the year 2050 (Material Economics, 2018).

Increasing plastic production and consumption results in more plastic reaching end-of-life and potentially increased risks of plastic leakage to the environment. According to the Organisation for Economic Co-operation and Development (OECD) (2022) global plastics outlook, only 9% of plastic waste was recycled, and 22 Mt of mismanaged plastic waste leaked into the environment in 2019 at a global scale. The OECD (2022) has recommended increasing the use of secondary plastic in order to reduce the carbon footprint and achieve net zero plastic leakage.

End-of-life (EoL) management of plastics is complex, because of several factors: 1) the large variety of plastic polymers used and the increase in composite materials; 2) the different lifespans of plastics depending on application; 3) cross-contamination issues; and 4) the technical challenges and economic viability of recovering plastics embedded in complex products (Allwood, 2014, Hahladakis and Iacovidou, 2018). These factors also create difficulties for tracking plastic flows, from product to waste management, across different applications and through time and space (Deloitte Sustainability, 2017). This has resulted in data gaps and limited understanding in the quantification of plastic waste reaching EoL, as well as uncertainty about the sources and quantity of leakage to ecosystems.

Recent years have seen increased public awareness of the potential damage arising from mismanaged plastic waste, particularly marine litter (Jambeck et al., 2015, Lau et al., 2020, Lebreton and Andrady, 2019). EU policy developments in the area have been notable. In 2015, plastics were identified as a priority material in the EU circular economy action plan (European Commission, 2015), which was followed by a strategy for plastics in 2018 (European Commission, 2018a). The EU has adopted several ambitious targets: 10 Mt of recycled plastics are to be used in new products by 2025; 55% of plastic packaging waste is to be recycled by 2030 (European Parliament, 2018); and beverage bottles should contain a minimum of 30% recycled content in 2030 (European Parliament, 2019).

Packaging has also been the target of a number of voluntary initiatives, such as the New Plastics Global Commitment (EMF and UNEP, 2019), the Circular Plastics Alliance's Voluntary Pledges (European Commission, 2019), Plastics 2030—Plastics Europe's Voluntary Commitment (Plastics Europe, 2019b), The European Plastics Pact (European Plastics Pact, 2020) and The UK Plastics Pact (WRAP, 2018).

Global developments around trade in plastic waste are having a significant impact on European plastic waste trade flows. In 2017, China introduced a ban on low-quality mixed plastic waste imports with strict contamination benchmarks (Brooks et al., 2018, Wang et al., 2019). Moreover, the Basel Convention has agreed on a new amendment to control mixed and contaminated plastic waste trade (UNEP, 2019).

A better understanding of plastic flows is important for addressing the plastic waste challenge, by identifying areas of inefficiency, material losses and potential leakage to natural systems. This has been acknowledged by the European Commission (2018a) and Plastics Europe (2018), who point to a lack of reliable data as a limiting factor for the introduction of effective policy and business measures to increase plastic circularity.

Secondary plastics currently demand accounts for only approximately 6% of plastics demand in the EU (European Commission, 2018a). To achieve a target of using 10 Mt of secondary plastics, strong demand for secondary plastics is the key (Dangis, 2018).

Yet the secondary plastics market faces numerous barriers, which have to some extent been discussed in the literature. The OECD (2018) identified the barriers and potential interventions for the global secondary plastic market. Existing studies focus mainly on the challenges and opportunities associated with mechanical recycling (Hopewell et al., 2009, Hahladakis and Iacovidou, 2019, Milios et al., 2018) and packaging (Bening et al., 2021), or specific actors in the value chain, such as converters (Dangis, 2018, Paletta et al., 2019), suppliers and retailers especially in the fast-moving consumer goods industry (Gong et al., 2020). However, there is less evidence on how barriers and drivers for secondary plastics are playing out across different end-use sectors and across the value chain. There have been calls for further investigation of interactions across different types of barriers (Bening et al., 2021).

In order to systematically assess the innovation transition of plastic production and plastic waste, Oyake-Ombis et al. (2015) applied a multi-level perspective (MLP) theory to assess the innovations to manage plastic waste in East Africa. The MLP is a widely used conceptual framework for understanding major shifts or 'transitions' in socio-technical systems. Oyake-Ombis et al. (2015) pointed out that MLP transition studies tend to focus on a single regime and recommended future research should explore regime interaction and integration with the actors. Further in-depth investigation on the barriers and drivers to increase the use of secondary plastics in multiple regimes of the socio-technical system is still needed.

According to the history and current applications of the circular economy reviewed by Winans et al. (2017), both plastic flows and the socio-technical changes across the plastic value chain are important to the circularity, and need further assessment. Hodson et al. (2012) specified the disconnection of material flow analysis and transition analysis in the field of urban sustainability, and a similar situation can be found in the existing studies of plastic circular economy. Current studies measure plastic material flows and assess plastic circular economy transition analysis separately. Hence, it is important to integrate the evaluations on both quantitative material flow analysis and qualitative transition analysis, in order to assess how the socio-technical regimes shape the material flows and explore the potential changes that can accelerate transitions.

1.2 Research aims and objectives

To fill these research gaps, this PhD research aims to address two main questions: How circular are plastics in the EU, and, how can the use of secondary plastics be increased? Specifically, the central questions this research intends to answer are:

1. What is the current status of plastic flows in the EU?
2. What are the destinations of the plastic waste generated by the EU?

3. What are the barriers and drivers reconfiguring the regime to increase the use of secondary plastics?

To answer these research questions, this study presents a material flow analysis (MFA) for plastics in the EU with detailed product categories and EoL routes. This study also assesses the barriers and drivers of using secondary plastics in socio-technical regimes, based on the different perspectives from the stakeholders along the value chain. This study further integrates the results from the material flow analysis (MFA) and transition analysis (TA) into the overall discussion, to develop a richer understanding of current plastic flows and the required socio-technical changes to increase plastic circularity in the EU. While there are different potential strategies for a plastic circular economy transition, this study focuses on closing the plastic material cycle and increasing the use of secondary plastics.

To summarise, the three objectives of this research are:

Objective 1: conduct an all-encompassing stationary material flow analysis (MFA) for plastics in the EU, with detailed analysis of the final destination of waste.

Objective 2: investigate the social-technical system transition toward plastic circularity based on the theoretical framework of a multi-level perspective and assess the barriers and drivers of using secondary plastics arising from the socio-technical regime level.

Objective 3: combine the findings of the MFA and transition analysis (TA) to discuss the reconfigured socio-technical changes for reshaping the plastic material flows.

1.3 Thesis structure

Figure 1-1 explains the thesis structure. Chapter 1 introduces background information on the problem with plastic. Chapter 2 reviews the classification of polymers, the lifecycle of plastics, and the state of the EU plastic value chain. The existing literature on the plastic material flows, barriers and drivers relevant to the plastic circular economy transition are also reviewed.

Chapter 3 introduces the methodologies of material flow analysis and multi-level perspective transition theory, and the procedures of data collection and analysis. Chapter 4 presents the results and discussion of plastic flows in the EU in 2016, while Chapter 5 presents the results and discussion of the multi-level perspective of the transition towards increasing the use of secondary plastics. Chapter 6 discusses the findings from both the plastic material flow analysis and the transition analysis, as well as indicating research limitations. Finally, Chapter 7 draws conclusions about the implications of the overall findings and offers opening avenues for further research.

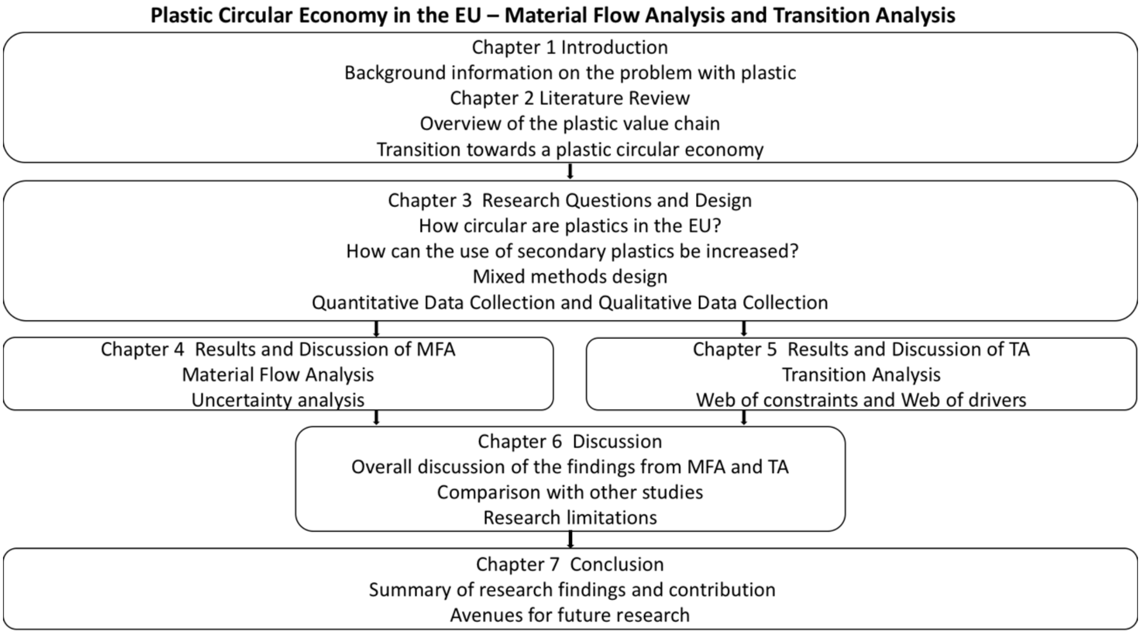


Figure 1-1 Thesis structure

2 Literature review

In Chapter 2, the existing literature is overviewed to understand the developing progress of the field of plastic material flow analysis and circular economy transition. Section 2.1 overviews the plastic value chain. From the material perspective, it is necessary to understand the classification of polymers, and the lifecycle of plastics, namely, production, manufacturing processes, consumption, and waste treatment. From the plastic industry perspective, the actors across the value chain and market size of the plastic industry in Europe are overviewed. The current studies of plastic material flows are reviewed to identify the need for and the position of the research in this field. Section 2.2 presents a brief overview of the circular economy, and the current studies on plastic circular economy transition analysis. Finally, a summary of the literature review and the reasons for conducting both MFA and TA for this research are given in section 2.3.

2.1 Overview of the plastic value chain

2.1.1 Classification of polymers

Understanding what plastic is begins with an understanding of the classifications of polymers. This will help with scoping the system boundaries of this study, understanding the goods classification of statistical datasets, and preparing for interviewing industry stakeholders. According to Askeland (1996, page 488), *'polymers – which include such diverse materials as plastics, rubbers, and adhesives – are giant organic, chain-like molecules having molecular weights from 10,000 to more than 1,000,000* $g.mol^{-1}$.' It is notable that many references do not provide clear definitions of polymers and plastics. For example, Eyerer (2010) describes plastics as produced through chemical reactions called polymerisation, by which low-molecular-weight monomer molecules join together to form polymers. Baur et al. (2019) argued that a *'polymer is applicable to all materials with a macromolecular structure, whereas plastics only describe polymers that are modified with additives to meet the requirements of industrial processing technologies, such as processing aids, stabilisers, pigments, fillers, and others (page 16).'*

The polymer chain consists of a backbone of carbon atoms and two hydrogen atoms bonded to each carbon atom in the chain (Askeland, 1996). Two common polymerisations are *polycondensation* and *polyaddition*. Polycondensation forms polymers by the combination of different monomers and releasing reaction products such as water, while polyaddition forms polymers by an independent addition of one new monomer via a stepwise process. Single types of monomers are polymerised to form a homopolymer, while more than one type of monomer is polymerised to form a copolymer. All the polymers have a three-dimensional structure.

Polymers can be classified in many ways according to their origin, structure, molecular forces, or the main existing mechanisms of polymerisation (Colmenares and Kuna, 2017, Demaid et al., 1996) (Figure 2-1).

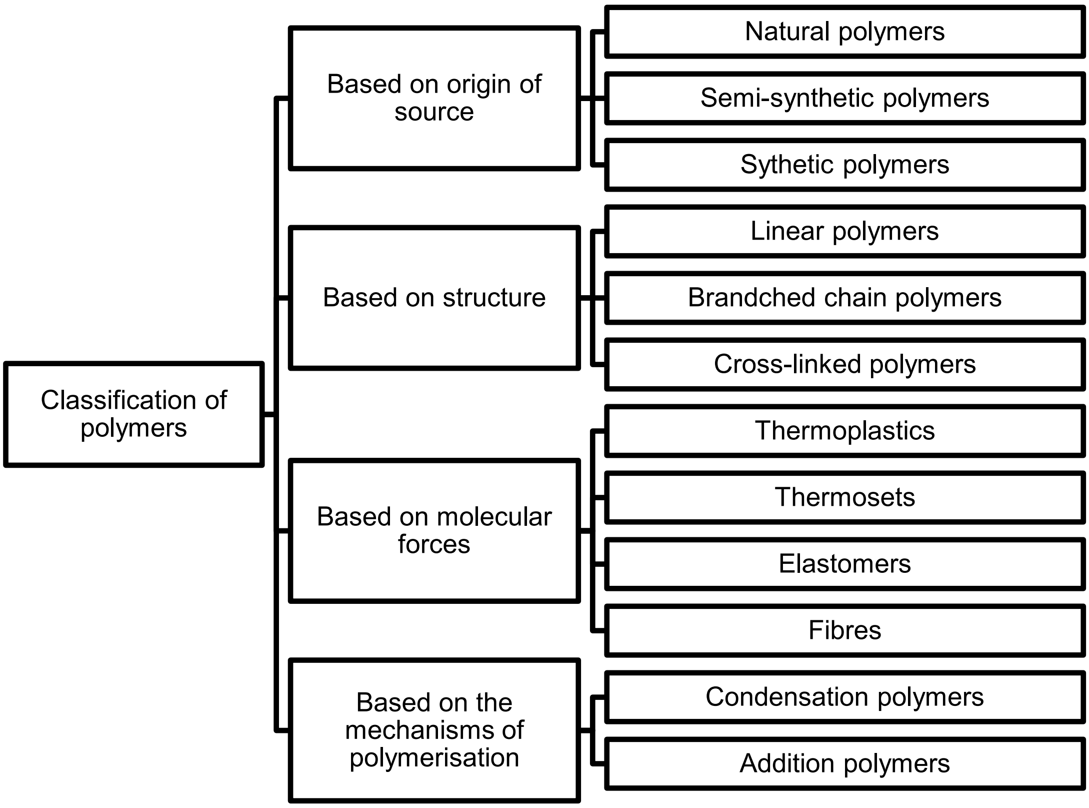


Figure 2-1 Different ways to classify polymers

From the classifications based on molecular forces and origin of sources, I classified polymers into four main types of polymers, as shown in Figure 2-2. These are fossil-based non-biodegradable polymers, fossil-based biodegradable polymers, bio-based non-biodegradable polymers, and bio-based biodegradable polymers. It is worth noting that this study mainly focuses on the thermoplastics, thermosets, and man-made synthetic fibres within the category of fossil-based non-biodegradable polymers, because these types of plastics dominate plastic markets and plastic waste streams. Bioplastics (bio-based and/or biodegradable polymers) and elastomers are outside the system boundary of this study.

The category of fossil-based non-biodegradable polymers includes thermoplastics, thermosets, elastomers, man-made synthetic fibres. Thermoplastics and thermosets are the focus of this study, as these are the dominant plastics found in waste streams. Thermoplastics have long linear or only slightly branched polymer chains and can be reheated and remoulded without chemical changes in their composition. Thermosets are plastics with cross-linked molecules to form rigid three-dimensional network structures and cannot be reheated and remoulded after initial formation due to chemical changes when heated.

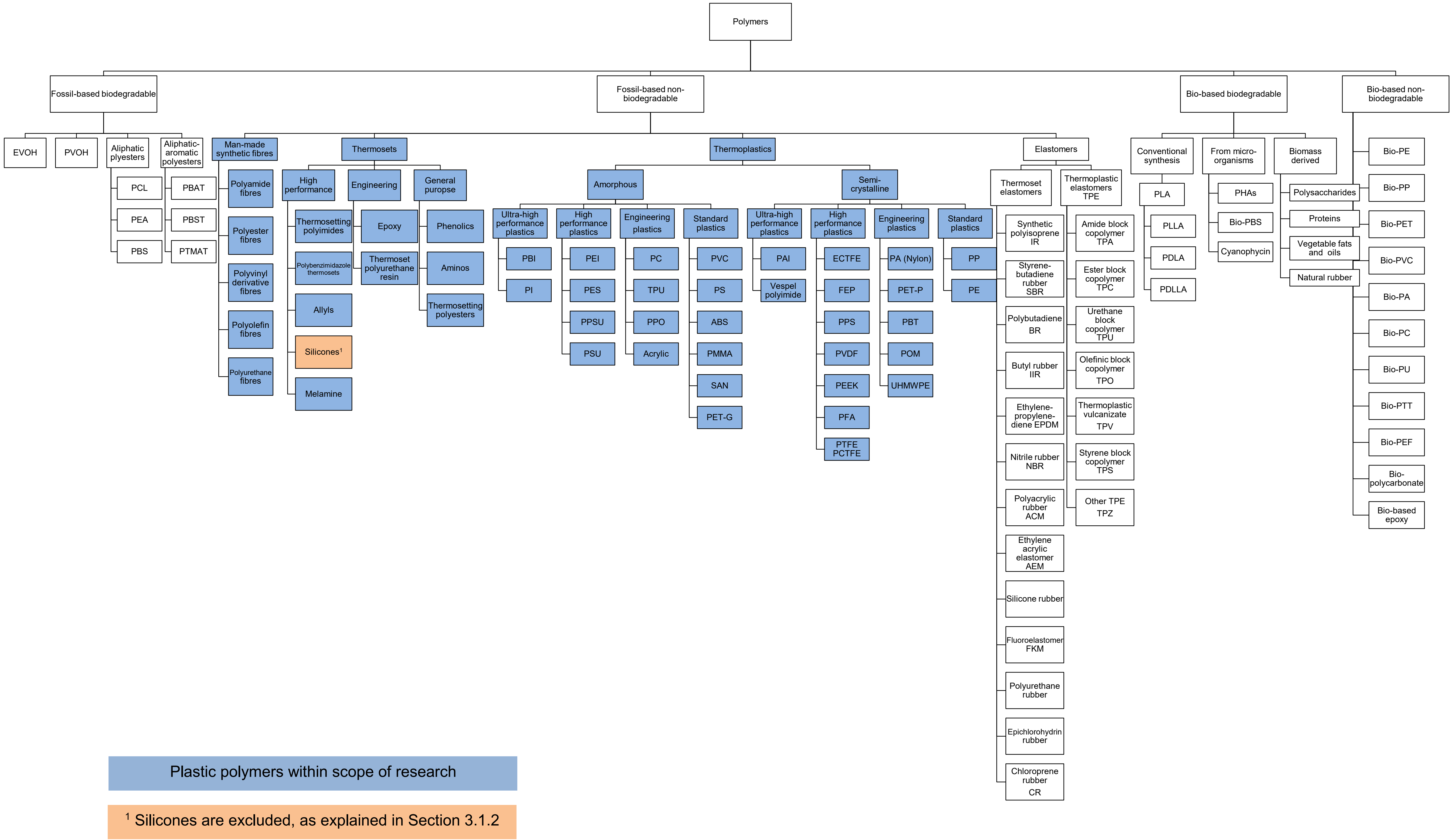


Figure 2-2 Classification of polymers

Thermoplastics can be categorised into amorphous and semi-crystalline based on the physical structures (Eyerer, 2010). Amorphous plastics have random structure with broad softening range, low shrinkage, usually transparent, low chemical resistance, poor fatigue and wear resistance (Crawford, 1998). Semi-crystalline plastics have a combination of amorphous (random) and crystalline (ordered) structure with sharp melting point, high shrinkage, usually opaque, high chemical resistance, good fatigue and wear resistance (Crawford, 1998). Amorphous plastics have a glass transition temperature (Tg), which is the temperature that plastics change from a hard and brittle glassy state to soft and viscous state.

Based on these physical structure classifications, the thermoplastics can be further categorised based on their application and its service temperature. Namely, standard plastics, engineering plastics, high-performance plastics, and ultra-high-performance plastics (de Leon et al., 2021). Similarly, thermoset can also be categorised into general purpose, engineering plastics, and high-performance plastics (Dodiuk, 2021) (see Figure 2-2).

Standard plastics have a service temperature <100°C, and can be manufactured in large quantities at a low cost, whereas engineering plastics often retain their properties between 100°C and 150°C. The continuous service temperature of high-performance plastics is >150°C, whilst ultra-high-performance plastics have a service temperature around 300°C. These continuous service temperatures are approximate ranges; the specific continuous service temperatures for each type of plastic may be very different. The plastics performance pyramid is shown in Figure 2-3.

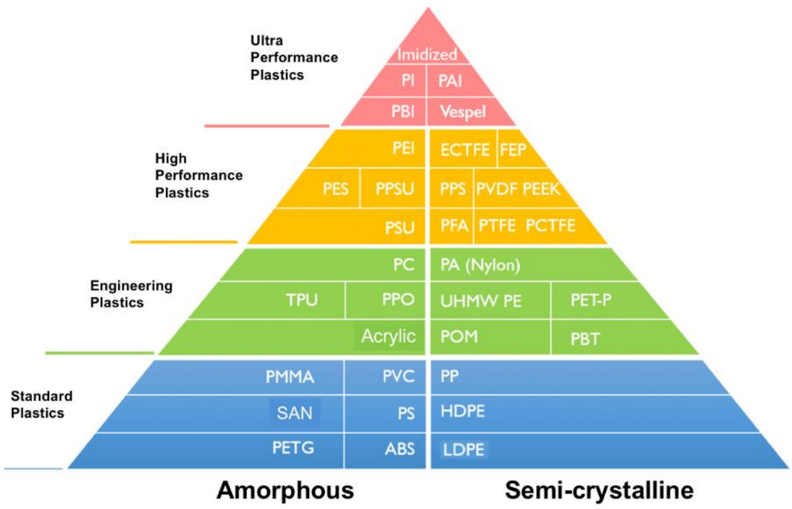


Figure 2-3 Plastics performance pyramid adapted from de Leon et al. (2021)

In 1988, the Society of Plastics Industry introduced a classification system called the SPI code or the resin identification code (RIC) for manufacturers to follow. Around 70% of global production plastics is concentrated into six main plastic polymer types. The properties and general applications of these six types and other plastics are briefly introduced as below. The resin code and structure of monomer are listed in Table 2-1.

1. **PET (Polyethylene terephthalate)**

Properties: clear, strong and lightweight.

General applications: water and beverage bottles, food jars, clothing and carpet fibres.

2. **HDPE (High-density polyethylene)**

Properties: stiff and hardwearing; hard to breakdown in sunlight and can be used with corrosive materials such as bleach.

General applications: detergent and bleach bottles, shampoo bottles, milk jugs.

3. **PVC (Polyvinyl chloride)**

Properties: can be rigid or soft via plasticisers.

General applications: windows and doorframes, pipes and fittings, wire and cable sheathing, vinyl flooring, blood bags, medical tubing.

4. **LDPE (Low-density polyethylene)**

Properties: lightweight, flexible, strong and can be used in corrosive environments.

General applications: packaging film, shopping bags, bubble wrap.

5. **PP (Polypropylene)**

Properties: colourfast, heat resistant, fatigue resistant and highly resistant to corrosion and chemical leaching.

General applications: bottle lids, drinking straws; diapers.

6. **PS (Polystyrene)**

Properties: lightweight; structurally weak; easily dispersed.

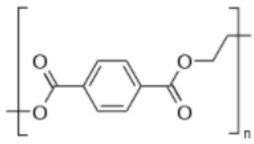
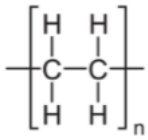
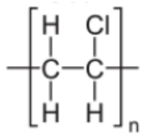
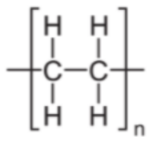
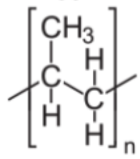
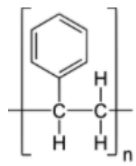
General applications: foam packaging, egg boxes, yogurt pots, disposable crockery.

7. **Other**

Types of plastics that do not fall into any of the other six categories.

General applications: baby bottles, water cooler bottles, nylon fabrics.

Table 2-1 Resin identification code and structure of monomer

Polymer		**Resin code**	**Structure of monomer**
PET/PETE	Polyethylene terephthalate	01 PET	
HDPE	High-density polyethylene	02 PE-HD	
PVC	Polyvinyl chloride	03 PVC	
LDPE	Low-density polyethylene	4 LDPE	
PP	Polypropylene	05 PP	
PS	Polystyrene	06 PS	
Other	Other plastics	7 OTHER	

As listed in Figure 2-2, the most common thermosets include:

1) General purpose: phenolics, amnions, thermosetting polyesters;

2) Engineering: epoxy, thermoset polyurethane resin;
3) High performance: thermosetting polyimides, polybenzimidazole thermosets, allyls, silicones, melamine.

Elastomers, including rubbers, are wide-meshed crosslinked polymers with viscoelasticity (Askeland, 1996, page 489). Elastomers include thermoplastic elastomers and thermoset elastomers (Eyerer, 2010). Thermoplastic elastomers (TPE) are defined by ISO 18064 as *'a polymer or blend of polymers that have properties at its service temperature similar to those of vulcanised rubber, but can be processed and reprocessed at an elevated temperature like a thermoplastic (Scholz and Gehringer, 2021, page 1).'* The classification of TPE in Figure 2-2 is based on Scholz and Gehringer (2021) and Baur et al. (2019). Unlike thermoplastic elastomers, which will soften and flow above a given temperature, thermoset elastomers have irreversible crosslinked elastomeric networks brought about by curing or vulcanising processes (Mark, 2017, James Walker, 2017, Stritzke, 2009).

Plastic polymers, as defined in the Eurostat databases where the MFA data is collated, is based on the NACE Rev2 (statistical classification of economic activities in the European Community). According to the NACE Rev2, plastics refer to *'resins, plastics materials and non-vulcanisable thermoplastic elastomers, the mixing and blending of resins on a custom basis, as well as non-customised synthetic resins (Eurostat, 2008)'*. However, thermoplastics, thermosets and man-made synthetic fibres shown in Figure 2-2 are the main focus in this study. Further explanation for the plastics included in this study is made in Chapter 3 and listed in the Appendix A.

Man-made synthetic fibres made with plastics are included in Figure 2-2. Based on Gordon Cook (1984), the classification includes polyamide fibres, polyester fibres, polyvinyl derivative fibres, polyolefin fibres, and polyurethane fibres. These textile fibres are woven into such products as clothes, towels, bed sheets, carpets, curtains, and safety belts. Many of the textile fibres become microplastics and enter into the ocean and environment (European Environment Agency, 2021).

According to European Bioplastics (2018), bioplastics are *'polymers that are bio-based, biodegradable, or features both properties'*. Bio-based polymers are derived from biomass such as corn, sugarcane, or cellulose. Biodegradable plastics are polymers that can be decomposed by microorganisms depending on the surrounding environmental conditions. Therefore, the bioplastics are allocated in the bio-based biodegradable polymers, bio-based non-biodegradable polymers, and fossil-based biodegradable polymers in Figure 2-2.

Based on Lackner (2015), Kabasci (2013), Zhong et al. (2020), bio-based biodegradable polymers can be further classified into three groups:

1) From biomass derived (polysaccharides, proteins, vegetable fats and oils, natural rubber);
2) From micro-organisms obtained by extraction (polyhydroxyalkanoates (PHAs), bio-based polybutylene succinate (Bio-PBS), cyanophycin);
3) From biotechnology which is conventional synthesis from bio-derived monomers (polylactic acid (PLA)).

Polysaccharides can be either plant-based or animal-based, including starch, cellulose, and other polysaccharides such as alginate, chitosan, chitin, hyaluronan, and carrageenan (Ibrahim et al., 2021). Proteins can also be either plant-based or animal-based, including wheat, corn, pea, potato, soy, casein, whey, collagen, albumin, keratin (Ibrahim et al., 2021). PHAs have a wide family. Among them, the most common one is Poly-3-hydroxybutyrate (PHB). PLA is a polyester derived from lactic acid during the fermentation of renewable biomass such as sugarcane, corn, cassava and sugar beet pulp. There are three different isomers of lactic acid which have different physical and chemical properties, namely, Poly L-lactic acid (PLLA), Poly D-lactic acid (PDLA), Poly DL-lactic acid (PDLLA).

Bio-based non-biodegradable polymers are called drop-in bioplastics. According to Bhagwat et al. (2020), drop-in bioplastics are *'bio-similar copies of the petrochemical plastics which are made from biomass instead of fossil-based and use the same degradation pathway as the petrochemical plastics (page 3057)'*. The bio-based non-biodegradable polymers include Bio-PE, Bio-PP, Bio-PET, Bio-PVC, Bio-PA, Bio-PC, Bio-PU, polytrimethylene terephthalate (Bio-PTT), Bio-polyethylene furanoate (Bio-PEF), bio-polycarbonates, bio-based epoxy.

Fossil-based biodegradable polymers can be classified into aliphatic polyesters, aliphatic-aromatic polyesters, poly(vinyl alcohol) (PVOH or PVA) and ethylene vinyl alcohol (EVOH) (Song et al., 2011, Ghosh et al., 2019, Bhagwat et al., 2020). Aliphatic polyesters include polycaprolactone (PCL), polyesteramide (PEA), polybutylene succinate (PBS). Aliphatic-aromatic polyesters include polybutylene adipate terephthalate (PBAT), poly(butylene succinate-co-terephthalate) (PBST), polymethylene adipate /terephthalate (PTMAT) (Song et al., 2011).

Figure 2-2 provides a more comprehensive classification picture of the polymers compared to the existing literature showing how this study considers thermoplastics, thermosets (except silicones), and man-made synthetic fibres within the system boundary. Bioplastics and elastomers are excluded from this research. I am, however, aware that some polymers are not listed in Figure 2-2, this is because they are new, emerging, or overlapping under this classification in Figure 2-2. For example, polyglycolic acid (PGA) can be either biobased or fossil-based biodegradable polymers (Samantaray et al., 2020), therefore, it is not listed in Figure 2-2. Oxo-degradable plastics, which are the conventional plastics incorporated with prodegradant additives, are also not included because they are not allowed to be commercialised under the EU Directive (2019/904) on Single-Use Plastics (Abdelmoez et al., 2021). Through overviewing the classification of polymers, the complexity of 'plastics' reveals the challenges to scope plastics and measure their material flows, as every study has different definitions of plastics.

Moreover, plastics have common material properties, but are often modified for specific use by additives. Databases such as Computer Aided Material Preselection by Uniform Standards (CAMPUS) and UL Prospector has collected the general material property information provided by the plastic producers. Several standards have specified the general material characteristics of plastics and standardised testing methods such as ISO 10350 Plastics — Acquisition and presentation of comparable single-point data and ISO 11403 Plastics — Acquisition and presentation of comparable multipoint data. The most important material properties include processing characteristics (e.g., rheological behaviour - melt mass flow rate), mechanical properties (e.g., impact behaviour), thermal properties (e.g., permissible service temperatures), electrical properties (e.g., electrical insulation properties), optical behaviour (e.g., colour), resistance to environmental influences (e.g., stress cracking resistance, chemical resistance, weathering), and friction and wear behaviour (Baur et al., 2019). These widely varied requirements of material properties rely on testing and third-party certification. With the stable quality of virgin plastics and the knowledge from the virgin plastic producers, the plastics are able to meet the specific requirements from the plastic users such as manufacturers, brand owners or retailers. However, it is challenging for using secondary plastics to meet specific requirements.

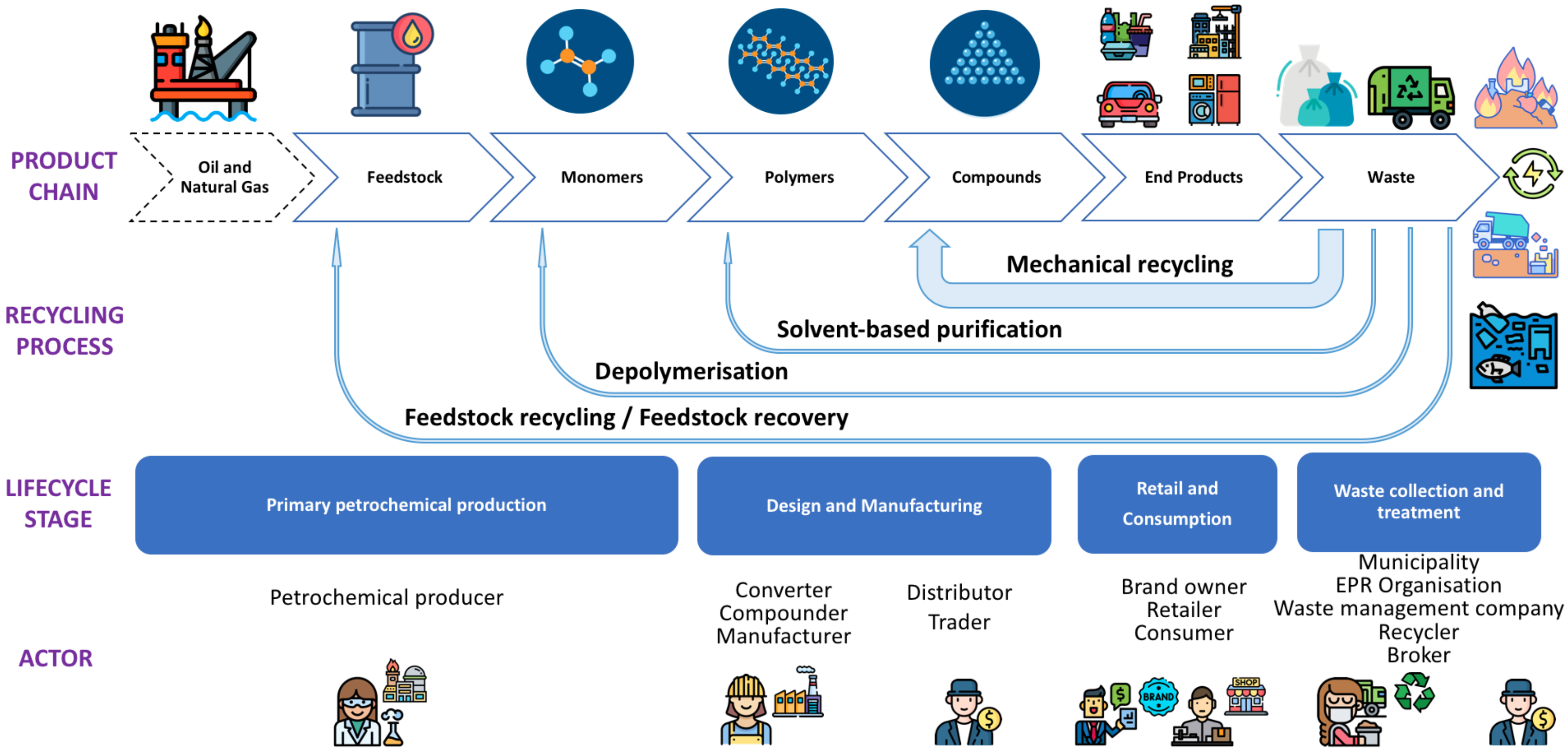


Figure 2-4 The plastic value chain, showing the actors, life-cycle stages, and key routes for secondary materials

2.1.2 Lifecycle of plastics

Figure 2-4 shows the overall plastic value chain. The plastic production starts from extracting oil and natural gas, through a cracking process to produce feedstock and monomers. Then, many monomers join to become polymers. Next is the mixing and blending of the plastic polymers with additives, such as dye, pigments, plasticisers, stabilisers, fillers and reinforcements, lubricants, flame retardants, and solvents foaming agents, to make compounds. After compounding, the plastic polymers need to go through various types of manufacturing processes to further manufacture and assemble end products. According to Stevens (2002), the most common processes include:

1) Extrusion: heated or unheated plastic is forced through a heated chamber by a screw in one continuously formed shape, such as film, sheet, or tubing;
2) Injection moulding: melting the materials in a molten state and under pressure to shoot into a mould cavity;
3) Compression moulding: a method in which the material is in a confined cavity, and heat and pressure are maintained until the moulding material has cured;
4) Blow moulding: forming of a hollow plastic object such as a bottle by inflating or blowing a molten tube known as a parison;
5) Transfer moulding: a process in which a pre-weighted amount of a polymer is preheated in a separate transfer pot, and then a plunger is used to push molten polymer into a preheated mould cavity until it is cured;
6) Vacuum forming: a heated sheet of plastic is stretched onto a single-surface mould, then forced against the mould surface by evacuating the air between the plastic sheet and the mould.

After different manufacturing processes, the end products are widely used. The qualitative part of this study focuses on four main application areas: packaging, construction, automotive, and electrical and electronic equipment (EEE). In the dominant 'linear economy' system, products reaching the end of life become waste and are sent to different waste treatments or mismanaged to the environment.

The origins and properties of plastic waste are complicated. Figure 2-5 gives an overview of the plastic waste mapping by Ragaert et al. (2017). The possible treatments of plastic waste from different origins are also identified in Figure 2-5 (Ragaert et al., 2017). The properties show the key factors that affect the quality of recycling include whether it is mono-plastic or mixed plastics, whether it is clean or contaminated, and whether the composition is known or unknown (Ragaert et al., 2017).

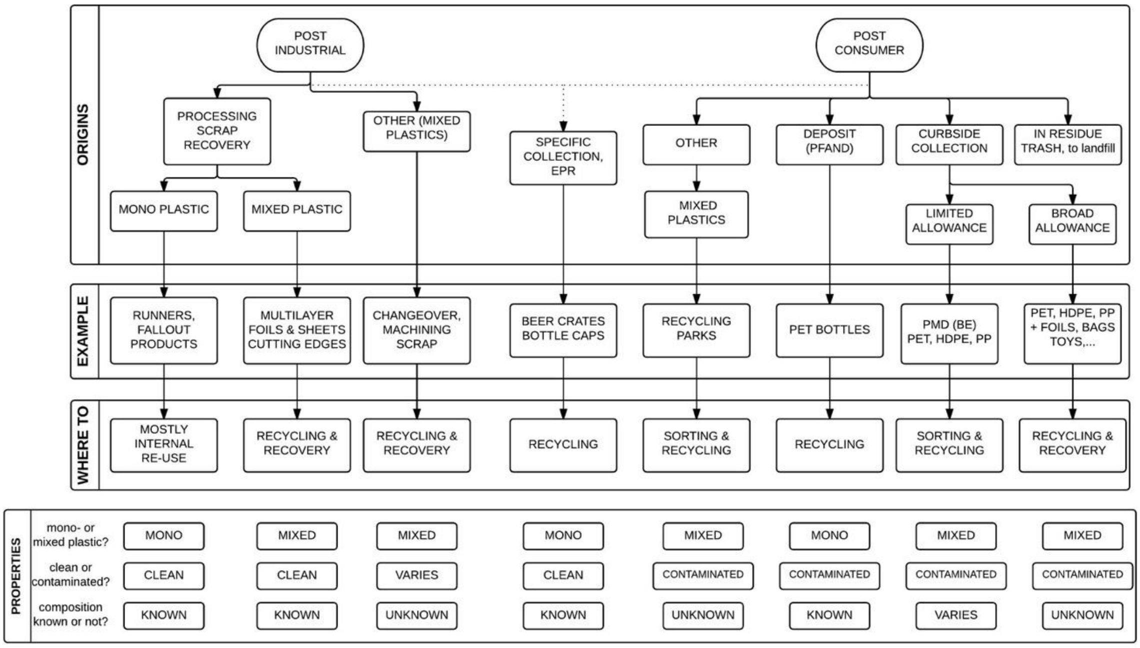


Figure 2-5 An overview of plastic waste origins, properties and treatments (Ragaert et al., 2017)

There are different recycling processes, including mechanical recycling, solvent-based purification, depolymerisation, and feedstock recycling/recovery (Figure 2-4). Currently, mechanical recycling is still the main plastic recycling process in Europe. The other recycling processes are more or less at laboratory scale, pilot scale or just about to be commercialised. Figure 2-6 shows different plastic waste recycling technologies in more detail. As bioplastics are not included within the system boundary of this study, industrial composting is not listed in Figure 2-6.

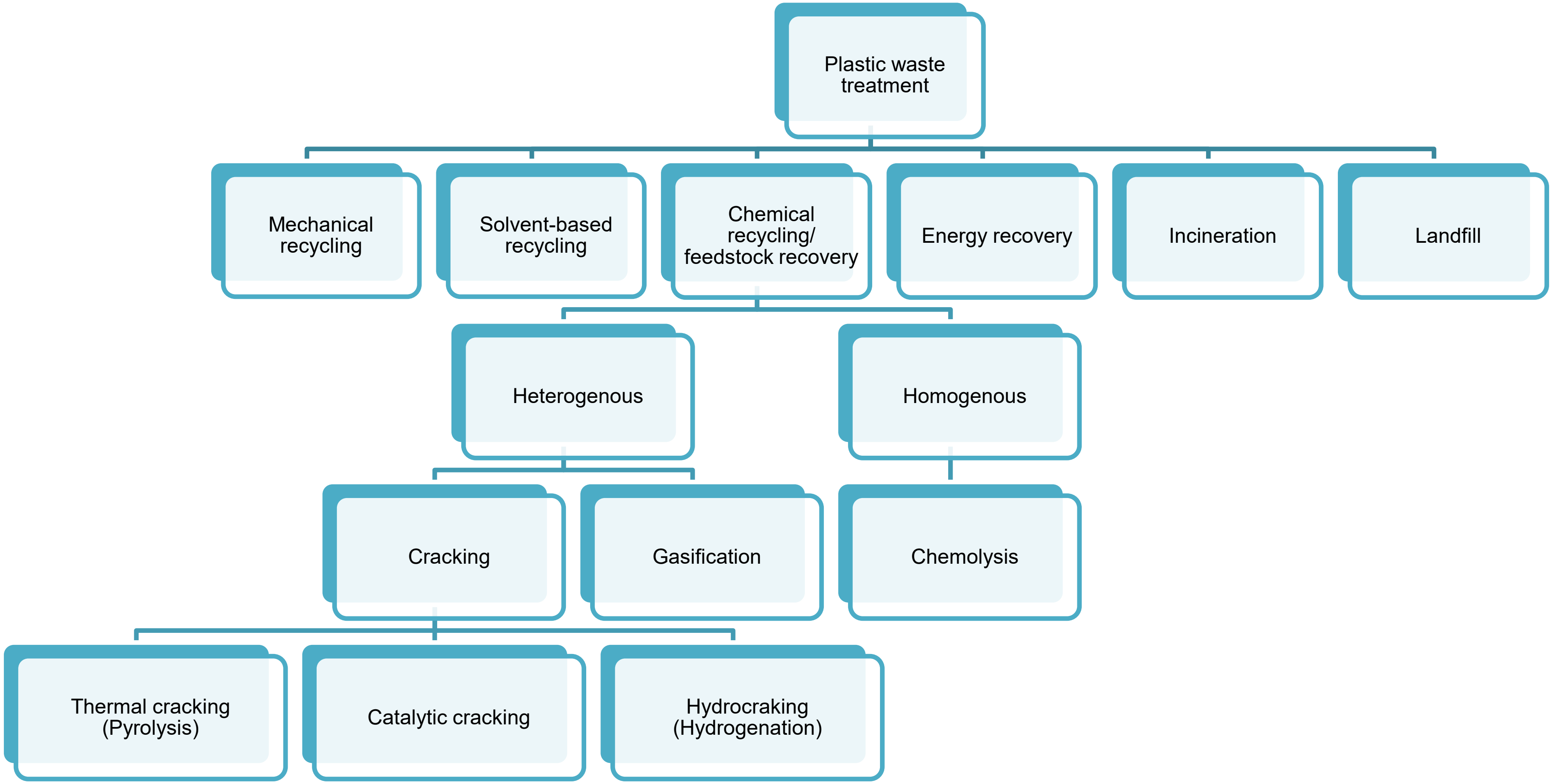


Figure 2-6 Plastic waste treatment adopted from Solis and Silveira (2020) and Schlummer et al. (2020)

Mechanical recycling processes separate plastic waste into single-polymer streams, which are then washed, granulated, and turned into recycled pellets through re-extrusion.

Solvent-based purification (Dissolution) is defined as a physicochemical treatment (D9) based on the Annex IV Basel Convention (Schlummer et al., 2020, UNEP, 2014). Some studies have defined solvent-based purification as chemical recycling (e.g., Hann and Connock (2020)). However, solvent-based purification physically alters polymers from solid to liquid and back to solid state to be reused, it does not change the molecular structure of the polymers through chemical reactions, therefore, it is also called physical recycling in some studies (e.g., Garcia-Gutierrez et al. (2023)).

Chemical recycling refers to the processes of depolymerisation or thermolysis through which plastic waste is converted into oligomers or monomers and then polymerised back into secondary plastics (so-called feedstock recycling). These technologies include chemolysis, gasification, pyrolysis, catalytic cracking, and hydrocracking (hydrogenation). When the processes alter plastic waste into chemical intermediates, such as fuel, gases, oil, or waxes, they are called feedstock recovery as they are suitable for the productions of other petrochemicals.

Energy recovery is a plastic waste treatment that generates electricity and heat, whereas incineration is a thermal treatment.

Chemolysis/solvolysis, including hydrolysis, alcoholysis, glycolysis, and methanolysis, depolymerise the plastic waste back into monomers by chemical agents (Kumar et al., 2011). General gasification converts plastic waste into hydrocarbons and synthesis gas by oxidation agents (e.g., plasma, air or steam) (Solis and Silveira, 2020).

Pyrolysis is a thermal decomposition technology that is able to convert plastic waste into organic vapours, gases, char, wax, and hydrogen chloride (HCl) through heat and pressure in the absence of oxygen (Maqsood et al., 2021). Pyrolysis can depolymerise the plastic waste which is difficult to mechanically recycle such as multi-layered plastic packaging, mixed PE/PP/PS, polyurethane construction and demolishing waste (Ragaert et al., 2017).

Catalytic cracking is a conversion process with a catalyst, which reduces the required temperature, raises the oil yield, and speeds up the reaction (Solis and Silveira, 2020). Catalytic cracking is normally used to treat pure polymers because it cannot tolerate the contamination within mixed plastic waste (Solis and Silveira, 2020). Different from thermal cracking, catalytic cracking can produce more gas oil constituents with less residuum (Speight, 2020).

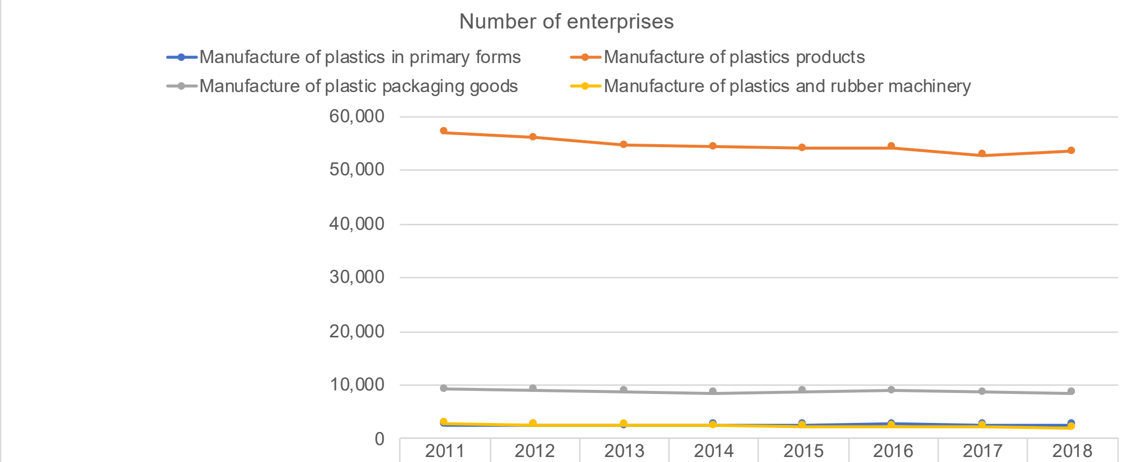
Hydrocracking (hydrogenation) adds hydrogen into the cracking process under high pressure to break down hydrocarbon molecules into simpler molecules. A catalyst can be added to stimulate the hydrogen addition. Hydrocracking can produce good quality liquid fuels and naphtha, however, the electricity needed to produce hydrogen is costly (Solis and Silveira, 2020, Ragaert et al., 2017).

2.1.3 State of the EU plastic value chain

In overviewing the state of the plastic value chain in the EU28, many actors are seen to be involved in different lifecycle stages as shown in Figure 2-4, including petrochemical producers, converters, compounders, manufacturers, distributors, traders, brand owners, retails, consumers, municipalities, extended producer responsibility organisations, waste management companies, mechanical/physical and chemical recyclers, and brokers.

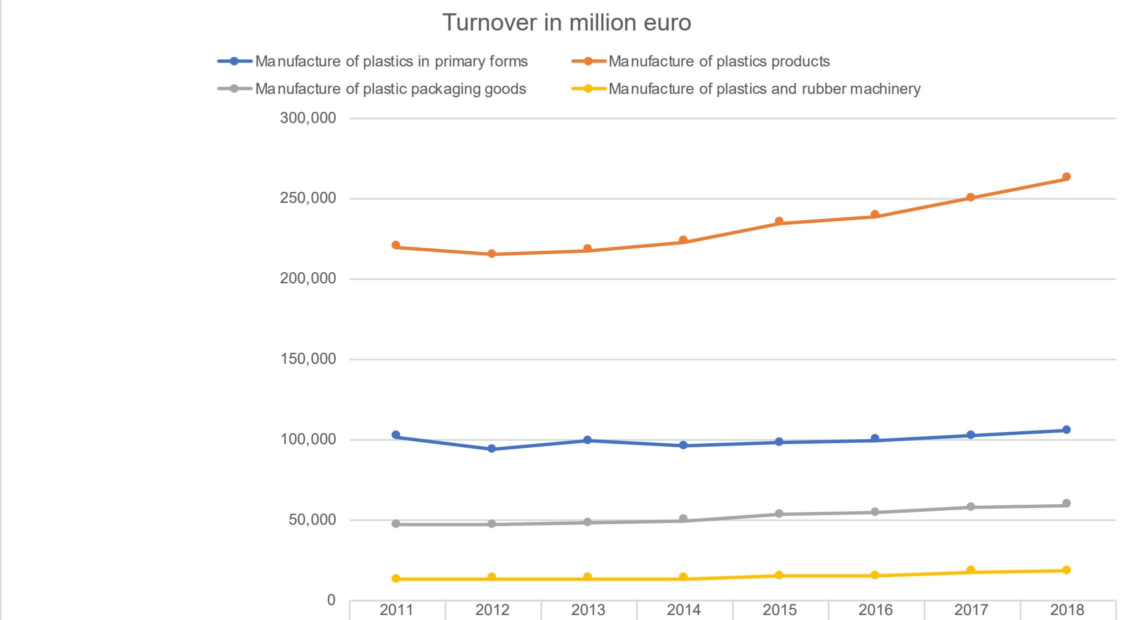
In this section, statistical data is presented to characterise the value chain in terms of numbers of enterprises, turnover, and installed plastic recycling capacity. This helps to illustrate the scale of the industry and the relative size of different plastic life cycle stages.

For the upstream of plastic value chain, the statistical data can be extracted from a database called ‘annual detailed enterprise statistics for industry (NACE Rev. 2, B-E)’ from Eurostat. Figure 2-7 depicts the numbers of enterprises as plastic producers (manufacture of plastics in primary forms), plastic converters/compounders /manufactures (manufacture of plastics products), plastic packaging manufacturers (manufacture of plastic packaging goods), and the enterprises for machinery (manufacture of plastics and rubber machinery) between 2011 and 2018. On average, there are 2,595 companies in the plastic production category. On average, there are 54,586 companies converting and manufacturing plastic; among these, 8,793 companies specifically manufacture plastic packaging; and 2,400 companies making machinery for the manufacturing of plastics. Figure 2-8 shows the turnover in the upstream of plastic industry between 2011 and 2018. The total turnover of manufacture of plastics in primary forms and manufacture of plastics products grew to 368,304 million euros in 2018. However, Plastics Europe (2021) indicated that the plastics industry had affected by the pandemic with the turnover slightly dropping to nearly 330,000 million euros in 2020.



	2011	2012	2013	2014	2015	2016	2017	2018
Manufacture of plastics in primary forms	2,600	2,557	2,495	2,626	2,606	2,654	2,589	2,636
Manufacture of plastics products	57,000	56,000	54,700	54,432	54,105	54,200	52,800	53,449
Manufacture of plastic packaging goods	9,145	9,010	8,745	8,569	8,802	8,872	8,668	8,535
Manufacture of plastics and rubber machinery	2,828	2,588	2,547	2,392	2,350	2,274	2,251	1,973

Figure 2-7 Numbers of enterprises in the upstream of plastic industry in the EU



	2011	2012	2013	2014	2015	2016	2017	2018
Manufacture of plastics in primary forms	101,991	93,941	99,169	95,947	97,912	99,703	102,315	105,562
Manufacture of plastics products	220,000	215,000	217,568	223,316	235,000	239,000	250,000	262,742
Manufacture of plastic packaging goods	47,022	46,979	47,980	49,825	53,585	54,769	57,644	59,393
Manufacture of plastics and rubber machinery	13,030	13,620	13,707	13,583	15,229	15,285	17,668	18,336

Figure 2-8 Turnover in the upstream of plastic industry between 2011 and 2018

In the downstream, there were more than 600 plastic recycling companies in 2019 and more than 3,000 million euros, according to the statistical data from Plastics Recyclers Europe (2020). Figure 2-9 depicts the total installed plastics recycling capacity across different European countries (Plastics Recyclers Europe, 2020). Approximately 8.5 Mt installed recycling capacity in the EU in 2019. Germany has more than a 1.5-million tonne recycling capacity, which is the highest in the EU. The second highest is Italy, with a recycling capacity is between 1 Mt and 1.5 Mt. There has been a significant increase in installed plastic recycling capacity in the last decade, reaching 11.3 Mt in 2021 (see Figure 2-10), with 730 recycling facilities and 8.6 billion euros turnover (Plastics Recyclers Europe, 2023).

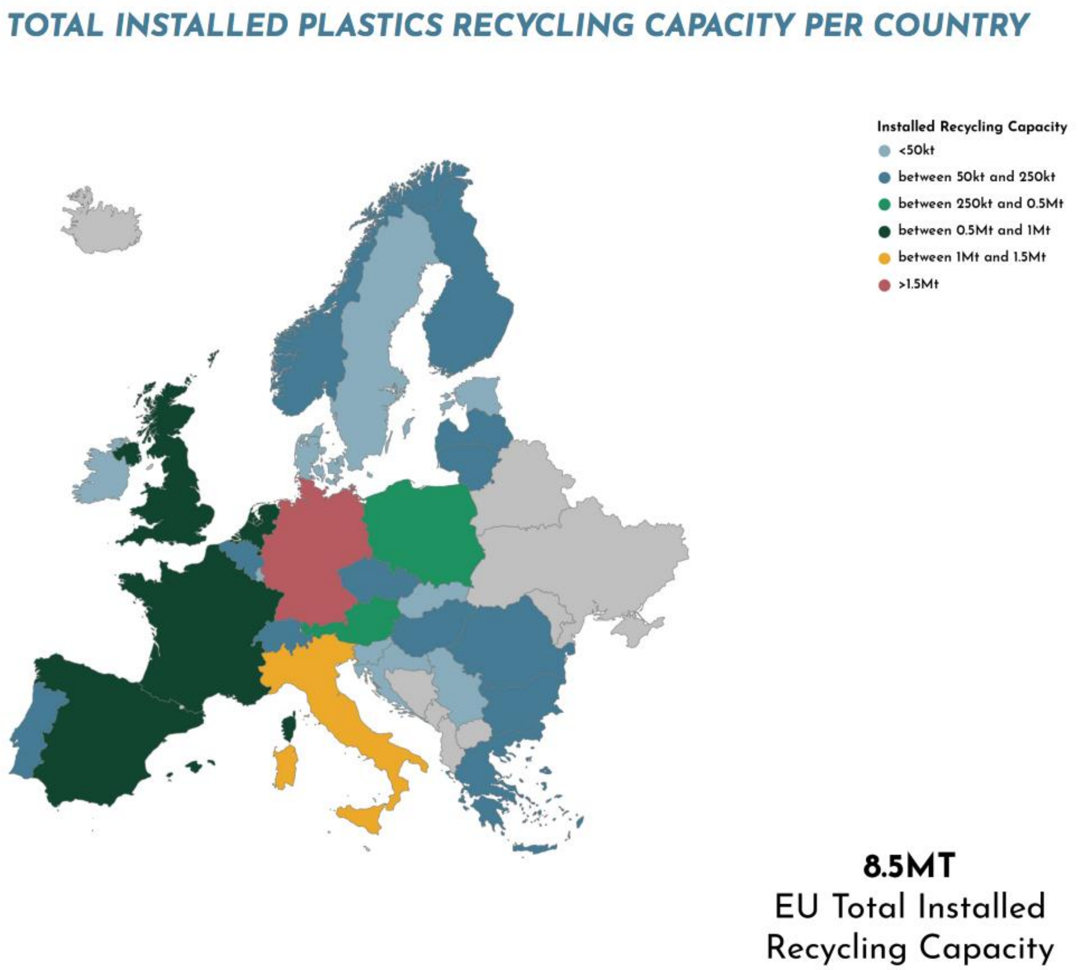


Figure 2-9 Total installed plastics recycling capacity in the EU in 2019 (Plastics Recyclers Europe, 2020)

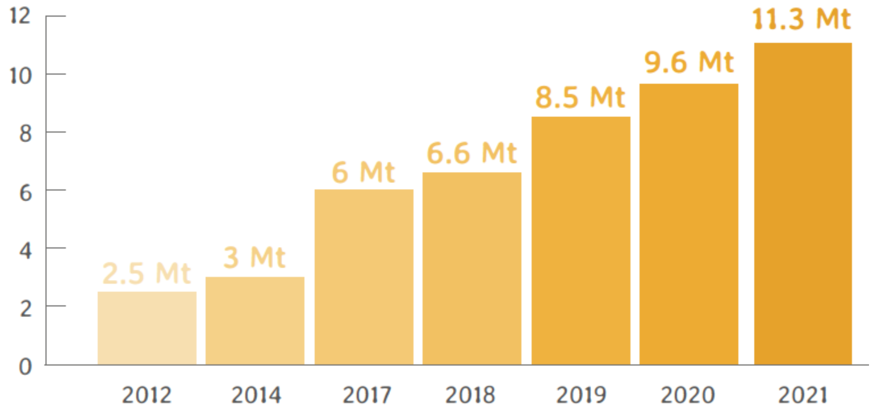


Figure 2-10 Evolution of installed plastic recycling capacity in the Europe (Plastics Recyclers Europe, 2023)

2.1.4 Current studies of plastic material flows

A number of plastic MFA studies provide worthy information of the flows in specific geographic boundaries, specific application of plastics, or specific types of polymers.

On the global scale, EMF (2016) proposed simplified global flows of plastic packaging materials in 2013, which show 32% of plastic waste became leakage and only 10% was recycled. Levi and Cullen (2018) have mapped flows of the entire petrochemical cycle in 2013, among them, the plastic flows were estimated from the fossil fuel feedstocks to chemical products (thermoplastics, thermosets, fibre, elastomers and additives). Their result shows that 280.8 Mt plastics and 53.9 Mt fibres were produced (Levi and Cullen, 2018). Geyer et al. (2017) provided an overview of the plastic flows, including resins, fibres and additives, with details of different types of polymers and application sectors. According to their results, approximately 4900 Mt plastics were discarded and either entered into landfills or became leakage into the environment, between 1950 and 2015 (Geyer et al., 2017). In terms of the losses of plastics in global plastic flows, Ryberg et al. (2019) reported around 6.2 Mt of macroplastics and 3.0 Mt of microplastics entered into the environment across different plastics life cycle stages in 2015. Wang et al. (2021) reviewed the data on global plastic stocks and flows. Four data gaps were identified: inconsistent classification of plastic materials, products and waste; missing data; conflicting data between government statistics and industry trade groups or international organisations; and non-explicit data for plastics products and waste, especially for the different waste treatment pathways and mismanagement waste (Wang et al., 2021).

Wang et al. (2021) suggested further studies to provide in-depth plastic flow analysis at regional level.

Focusing on the European countries, plastic MFA has been established over the past two decades. Patel et al. (1998) combined physical and monetary data to establish a snapshot of comprehensive plastic flows in Germany in 1994, including a forecast of the business-as-usual scenario until 2050. Kleijn et al. (2000) developed a dynamic MFA of PVC in Sweden, whilst Joosten et al. (2000) conducted supply and use tables to estimate 1260 kt of plastic was consumed in the Netherlands in 1990, generating 904 kt of plastic waste. Bogucka et al. (2008) applied the results of plastic flows and stocks in Austria (1994 and 2004) and in Poland (2004) to suggest policy for plastic waste and its management. Furthermore, Salmons and Mocca (2010) mapped the plastic flows in the UK between 2004 and 2007, by splitting the flows into packaging and other products.

Most of these early studies treated consumption in summation without distinguishing the distribution of different application fields, and they ignored potential losses (Van Eygen et al., 2017, Graedel, 2019). As socioeconomics and technologies change over time, Graedel (2019) suggested updating the MFA no less frequently than every three to five years and extending its details in order to improve the accuracy for policy utility.

More recently, Sevigné-Itoiz et al. (2015) established a dynamic MFA of plastics from 1999 to 2011, in Spain, with consideration of the recycled plastics showing that losses were still significant with 30 Mt sent to landfills and possible leakage to the environment between 1999 and 2011. According to their results, Spain achieved a 40% recycling rate from its selectively collected plastic waste, of which, around 86% became recycled polymers (Sevigné-Itoiz et al., 2015). Conducting a similar plastic budget model, Van Eygen et al. (2017) established the static plastic flows in Austria showing a mechanical recycling rate of 21% and a chemical recycling rate of 10% in 2010. Olli Sahimaa (2017) analysed Finnish plastic flows showing a mechanical recycling rate of 12% in 2013.

The Danish Environmental Protection Agency applied a different plastic budget model to report a preliminary assessment of plastic material flows in Denmark (Pivnenko et al., 2019). Its report includes overall flow of plastics and the individual flows of PET, PE, PP and other plastics, but the exercise also shows important data gaps and data fragmentation. Pivnenko et al. (2019) show approximately 22-26% plastic recycling rate in Denmark in 2016, excluding consideration of loss flows. Another Danish study applied MFA to evaluate recyclability by tracking the mechanical recycling chain of plastic waste and found a 52% recycling potential for hard plastics, 59% for films and 79% for PVC waste (Faraca and Astrup, 2019).

Micro-plastics have also been the focus of substantial research in recent times linked to the important associations with health and eco-system toxicity. With regard to the emission flows of macro- and microplastics, Kawecki and Nowack (2019) applied a probability MFA approach to map the emission pathways of seven polymers in Switzerland, in 2014. The results estimated that around 540 ± 140 g/cap/a macroplastics and 73 ± 14 g/cap/a microplastics are emitted into soil, while 13.3 ± 4.9 g/cap/a macroplastics and 1.8 ± 1.1 g/cap/a microplastics are emitted into freshwater (Kawecki and Nowack, 2019).

As packaging has the highest application rate and draws lots of attention, Valpak Consulting and WRAP provided the plastic packaging flows divided by different product types from consumer and non-consumer, in the UK, in 2013, with a 2020 projection scenario (McCaffery et al., 2014). Van Eygen et al. (2018) analysed plastic packaging across different product types and polymer compositions, in Austria, in 2013. According to these MFA studies, the plastic packaging recycling rate in the UK was 32%, while the plastic packaging recycling rate in Austria was 26%±7% (McCaffery et al., 2014, Van Eygen et al., 2018).

Prior to the commencement of this research, there were only a few studies focused on plastic MFA at the EU level. Deloitte Sustainability (2017) extrapolated the data from five member states to analyse the flows of plastic packaging in the EU, in 2014. Their results show that the EU had a plastic waste collection rate of 37%, but that the recycling rate is only 13% (Deloitte Sustainability, 2017). Ciacci et al. (2017) conducted a comprehensive estimation of the European PVC cycle from 1960 to 2012, finding the largest application sector is construction and the largest waste generation sector is packaging. Based on a probabilistic MFA, Kawecki et al. (2018) described the flows of seven commodity plastics in Europe, showing that the order of consumption is PP>LDPE>PET>HDPE>PVC>PS>EPS. Interestingly, Kawecki et al. (2018) show PVC has the highest recycling share, whereas Ciacci et al. (2017) found only a small amount of PVC waste was recycled, and most of it entered landfill. Finally, Bishop et al. (2020) analysed the flows of PE waste after recycling in the EU28, Norway and Switzerland, in 2017. Their research found that 46% of post-consumer plastic in Europe, that had been collected for recycling was exported, whilst approximately 7.3% of the PE waste that had been exported, entered the ocean (Bishop et al., 2020).

These recent studies highlight the challenges of using MFA to quantify plastic flows in Europe. Kawecki et al. (2018) especially studied plastic waste recovery and disposal and provided an estimation of recovery and disposal rates, in Europe. However, important data gaps still exist, fundamentally related to the outputs of recycling and recovery processes and use of secondary plastics in the economy, as well as the size of the potential leakage to the environment. Therefore, a comprehensive all-encompassing analysis of the plastic flows in Europe is still needed, with a focus on opportunities to increase circularity.

A key methodological challenge relates to the requirement to account for plastic embedded in complex products. Previous studies have used rather broad product group categories, for example, Kawecki et al. (2018) used eight aggregated plastic-containing product group categories. However, such aggregated product categories generate large uncertainties in the final material flows. In this thesis, I have used disaggregate data on more than 400 product categories, enabling a more detailed assessment of plastic flows than in previous EU studies. Such a comprehensive analysis provides the basis for a better understanding of the implications of policies and targets for plastics currently being discussed by regulatory bodies, and industry, and so forth. The proposed methodological framework also enables future updates, both at EU level and at member state level.

2.2 Transition towards a plastic circular economy

2.2.1 A brief overview of circular economy

This subsection briefly reviews the development of the circular economy. The Circular Economy (CE) has been identified as a sustainable alternative to a conventional take – make – dispose linear economy. The original concept of the CE can tracked back to the mid-to-late 20th century. Boulding (1966) described the Earth as a spaceship, the Spaceship Earth is a closed system which has limited resources. If human activities use unlimited natural resources, produce waste and pollution, then Spaceship Earth will exceed its carrying capacity. Thus, to sustain human life, the spaceship must rely on renewable energy, reuse resources, and minimise waste (Boulding, 1966).

Stahel and Reday (1976) conceptualised a loop economy and analysed that the product-life extension has the potential to substitute manpower for energy and create job opportunities. Stahel (1982) emphasised a self-replenishing system with spiral-loops that minimised the flows of material and energy to optimise the overall product lifespan, including reuse of goods, repair of goods, reconditioning/rebuilding of goods, and recycling of raw materials. Stahel and Clift (2016) argued that the circular economy is part of a performance economy (Stahel, 2010), and further argued that a circular economy focuses on the circularity of material flows, while a performance economy focuses on managing the quality and value of in-use stock.

Pearce and Turner (1990) proposed the term, circular economy, to describe the circular use of resources. They developed the first circular economic conceptual framework (Figure 2-11) to identify the economic utilities of material and energy flows, which also showed the benefits and effects. To be more specific, the concepts are that resources extraction cannot be faster than the speed of resource regeneration. On the other hand, waste cannot be more than the environmental capacity (Pearce and Turner, 1990). Parallel to this, Graedel and Allenby (2003) also demonstrated that the ideal industrial system should be made up of cyclic material flows. More recently, the Ellen MacArthur Foundation (2013) proposed the well-known butterfly diagram of the CE which illustrates the continuous flow of materials (Figure 2-12).

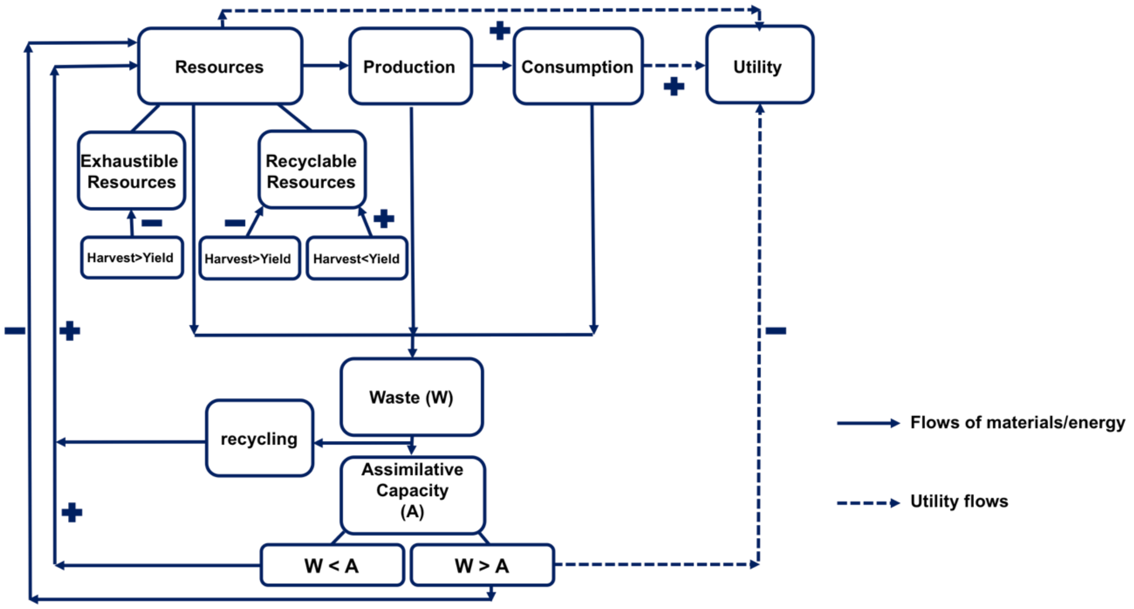


Figure 2-11 Circular economy conceptual framework (Pearce and Turner, 1990)

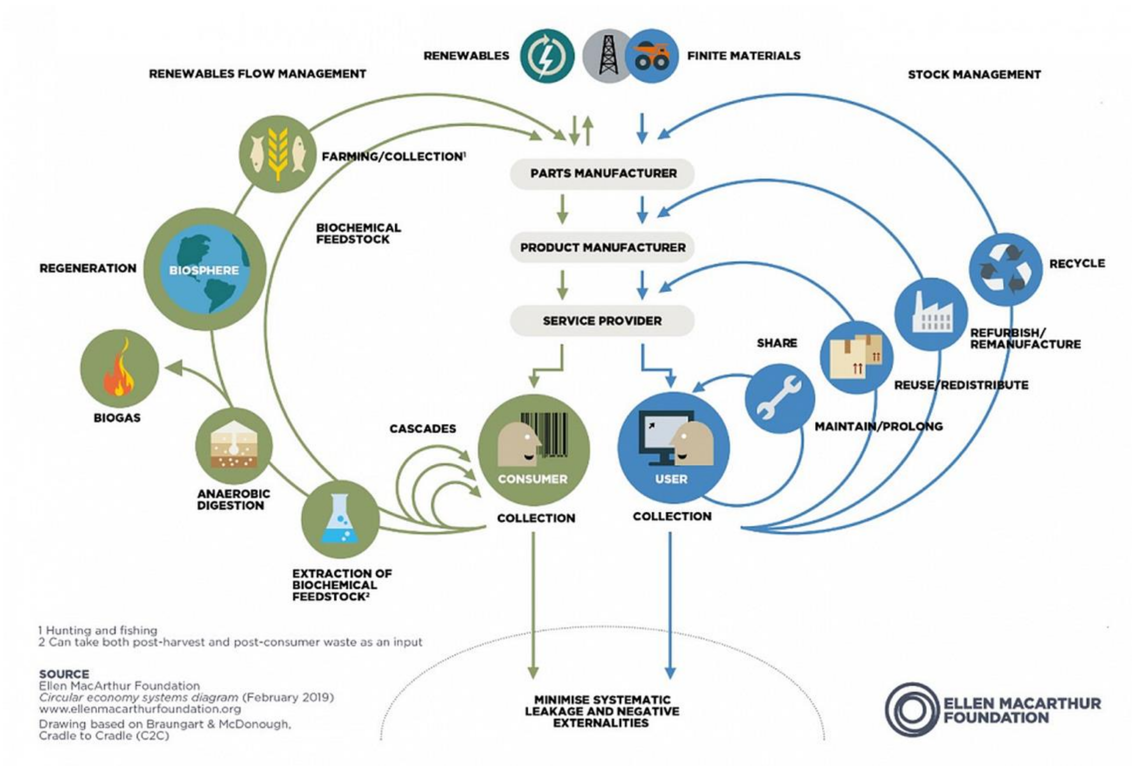


Figure 2-12 Butterfly diagram of the circular economy (Ellen MacArthur Foundation, 2013)

Alongside the idea of a circular economy, some terms that shares similar concepts have been proposed in the last two decades such as Industrial Ecology, Cradle to Cradle, Sustainable Material Management, Blue Economy, and Green Economy. Kirchherr et al. (2017) reviewed 114 definitions of CE and found that the slogan of 3R (reduce, reuse and recycle), was the most popular description. Moreover, economic prosperity and environmental quality were the important elements according to their results. Further detailed history and concepts of the circular economy can be found in Reike et al. (2018), Sillanpää and Ncibi (2019), Tuladhar et al. (2022), Winans et al. (2017), Stahel (2020), Calisto Friant et al. (2020).

In summary, the key principle of a CE is that the materials circulate at the highest value (Ellen MacArthur Foundation, 2016, Bocken et al., 2017). In this study, a CE is presented as an economic system that circular materials flow through, reducing both raw material consumption and waste, and reutilising resources to keep the highest value of resources within an economic system.

Despite the recent proliferation of CE studies, there is a widely acknowledged need for further research in this area. Alnajem et al. (2021) reviewed circular economy research between 2009 and 2018. They identified system transition as the key gap for further research (Alnajem et al., 2021).

Plastic has been prioritised as a key sector for promoting circular economy by the European Commission (2015). The Ellen MacArthur Foundation (2016) proposed a New Plastics Economy to transform the global plastic packaging value chain through three strategies, namely, fundamental redesign and innovation, reuse, and recycling with radically improved economics and quality. Johansen et al. (2022) reviewed the circular economy along the plastic value chain and found that most of the studies focused on the end-of-life phase but neglected studies on the plastic circular economy transition through the whole value chain. They recommended that more holistic research on a plastic circular economy transition is needed. The Royal Society of Chemistry (2020) suggested four major research themes: the impact of plastics throughout their life cycles; new sustainable plastics (e.g., bioplastics); closing the loop recycling; and degradation of plastics. Following the direction of future plastic circular economy research, this study mainly focused on closing the loop through recycling plastic waste and using secondary plastics in the plastic system transition.

2.2.2 Current studies of plastic circular economy transition analysis

In reviewing the existing studies relevant to the barriers and drivers of plastic circular economy transition, it is clear that most of the studies have mostly focused on the economic, technical, regulative, cultural barriers individually. The OECD (2018) analysed the global barriers to plastic recycling and potential interventions for secondary plastics market. Although the EU is seen as a forerunner in adopting the plastic circular economy, the EU has confronted similar barriers as the global secondary plastic market in particular economic and technical barriers.

Hahladakis and Iacovidou (2019) provided an in-depth overview of the challenges and trade-offs regarding mechanical recycling of plastic waste. They also highlighted that communication and collaboration among stakeholders is the key to closing the plastics loop. Their results reveal the importance of exchanging data, information and knowledge with different actors participating in the plastic circular economy transition.

Kirchherr et al. (2018) analysed the broader CE barriers in the EU, which included a lack of consumer awareness and hesitant company culture. They recommended investigating specific sectors. Therefore, this study investigates the plastic industry sector.

In the plastic industry sector, the European Commission (2018a) identified the barriers of the plastic circular economy and provided solutions at different plastic life cycle stages, including organising a higher level working group to encourage communication across the value chain. This has led to the European Commission working with industry through the Circular Plastic Alliance. Moreover, the PolyCE (Post-consumer high-tech recycled polymers for a circular economy) project, an EU Horizon 2020-funded project, identified the main barriers of secondary plastics used in EEE, which include waste and secondary plastics, lack of reliable supply and demand, fragmented regulation, and lack of communication (Wagner et al., 2018). Recently, Baldassarre et al. (2022) further identifies four drivers (cultural, regulatory, economic and technical) and four barriers (cultural, regulatory, economic and technical) to the use of recycled plastics in the automotive sector in the EU.

Studies produced at the European national level, include Milios et al. (2018), who identified the main barriers to plastic recycling in the Nordic region, which are the higher cost and lower quality of secondary plastics, as well as the constraints between economics and technology leading to the lack of demand for secondary plastics. The main discussion in their study tends to focus on plastic waste from the municipal waste stream. According to their results, value chain coordination and investment in innovation and technology development are key enablers.

Paletta et al. (2019) investigated barriers and challenges to plastics valorisation through surveys of converters in Italy. Their findings show that legislative barriers are the REACH (Registration, Evaluation, Authorisation and Restrictions of Chemicals) (EC No 1907/2006) Regulation and the RoHS Directive (Restriction of Hazardous Substances Directive 2011/65/EU), technical barriers are quality issues, economic barriers are lack of constant demand, availability and high cost, and social and cultural barriers are either hostility or inert attitude to the innovation (Paletta et al., 2019). Socio-cultural norms and socio-demographic characteristics also influenced different actors' perception to the recycling and using secondary plastics (Galati et al., 2020). According to Paletta et al. (2019), the joint-venture business model between manufacturers/converters and mechanical recyclers was the main change along the plastic value chain between 2012 and 2018.

Recently, Gong et al. (2020) investigated four cases of the fast-moving consumer goods industry in the UK to explore suppliers' and retailers' motivations, enablers, and barriers associated with plastic circular economy initiatives. Bening et al. (2021) analysed the legislative barriers interacting with economic and technical barriers on flexible plastic packaging in municipal solid waste stream. Their study highlighted three challenging issues which are still under debate, including an ambitious target for recycled plastics, the degree of intervention on policies between demand-pull and technology-push, and the bioplastics as an alternative material. Bening et al. (2021) also pointed out that it is necessary to systematically investigate the interrelations of the barriers along the value chain.

Some previous research has also highlighted information-related barriers and knowledge gaps that inhibit the achievement of greater circularity (Simpson, 2012, Kouhizadeh et al., 2019). In order to transition the plastic system to meet SDG (Sustainable Development Goals) 12 to create a circular and responsible consumption and production, designers (Hou et al., 2018) and manufacturers (Klemeš et al., 2021) need to provide more information and knowledge to the actors downstream, including retailers, consumers and recyclers. Some European firms have started to apply digital technologies to support the plastic value chain by tackling barriers such as the lack of data and information for secondary plastics (Chidepatil et al., 2020, Tramutola, 2019).

Galati et al. (2022) found that information regarding secondary plastics can shift consumers' behaviour. van Bruggen et al. (2022) highlighted that different types of barriers preventing use of secondary plastics in the automotive sector are connected and require a system change, including improving data collection and information sharing. However, no previous study has provided a systematic analysis on how the role of data-information-knowledge plays across different lifecycle stages, and what the barriers and drivers are for different actors to enhance the transparency and traceability of plastic waste and secondary plastics.

The ongoing discussion tends to focus on plastic packaging from the municipal solid waste stream through mechanical recycling, emphasising the economic and technical barriers along the way and showing that the high cost and low quality of recycled plastics lock in the transition towards the use of secondary plastics. This discussion normally explains the barriers on economy and technology separately, with some links to legislation and lack of traceability. Many of the references in this literature review section have identified barriers regarding lack of public awareness and lack of collaboration.

The legislation, market, technology, socio-cultural norms and business networks have rapidly changed in the past few years ever since the European Commission adopted the *European Strategy for Plastics in a Circular Economy*. This study responds to the need to further understand not only the dynamic reconfiguration of the regime, but also the role of data-information-knowledge and its interaction with different types of barriers and drivers that contribute to SDG12 and the ongoing development of European plastic markets.

Siltaloppi and Jähi (2021) recently analysed the barriers to the sustainable plastic value chain in Finland and northern Europe focusing on bioplastics and recycled plastics. Their results highlighted three main conundrums: limited production of sustainable plastics, lack of uses and demand for them, and missing economic logic for recycling development. Four solutions are suggested: from the supply of bulk materials to material solutions; from firm-centric material development to cross-tier collaboration; from price competition to competition on sustainability benefits; and from isolated technologies to infrastructure development (Siltaloppi and Jähi, 2021). However, an obstacle that may frustrate these solutions is that bioplastics face different barriers compared to secondary plastics, with some barriers probably overlapping. Bioplastics have a very small share in the European plastic market which accounts for 0.22%-0.4% of total plastic output (Escobar and Britz, 2021, Spekreijse et al., 2019). Also, the specific solution mechanisms for bioplastics and secondary plastics would be different. As bioplastics is a contested solution (Bening et al., 2021) and the European Commission has set a clear target for using secondary plastics, this study mainly focuses on the secondary plastics.

Findings by Siltaloppi and Jähi (2021) showed the interactions with different types of barriers, however, more drivers and barriers have emerged in the past few years which have not been discussed in previous studies. There is little evidence available showing how barriers and drivers are playing out across different end-use sectors and across the value chain. Additional research is needed to investigate the transition dynamics. Siltaloppi and Jähi (2021) also call for additional research on this topic, especially on ways the changing networks and business models contribute to speed up the plastic circular economy transition.

2.3 Summary of the literature review

The European Commission has already made the move to adopt the CE package and strategies for a circular plastic economy. To this end, the material flow analysis will be a useful tool to assess the current plastic flows, identify the non-circular hotspots, and suggest circular pathways accordingly. The plastic system in Europe has seen rapid changes in the past few years. As material flows are embedded in multi-layered systems of transition governance with different actors involved in a socio-technical system, Hoffman (2003) suggests linking a quantitative material-oriented analysis with a social systems analysis to expand toward a broader perspective of systemic factors, in order to consider the practical feasibility of transformational change. Jäger-Roschko and Petersen (2022) recommend future research should apply a theoretical framework to explore the factors for improving information flows. Borrello et al. (2020) further suggests applying the multi-level perspective transition theory to analyse circular economy transition and identify regime constraints. This study, therefore, aims to apply the multi-level perspective to explore the complex dynamic of this ongoing change process.

In this study, the multi-level perspective can help us to better understand the ongoing transition to increase the use of secondary plastics through the following approaches:

- Co-evolutionary and systemic approach focusing on co-evolutionary developments of policies and standards, markets and business models, technology, consumer preferences and behaviours, and interactions between these different sub-regimes;
- Actor-based approach covering actors along the value chain, which include petrochemical producers, converters/manufacturers, brand owners, retailers, physical/mechanical recyclers, chemical recyclers, intermediaries, and an extended producer responsibility organisation;
- The approach highlights sources of both stability and change in socio-technical systems, enabling exploration of the barriers and drivers across the value chain and four application areas (packaging, construction, automotive, electrical and electronic equipment);
- Complex dynamics, which shows the dynamics of regimes in the past few years, as well as the dynamic of change within each sub-regime.

Different from the existing studies, this research further explores the role of data, information and knowledge as well as networks.

Taking up the call from Siltaloppi and Jähi (2021) for additional qualitative and quantitative research may provide an understanding of how potential solution mechanisms reshape plastic flows towards a plastic circular economy transition. This PhD research, therefore, applies both material flow analysis and transition analysis to provide systematic findings and discussion.

3 Methodology

A mixed-method (Creswell and Creswell, 2017, Creswell and Clark, 2017, Creamer, 2018, Johnson et al., 2007) is required to track and quantify the flows and qualitatively identify the barriers and drivers of the socio-technical system of plastic in the EU. The material flow analysis (MFA) is a tool limited to only presenting the quantification of flows; so, further linking and merging with a qualitative method can widen the analytical lens. The transition analysis (TA) helps to explore the different barriers and drivers of socio-technical regimes engaged with secondary plastics use, as well as different actors along the value chain interacting with plastic waste and secondary plastics. Hence, the mixed method, which combines the quantitative MFA and qualitative TA, gives stronger insights in explaining the interactions between different sub-regimes and actors, which affect the plastic flows.

This section presents the research methods. The MFA in Section 3.1 and TA in Section 3.2 are introduced separately. The theories of each method are introduced, and the data collection and analysis are explained.

3.1 Material flow analysis

3.1.1 Material flow analysis

This study uses a material flow analysis (MFA), a systematic approach to assess the flows and stocks of materials through a system within a defined spatial and temporal boundary (Brunner and Rechberger, 2016). Based on the principle of mass conservation, inputs from nature used by the socio-economic system are balanced by all the processed outputs (or residuals) generated by the system, plus the additions to the socio-economic stock.

Following MFA methodological guidelines (Brunner and Rechberger, 2016, European Commission, 2018b), the system boundary in this study is the EU28, according to its definition in 2016. It is worth noting that Europe in the study refers to the same system boundary as EU28. For the temporal boundary, 2016 is chosen as a reference year because it had the most up-to-date and comprehensive datasets when this analysis was conducted. The biennial datasets of waste streams are published with a few years' delay. Plastic MFA in 2016 is also suitable as a baseline scenario for measuring plastic circularity, as the circular economy action plan started in 2015, and the relevant policies and targets were set afterwards. Figure 3-1 displays the system boundary. The resource flow has been analysed according to five main phases that cover the entire life cycle of plastics, including:

1) production and consumption of plastic polymers/fibres;

2) manufacturing of plastic products;

3) plastic products consumption and in-use stock;

4) plastic waste generation and collection; and

5) plastic waste treatment and other destinations.

Initial extraction of primary materials (e.g., fossil fuels) and manufacturing of monomers lie outside the defined system boundaries for this study.

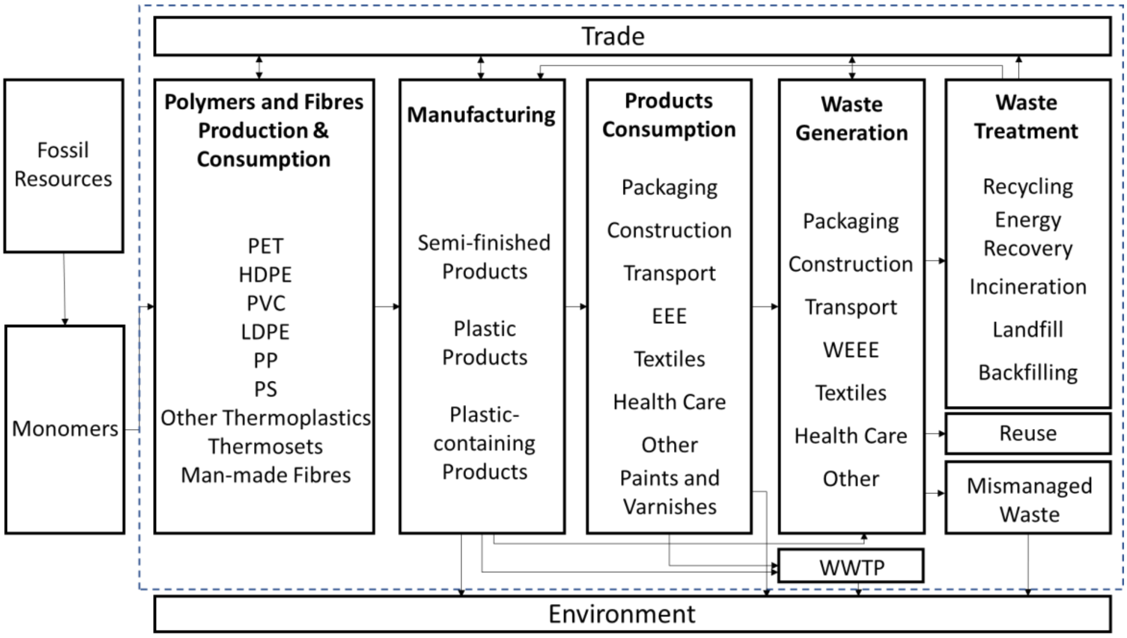


Figure 3-1 System boundary

Figure 3-2 depicts the fundamental framework of plastic data. Plastic flows include fossil-based non-biodegradable plastic polymers and synthetic fibres (see Appendix A). With regard to the plastic products, a total of 416 plastic-containing products have been identified from the PRODCOM (production of manufactured goods) database (Eurostat, 2016) and by Scudo et al. (2017) for the personal care and cosmetics products (PCCP) (see Appendix B).

For the calculation of plastic waste flows, product categories have been linked to waste categories in order to match the plastic-containing waste categories from the European Waste Catalogue (see Table 3-1).

Additives used in plastic production are also embedded in plastic material flows. Geyer et al. (2017) estimate that approximately 7% of all plastic products may contain additives. However, due to poor quality data and the relatively small share of additives in the total mass of plastic, additives are not considered in this study. Further discussion about additives in plastics can be found in Hahladakis et al. (2018).

The approach to the estimation of plastic losses is based on the method of Ryberg et al. (2019), which has different formulas and/or transfer coefficients for estimating each losses. The estimation includes the losses from manufacturing, washing of textiles, microbeads of PCCP, waste-water treatment plants (WWTP), mismanaged plastic waste, and recycling processes. Using balancing equations, estimations are calculated and then validated by other sources of data. Overall recycling losses were estimated based on a case study by Recycling Technologies (2016), and were subsequently validated through expert interviews. Four interviews were conducted: two representatives of large integrated waste management companies, one recycler, and a recycling consultant – all of whom have experience across Europe.

To be consistent with the system boundary of this study, the losses relevant to rubber (e.g., tyre abrasion, city dust), weathering of marine coatings, fishing nets and maritime-related losses are excluded. Paints are coatings on other non-plastic products and thus follow other waste collection routes, so abrasion of paints (including road markings) are not considered further in the analysis.

3.1.2 Data collection and estimation

Table 3-2 lists the sources of data and main assumptions for the plastic MFA. There are seven principal types of data used in this study:

1) Trade and production data on plastic polymers/fibres, intermediate goods and manufactured products (Eurostat, 2017), and secondary plastics (Stadler et al., 2018);
2) Data on the plastics embodied in products (Swedish Chemicals Agency, 2015);
3) Data on mass per unit of item (Amazon, 2018);
4) Trade data on plastic waste (UN COMTRADE, 2018);

5) Data on generation and treatment of waste (Eurostat, 2013);
6) Data on the plastic fraction of different waste streams;
7) Transfer coefficient of losses along the life cycle stage (Ryberg et al., 2019).

Estimation of recycling losses derived from the MFA was subsequently validated through an expert interview process. All the data documentation and calculations were processed using Microsoft Excel. The details on data collection and estimation are explained below.

- **Plastic polymers and fibres**

The data for plastic polymers in production and trade are extracted from the PRODCOM database. The plastic polymers from NACE Rev2 (Statistical classification of economic activities in the European Community) refer to *'resins, plastics materials and non-vulcanisable thermoplastic elastomers, the mixing and blending of resins on a custom basis, as well as non-customised synthetic resins (Eurostat, 2008)'*. The polymers from the class of 'manufacture of plastics in primary forms' were included (code 20.16) except for silicones (as these could be resins or elastomers), polyethylene glycols, natural and modified natural polymers. Man-made fibres (code 20.60) made from fossil-based plastics were also included. The plastics in 'manufacture of synthetic rubber (code 20.17)', a category which includes styrene-butadiene rubber used in tyres, were not considered. Appendix A lists plastic polymers and fibres that were included in the MFA study.

- **Plastic products**

For the semi-finished plastic products and final plastic-containing products, a total of 416 products were identified and included from those PRODCOM list (Eurostat, 2016) and from Scudo et al. (2017) for the personal care and cosmetics products (PCCP). This was based on secondary sources, including the plastic products list from Van Eygen et al. (2017) and information from the commodity guide database (Swedish Chemicals Agency, 2015). However, where adequate information was unavailable, it was necessary to resort to judgement of whether each product category contains plastic. Product categories with less than 10% plastic content or without production data were excluded.

For the fraction of plastic contained in the products, the data was mainly collated from the commodity guide database established by the Swedish Chemicals Agency (2015) and the literature (e.g., Buekens and Yang (2014), Mashek et al. (2016)). The mass per unit of plastic-containing products was taken from various sources, including academic literature, market reports and websites (Amazon, 2018, Asayesh et al., 2018, Forti et al., 2018, International Council on Clean Transportation Europe, 2017, Vats and Singh, 2015, Whigham et al., 2013). Calculating the quantity of plastics within each product category relies on:

1) the amount of products (kilogram) multiplied by the plastic fraction (%);
2) the number of items multiplied by mass per unit and plastic fraction; or
3) volume (m^3) (area (m^2) x thickness (m)) multiplied by density (kilogram /m^3)

In order to balance production and consumption phases, the total consumption was calculated based on the equation: apparent consumption = production + imports – exports, and by following the PRODCOM User Guide (Eurostat, 2017) and law of conservation of mass. Inter-economy flows considered plastic products by application area, namely: packaging; construction; transport; electrical and electronic equipment; textiles; healthcare; other; and paints and varnishes. Appendix C lists the plastic products in categories of other. The 'other' application area also includes personal care and cosmetics products (PCCP). This study assumed that 1,318 tonnes of plastic were equally produced and consumed in PCCP (Scudo et al., 2017).

The data extracted from the class of manufacture of plastics plates, sheets, tubes and profiles (code 22.21) could be either semi-finished products or final products. This study assumed that imports and exports of code 22.21 products are all semi-finished products. With regard to the production data, these code 22.21 products may be used as semi-finished products (e.g., pipes, hoses, and strips) for manufacture and assembly of final products. Although some parts of these semi-finished products might be used to manufacture packaging or EEE, it is difficult to split the product categories into different applications, because many product categories aggregate plates, sheets, film, foil and strip, or aggregate tubes, pipes and hoses. Due to the lack of further information, this study estimated packaging mainly from the class of manufacture of plastic packaging goods (code 22.22). I then assumed the production and consumption of semi-finished products (code 22.21) to be equally allocated to the construction, transportation, and other application areas, which might need a larger amount of code 22.21 products to further manufacture and assemble final plastic-containing products.

As this study only looks at a one-year static MFA, the stocks are estimated based on the mass balance principle between plastic consumption and plastic waste generation.

- **Plastic waste**

Plastic product waste was quantified by the database called 'generation of waste by waste category, hazardousness and NACE Rev. 2 activity'. The waste category, which includes plastics, was identified based on the definition of waste categories from the 'Manual on Waste Statistics (Eurostat, 2013)' and 'Guidance on classification of waste according to EWC-Stat categories (Eurostat, 2010)'. Thus, plastic-containing waste includes healthcare and biological waste, plastic wastes, discarded equipment, discarded vehicles, household and similar waste, mixed and undifferentiated materials, and 'mineral waste from construction and demolition (considering European Waste Catalogue (EWC) code 17 02 04 includes plastics)'. These plastic fractions of waste categories were collected from different references shown in Table 3-3. It is worth noting that the 0.16% plastic fraction in the 'mineral waste from construction and demolition' is estimated, based on the mixed construction waste (EWC code 17 02 04) divided by total construction waste (WRAP, 2010). This is aligned with Gálvez-Martos et al. (2018) showing 0.1%-2% plastic waste in construction and demolition waste.

Plastic packaging was included in the waste categories of plastic waste, household and similar wastes, mixed and undifferentiated materials. The plastic packaging fraction was estimated based on other references. Casares et al. (2005) estimated 13% packaging in industrial waste. The plastic packaging in the service sector and household plastic waste were estimated based on average of Villanueva and Eder (2014) (70%) and Dahlbo et al. (2018) (90%).

Manufacturing waste was estimated from the data of waste generated from 'manufacture of plastic products'. With regard to waste arisings by source, the definition of the source followed the economic activities in NACE Rev. 2. (Eurostat, 2008). The plastic waste generated from 'waste collection and treatment', and 'wholesale of waste and scrap' was excluded to prevent double counting.

The United Nations Commodity Trade Statistics Database (UN COMTRADE, 2018) was used to extract the data of plastic waste trade, including PE waste, PVC waste, PS waste, other plastic waste, man-made fibres and textile waste. Export of waste electrical and electronic equipment (WEEE) was extracted from the database of 'Waste electrical and electronic equipment by waste management operations [env_waselee]'. The plastic fractions of these trade textile wastes and WEEE are the same as Table 3-3.

A waste treatment database, entitled ‘treatment of waste by category, hazardousness and waste operations,’ provides the data for plastic waste entered into different waste treatments. The identification of waste categories and estimation of plastic fraction was the same as the stage of waste generation and collection. The definition of plastic waste treatment in this study followed the ‘Manual on Waste Statistics (Eurostat, 2013).’ Thus, recycling refers to reprocessing and recycling of plastic waste (mechanical recycling, gasification and pyrolysis using the components as chemicals). The amount of plastic waste is allocated to energy recovery when the waste is used to generate heat or electricity and fulfil the energy efficiency standards set in Annex II of the Waste Framework Directive (see Manual on Waste Statistics (Eurostat, 2013), page 37 and page 38). If the waste goes to thermal treatment and it is not able to be used for energy production, then it is allocated to incineration (see Manual on Waste Statistics (Eurostat, 2013), page 38). Backfilling means plastic waste used in excavated areas (Eurostat, 2013).

- **Secondary plastics**

Total secondary plastic (also called recycled plastic) used within the EU was extracted from the use table of the EXIOBASE 3 database (Merciai and Schmidt, 2016, Merciai and Schmidt, 2018, Stadler et al., 2018). There is currently no reliable statistical data for the export of secondary plastics. This study applied 25% as a transfer coefficient for the export of secondary plastics from the EU and was based on secondary data, which relied on expert judgment (Simon, 2015). This transfer coefficient describes the fraction of plastic within the waste recycling process that is transferred into the output flow.

- **Reuse**

Due to the data limitation, plastic reuse only included WEEE, end-of-life vehicles (ELVs) and textiles. Plastic waste within discarded equipment and automotive were estimated based on the Eurostat database of ‘Waste electrical and electronic equipment by waste management operations [env_waselee]’ and ‘End-of-life vehicles - reuse, recycling and recovery, totals [env_waselvt]’. The plastic fractions in WEEE and ELVs are the same as those shown in Table 3-3. Textile reuse in the EU was estimated according to the 10% of transfer coefficient from Beton et al. (2014).

- **Losses**

Table 3-4 displays the plastic losses along the life cycle in this study. Losses of plastic pellets during the manufacturing stage is about 0.001% of plastic polymer consumption, according to the data inventory of plastic processing companies in Denmark by the Danish Plastics Federation (Lassen et al., 2015). Hence, this study estimated 0.001% of total plastic polymers, fibres and secondary plastic consumption lost at the manufacturing stage. These manufacturing losses are assumed to enter wastewater treatment plants (WWTP) directly. It is assumed 5% microplastics are lost to the environment after entering sewage networks (Ryberg et al., 2019).

At the product consumption stage, losses came from the use of PCCP, and washing of synthetic clothing textiles. Plastic microbeads amounting to 1,318 tonnes were used in PCCP per year (Scudo et al., 2017). This study assumed all these microbeads entered wastewater and were captured in the WWTP, and 5% of microbeads were lost to the environment after entering sewage networks (Ryberg et al., 2019). While washing synthetic clothing textiles, 2% of plastics in wearing apparel are lost (Boucher and Friot, 2017) and 7% of microfibers are lost to the environment after entering sewage networks (Ryberg et al., 2019).

It is worth noting that all the percentages of losses to the environment from WWTP in this study were estimated based on the microplastics lost to the environment after entering sewage networks in the region of western Europe from Ryberg et al. (2019) (see Table 3-4). An application of 38% of wastewater sludge on agricultural fields would also become losses that enter the environment (Ryberg et al., 2019). Wastewater sludge was estimated based on the amount of microplastics in wastewater entering the WWTP multiplied by the WWTP microplastics removal rate (removal rate of microbeads is 97.4% and removal rate of microfibres is 95.3%) (Ryberg et al., 2019).

At the waste generation stage, the mismanaged plastic waste was estimated from the mass balance (Mismanaged plastic waste = Plastic waste generation + Import of plastic waste – Plastic waste treatment – Export of plastic waste – Reuse). For the losses during the recycling process, Recycling Technologies (2016) estimated 5% entered landfill, while 43% entered incineration, based on a case study of household and industrial waste treated through plastic recovery facilities (PRF) in Scotland in 2016.

Source: Sold production, exports and imports by PRODCOM list (NACE Rev. 2) - annual data [DS-066341]					
	PRCCODE/INDICATORS	EXPORT (EXPQNT)	IMPORT (IMPQNT)	PRODUCTION (PRODQNT)	CONSUMPTION
Plastic Polymers	20.16 Manufacture of plastics in primary forms				
Plastic Fibres	20.60 Manufacture of man-made fibres				
Semi-finished/final plastic products	22.21 Manufacture of plastic plates, sheets, tubes and profiles				
Packaging	22.22 Manufacture of plastic packing goods				
Construction	22.23 Manufacture of builders' ware of plastic				
EEE	26 Manufacture of computer, electronic and optical products				
	27 Manufacture of electrical equipment				
Transport	29 Manufacture of motor vehicles, trailers and semi-trailers				
	30 Manufacture of other transport equipment				
Textiles	13 Manufacture of textiles	Multiple plastic fraction/ weight per unit			IMPQNT+PRDQNT-EXPQNT
	14 Manufacture of wearing apparel				
Other (includes Health Care)	22.29 Manufacture of other plastic products				
	15 Manufacture of leather and related products				
	17 Manufacture of paper and paper products				
	25 Manufacture of fabricated metal products, except machinery and equipment				
	28 Manufacture of machinery and equipment n.e.c.				
	31 Seats and parts thereof; parts of furniture				
	32 Other manufacturing				
Paints and varnishes	20 Manufacture of chemicals and chemical products				

Source: Generation of waste by waste category, hazardousness and NACE Rev. 2 activity [env_wasgen]									
NACE_R2/ WASTE	Health care and biological waste	Plastic wastes	Textile wastes	Discarded equipment	Discarded vehicles	Household and similar wastes	Mixed and undifferentiated materials	Mineral waste from construction and demolition	Plastic packaging
Agriculture, forestry and fishing									
Mining and quarrying									
Manufacture	Multiple plastic fraction in each waste category								Split from the waste category of plastic wastes, household and similar wastes
Construction									
Services									
Households									

Source: Treatment of waste by waste category, hazardousness and waste management operations [env_wastrt]								
NACE_R2/ WASTE	Health care and biological waste	Plastic wastes	Textile wastes	Discarded equipment	Discarded vehicles	Household and similar wastes	Mixed and undifferentiated materials	Mineral waste from construction and demolition
Disposal - landfill (D1, D5, D12)								
Disposal - incineration (D10)								
Recovery - energy recovery (R1)	Multiple plastic fraction in each waste category							
Recovery - recycling								
Recovery - backfilling								

Figure 3-2 Fundamental framework of plastic data

Table 3-1 Product categories and examples map of waste categories

Product categories	Products examples	Waste categories
Packaging	Sacks and bags, boxes, bottles, stoppers, lids, caps, capsules	Packaging waste was split from other product categories
Construction	Floor covering, baths, lavatories, reservoirs doors, window frames, shutters, blinds, fittings	Mineral waste from construction and demolition; plastic waste from construction sector
EEE	Laptop, PCs, printers, keyboards, TVs, vacuum cleaners, microwave ovens, valves, hand tools, saws, fans	Discarded equipment
Transport	Vehicles, caravans, safety seat belts, bumpers, sailboats, baby carriages	Discarded vehicles
Textiles	Yarn, woven fabrics, bedspreads, tents, carpets, fishing nets, workwear, outwear, underwear, raincoats, gloves, swimwear	Textile waste; plastic waste from manufacture of textiles
Health Care	Syringes, catheters, blood bags	Healthcare and biological waste
Other	Luggage, footwear, napkins, tampons, furniture, sports equipment, toys, sunglasses, goggles, brooms and brushes, hard hats, personal safety equipment, personal care and cosmetic products	Plastics waste; Household and similar waste; Mixed and undifferentiated materials
Paints and Varnishes	Paints and varnishes	-

Table 3-2 Sources of data and main assumptions for plastic MFA

Process	Data source / Assumption
Trade of plastic polymers and products	Sold production, exports and imports by PRODCOM(production of manufactured goods) list (NACE Rev. 2) - annual data [DS-066341]
Production	Sold production, exports and imports by PRODCOM(production of manufactured goods) list (NACE Rev. 2) - annual data [DS-066341]
Manufacturing waste	Generation of waste by waste category, hazardousness and NACE Rev. 2 activity [env_wasgen]
Consumption	Apparent consumption = production + imports – exports
Plastic fraction	Commodity guide database (Swedish Chemicals Agency, 2015) and other journal articles (e.g., Buekens and Yang (2014), Mashek et al. (2016))
Mass per items	Literature, market reports or websites (Amazon, 2018, International Council on Clean Transportation Europe, 2017, Forti et al., 2018, Asayesh et al., 2018, Whigham et al., 2013, Vats and Singh, 2015)
Waste generation	Generation of waste by waste category, hazardousness and NACE Rev. 2 activity [env_wasgen]
Waste treatment	Treatment of waste by waste category, hazardousness and waste management operations [env_wastrt]
Trade of plastic waste	United Nations Commodity Trade Statistics Database; Waste electrical and electronic equipment by waste management operations [env_waselee]
Secondary plastics	Use table of the EXIOBASE v3 - 'Secondary plastic for treatment, Re-processing of secondary plastic into new plastic'
Export secondary plastics	Transfer coefficient:25% (Simon, 2015)
Reuse - WEEE	Waste electrical and electronic equipment by waste management operations [env_waselee]
Reuse - ELV	End-of-life vehicles - reuse, recycling and recovery, totals [env_waselvt]
Reuse - Textiles	Transfer coefficient:10% (Beton et al., 2014)

Table 3-3 Sources of data for plastic fraction in different waste categories

NACE_R2/WASTE	Plastic fraction	Data source
Plastic wastes	100%	Own estimation
Plastic packaging fraction in industrial waste	13%	Casares et al. (2005)
Plastic packaging fraction in household waste	80%	Average from Villanueva and Eder (2014) and Dahlbo et al. (2018)
Healthcare and biological waste	12%	Tudor et al. (2008)
Textiles	49%	Bartlett et al. (2013)
Discarded equipment	23%	Buekens and Yang (2014)
Discarded vehicles	10%	Mashek et al. (2016)
Household and similar wastes	10.8%	Median of European countries from Edjabou et al. (2015)
Mixed and undifferentiated materials	10%	Own estimation
Mineral waste from construction and demolition	0.16%	WRAP (2010)

Table 3-4 Sources of transfer coefficient of losses at different life cycle stage

Stage	Losses	Transfer coefficient	Data source / Assumption
Manufacturing	Losses from manufacturing	0.001%	Lassen et al. (2015)
	Losses from transport and handling	0.0035%	Ryberg et al. (2019)
	Microplastics lost to the environment from WWTP	5%	Ryberg et al. (2019)
Consumption	Microbeads in personal care and cosmetics products(PCCP) in wastewater	-	Consumption of plastic microbeads in PCCP (Scudo et al., 2017).
	Microbeads lost to the environment from WWTP	5%	Ryberg et al. (2019)
	Losses of microfibres in wastewater	2%	Boucher and Friot (2017)
	Microfibres lost to the environment from WWTP	7%	Ryberg et al. (2019)
	Lost from application of wastewater sludge on agricultural fields	38%	38% of the captured microplastics are applied to agricultural soil which would loss to the environment.
Waste generation (End-of-life)	Mismanaged plastic waste	-	Mismanaged plastic waste = Plastic waste generation + Import of plastic waste – Plastic waste treatment – Export of plastic waste – Reuse
Waste treatment	Recycling losses to landfill	5%	Recycling Technologies (2016)
	Recycling losses to incineration	43%	Recycling Technologies (2016)

3.1.3 Uncertainty analysis

An uncertainty analysis was undertaken to estimate the level of intrinsic uncertainty of the model. This study followed the MFA uncertainty analysis framework developed by Laner et al. (2015). The method proposed by Laner et al. (2015) allows comprehensive data quality assessment and uncertainty characterization to understand the reliability of MFA results and identify the flows that have poor data quality. This approach estimates uncertainties derived from data gaps, and uses a qualitative assessment of the uncertainty method to calculate quantitative probability distributions that are then used for the MFA data reconciliation process using STAN software (Cencic and Rechberger, 2008). Laner et al. (2015)'s method is shown in Table 3-5. There are five main indicators. The 'source reliability' indicator focuses on the quality of documentation for data generation. The 'completeness' indicator refers to comprehensiveness of data sources and whether the data includes all the relevant flows or not. 'Temporal correlation' and 'geographical correlation' evaluate the congruence of the available data with respect to selected time and geographical boundary respectively. 'Other correlation' evaluates the congruence of the available data with respect to variety of products and technologies. Indicators are scored 1 to 4 ranging from very good, to very poor data quality, respectively. Secondary data derived from expert judgement is assessed differently with an assessment of source reliability.

The second step was to use those qualitative scores to generate a quantitative measure of data uncertainty, expressed as the coefficient of variation (CV). This involved combining the score for each attribute of data quality with a sensitivity parameter, used to reflect a judgement about the relative importance of each specific attribute of data quality. In other words, the level of sensitivity is chosen depending on how a change in a particular indicator can affect the quantities of interest. Some attributes might not be as affected by larger changes. For example, the plastic fraction embedded in electronic products has low sensitivity to the indicator of geographical correlation because the electronic products might have similar material composition no matter where they are manufactured and sold. Some attributes might be strongly affected by even a small change in the indicator. For example, the plastic fraction embedded in the electronic products may have higher sensitivity to the indicator of temporal correlation due to technology evolution and market changes (Laner et al., 2015). Parameters *a* and *b* for each sensitivity level were defined by Laner et al. (2015). The CVs were parameterized based on the equation [1] and [2], shown in Table 3-6. For the secondary data from expert judgement, the criteria of estimation are shown in Table 3-5 and Table 3-6.

$$CV_{source\ reliability} = \mathrm{a} \times e^{b \times score} \quad [1]$$

$$CV_{completeness;temporal\ correlation;geographical\ correlation;other\ correlation} = a \times e^{b \times (score-1)} \quad [2]$$

Thirdly, the total CV was assessed by aggregating the individual CV based on equation [3]. The addition of individual flows (M_A, M_B) was estimated based on equation [4], while the multiplication of the amount of products, plastic contents and mass per unit was based on equation [5]. Finally, the CV_{total} (or CV_c) could be applied to characterise the uncertainty of each flow.

The CV values for each parameter describe a probability distribution, which is assumed to be normal. The data reconciliation process in STAN then allows deviations from the central values of these distributions (assumed to be the mean of this distribution), by minimising the sum of squared errors. Parameters with estimated lower 'data quality' have wider distributions, providing greater flexibility to identify a more likely accurate value given the other material flow data during the reconciliation process in STAN.

$$CV_{total} = \sqrt{CV^2_{source\ reliability} + CV^2_{completeness} + CV^2_{temporal\ corr.} + CV^2_{geographical\ corr.} + CV^2_{other\ corr.}} \quad [3]$$

$$\left(M_C \times \frac{CV_C}{100}\right)^2 = \left(M_A \times \frac{CV_A}{100}\right)^2 + \left(M_B \times \frac{CV_B}{100}\right)^2 \quad [4]$$

$$CV_C^{\ 2} = CV_A^{\ 2} + CV_B^{\ 2} \quad [5]$$

Table 3-5 Data quality indicators and qualitative evaluation criteria

Data quality indicator	**Very good Score:1**	**Good Score:2**	**Poor Score:3**	**Very poor Score:4**
Source reliability	Official report; Peer reviewed paper	Public report; market data	Qualified estimate	Non-qualified estimate
Completeness	Includes all relevant processes/flows	Includes main processes/flows	Partially including main processes/flows	Important processes/flows are missing
Temporal correlation	2016	2011-2015, 2017-2020	2006-2010	Prior to 2006
Geographical correlation	Same region	Socioeconomically similar region	Socioeconomically different region	Socioeconomically very different region
Other correlation	Value relates to the same product, the same technology, etc.	Value relates to the similar product, technology, etc.	Value deviate from different product, technology.	Value deviate strongly from product, technology.

Expert estimate	Formal expert elicitation with (empirical) database – transparent procedure and fully informed experts on the subject.	Structured expert estimate with some empirical data available or using transparent procedure with informed experts.	Expert estimates with limited documentation and without empirical data available.	Educated guess based on speculative or unverifiable assumptions.

Table 3-6 Quantitative uncertainties within different sensitivity levels for different indicators

Data quality indicator	Sensitivity level	Score:1	Score:2	Score:3	Score:4
Reliability	-	4.5	13.7	41.3	124.6
Completeness/ Temporal/ Geographic/other correlation	High	0.0	4.5	13.7	41.3
	Medium	0.0	2.3	6.8	20.6
	Low	0.0	1.1	3.4	10.3
Expert estimate	-	4.5	13.7	41.3	124.6

3.2 Transition analysis

3.2.1 Multi-level perspective on transitions

A multi-level perspective (MLP) on transitions was used as a conceptual theory which framed the qualitative analysis within this research. The MLP on transitions classified the socio-technical system into three levels, namely, landscapes, regimes, and niches (Geels, 2002, Geels and Schot, 2007). Figure 3-3 depicts the theoretical framework of the MLP on transitions.

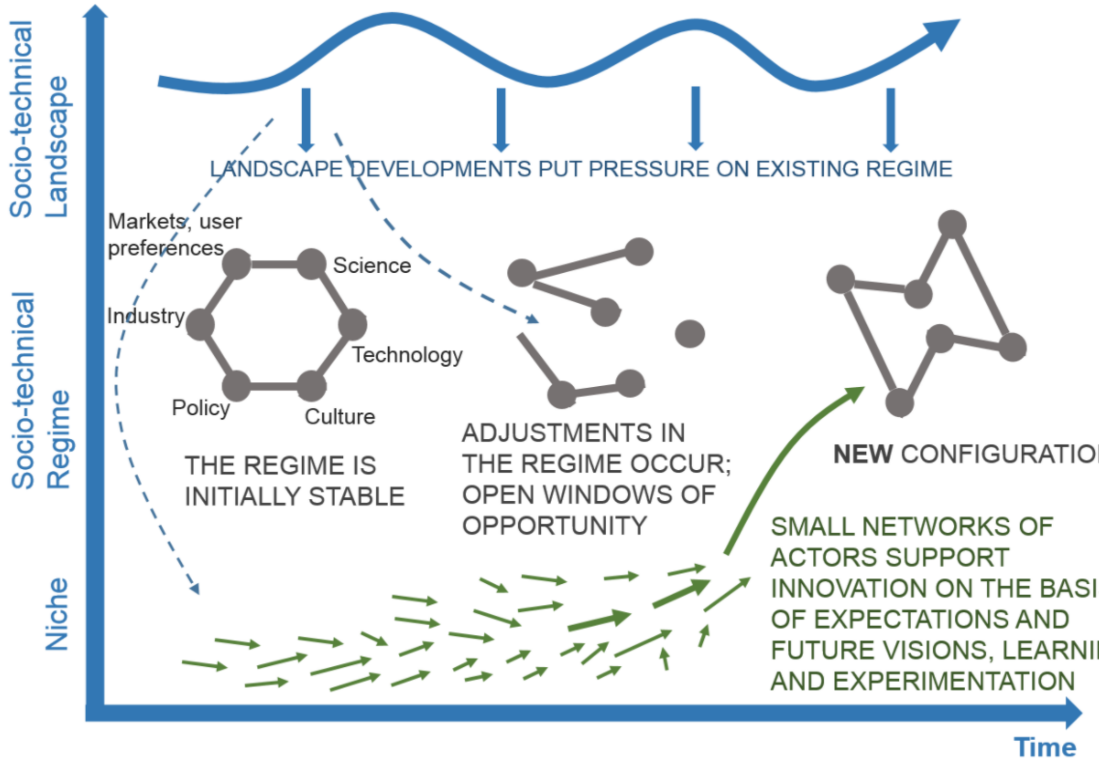


Figure 3-3 Theoretical framework of the multi-level perspective on transitions adopted from Geels (2002)

Source: BioKum research project website - https://biokum.de/en/research/

Landscapes are the exogenous background of macro-economic trends, macro-political frameworks, demographical trends, societal values, and cultural patterns. Landscape changing can be either sudden external shocks (e.g., oil price shocks, crisis) or gradually slow changes (Geels, 2002). As a wider external context, landscapes cannot easily be changed by actors in a short period of time.

Regimes constitute a cluster of elements that form the structure to stabilise the whole socio-technical system. Regimes interlink rule-regimes with actors to create dynamic interactions (Geels, 2004). Geels (2004) defined regimes as semi-coherent rule-sets which were used to characterise regime levels in five elements: technological sub-regime; science sub-regime; policy sub-regime; socio-cultural sub-regime; and user and market sub-regime. However, different studies have constituted diverse sub-regimes without a solid analytical structure. It has been argued that the empirical operationalisation and specification in the regime level are unclear (Berkhout et al., 2004, Genus and Coles, 2008). Geels (2011) further suggests the analyst demarcates the research object first, and then operationalises different analytical levels. Another suggestion is to investigate the intangible deep structure behind the activities.

In this study, the sub-regimes were constructed based on both the existing literature and the themes generated through the coding process. This study mainly focused on the key actors along the plastic value chain. Other external actors outside the plastic value chain, such as policy-makers, and advocates from the non-governmental organisations (NGOs) were not selected to be the interviewees.

Niches are protected spaces where radical innovations are developed. Most of the previous studies focused on analysis of niche innovation as the niches are originally identified as the key units of analysis (Geels and Schot, 2007, Kemp et al., 1998). The radical innovations could be new technologies, new infrastructures, new business models (e.g., product service systems), or grassroots and social innovations (e.g., repair café) (Geels, 2019).

The concepts of the MLP construct crossover evolutionary economics, science and technology, neo-institutional theory and structuration theory (Geels, 2004, Geels, 2010). The MLP has been widely applied to explain the complex and dynamic socio-technical transitions relevant to energy transition, low-carbon transition, and sustainability transition (e.g., Moradi and Vagnoni (2018), Lin and Sovacool (2020), Berkeley et al. (2017), Schot et al. (2016)), and to explore the interactions across the landscape level, regime level, and niche level. It could be utilised to explore not only a historical time period of development trajectories but also ongoing transition processes (Lawhon and Murphy, 2012, Geels, 2011).

Three factors in the niche- and regime-specific context could disrupt the stable system structure and response to external pressures from the landscape level. Firstly, some problems have arisen in the existing regime which creates misalignments among different actors (Van De Poel, 2000). Secondly, radical innovations can become potential solutions. Thirdly, when innovations begin to be adopted, they build up internal momentum (Geels, 2005, Elzen et al., 2004). These factors lead to four transition pathways: transformation, reconfiguration, technological substitutions, and de-alignment or re-alignment (Geels and Schot, 2007).

The MLP has three dimensions: socio-technical systems, socio-technical regimes, and actors and social groups embedded in networks (Geels, 2004). Socio-technical systems consist of elements and resources (e.g., material, knowledge, and cultural meaning) to fulfil the societal functions, such as communication and transport (Geels, 2004). The socio-technical regime provides guidance to actors' perceptions and activities. Actors and social groups play the role of maintaining and/or changing the system. These three dimensions dynamically interact with each other (See Figure 3-4). Namely, each sub-regime evolves not only under its own dynamics, but also influences other sub-regimes through coevolutionary processes within the whole system (Foxon, 2011).

Thus, the MLP approach was a key strength for analysing this study because it allowed the sub-regimes to be semi-autonomous, but also dynamically linked between different sub-regimes and actors within a socio-technical system. The MLP also presented the dynamic transition rather than simply a list of types of barriers and drivers.

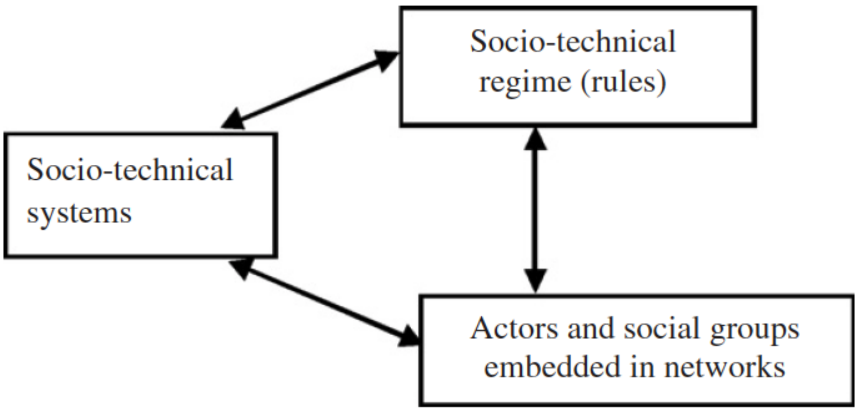


Figure 3-4 Three dimensions of MLP (Geels, 2004)

Similar to other sustainability transitions, the plastic circular economy transition comprises dynamic structural change interacts with multiple actors. The deep-structure socio-technical system has been changing to address the path dependence and lock-in mechanisms of the contemporary linear economy system.

According to the literature review in Chapter 2, increasing the use of secondary plastics is one of the elements of increasing plastic circularity, although there are many plastic circular economy strategies. Therefore, the scope of this study is mainly focused on increasing levels of use secondary plastics. The other potential transition pathways for radically alternative paradigms (e.g., bioplastics) were not explored or included.

Geels (2011) defines transitions as shifts from one regime to another regime, and niche and landscape levels are derived from the existing regime. Regimes are the heart of transition process and analysis (Kemp, 2010) and have drawn increasing attention for their critical dimensions that link diverse actors together (Lawhon and Murphy, 2012). Thus, the analysis in this study focused on how the sub-regimes interacted with multiple actors to reconfigure the regime. In other words, the analysis explored the barriers and drivers of secondary plastics use, which prevented and/or pushed reconfiguration of the sub-regimes in the plastic system. The spatial system boundary of the MLP was the EU28 so that it aligned with the MFA for further integrated discussion. The following subsections provide further details on the data collection and analysis.

3.2.2 Data collection and interview design

This body of qualitative research combined primary data collection, through semi-structured interviews, with a review of the literature and supporting documents as secondary data. The supporting documents were provided by interviewees, such as published case studies, brochures, project slides, and firm websites. Based on the interview guide listed in Appendix D, the interview questions were further tailored based on each participants' role and relevant business of secondary plastics in their firms. The semi-structured format allowed the participants to expand on their responses in areas which they deemed relevant to the topics. The main discussion was centred on plastic use and/or plastic waste treatment in each participants' business, the key factors and main barriers for the interviewees, and/or their clients use of secondary plastics, their thoughts about interventions to enable the use of secondary plastics. The interviewer asked follow-up questions to encourage interviewees to further explain their business experiences and thoughts when necessary.

Table 3-7 lists the general information of the interviews, in order to preserve anonymity. The column '#' refers to a unique number given to each firm/organisation. A total of 25 firms/organisations (26 interviewees) were selected using a convenience sample and snowballing techniques to reach key stakeholders including the members of plastic industry associations and secondary plastic users.

Most of the interviewees were contacted through LinkedIn and emails. Information sheets for participants (Appendix E) and a consent form were sent before the interview to inform them the data would be anonymised and explain the data protection procedure. All the interviewees were also informed that the ethics application of this interview study had been approved by the Research Ethics of UCL's Bartlett School of Environment, Energy and Resources. The roles of participants were across the plastic value chain, including petrochemical producers, manufacturers, brand owners, retailers, construction managers, a trader, a broker, mechanical recyclers, a solvent-based recycler, feedstock/chemical recyclers and an extended producer responsibility organisation. Most of the participants' businesses were from different member states within the EU, although they were based in Germany, the Netherlands, Belgium, France, Sweden, Austria, the UK. The main application areas of secondary plastics covered different sectors, namely, packaging, construction, automotive, electrical and electronic equipment, and other.

The semi-structured interviews were held through video/audio calls or face-to-face between October 2019 and November 2020. The interview duration range was around 30 to 75 minutes, and all the interviews were digitally recorded. The total number of interviews in this study was in line with Morse (1994) who suggests that 20 to 40 interviews are necessary for data duration in the case of diverse respondents. Thus, the data collection in this study was sufficient to represent the ongoing transition situation in the EU and to justify the conclusions.

Table 3-7 General information of the interviews

#	Date	Role	Based	Main application area	Duration (Hours: Minutes)
1	10/12/2019	Petrochemical producer / Specialist	Belgium	All	01:06
2	17/01/2020	Petrochemical producer / Recycler	Netherlands	All	00:38
3	30/01/2020	Petrochemical producer / Mechanical recycler	Belgium	All	00:27
4	05/02/2020	Petrochemical producer / Chemical recycler	Germany	All	00:50
5	06/02/2020	Petrochemical producer / Recycler	Netherlands	All	00:31
6	09/12/2019	Manufacturer	UK	Packaging / Construction / Automotive	00:40

7	16/12/2019	Manufacturer	Germany	Construction / Automotive / EEE / Furniture / Other	01:03
8	04/02/2020	Manufacturer	UK	Packaging / Construction	00:41
9	29/10/2019	Manufacturer / Brand owner	France	Automotive	01:09
10	06/11/2019	Manufacturer / Brand owner	Netherlands	EEE / Healthcare	00:29
11	16/12/2019	Manufacturer / Brand owner	UK	Packaging	00:48
12	14/10/2020	Retailer / Brand owner	Austria	Packaging / Other	01:08
13	03/11/2020	Retailer / Brand owner	Netherlands	Packaging / Other	00:56
14a, 14b	25/10/2019	Construction manager	UK	Construction	01:01
15	10/12/2019	Construction manager	France	Construction	00:57
16	18/10/2019	Mechanical recycler and consultant	Netherlands	Packaging	00:58
17	31/10/2019	Mechanical recycler	UK	All	01:05
18	25/11/2019	Mechanical recycler and consultant	UK	All (EEE/ Automotive)	01:15
19	24/01/2020	PVC windows recycler	UK	Construction (PVC windows)	00:36
20	27/12/2019	Solvent-based recycler	Netherlands	Construction / Other (PS waste)	00:45
21	30/01/2020	Chemical recycler	UK	All	01:04
22	13/10/2020	Trader / Mechanical recycler	Germany	Construction/ EEE	01:05
23	21/09/2020	Broker	Sweden	Construction/ Automotive	00:49
24	04/12/2019	Specialist	Germany	EEE	00:57
25	22/07/2020	Extended producer responsibility organisation	France	Packaging	01:09

3.2.3 Data analysis

The audio and/or video recorded interviews were manually transcribed into written form. A thematic analysis method was conducted through the NVivo 2020 software, to identify the themes across a qualitative data set (Braun and Clarke, 2006). These themes represent patterns of meaning. Patterns can help to identify the similarities and differences between the participants' viewpoints.

Figure 3-5 depicts the six recursive phases to conduct thematic analysis, which was originally introduced by Braun and Clarke (2006), and it was further adapted for this study:

1. Organisation of and familiarisation with data: the transcriptions transforming verbal data into written text were prepared. The transcriptions and the supplementary documents provided by interviewees were repeatedly read through to get the initial ideas.

2. Coding data: the important and interesting elements were coded into meaningful groups (Tuckett, 2005) from the all the data extracts. The coding process is flexible and changes over time. This back-and-forth coding process can keep track of what participants think are important.

3. Searching for the themes: this process searches for coherent and meaningful patterns in the data and combines the codes at a broader level. This process generates the initial themes according to the descriptive responses from participants and the analytical concept of different sub-regimes, as well as landscape and niche. The themes of barriers and drivers within different sub-regimes were deductively identified as a pre-existing coding frame. The potential sub-themes emerged inductively when reading through the codes.

4. Review themes: all the codes were checked to see if the set of candidate themes worked, then, the themes were refined and generated into a new thematic map of the analysis.

5. Defining and naming themes: four main themes were checked and generated into sub-regimes. Four 'main themes' included the sub-regimes of 'policies and standards'; 'markets and business models'; 'technology'; and 'consumer preferences and behaviours'. Using *in-vivo* quotation as one of the strategies, the sub-themes were refined and named to allocate to the main themes and tell the overall story.

6. Writing up: the special highlights and quotation examples were extracted to answer the research questions based on the structure of the MLP. Results and discussion is presented in Chapter 5.

Figure 3-5 Six recursive phases of thematic analysis

3.2.4 Causal loop diagrams

To summarised the findings of the transition analysis, causal loop diagrams (CLDs) are applied to show the web of constraints and web of drivers in Section 5.7. CLDs highlight the systematic interactions of key barriers and drivers and help to identify the feedback loops (Sterman, 2000, Haraldsson, 2000). Arrows in CLDs represent the relationship between two variables. The standard CLD convention of positive and negative signs is used to indicate one variable's influence on another variable (Sterman, 2000). A positive (+) causal relationship reveals the variables are moving in the same direction, whilst a negative (-) causal relationship indicates the variables are moving in the opposite direction. The polarity of the causal loops is then identified as reinforcing or balancing, depending on the net change effect in reference to the initial change in the variable chosen as a starting point. A reinforcing loop (R) is created when there are an even number of negative connections, whereas a balancing loop (B) is created when there are an odd number of negative connections. The reinforcing loop amplifies and enhances whatever direction of change is imposed, while the balancing loop stabilises and regulates the system. Two hash marks represent a delay, which is a situation that takes time before the effect occurs.

4 Results and discussion of plastic material flow analysis

4.1 Plastic material flows analysis

4.1.1 Plastic flows

The results from the MFA of plastic in the EU28 in 2016 are summarised in Figure 4-1. As shown in Figure 4-1, total virgin plastic polymer and fibre production in the EU28 amounted to 66,786 kilotonnes (kt). This included PET, HDPE, PVC, LDPE, PP, PS, other thermoplastics, thermosets, and man-made fibres. Consumption of plastic polymers and fibres accounted for 66,623 kt. The most consumed plastic polymer was PP, closely followed by LDPE, HDPE, PVC, PET and PS respectively. Consumption of man-made fibres, which are mainly polyamide, polyester and PP, was around 2,544 kt. While the major groupings (PP, PE, PVC) make up a substantial share of total plastics, there is a very large range of other plastic polymers. In fact, 'other thermoplastics' represented 15,823 kt, while 'other thermosets' represented 11,140 kt in 2016 (see Figure 4-7 and Appendix A). The array of different types of plastics is the result of different product specifications, which create challenges for sorting and segregation at the EoL.

EU trade of plastic polymers and fibres was very significant, with a positive trade balance of virgin plastic polymers. In total, the EU exported 10,864 kt plastic polymers to other countries. However, plastic fibres showed a trade deficit (1,410 kt imported and 250 kt exported). As shown in Figure 4-1, there was a positive trade balance in semi-finished products (1,938 kt imported and 2,512 kt exported), while final products showed a trade deficit, with net imports of around 5,648 kt plastic in final products.

Plastic polymers were compounded and moulded into different types of products. The mass of plastic in plastic-containing products assembled and distributed into different applications was 73,481 kt (Figure 4-1). Figure 4-1 displays the consumption of plastic and plastic-containing products by segment. Packaging accounts for 26%, followed closely by 'other' (25%), construction (17%), transport (14%), EEE (8%), textiles (6%), health care (2%), and paints and varnishes (2%). These included virgin and secondary plastics. The product list of 'other' is shown in Appendix C.

Additions to stock have been estimated at 37,696 kt as indicated in Figure 4-1, representing plastic and plastic-containing products that remain in use in the socio-technical system. Packaging (+3,339 kt) and healthcare (+879 kt) had small additions to stock due to their short product lifetimes. Additions to stock were higher in the case of construction (+10,760 kt) and transport (+9,768 kt) products as plastics in these applications have longer product lifetimes. Stocks accumulated in the system are important to account for as they will become future waste.

At the EoL stage, the MFA reported 2,237 kt of waste generated from plastic manufacturing processes and 34,355 kt of post-consumer plastic waste in 2016 (see Figure 4-1). The plastic waste generated from manufacturing processes excludes the plastic waste recycled back into the production system.

As shown in Figure 4-2, the two largest flows of post-consumer plastic waste are ‘packaging’ and ‘other’, which accounted for 47% and 40%, respectively. This 40% of ‘other plastic waste’ is a heterogeneous mix of different waste streams, including the following categories: plastic waste; household and similar waste; mixed and undifferentiated materials. ‘Plastic waste’ refers only to plastic separately collected from economic activities. ‘Household and similar waste’ is a combination of mixed municipal waste, waste from markets, bulky waste, and street cleaning waste. ‘Mixed and undifferentiated materials’ contain undifferentiated plastic-containing waste from different economic activities. The heterogeneity of ‘other plastic waste’ creates difficulties for adequately tracing and recovering plastic waste in this category.

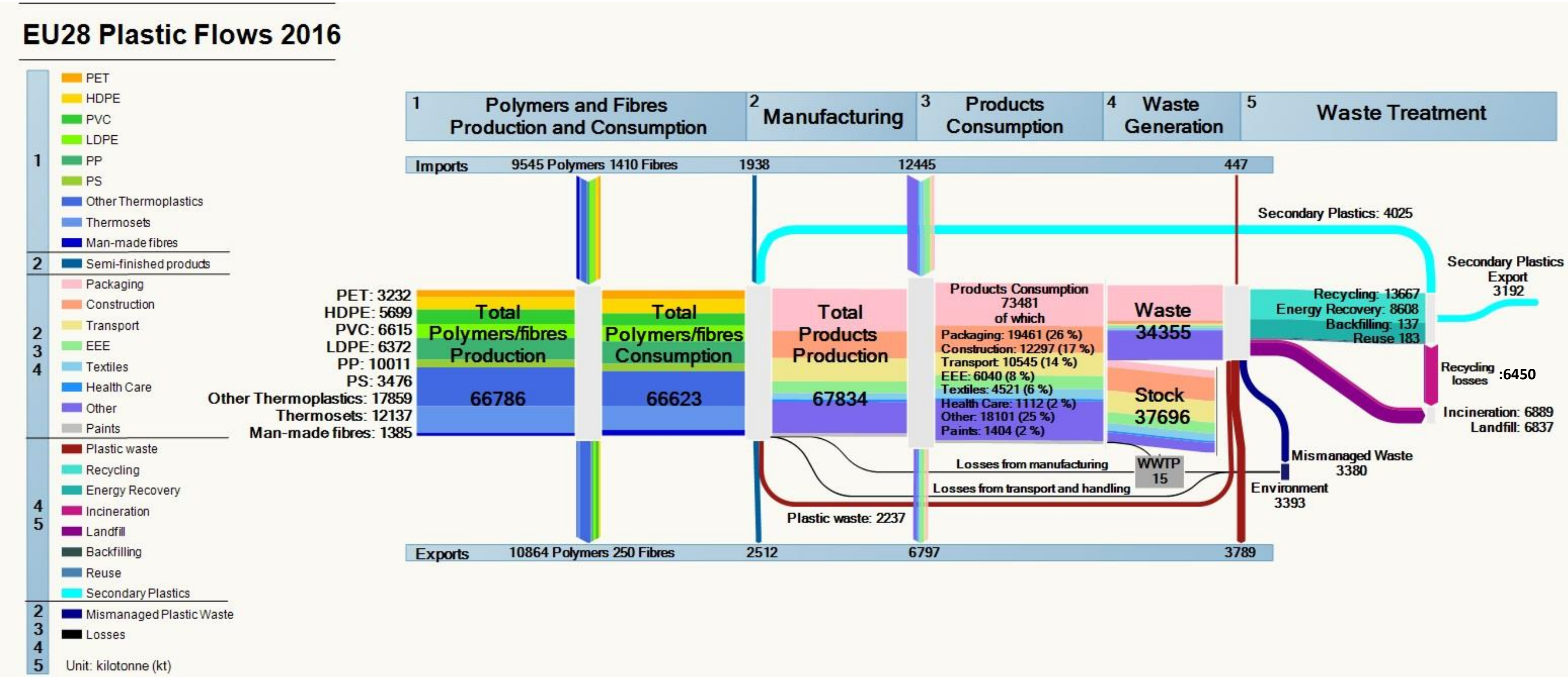


Figure 4-1 Plastic flows in the EU28 in 2016

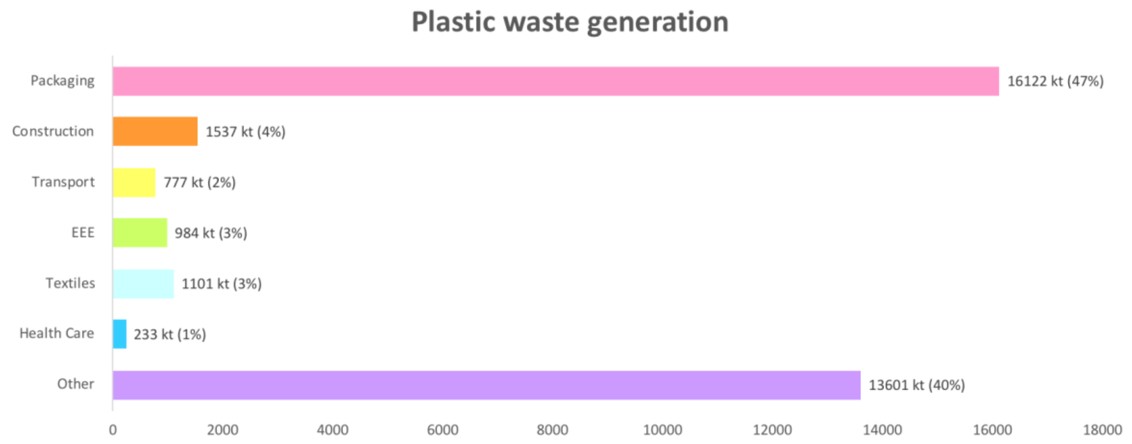


Figure 4-2 Plastic waste generation

'Other plastic waste' is followed by construction plastic waste (4%), WEEE (3%), textiles (3%), transport (2%), and healthcare waste (1%). Paints and varnishes are coatings applied on other products, and so are embodied in other waste streams (e.g., wood waste, plasterboard, etc.). Paint and varnish also dissipate to the environment directly from in-use products. As a result, estimates of the final destinations of these products have not been included in the calculation of plastic waste.

Figure 4-3 displays the waste arisings by source, distributed across households (50.5%), services (21.6%), construction (5.8%), manufacturing sectors (20.2%), agriculture, forestry, and fishing (1.9%).

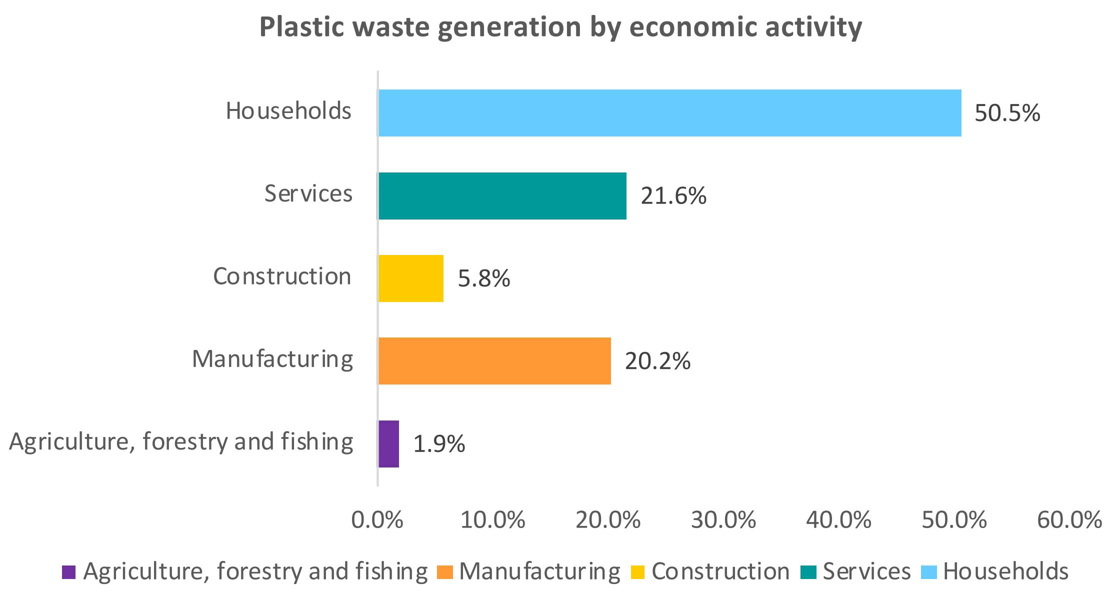


Figure 4-3 Plastic waste generation by economic activity

A total of 37,068 kt of plastic waste was generated in 2016. Figure 4-4 details the main destinations of all plastic waste and estimated losses along the life cycle. Although 13,667 kt of plastic waste was sent to recycling, the model estimates losses of 6,450 kt (47%) associated with initial sorting, pre-processing, changes in moisture content and efficiency losses from recycling processes. The MFA estimate of losses from recycling processes is based on the literature (Recycling Technologies, 2016) (Figure 4-1).

In order to verify this result and investigate the details on different stages of the recycling process, I validated this with experts. Their estimates for recycling losses are in the range 20–50%, representing the state of play across Europe. However, the estimates at the low end of that range focused on losses associated with relatively pure waste streams (e.g., HDPE milk bottles) following some separation. Estimates at the higher end of the range took account of segregation losses. From among these experts, the most detailed breakdown was provided by Freegard (2019), who is a Director and Founder of an UK's leading plastic recycling company with over 30 years of operational experience, plastic advisor to the European Recycling Industries' Confederation (EuRIC), Vice Chairman of the British Plastic Federation's Recycling Group and a non-Executive Director of OPRL – the on-pack recycling label scheme for consumer packaging. Freegard (2019) broke the losses down as follows:

a) 10–20% of losses occur at primary sorting at a material recycling facility (relating to commingled waste resulting from poor sorting technology and inaccurate hand-sorting);

b) a further 10–20% loss occurs at a plastics recycling facility when separating the polymer grades and making bales of different polymer types, coloured and clear natural;

c) further losses occur in specialist plastic recycling plants in the recycling process, due to contamination from labels, bottle caps, and inaccurate polymer sorting (Freegard, 2019).

Given the variety of plastic polymers in the market and different organisations and technology levels across collection, processing and recycling systems in the EU, calculation of recycling losses have an inherent uncertainty (variations occurring for different plastic products and across segregation systems, sorting technologies and recycling systems). The model estimates that only 53% of plastic waste sent to recycling was transformed into secondary plastics. From that, it is estimated that approximately 4,025 kt was transformed into secondary materials in EU plants and sold as recycled plastic polymers for transformation within the EU, while 3,192 kt plastic was treated in

EU plants and sold as secondary plastics to other countries. This means that, despite improved recycling rates, only 11% of all the plastic waste generated along the value chain was reprocessed and used as secondary plastics in the EU.

Furthermore, the results show more than 34 Mt of plastic waste was generated after the consumption stage, and approximately 13 Mt of plastic waste entered recycling facilities in 2016 (see Figure 4-1). Those 13 Mt included plastic embedded in WEEE, ELVs, etc, rather than just the plastic in the pure plastic waste stream. The installed plastic recycling capacity can be interpolated from Figure 2-10 as being less than 6 Mt in 2016. This installed plastic recycling capacity represents the recycling facilities specifically dealing with plastic waste. Therefore, it appears that all of the specific plastic recycling capacity within the EU was fully utilised, and that plastic recycling capacity was insufficient.

Overall, 8,608 kt of plastic waste went to energy recovery, 6,889 kt to incineration, and around 6,837 kt were sent to landfill. These non-circular treatments include the treatment of losses from recycling. Backfilling accounted for only 137 kt (see Figure 4-4).

Reusing plastic products and components and increasing the quality of recycling, such that secondary plastics can substitute for primary materials are important strategies towards circular plastics. However, data around reuse is highly fragmented and limited. It is worth noting that the reuse flows here only include WEEE, ELVs and textiles because there are insufficient/inadequate data on other plastic-containing products. Approximately 183 kt of plastic waste was recorded as re-used in the EU, but this is likely to be underestimated as a large share of peer-to-peer reuse is not recorded and escapes official statistics. Most of the 'reuse' happens at the in-use stock stage, while the flows of 'reuse' in Figure 4-1 and Figure 4-4 represent the reuse recorded after the waste collection stage. This reveals the difficulties of measuring circular flows, and further study is needed to clarify the taxonomy and measure the reuse flows and other inner circular flows.

Regarding the trade of plastic waste, Figure 4-1 shows that while plastic waste imports (447 kt) were minimal, 3,789 kt of plastic polymer-based, fibre and plastic-containing (WEEE and textiles) waste were exported for recycling outside of the EU. Generally, exports of the plastic waste to other countries are dominated by lower quality plastic waste with higher cross-contamination (Crippa et al., 2019). Some studies have pointed to the lack of traceability of exported plastic waste as an issue that may lead to ocean plastic waste pollution (Bishop et al., 2020).

Figure 4-5 shows the destination of overall plastic polymer-related waste, including PE, PVC, PS, other plastic waste, and excludes other plastic waste in plastic-containing products. This shows the lack of traceability of trade of plastic waste embedded in plastic-containing products. The main destination of plastic waste in 2016 was still China, before the introduction of its ban on the import of plastic waste (Figure 4-5). In the ranking, China (1,636 kt) was followed by Hong Kong (765 kt), Malaysia (154 kt), Vietnam (134 kt), and India (128 kt), with all other destinations adding up to 302 kt (see Figure 4-5). Plastic waste exports were associated with insufficient recycling capacity in the EU and the economics of plastic recycling, with more competitive prices offered outside of the EU (OECD, 2018).

Figure 4-1 and Figure 4-7 show the losses along the life cycle. At the manufacturing stage, it was estimated that around a 1 kt spill of pellets from the production line may have been eventually released to drains and captured in wastewater treatment plants (WWTP). Around 2 kt of pellets were lost during transport and handling and potentially released to the environment through urban runoff and other forms of dispersion. At the consumption stage, 24 kt of microfibers were lost during washing clothes from households and industrial laundries, whereas 1 kt of microbeads from PCCPs were lost from households, sport facilities and hotels. Most microfibres and microbeads were channelled from sewage systems to the WWTP, and about 15 kt of plastic waste were captured at WWTP stage. However, the model estimates 11 kt total losses from WWTP, including 2 kt of microfibres from textiles potentially entering into the ocean from the EU in 2016, and 9 kt leaking into soils through the application of wastewater sludge on agricultural fields. Microbeads lost to the environment (~1 kt) constitute a relatively small amount, which was not considered further in this analysis.

It is worth noting that 1,404 kt of paints and varnishes were consumed, coated on non-plastic products, and were lost in the EoL management routes of these coated products (e.g., walls and plasterboard in demolition waste). The EoL destination of paints and varnishes was a mix of dissipative losses and disposal with the other products. Dissipative losses accounted for 23%–43% (up to 100%) of road markings (Toben, 2017) and approximately 1%–6.5% of losses during the use of other coated products (e.g., building paints, transport equipment painting, and furniture coatings) (OECD, 2009). The remainder of plastic in paints and varnishes at EoL was treated embedded in the products (e.g., wood, plasterboard, etc.) through other waste routes (e.g., incineration, landfill) (OECD, 2009).

The majority of losses occurred at the waste generation stage, with an estimated total of about 3,380 kt mismanaged plastic waste. This included cross-contamination and illegal dumps (Murgese, 2020, Pittiglio et al., 2017), deposits in non-compliant landfills which failed to comply with the Landfill Directive, and the littering of single-use plastic packaging on the streets or in natural surroundings. Littering is problematic in some EU member states such as Greece, Slovakia, Italy, and Bulgaria (Eurobarometer, 2014). Major illegal exports of plastic waste were reported to be shipped from the UK, Germany, and Italy to Malaysia (Greenpeace Malaysia, 2018, Murgese, 2020, Pittiglio et al., 2017); however, traceability and magnitude of this are difficult to establish. Overall, the model estimates that around 3,393 kt mismanaged plastic waste and losses accumulated in the environment.

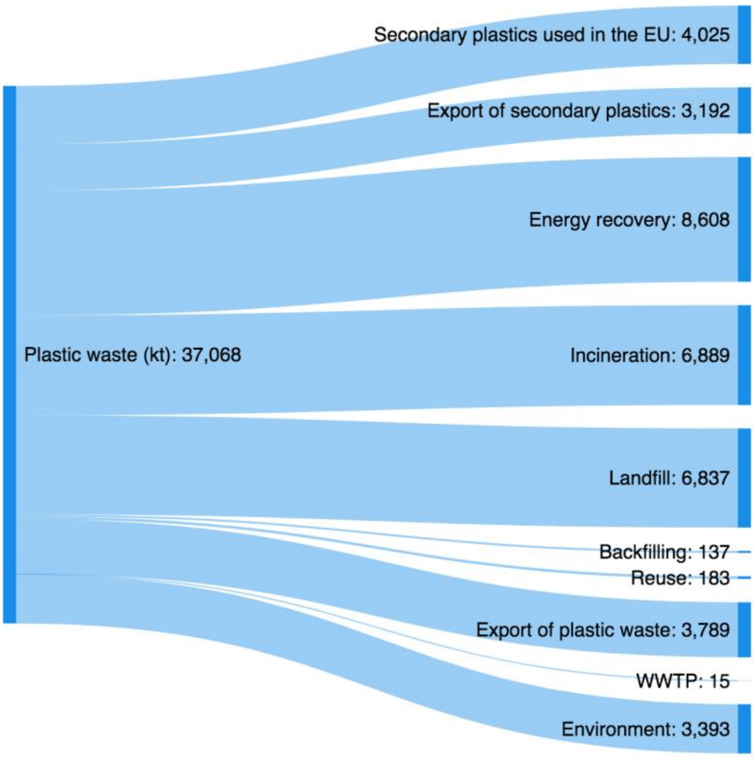


Figure 4-4 Destinations of plastic waste

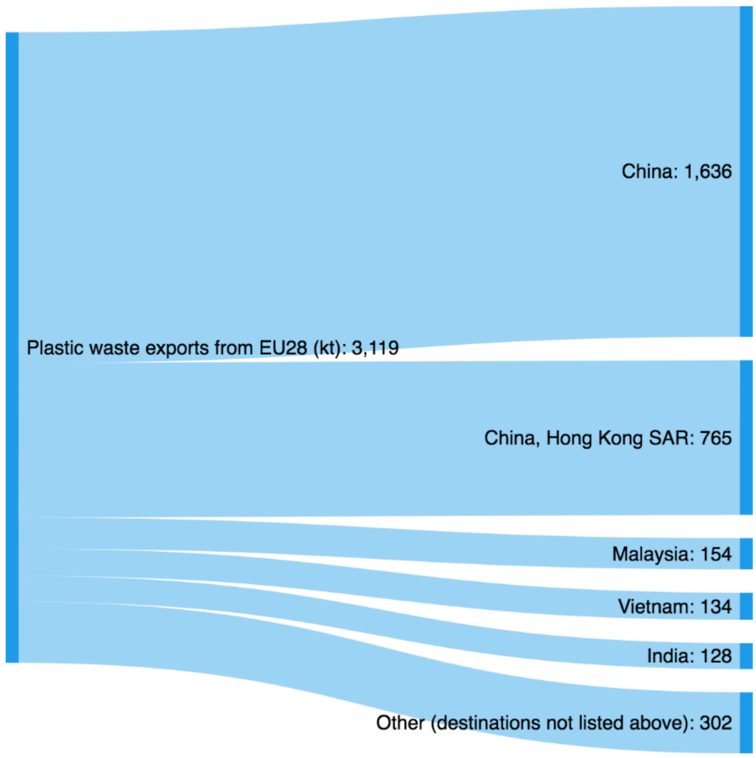


Figure 4-5 Export destinations of plastic polymer-related waste

4.1.2 Uncertainty analysis

4.1.2.1 Assumptions on the level of sensitivity and data gaps

Figure 4-6 show the original input data of plastic flows in the EU in 2016 prior to the data reconciliation. Quantitative uncertainties attributed to each flow are shown in Figure 4-7. Table 4-1 lists the adjusted uncertainty after data reconciliation. Each uncertainty is described as a coefficient of variation (CV), expressed as a percentage. This CV describes a distribution, assumed to be normal, within which the true value of each flow is believed to lie. Data reconciliation helped to reduce the uncertainties of the flow estimates.

The current model relies heavily on data from Eurostat product and waste databases. Following the approach to characterising uncertainty developed by Laner et al. (2015), the Eurostat data are rated highly in terms of source reliability, because they are derived from an official statistical body with associated methodological rigour. However, there are widespread concerns that the Eurostat data in this area are relatively weak. I, therefore, assigned a high level of sensitivity to the source reliability scores for parameters derived from Eurostat. The secondary plastic data from references is derived initially from expert estimation. For this data, the qualitative evaluation criteria follow the expert estimate criteria.

The model makes assumptions were where data gaps exist. In particular, it was necessary to make allocations of intermediate plastic products to final consumption groups, as data available to convert intermediary flows into final goods for specific product categories (e.g., construction, transport, and general 'other') is limited. While this allocation introduces uncertainty of the flows of intermediary products into final product categories, this is not fully reflected in the uncertainty method developed by Laner et al. (2015), suggesting that for this flow the true uncertainty range may be higher than that suggested by the derived CV.

4.1.2.2 Uncertainty of upstream and downstream flows

Upstream flows of plastic polymers and fibres were based on data from the PRODCOM database, which is relatively high quality, so the uncertainty range was moderately small (up to ±6.4%). Among plastic polymers, PVC has higher uncertainty due to the estimation of PVC's fraction within the categories of 'PVC mixed with any other substances'. There is higher uncertainty for the manufacturing and consumption stages of plastic-containing products, for which uncertainty ranges from ±5.1% (for the consumption of paints) to ±21.2% (for EEE consumption), and the highest uncertainty occurring within imports of EEE (±22.3%).

The waste generation flows were found to have uncertainty ranges from ±8.2% (for WEEE) to ±21% (for transport waste). Transport waste only included discarded vehicles, data for which lack completeness (e.g., other transport equipment). Uncertainty associated with waste generation was propagated from the uncertainty associated with the estimation of plastic fraction for product categories. Larger uncertainties came from the temporal mismatch between data sources for estimating plastic content of packaging, construction and healthcare waste, and from the heterogeneity of products within household waste and mixed waste.

The model uncertainty decreased for the trade of plastic waste as these flows mainly relied on official data. The uncertainty lay in the waste generated from 'other applications' as this spread across different waste categories. For the 'mixed and undifferentiated materials' waste category, an assumption of 10% plastic fraction was made. Hence, the overall amount of waste generated from 'households' and 'services' in this study was aligned with ‘municipal waste data’ from Eurostat and ‘post-consumer waste’ data from Plastics Europe (2017). Although the uncertainty of this mixed waste flow was very high (±43.7%), the aggregation of all different plastic waste flow uncertainties compensated, leading to a lower overall uncertainty.

Data on the quantities of both products and waste came from official databases with the same temporal and geographical system boundary, enhancing consistency of the analysis. The main sources of uncertainty relate to the estimation of plastic content and mass per unit in product and waste categories, given variations in plastic content over time due to technological progress and market changes. This is particularly true for vehicles and EEE, which have shown progressive replacement of metal components by plastic.

The destination of plastic waste faces a number of areas of high uncertainty. Uncertainties associated with the estimation of landfill and incineration are higher than those associated with recycling and energy recovery. This is because a larger share of household waste and mixed waste (which are associated with higher uncertainties) ends up in landfill and incineration compared to other waste categories. The reuse data is probably underestimated, given robust second-hand markets for clothes, vehicles, toys and other product categories, which in most cases escape official records. Data on recycling losses as estimated by the model have been validated by the literature and expert interviews; however, great uncertainty remains (±44.3%). The export of secondary plastics is also highly speculative, which is reflected in uncertainty scores of ±30.9%, due to data gaps. As one would expect, areas of highest uncertainty also relate to the losses and leakage to the environment (up to ±42%) due to lack of available data.

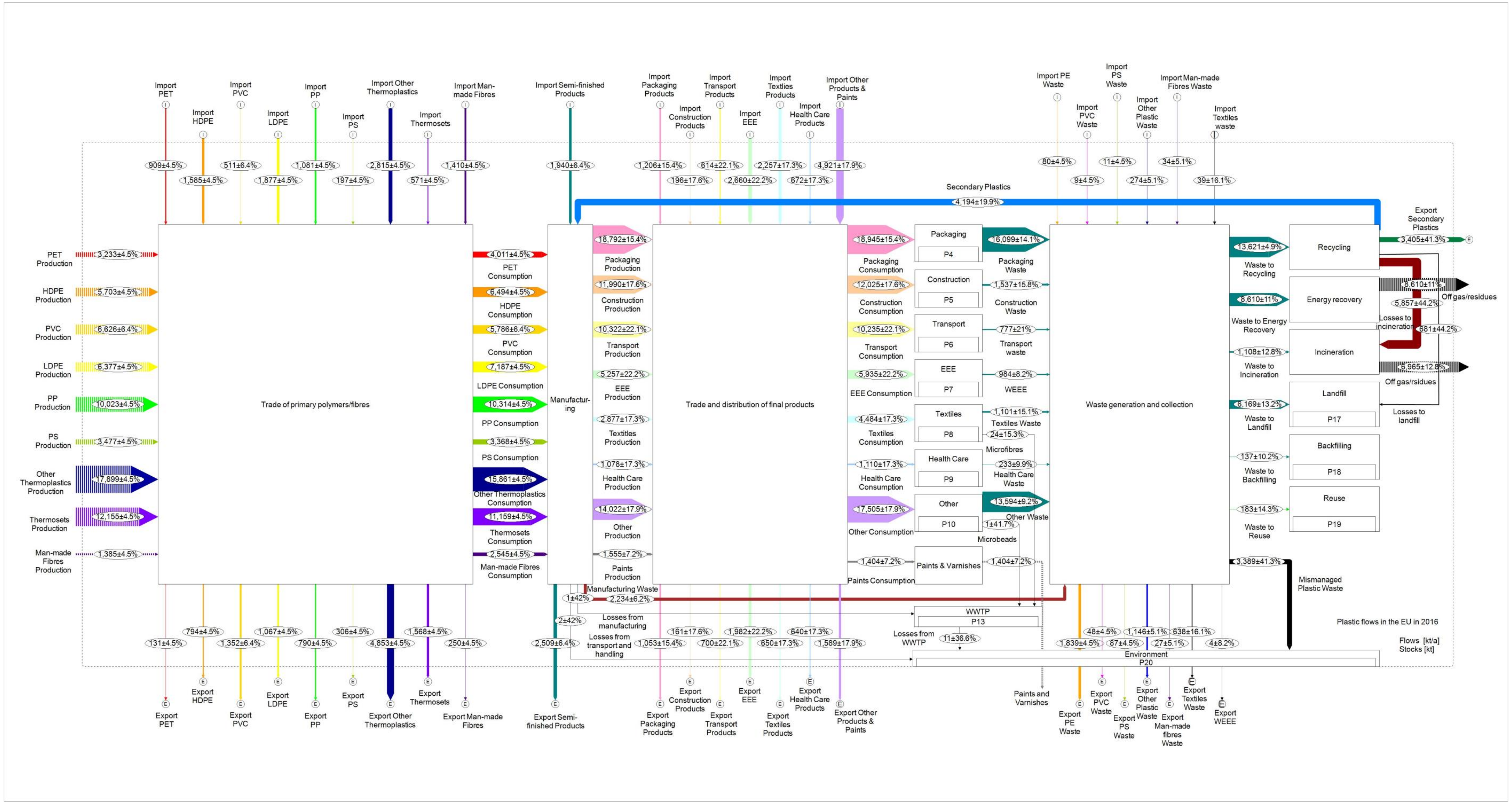


Figure 4-6 Input data of plastic flows in the EU28 in 2016

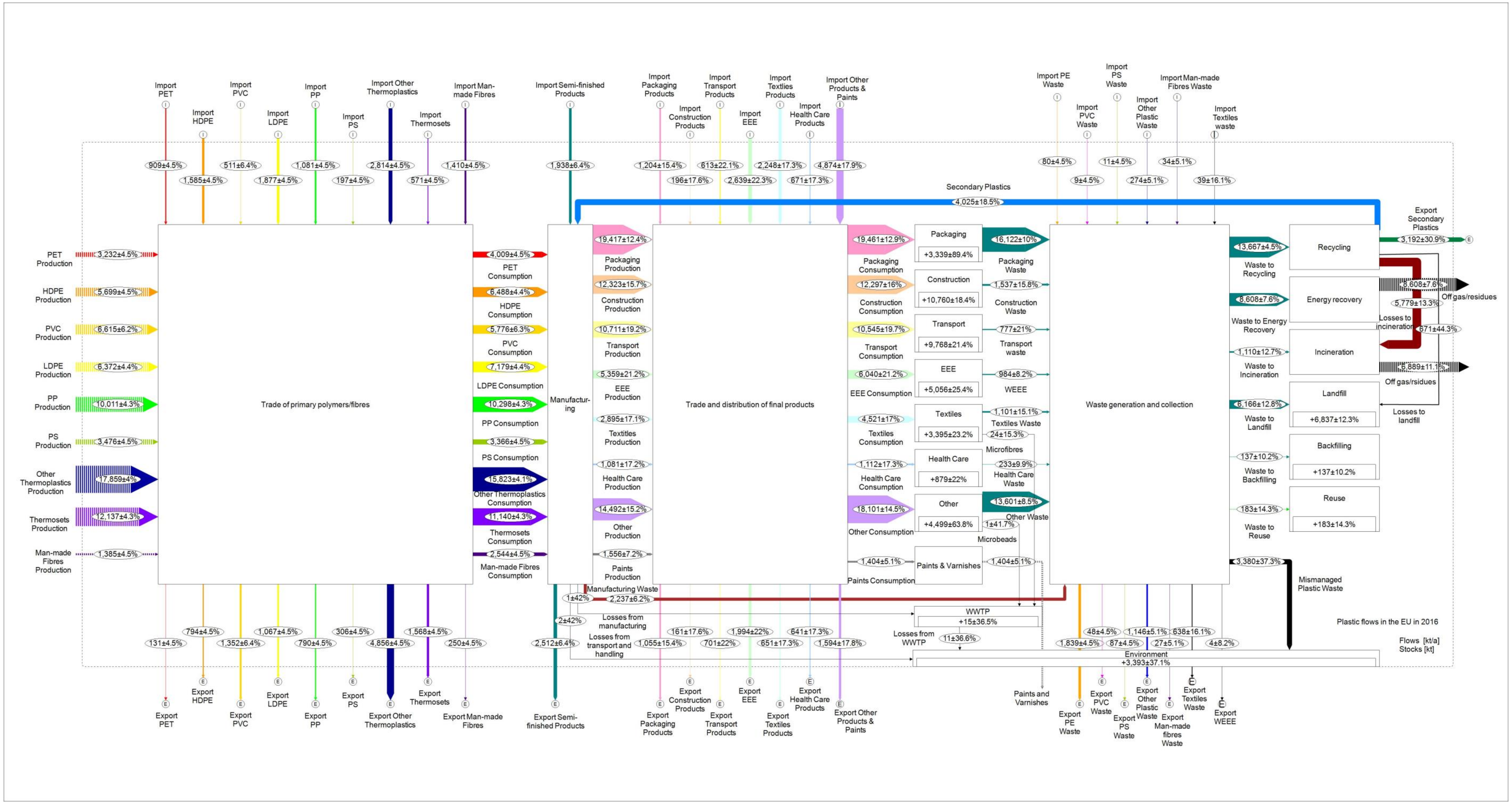


Figure 4-7 Results of plastic flows in the EU28 in 2016

Table 4-1 List of adjusted uncertainty

Process	Flows and stocks	Adjusted uncertainty										
Trade of primary polymers		PET	HDPE	PVC	LDPE	PP	PS	Other Thermoplastics	Thermosets	Man-made fibres		
	Imports	4.5%	4.5%	6.4%	4.5%	4.5%	4.5%	4.5%	4.5%	4.5%		
	Exports	4.5%	4.5%	6.4%	4.5%	4.5%	4.5%	4.5%	4.5%	4.5%		
	Production	4.5%	4.5%	6.2%	4.4%	4.3%	4.5%	4%	4.3%	4.5%		
	Consumption	4.5%	4.4%	6.3%	4.4%	4.3%	4.5%	4.1%	4.3%	4.5%		
Manufacturing		Semi-finished products										
	Imports	6.4%										
	Exports	6.4%										
Trade and distribution of final products		Packaging	Construction	Transport	EEE	Textiles	Healthcare	Other	Pains & Varnishes			
	Imports	15.4%	17.6%	22.1%	22.3%	17.3%	17.3%	17.9%				
	Exports	15.4%	17.6%	22%	22%	17.3%	17.3%	17.8%				
	Production	12.4%	15.7%	19.2%	21.2%	17.1%	17.2%	15.2%	7.2%			
	Consumption	12.9%	16%	19.7%	21.2%	17%	17.3%	14.5%	5.1%			
In-use stocks		Packaging	Construction	Transport	EEE	Textiles	Healthcare	Other				
	Stocks	89.4%	18.4%	21.4%	25.4%	23.2%	22%	63.8%				
Waste generation and collection		PE waste	PVC waste	PS waste	Other plastic waste	Man-made fibres waste	Textiles waste	WEEE				
	Imports	4.5%	4.5%	4.5%	5.1%	5.1%	16.1%					
	Exports	4.5%	4.5%	4.5%	5.1%	5.1%	16.1%	8.2%				
Waste generation and collection		Packaging waste	Construction waste	Transport waste	WEEE	Textiles waste	Healthcare waste	Other waste				
	Waste generation	10%	15.8%	21%	8.2%	15.1%	9.9%	8.5%				
Waste treatment and waste to the environment		Recycling				Energy recovery	Incineration	Landfill	Backfilling	Reuse	WWTP	Environment
	Waste treatment	4.5%				7.6%	12.7%	12.8%	10.2%	14.3%		
	Stocks							12.3%	10.2%	14.3%	36.5%	37.1%
Outflows of waste treatment		Secondary plastics	Export secondary plastics	Recycling losses to incineration	Recycling losses to landfill	Off gas/residues from energy recovery	Off gas/residues from incineration					
	Outflows of waste treatment	18.5%	30.9%	13.3%	44.3%	7.6%	11.1%					
Losses		Manufacturing waste	Losses from manufacturing	Losses from transport and handling	Microfibres	Microbeads	Pains & Varnishes	Losses from WWTP	Mismanaged plastic waste			
	Losses	6.2%	42%	42%	15.3%	41.7%	5.1%	36.6%	37.3%			

0% - 20%	20% - 40%	40% - 60%	> 60%

4.2 Directing plastic waste destinations to circular pathways

This study highlights that the EU still has a long way to go to achieve a more circular plastics system. Based on the findings from the study, I propose six key complementary strategies for circular pathways of plastics and improved traceability of plastic flows along different life cycle stages, which are discussed below.

1. **Eco-design of plastic products at the production and manufacturing stages**

The results show approximately 30 Mt of other thermoplastics and thermosets are manufactured in the EU, creating challenges for circularity. For these types of plastics, waste destinations are largely non-circular. Therefore, a fundamental element leading to circular pathways would be eco-design of plastic products to ensure easy recycling. This is especially relevant for complex products containing different types of plastic polymers. This requires collaboration between product designers and recyclers to gain knowledge of current and forthcoming sorting and recycling technologies, and to redesign plastic products that can be effectively recycled. This also requires the development of design guidelines for better recycling, and improved knowledge of the relationship between product material choices and different EoL pathways.

2. **Reuse and repair plastic products at the consumption and in-use stock stage**

The large scale of the in-use stock (37,696 kt) highlights the potential importance of extending product lifespans through reuse and repair. Innovative circular business models and networks across the EU, such as RREUSE, facilitate the reuse and repair of plastic-containing products. As the findings of reuse mainly include textiles, WEEE and discarded vehicles, the findings show very poor data on current reuse of plastic, and further research is necessary to examine both physical and online markets for second-hand goods.

3. **Manage non-circular treatment and trade at the waste generation and treatment stage**

This study found that 17,515 kt of plastic waste went through non-circular treatment and exports. Regarding the 3,789 kt export of plastic waste, the EU not only needs to work on increasing recycling capacity locally, but also needs to better monitor the trade of plastic waste and collaborate with countries that receive EU plastic waste, to improve recycling quality and to share the responsibility for plastic pollution at the global scale.

The Waste Shipment Regulation of the UN Basel Convention and China's waste import ban have reportedly reduced the amount of plastic waste export, but have increased the waste to landfill in the short term (European Environmental Agency, 2019). There is a need to assess options to further reduce the amount of plastic waste entering landfill (from the 6,837 kt identified here), including a possible landfill ban for plastic waste. There are still some illegal exports of plastic-containing waste resulting in a lack of traceability. Data on waste flows are likely to improve as a result of increased policy focus on the waste trade. China's ban and the resulting scrutiny of waste exports show the need for better traceability of plastic waste in order to prevent illegal trade and dumping.

4. **Strengthen the role of chemical recycling at waste treatment stage**

The findings show a significant mass of plastic waste (13,667 kt) is sent for recycling. However, recycling losses significantly compromise secondary plastic production. The main problems arise from flaws in processes of collection and segregation, and because of cross-contamination. There is still a high proportion of plastics going to landfill or incineration, highlighting the need to develop better segregation and collection systems.

The high share of plastic that is not recycled also suggests a need to further develop options for chemical recycling, which would enable recovery of energy or monomers for re-polymerisation for plastics unsuited to mechanical recycling. Currently, chemical recycling is rare and not accounted for separately in the recycling fraction from the official databases at the EU level. There is some ambiguity about this in the relevant waste legislation, which has been under discussion and needs to be clarified. There is an ongoing discussion about using chemical mass-balance approaches to measure the performance of chemical recycling in the plastics industry (Ellen MacArthur Foundation, 2020), and further research and standards are needed to assess recycled materials from chemical recycling.

5. **Increase the quantity and quality of secondary plastics at the waste treatment stage**

According to the results, around 4 Mt of secondary plastics were used in the EU, 6 Mt below the target of 10 Mt in 2025. Secondary plastics used in packaging have been prominent in recent public debate. The EU policy target of 30% recycled content in PET bottles in 2030 could create a 123 kt demand for secondary plastics in the EU. Applying this commitment to all packaging would increase secondary plastic demand to approximately 5,638 kt, according to MFA model calculations in this study. Clearly, not all applications can accommodate secondary plastics given current technology or quality specifications. The promotion of secondary markets needs to be accompanied by efforts in infrastructure and technology development and stringent quality standards to further develop the secondary plastics market. The key to increasing the quantity and quality of secondary plastics would be policy interventions, such as extended producer responsibility schemes and tax incentives for the use of secondary plastics.

Moreover, data on secondary plastic flows need to be improved. Official databases record trade of plastic waste but not secondary plastics. Since the future target is to increase to 10 Mt of secondary plastics demand, it is important to track destinations of secondary plastics and include further specification of plastic waste by type of polymer. Plastics Europe (2019a) shows most secondary plastics are used in the construction sector, and some of them could be considered downcycling applications. It is also important to develop platforms on trade of secondary plastics to improve traceability and transparency for closing loops, and to facilitate monitoring and analysis of secondary plastic flows at the European level.

6. Reduce losses along all stages of the plastic life cycle

Losses pose a critical challenge for increasing plastic circularity, requiring a variety of policy measures, behavioural changes, and technological interventions across the life cycle of plastic. The MFA demonstrated considerable mismanaged plastic waste in the EU, causing 3,393 kt of plastic waste lost to the environment. The results show the main areas of losses are: 1) manufacturing; 2) microfibre losses during the use stage; 3) littering and 4) losses from recycling processes. Strategies on tackling plastic losses of manufacturing, pellet transport and prevention of losses to wastewater systems have been put forward in policy strategies like Operation Clean Sweep programme (Plastics Europe, 2019c), but current measures face obstacles such as high costs relative to the low economic value of losses, and an absence of stringent environmental monitoring systems that account for leakage and its socio-economic and environmental impacts.

The majority of losses during product use stems from microfibres lost during clothes washing. Proposals for developing standards to restrict the maximum losses threshold of fibres have been suggested (Hann et al., 2018), combining behavioural interventions, such as consumer education campaigns focused on washing habits, and technological interventions (e.g., fitting washing machine filters). However, further restrictions to limit the amount of microplastics through the Sewage Sludge Directive to minimise plastics entering the environment are still needed (Stubenrauch and Ekardt, 2020).

For littering, education-based campaigns and adequate waste collection infrastructure are key. Data in this area are weak, and there is a need for further investigation of the volume and impacts of losses caused by littering, illegal dumps, and illegal export. Approximately 47% of losses from recycling processes are associated with poor segregation and collection practices. Positive and cost-effective impacts could be achieved in this area through behavioural, technological, and policy interventions, to drive improved recycling efficiency and collection infrastructures, combined with novel sorting technologies.

5 Results and discussion of the transition analysis

5.1 Transition towards increasing the use of secondary plastics

This section applies the multi-level perspective (MLP) framework, presenting the barriers and drivers on a landscape, regime and niche level with a particular focus on the regime level. Initially, I explored how landscape pressures have emerged and how these landscape pressures are experienced by the regime and are understood by the interviewees. Next, I explored the barriers and drivers of change at the regime level. To be more specific, I analysed what motivates the regime actors to seek new ways of increasing secondary plastics use and the factors that inhibit the use of these plastics. To structure the analysis, I made an analytic distinction between a set of 'sub-regimes,' drawing on the concepts proposed by Geels (2004), in which he articulated the regime as comprising co-evolving subsystems, which was overviewed in Chapter 3. These analytic distinctions can help to categorise barriers and drivers, as well as to understand how different factors interact and mutually support or inhibit each other. As stated in Chapter 3, the results are not only based on the transcriptions from the interviews, but also supporting reports provided by the interviewees, the companies' websites and the governmental reports. Peer-reviewed journal papers are also included to gain a greater understanding of the reconfiguration of the regime.

To complete the MLP analysis, I also considered how regime actors relate to activities at the niche level, namely, the activities associated with protected spaces that enable radical innovation to develop. Figure 5-1 shows a complete picture of a MLP. Three levels, separated by blue dash lines are porous, so the barriers and drivers can flow across the boundaries from one layer to another. The red arrows are barriers. The green arrows represent drivers. At the landscape level, the barriers come from the cheap oil price, which makes virgin plastic cheaper than recycled plastic, as the cost of waste sorting and recycling is expensive. The drivers come from the circular economy initiatives, especially from the EMF and European Commission's circular economy package, and the United Nations Sustainable Development Goals (SDGs), China's plastic waste import ban, climate change policies and increasing concern about plastic pollution. The pandemic became both a driver and a barrier. At the niche level, there are four innovations including: radical technical; infrastructural; business model; and grassroots and social innovation. As this study mainly focuses on the regime level, four sub-regimes (policies and standards; markets and business models; technology; and consumer preferences and behaviours) and their interactions are analysed in detail below. Moreover, the role of data, information and knowledge and networks are analysed.

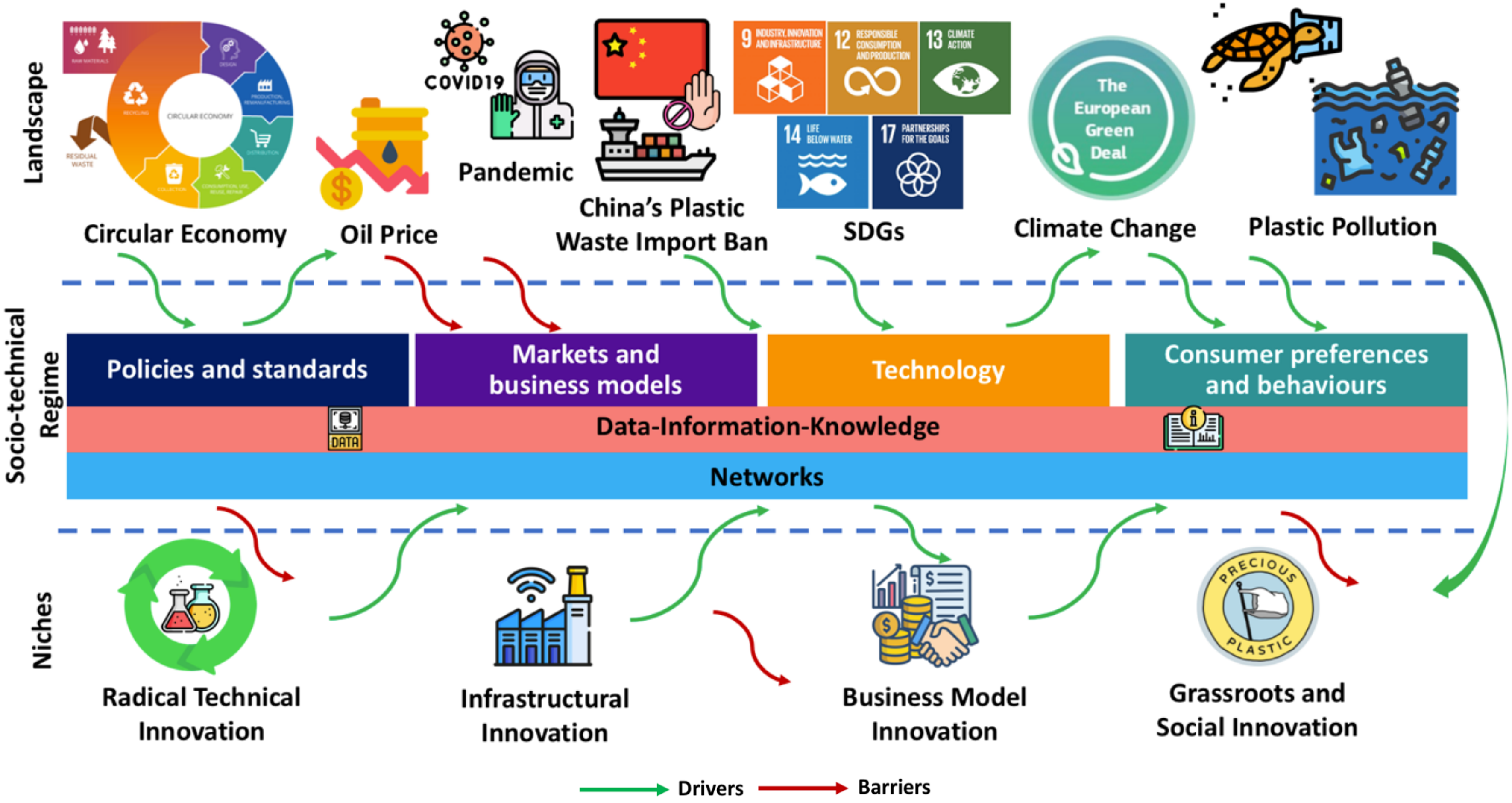


Figure 5-1 MLP of plastic circular economy transition in the EU

5.2 Barriers and drivers on the landscape level

In the 20th century, the petrochemical industry continued to introduce a wide variety of plastic polymers. Since World War II, plastics have been widespread and engendered a convenient ‘throw away’ lifestyle through disposable packaging and durable products. However, plastics eventually created environmental problems due to inadequate waste treatment. Plastic polluting the environment raised public awareness, whilst plastic production contributed to the impact of climate change.

The resulting plastic system landscape has been rapidly changing over the past few years, calling for a transition toward a circular plastic system. In this study, the landscape presents the broader influence from the outside on the use of secondary plastics to the regimes and actors. Six factors were identified including sustainable development goals (SDGs), climate change, circular economy, plastic pollution, China’s plastic waste import ban, and the COVID-19 pandemic. The following subsections provide details discussion:

5.2.1 Sustainable Development Goals (SDGs)

In 2015, United Nations established SDGs known as the ‘2030 Agenda for Sustainable Development’, which is a global shared blueprint for peace and prosperity for people and the planet with seventeen interlinked global goals and 169 targets built on the United Nations’ Millennium Development Goals, intended to be achieved by 2030 (United Nations, 2015). The main 'landscape' issue for plastics is about the increasing global governance arrangements in support of sustainable development and environmental sustainability. The SDGs are a manifestation of that broader trend.

In order to achieve SDGs, circular economy practices can take an implementation approach (Schroeder et al., 2019). Among the SDGs, ‘SDG 12: Ensure Sustainable Consumption and Production Patterns’ is highly relevant to the plastic circular economy, because both aim to achieve sustainable management and efficient use of the resources and reduce waste generation. SDG 12 also aims to ‘encourage companies to adopt sustainable practices and to integrate sustainability information into their reporting cycle (Target 12.6)’ (United Nations, 2015). As a broader factor shaping the plastic issue, brand owners, retailers and some manufacturers have adopted the use of secondary plastics. This shows their efforts and achievements are aligned with the SDGs, which can be seen in many European companies’ sustainability reports.

Increasing the use of secondary plastics can be one of the strategies to achieve SDG Sustainable Consumption and Production. On the other hand, SDGs also can facilitate the circular economy transition, such as 'SDG 9: Industry, Innovation and Infrastructure', 'SDG 13: Climate Action', and 'SDG 17: Partnership for the Goals'. These SDGs from the landscape level help to shape the regimes to stimulate the use of secondary plastics.

5.2.2 Climate change

As climate change has been a serious challenge and concern for human beings, governments and firms are working hard to reduce carbon emissions worldwide. In 2015, the Paris Agreement, set up at the United Nations Climate Change Conference (COP21), became the first legally binding international treaty to limit global warming below 2°C, preferably to 1.5°C above pre-industrial levels. The European Green Deal provides an action plan to be climate neutral in 2050. These lead to clear targets to reduce greenhouse gas emissions, and indirectly put pressure to increase the use of secondary plastics as alternative materials to virgin plastics. Volk et al. (2021) applied life cycle analysis to compare primary plastic production and different plastic recycling paths (mechanical, chemical and combined recycling) of separately collected mixed lightweight packaging waste concerning costs, carbon efficiency, cumulative energy demand (CED), and global warming potential (GWP). This German case study demonstrated that secondary plastics (PP, PE, PVC, and PS) have lower GWP, lower CED and higher carbon efficiency than virgin plastics (Volk et al., 2021). Gu et al. (2017) also showed evidence that mechanical recycling the plastic waste (PE and PP) has more environmental benefits, and the substitute virgin materials can reduce carbon emissions by avoiding 45,830 tonnes of CO2 eq. Rajendran et al. (2012), Stichnothe and Azapagic (2013), Wäger and Hischier (2015) all support that secondary plastics as substitute materials to virgin plastics bring more environmental benefits, including reduction of carbon emissions. This factor becomes a driver for different actors to seek ways to use secondary plastics in their products.

A petrochemical producer highlighted the global agreement on climate change drives the petrochemical industry to get involved in a plastic circular economy:

> *'They [petrochemical producers] have their promises and their objectives around the Paris treaty and with for CO2. There's also a strong demand from regulators towards the chemical industry to be more carbon efficient, and to solve part of the waste problem' (#2 Petrochemical producer / recycler).*

A chemical recycler also mentioned:

> *'The petrochemicals [companies] are also responding to the need to decarbonise, and so, that is decoupling their production from fossil fuels. And many petrochemical companies are looking for renewable feedstocks, and also see waste feedstocks as another source of material for their processes' (#21 Chemical recycler).*

In addition to the petrochemical industry, the recycling industry is also driven by decarbonisation, as the chemical recycler further explained:

> *'There's a clear need to decarbonise and reduce the* dependency *on things like incineration and, therefore, the growth of the circular economy and resource efficiency will address not just the needs of the plastic industry, but also the net zero agenda as well' (#21 Chemical recycler).*

5.2.3 Circular economy

Although the original concept of circular economy was proposed between the mid and late-20th century, the beginning of active initiatives started with the establishment of the Ellen MacArthur Foundation (hereinafter, EMF), in 2010, which aims to promote and accelerate the transition to a circular economy worldwide.

The European circular economy action plan covers a broader scope, which goes beyond plastics. Therefore, it is recognised as a factor at the landscape level in this study. The European Commission enacted the first EU Circular Economy Action Plan in 2015 leading the EU towards a circular economy transition. Following this Circular Economy Action Plan, the EU has been amending many relevant regulations and directives, and developing new policies, with a focus on closing the loop of resources (Calisto Friant et al., 2021).

The actions from the EMF and governments have been influencing the corporate sector to work together to find innovative solutions. Moreover, *Nature* published a special issue on the circular economy in 2016, and the topic has increased the continuing research and discussion in academia. This gradual transition progress has also emerged in the alliances among government, university, industry and institute.

Under the umbrella of the circular economy, plastic is identified as a significant and priority material to implement the circular economy practices by the European Commission in 2015. The EMF started an initiative on the New Plastics Economy in

2016. In 2018, the EMF collaborated with UN Environment Program (UNEP) and more than 450 organisations on the New Plastics Economy Global Commitment to set up voluntary targets toward a plastic circular economy. In the same year, the European Commission announced a European strategy for plastics in a circular economy. This pressure, starting from the circular economy initiative, drives the ongoing movements towards a plastic circular economy by gathering a wide range of actors together.

5.2.4 Plastic pollution

Plastic pollution is an emerging Anthropocene* risk that influences the Earth system, as plastics are widely dispersed in sedimentary deposits (Zalasiewicz et al., 2016). Irreversible plastic pollution has created global impacts on the marine environment, carbon and nutrient cycles, and habitat changes within soils and sediments (Villarrubia-Gómez et al., 2018, MacLeod et al., 2021), thus, plastic pollution threatens the safe operating space of the planetary boundary (Persson et al., 2022, Bachmann et al., 2023).

Globally, 6,300 Mt of plastic waste had been generated by 2015, but only 9% has been recycled (Geyer et al., 2017). Jambeck et al. (2015) estimated 31.9 Mt of land-based plastic waste were mismanaged and an estimated 4.8 to 12.7 Mt entered the ocean in 2010. Plastic pollution is a growing problem. In 2019, 22 Mt of plastic waste leaked into the environment (OECD, 2022). According to the plastic MFA results from Chapter 4, the EU contributed more than 3 Mt mismanaged plastic waste, which would potentially enter into the environment. The broader global concern of plastic pollution on the landscape level has raised public awareness. In 2022, the fifth United Nations Environment Assembly (UNEA-5.2) launched plastics treaty negotiations for a legally binding global agreement on plastics by 2024, considering the entire lifecycle of plastics to curb plastic pollution (United Nations Environment Assembly, 2022). Plastic pollution has shifted public policies and civil society from articulating around a few specific plastic packaging products to the entire plastic system (Nielsen et al., 2020). This landscape factor influences the reconfiguration of the regime to increase the levels of secondary plastics use.

* Anthropocene is a geological epoch of significant human impact on Earth's geological processes and ecosystems within the Geological Time Scale starting around the mid-20th century.

5.2.5 China's plastic waste import ban

In response to growing concerns about the domestic environmental burdens created by poor management of imported waste, China's plastic waste import ban was enacted in January 2018. This is one of the factors affecting the European plastic waste market as the EU is one of the largest exporters of plastic waste in global plastic waste trade networks (Wang et al., 2020). In the short term, the EU have increased its exports of plastic waste to other Southeast Asian countries, however, this could be a driver to force the EU to expand the domestic recycling capacity and increase the use of secondary plastics within the EU market (Huang et al., 2020). Interviewees pointed out that the EU also has an environmental responsibility for global plastic pollution, and this change from the landscape leads to collaborations such as the Alliance to End Plastic Waste (#4, #5).

5.2.6 COVID-19 pandemic

The Covid-19 pandemic increased the use of single-use plastics, including the use of face masks, gloves and other personal protective equipment (PPE) for health essentiality and safety protection, food packaging from takeaway services and another packaging from online shopping delivery (Parashar and Hait, 2020, Prata et al., 2020, Klemeš et al., 2020, Patrício Silva et al., 2020). Relevant policies to support the use of secondary plastics have been postponed (Prata et al., 2020). Since the pandemic there have been changes in people's behaviour in terms of plastic use. Makki et al. (2021) point out that some new behaviours may increase the unnecessary demand for single-use plastic packaging which may not provide additional protection against the coronavirus, and the hygienic concern may also affect the use of reusable and recyclable plastics.

Klemeš et al. (2020) provide suggestions on plastic waste management to minimise the plastic waste caused by the Covid-19 pandemic, pointing out the high waste treatment costs with challenges to destruct residual pathogens, and improper disposal behaviour of consumers would make these contaminated single-use plastics eventually end up on non-circular pathways such as incineration, landfill, or as mismanaged plastic waste entering to the environment (Fadare and Okoffo, 2020, Vanapalli et al., 2021, Prata et al., 2020). Furthermore, the pandemic travel restrictions and lockdown reduced transportation activities, causing crude oil prices to plummet. This has led to the challenges of plastic recycling, increasing the price of secondary plastics, and reducing the amount of supply and demand of secondary plastics (Parashar and Hait, 2020, Patrício Silva et al., 2020).

5.3 Barriers and drivers on the niche level

There is a range of 'niches,' which are protective spaces that foster the emergence of circular business models and technologies for greater use of secondary plastics. Many niches are created due to:

- consumer concerns around plastic waste, which are largely related to packaging (Hafsa et al., 2022);
- brands seeking to exhibit green credentials, which occur across all sectors;
- research and development (R&D) and demonstration trials, many of which are carried out by incumbents as strategic investments in radically transformative technology.

Four types of innovations on the niche level proposed by Geels (2019) can also be found in the cases of greater use of secondary plastics, including radical technical innovation, infrastructural innovation, business model innovation, grassroots and social innovation.

Radical technical innovation includes digital tracing technologies, innovative collection, and sorting and recycling technologies, for example, innovative tracer-based-sorting technology, based on a combination of fluorescent tracers and a corresponding detection unit for sorting plastic packaging (Gasde et al., 2021). Moreover, there are many innovative solvolysis, pyrolysis and dissolution/precipitation processes, including supercritical fluids, microwave reactors, mechanochemistry and biotechnology, to address problems encountered in conventional chemical recycling processes (Vollmer et al., 2020, Thiounn and Smith, 2020). Sakthipriya (2022) overviewed many recent innovations in pyrolysis technology in the European plastic industry. Many of these radical technical innovations on the niche level may face the barriers associated with lack of financial investment and clear regulations, making scaling up difficult.

Infrastructural innovation is emerging, such as advanced plastic manufacturing factories, innovative collection infrastructures, smart sorting infrastructures, and novel recycling facilities.

Business model innovation tends to emerge along with new technologies such as digital technologies and chemical recycling technologies. Namely, actors tend to seek new business models when investing and/or applying new technologies. For example, more new online trading platforms for plastic waste and secondary plastics emerged with the support of digital technologies, allowing different firms to bid for secondary plastics or meet specific requirements (Langley et al., 2021). Chemical recyclers seek new business partners with municipalities, brand owners, retailers and petrochemical producers to purchase the plastic waste and sell their new products (recycled feedstock) (#21).

Grassroots and social innovation can play a role in educating consumers and fostering consumers to change their purchasing and recycling behaviours. Grassroots and social innovation also have the potential to reconfigure the regime from the social aspect. An example is the Precious Plastic project proposed by a Dutch designer, Dave Hakkens, due to the concern about plastic pollution. This project creates a community platform which provides open sources for local communities to build machines to recycle plastic waste and use recycled plastics. Actors involved in this project develop knowledge and exchange experiences for educational initiatives to encourage consumers to live more sustainably, increase awareness about the problems surrounding plastic waste, and prevent plastic waste from entering the environment (Spekkink et al., 2020).

These niches are applicable at the whole EU level. Niche innovations involve many learning processes and experiments with some successes and some failures. Various actors within the regime are both creating and supporting niches with a view to learning about possible future business models, and looking at developments in niches to understand how the landscape might change and what innovations may emerge.

It is worth noting that this study examines the higher use of secondary plastics and a reconfiguration of the regime that does not necessarily require radically transformative new technologies. Therefore, innovations are concerned with alternative business models, combined with incremental development of key technologies, which include tracing, advanced sorting, mechanical, solvent-based and chemical recycling. While activities at the niche level are important, the strategy of increasing the use of secondary plastics tends not to be a story about the nurturing of radically novel technologies. Instead, it is more about radically novel business models combined with incremental technological change.

While this section has explored a growing proliferation of innovation within niches, the key issue addressed in this thesis is how the socio-technical regime around plastic is driven to adopt and scale up these emerging innovations, and what prevents it from doing so. The next section addresses this issue.

5.4 Barriers and drivers on the regime level

According to the transcriptions and references, I coded a large number of barriers and drivers to plastic circularity, and further identified how each of these factors relates to key 'sub-regimes.' This relates the barriers and drivers to a set of underlying dynamics within each sub-regime. Four sub-regimes, including policies and standards, markets and business models, technology, and consumer preferences and behaviours, are classified. These classifications to some extent reflect conceptual categories suggested by Geels (2004), but have been refined based on the interview data to use the categories that best reflect the dynamics of the regime.

The analysis proceeded as follows. First, I assessed barriers and drivers within each sub-regime. I then explored how they played out across the value chain, and highlighted key differences relating to different application areas. As the analysis becomes clear in Section 5.4, a key insight of the work is the importance of data-information-knowledge. Thus, I dedicated Section 5.5 to explore how the role of data-information-knowledge relates to each sub-regime. Finally, the networks within the socio-technical regime are further investigated in Section 5.6, as networks are largely about creating the relationships that enable information sharing and knowledge diffusion.

In the sections that follow, I present the findings from the interviewees, and highlight where this is further supported by relevant evidence from the academic or grey literature, as a form of data triangulation.

5.4.1 Policies and standards

Government policies and standards play a crucial role in expanding secondary plastic markets. Government policy comprises policies from the European Commission, national governments and local governments. Policy drivers are well reflected in the wider literature on the circular economy. Syberg et al. (2021) overviewed the historical development of policy initiatives and legislation for a plastic circular economy at each lifecycle stage. According to the findings from Syberg et al. (2021), plastic regulations have gradually shifted from mainly focusing on the end-of-life stage to the regulations for different lifecycle stages across the plastic value chain. Most of the policies are driven by the concern of plastic pollution, and banning single-use plastics and packaging is a popular policy measure. The regulations related to the production and consumption of secondary plastics still have many barriers hindering the transition.

In this sub-regime, key factors include regulations of food contact restriction, regulations of chemicals, waste framework directive, mandatory targets, extended producer responsibility schemes (EPR), deposit return schemes (DRS), standards and labelling (labels for recyclability, recycled content, and recycling instructions) for international and European levels, as well as the factors of different systems in different regions.

Key barriers related to policies and standards

- **Lack of standards and clarity in definitions**

Standards comprise technical specifications and/or the documented criteria to be the guidelines and definitions, in order to consistently facilitate the recycling of plastic waste and production of secondary plastics. Standards were mentioned by several interviewees (#1, #4, #7, #11, #12, #25). International standards such as ISO 1043 and ISO 11469 provide generic guidance for making plastics. Shamsuyeva and Endres (2021) overviewed the existing standards at the international and European levels on plastics recycling, product-specific plastic recyclates, and data requirements for the characterisation of plastic polymer recyclates. However, the progress to transparent secondary plastic markets has been limited.

Currently, the Waste Framework Directive (2008/98/EC) provides definitions of waste, by-products, and end-of-waste status. New chemical recycling technologies are being developed, producing new feedstock and monomers from the new manufacturing routes. Chemical recycling is an overarching name for many different technologies, including the routes of use as refinery feedstock, fuel production, monomer production and other chemical upcycling. These different routes are not differentiated in the Waste Framework Directive. Lack of standards and clarity in definitions creates a barrier to trade waste and new feedstock on the market. An interviewee highlighted:

> *'When regulation has been drafted, this technology was not there. Not really clear is it now included or is it excluded?' (# 4 Petrochemical producer / Chemical recycler).*

The other interviewee also mentioned:

> *'If you have something which has been a waste, you cannot feed it back into product, again, there is a legal step necessary there to clean it up or to clear it as a waste and to say it's a product again, that's a sensitive one' (#2 Petrochemical producer / recycler).*

Another interviewer explained:

> *'Now, there are some questions about the statute of wastes. With chemical recycling, it's still like a waste or is it still like a new product? So there is like a grey zone from a legal point of view' (#25 Extended producer responsibility organisation).*

Literature suggests this is a wider issue. A lack of harmonised EU end-of-life criteria for plastics, and the interplay between Registration, Evaluation, Authorisation and Restrictions of Chemicals (REACH) (EC No 1907/2006) and the Waste Framework Directive are reported to have created barriers for recyclers to comply with the REACH requirements (de Römph and Van Calster, 2018, De Tandt et al., 2021).

Moreover, labels on plastic packaging and products are one way to communicate with different actors. There are different purposes for labelling, namely, labelling for recycled content, labelling for recyclability and labelling for recycling instruction. Labelling for recycled content and for recyclability provide marketing purposes. Although some international standards and EU policies regulate labelling systems, there are no harmonised standards for labelling in the EU at the moment, and a lack of clear standards in this area was cited as a problem by interviewees (#1, #7, #12, #13, #19, #25). To tackle this barrier in the short-term, Plastic Recyclers Europe has been working on a cross-industry initiative called RecyClass and have published guidelines and definitions for recyclability and recycled plastics. This barrier is currently under discussion in the European Commission. In the long-term, legislation and policy need to clarify the definitions between plastic waste and recycled feedstock, as well as the labelling systems.

Lack of standards and clarity in definitions also shows the difficulties for governments to understand the challenges faced by businesses. To be more specific, policy frameworks do not always recognise the complexities faced by businesses in the transition process.

- **Diversity of waste collection and treatment across Europe**

Legislation can be different between the EU level and member states, as well as between different member states. An interviewee pointed out:

> *'When I look at the European level, we do have some efficient of recycling and relevant so-called Waste Framework Directive which is technology neutral, so chemical recycling is in there, as well as mechanical recycling. And then, when*

you go to national and also local orientation level legislation, sometimes they have the differences' (#4 Petrochemical producer / Chemical recycler).

Petrochemical production business and recycling markets in the EU are often across the borders of the member states, so different national laws may also cause some difficulties for the secondary plastics markets. Cumbersome paperwork on the waste transfer across the border creates a barrier as it is costly and time-consuming (#18, #20).

Furthermore, different waste collection systems across the EU also create barriers for actors to provide accurate labelling for recycling instructions. An interviewee said:

'We don't (have any labels for recycling instructions) because we are selling in more than 10 different countries, and in different countries, recycling works differently. So, we don't put any labels on how to dispose of products' (#13 Retailer / Brand owner).

- **Problems of the collective extended producer responsibility scheme**

Although there are some drivers from the collective extended producer responsibility (EPR) schemes, the schemes also have some barriers that lock in the use of secondary plastics. Watkins et al. (2017), Leal Filho et al. (2019) have analysed some problems of current EPR schemes, including lack of harmonisation, different implementation across the member states, and lack of incentives to improve the recyclability and use recycled content. Interviewees further pointed out several weaknesses of current EPR schemes. For an example, some schemes did not cover commercial and/or industrial packaging:

'What is not subsidised is the collection of the same types of packaging at the B2B. So, an office that wants to separate their plastic, actually pays a lot more for the collection than a household' (#16 Mechanical recycler and consultant).

The interviewee also mentioned the lack of incentives in EPR schemes, as most of the actors then achieve no more than the binding recycling targets (#16). Contrary to individual EPR schemes, the charging fee in collective EPR schemes tends to pay a variable mass-based or fixed fee, rather than based on the materials' recyclability. A lack of the differentiation across products and materials for the collective EPR is mentioned as a barrier (#10). EEE manufacturers lack economic incentives to choose the materials which can be recycled and used as the secondary plastics (#10). Therefore, there is still room to improve EPR schemes in providing incentives, and this issue is under current discussion across different actors.

Key drivers related to policies and standards

- **Governments introducing policies to drive transition: EPR and taxes, etc.**

Packaging and Packaging Waste Directive (Directive (EU) 2018/852 amending Directive 94/62/EC) has enforced EPR schemes for all plastic packaging. This is the driver specifically relevant to plastic packaging designers and manufacturers. It is argued that the economic incentives from EPR schemes are insufficient to increase the use of secondary plastics, while some collective EPR schemes have started to provide economic incentives for using secondary plastics. An interviewee explained some new changes of EPR schemes:

> *'Extended producer responsibility systems are getting more and more eco motivation. So, if you have recyclable packaging, you get a bonus, you have to pay less; if you are not recyclable, you get a minus, and you have to pay more. So that's one. The other one is using recycled content. Some EPR systems are now also thinking about how they can stimulate the use of recycled content in packaging, but also giving a bonus if you use over 80% of recycled material. So that the EPR fees are also important' (#16 Mechanical recycler and consultant).*

To drive the transition, governments are introducing policies using a carrot-and-stick approach. Another example of an EPR schemes is mentioned by an interviewee:

> *'We put a specific bonus if you put the sorting instruction on your packaging […] but at the end, the brand owners will not have any bonus, because now it's under the law, you need to put sorting instructions' (#25 Extended producer responsibility organisation).*

Economic incentives may affect the options of plastic waste collection systems. There are many different systems under the principle of EPR to collect plastic bottles, including kerbside collection, the deposit return scheme (DRS), and reverse vending machines (RVM). DRS provides economic incentives that can help change consumers' recycling behaviours and create a pure waste stream. Bünemann et al. (2021) explained different structures and operations of EPR schemes and provided a toolbox on how to establish EPR schemes for packaging. Each region and/or country needs to find an EPR scheme which suits their market in order to manage financial responsibility and operational responsibility across different actors to improve plastic circularity.

Moreover, mandatory targets, plastic tax, and green public procurement stimulate demand. The European Commission has set up mandatory targets to have at least 30% recycled content in plastic bottles by 2030. Some member states also have demand-pull policies for some products. An interviewee gave an example:

> *'If you want to tender for buildings of the city of Dusseldorf, for windows, you have to have a certain recycling content in your frame' (#7 Manufacturer).*

Another example is linked to driver of lower carbon emissions:

> *'In Holland, there is a green procurement from authorities they are demanding that you put and use materials with the lowest carbon footprint and the carbon footprint of our recycled polystyrene is about 50 to 70% lower. So, that's the reason why recycled material is getting higher amount of money because there is very little recyclate high quality available. And there is a high demand' (#20 Solvent-based Recycler).*

Considering the EU climate-neutral strategy, the carbon taxes become another drive to increase the use of secondary plastics. An interviewee explained:

> *'It's like every proportion of recycled plastics is minimising our carbon footprint. […] As we know, the carbon emission taxes are coming worldwide and will be in Europe, we've got an increase of the carbon emission certificates in the end parts that are made out of virgin material will be more expensive than parts where you have got recycled material inside' (#7 Manufacturer).*

- **Potential local economic benefits drive local governments to be interested in developing local waste collection and recycling capacity**

The potential for benefiting local prosperity, increasing of recycling capacity, and green job creation drives municipalities to invest in developing local waste collection and recycling capacity. A chemical recycler explained:

> *'We collaborate with local authorities who are interested in improving their recycling and what they recycle, but they're also interested in low carbon jobs, local prosperity... with an installation of new capability, there's also the creation of jobs and, therefore, building up of local prosperity and technical infrastructure as well' (#21 Chemical recycler).*

This shifts value creation from distant petrochemical producers to local recycling facilities.

Policy and standard barriers and drivers play out across the value chain

Policy actors have tried to design policies that drive action across the value chain, and that appears to be working. However, several barriers in the sub-regime of policies and standards still hinder the transition across the value chain. One of the barriers in creating circular loops is the uncertainty about the definitions of recycling and what counts. This is particularly important for chemical recyclers, and for the primary petrochemical producers that would be purchasing the outputs of those using chemical recycling technologies.

Anticipated future policy is driving activities across the value chain. A brand owner said:

> '*This is not only something we want from a certain intrinsic motivation, but it's also something we just want to do, because legislation will catch up with us if we don't' (#13 Retailer / Brand owner).*

This shows that preparing for the future legislation also drives retailers and brand owners to start using secondary plastics. This is why many companies have been working on setting the voluntary targets beyond the current mandatory targets. However, there is still a lack of standardisation to measure the progress of these targets, which may create a greenwashing risk.

At the waste collection and treatment stage, a key problem is national and local authorities playing a key role in the system as the architects of the collection regime, and the authorities are currently struggling to co-ordinate. Another key barrier is how to fulfill the regulations (e.g., REACH (EC No 1907/2006), Food contact legislation (EC No 1935/2004, EC No 282/2008)) (de Römph and Van Calster, 2018, De Tandt et al., 2021). It is challenging for the recyclers to provide information regarding safety and traceability to manufacturers.

Policies and standards across different application areas

There are differential policies focusing on different areas. Some restrictions regarding hygiene and safety have become barriers limiting the use of secondary plastics. Food grade has drawn more attention, because the regulations for using secondary plastics in food contact packaging require the traceability of secondary plastics. An interviewee explained:

'European Food Safety Authority has said that when you want to make a re-granulate going into food application, you should be sure, and you can proof and certify that 95% of your input actually already had a prior food grade application. And this is obviously very difficult to do' (#16 Mechanical recycler and consultant).

Others have echoed these findings. De Tandt et al. (2021) pointed out the barriers regarding traceability, input contaminations, and the determination of decontamination efficiency to fulfil EC No 282/2008 on recycled plastic materials intended to come into contact with food. Currently, the European Food Safety Authority (EFSA) only developed guidelines for PET recycling safety evaluation. Therefore, only rPET can be used in the food contact packaging at the moment. The mixed waste stream has made it difficult to identify the traceability of origins, and to separate food grade plastics in the pre-treatment process, therefore, it has become a legislative barrier to use the secondary plastics in food contact packaging.

Several regulatory barriers for flexible plastic packaging were identified by Bening et al. (2021), including ineffective policies, waste laws not aligned with other laws, recyclates excluded from reuse for food-grade material, disincentivised collaboration through antitrust laws, lack of financial support, insufficient standards and labelling, insufficient measurements and monitoring, lack of system transparency and data to design appropriate policies, cumbersome interaction with authorities, and insufficient alignment across governance levels. Many of these barriers were mentioned and confirmed by the interviewees (#1, #2, #5, #6, #8, #11, #12, #13, #16, #17, #18, #21, #25).

The legislation regarding hazardous chemicals has safety restrictions limiting the use of secondary plastics and recycled plastic waste. A manufacturer pointed out this barrier for the use of secondary plastics:

'Chemical rules. For instance, REACH and RoHS (Restriction of Hazardous Substances Directive 2011/65/EU). It is still very complicated to sometimes meet those requirements for recycled materials' (#10 Manufacturer / Brand owner).

On the other hand, the legislation also hinders the plastic waste recycling creating technical and economic barriers:

'I have to sort out the ones that have got brominated flame retardants in it because they've been banned. Double check that there's no lead or cadmium. And then what keeps happening is (that) the European Parliament and the Basel Convention keep banning chemicals and additives that have been used 10 or 15

years ago, but they keep coming out of the waste stream' (#18 Mechanical recycler and consultant).

Compliance with such legislative restrictions is identified as a barrier according to the interviews. As society identifies new concerns, and as society's standards for chemical safety grow more stringent over time, this is unlikely to be a transitory problem. Rather, recycling systems will need to continue to adapt to changing requirements, while dealing with legacy waste streams.

Two journal papers published while the research for this thesis was underway further support these findings. Overviewing the EU regulations related to E-plastics and legacy additives, Barouta et al. (2022), Wagner and Schlummer (2020) also highlighted that it is difficult to increase the circularity of E-plastics, because, in practice, the identification of hazardous substances in accordance with continuously updated restricted threshold limits, is inadequate when using existing recycling technologies. Moreover, WEEE is collected based on 10 EEE categories from the WEEE Directive (2012/19/EU), rather than plastic polymer types, so it is difficult to separate plastic waste at the sorting stage. An interviewee explained:

'The WEEE categories are not ideally clustered, like, for example, we have large households and devices, and cluster is not made by the most common plastic type. It's just made up by the size and some (cluster) doesn't have like, material point of view' (#24 Specialist).

It is worth noting that much of the plastic circular economy policy focuses more on packaging and much less on promoting secondary plastics used in the construction sector. EPR schemes have been adopted in packaging, WEEE and ELVs in the EU. EPR schemes can help to drive the transition, particularly in plastic packaging applications. So far, only plastic bottles have set up the mandatory targets at the EU level, however, setting up reasonable and achievable mandatory targets for a plastic circular economy requires comprehensive assessment of the technical and market factors and communication across different actors. In the past, some European member states have failed to achieve the 95% recycling rate target for ELVs. An interviewee explained:

'*So if you take automotive, for example, ages ago, they said, under the automotive directive (sic), you have to recycle 95% (ELV). [...] And I know that the average level of recycled plastic on a car at the moment, certainly less than 5% in Europe, probably less than 2%. So the big automotive companies said, "oh* *yeah, we put products on the market where if you recycle it, you could recycle 90% of the plastic." And it just doesn't add up' (#18 Mechanical recycler and consultant).*

This quote highlights recycling rate does not reflect the amount of secondary plastic used back in the new manufacturing process.

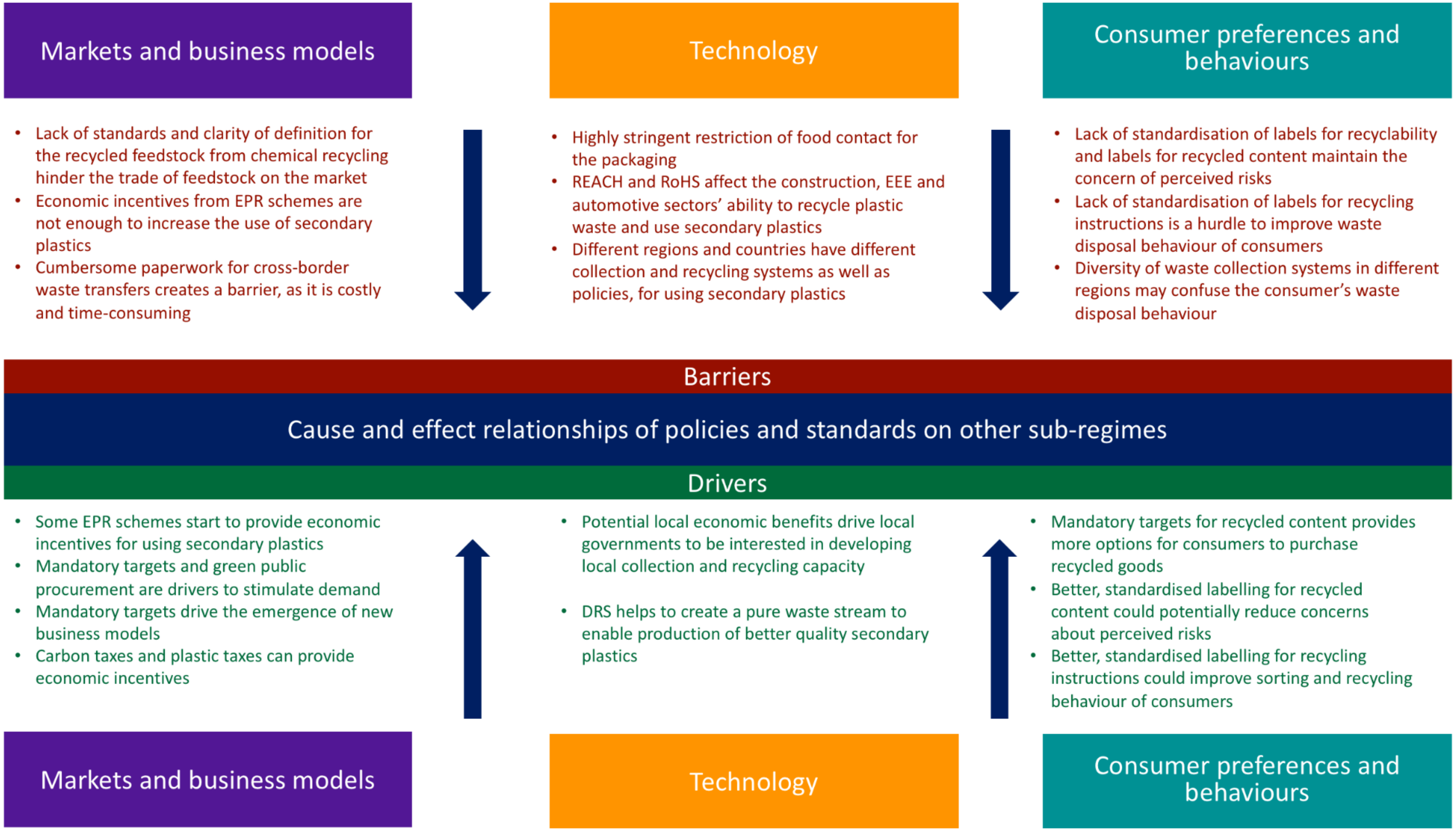


Figure 5-2 Cause and effect relationships of policies and standards on other sub-regimes

Summary of sub-regime of policies and standards

Figure 5-2 shows how the policies and standards have the ability to affect other sub-regimes. The relationships between sub-regimes are complex. The analytical structure is an attempt to bring some order to this complexity, and to demonstrate specifically the flows of effects from the policies and standards to other sub-regimes.

Key dynamics are the EU policy on promoting a plastic circular economy drives the change in markets and business models. Current legislation and standards cannot cope with imminent changes in new recycling technologies and so have restricted the use of secondary plastics in some products.

The plastic system is in transition, and there is a lack of alignment around key issues: the absence of standards with the development of new standards requiring significant work. This also leads to the challenges of an adaptive policy framework that can also handle legacy materials. Significant information asymmetries, non-harmonised EPR schemes, and diversity of collection and recycling systems, make governance complicated. The plastic circular economy is more complex than single-pressure issues, therefore, the creation of effective demand-pull is not straightforward, which makes it challenging to design policies that create the demand-pull for plastic circularity. Although carbon taxes and plastic tax may work, major leakage issues create difficulties for pricing the pollution of littering.

5.4.2 Markets and business models

This sub-section analyses the sub-regime of markets and business models. Dijkstra et al. (2020) found that one of the most popular plastic circular business models focuses on recycling and creating value from waste. In this study, the sub-regime of markets and business models focuses on the supply and demand of plastic waste and secondary plastics, brand value, and business strategies. The key barriers are high costs and small markets, established norms and routines, high risk aversion, and uncertainty over the available quality and quantity of secondary plastics and plastic waste. Key drivers are brand value, direct customer demand, and searching for competitive advantage in the face of possible disruption. These barriers and drivers are aligned with the literature on broader sustainable plastic management business models (Dijkstra et al., 2020). Based on these current studies, this thesis further investigates the ongoing transition dynamic of the markets and the interactions between these barriers and drivers. The multiple roles of different actors in circular business models are analysed with some interesting cases.

Key barriers related to markets and business models

- **High costs and small markets**

High costs and small markets prevent the widespread use of secondary plastics. In some cases, the upstream markets need to upgrade their manufacturing processes with additional equipment to incorporate secondary plastics, while the downstream markets have problems with technology immaturity and the small scale of collection and recycling. The barriers to using secondary plastics are similar to the classic barriers to new technologies in sustainability transitions, such as the high cost of new equipment, the high cost of good quality recycled materials, and technical complexity. In some cases, these are issues associated with technological immaturity, which are discussed in the sub-regime of technology. In other cases, there is simply a strong scale effect, suggesting that a tipping point could enable a more rapid adoption of recycling if the market were to cross a scale threshold.

On the upstream, both producers and manufacturers may incur additional costs to change the production infrastructures in some cases. An interviewee pointed out the lock-in of established infrastructure and practices:

> *'Typically, changing an entire production line of packaging is quite costly. And before you decide to do that might sometimes take a couple of years' (#16 Mechanical recycler and consultant).*

Another example is the window frames:

> *'You have to change your production process […] on the outside, you have got the white, and on the inside, you've got the recycling material. And that is called co-extrusion […] To have a certain proportion like the 50% (of recycled plastics), you have to change all your processes in all production plants, and we have a lot of production plants in Europe and outside, and therefore, that takes time' (#7 Manufacturer).*

On the downstream, there is high cost partly because of lack of economies of scale. A recycler mentioned the lack of recycling capacity:

> *'In the [waste management company] has a procurement team, even though they manage 100,000 tonnes of recyclable material. That's about 60,000 tonnes of plastic, but it's still not enough to maximise their customer demand. So, the moment customer demand is high, [waste management company] are using all*

their internal material, and going into the open market and buying additional tonnage (sic)' (#17 Mechanical recycler).

An interviewee explained:

> *'The (recycling) process is expensive. You can buy low-quality plastics, and it's cheap. But to buy high-quality, sorted, clean (recycled) HDPE, 90% (recycled) HDPE is very expensive […] the process, the sorting, the shredding, the washing, because it's hot wash, and the sorting of the flakes, drying and granularization these are all energy-intensive processes […] the energy use which equates to the cost in the process is high, and you don't have that economies of scale benefit than you do if you're making virgin plastics' (#17 Mechanical recycler).*

Therefore, the high costs and small amount of secondary plastic production can hardly compete with the large amount of virgin plastic production and the fluctuation of oil prices on the landscape. These factors lock-in the transition.

Some plastics are also facing similar barriers of small markets:

> *'The problem is the scale of economy. So for example, PMMA (Polymethyl methacrylate) that is the front of your television. It's very nice product. It's high quality. You can't recycle it because you don't have quantities. It's the same the other plastics like PBT (Polybutylene terephthalate) connectors in electronics, they are excellent for recycling but you can't collect them' (#20 Solvent-based Recycler).*

These plastics, shown as 'other plastics' in the MFA results, provide specific technical properties, and each type has a smaller amount in the market compared to the other six main types of plastics, so it is challenging to create plastic circular loops, and they normally end up in incineration. In this situation, both technological innovation (e.g., advanced sorting and recycling systems) coupled with a viable business model is necessary. However, this is high risk for innovators.

When the recycling cost is more expensive than the purchase of virgin plastics, it becomes an economic barrier. The following observation shows the economic value competition between the energy recovery and secondary plastics/feedstock recycling:

> *'When the prime [virgin plastic] price goes down, it makes things [plastic waste] very difficult to sell, recycle, because you have all the fixed costs. So then, it becomes very difficult to compete. And then you will need maybe to get paid to*

collect the material. And then, that makes it so much easier just to incinerate, because that's good energy value of plastics' (#23 Broker).

The complexity of the price of secondary plastics not only depends on the quantity and quality of plastic waste and re-granulates, but also has market price competition between crude oil and different waste treatment options.

- **Established norms and routines**

Socio-technical transition studies highlight the role of 'soft' institutions, such as norms and routines, in inhibiting radical change. My observations here are consistent with that view, since companies' established routines appear to prevent consideration of circular designs. Profit-driven businesses have historically had a production orientation that disregards design for/from recycling, and this inhibits the transition. An interviewee gave an example of products for the construction sector:

> *'When I was selling (recycled granules for PVC windows), to try and get a product into specifications to architects for designing some new buildings, you'd find that the people designing the building would cut and paste the information from a previous job, which might be completely out of date and wrong, […] which would stop you giving them a better product because the specification now is wrong' (#19 PVC windows recycler*).

People who 'cut and paste' old requirements without re-thinking them show that 'business as usual' practices create linear path dependency and hinder transition. The routines and habits reinforce existing systems and take time to shift. This highlights the need for education, and the general lack of awareness of and knowledge about options for secondary materials.

- **High risk aversion**

Because developing new technologies and infrastructures is a long-term investment, many actors do not want to take risks. A recycler mentioned:

> *'No one wants to have the risk. Plastic producers do not want to pay. Banks do not want to give loans because it's a high risk, and subsidies from the European Commission, they are all for lab scale and pilot scale [...] So, in Europe, no one wants to take the risk. So, small companies cannot take the risk' (#20 Solvent-based recycler).*

A construction manager emphasised that risk aversion in the construction sector hinders the use of secondary plastics:

> *‘I think the construction (sector) is very risk averse, and so that is a challenge […] because people are always wary of using a new material […] So, for thinking about using it in the actual construction, using recycled plastics, if it's not something people have done before, they'll want to be really sure that, it's going to behave in the way that you would expect it to, or in the same way as a virgin material’ (#14 Construction manager).*

- **Uncertainty over the available quality and quantity of secondary plastics and plastic waste**

Except for the price fluctuation of secondary plastics, unstable availability of secondary plastics is also a barrier. An interviewee explained the market change and the lack of availability:

> *‘The consumer goods industry is trying desperately to catch up because they're always identified as the number one cause of ocean pollution...They're always identified as the big polluters. So, they are having a big push and that's why there are challenges with availability of recyclate because they're buying everything’ (#17 Mechanical recycler)*.

Lack of confidence in the supply chain regarding quality and long-term availability leads to huge co-ordination barriers. An interviewee explained the problems of manufacturers buying the secondary plastics:

> *‘From the production side, the quality is varying all the time…the long term availability is not there [...] And then, also the reliability […] If you are a manufacturer, you can make a contract with a recycling material supplier, but you can't be sure that you really get the material in the end. Sometimes, there are distributors, so they sell recycling material, although they don't have it yet […] he (distributor) buys it from somewhere maybe from different sources’ (#24 Specialist).*

This view also reveals the barriers to incomplete contracts and huge transaction costs and risks. Another recycler used their example of PVC window frames to point out the barrier to availability:

‘We sold out, we don't have any spare material at the end of each month […] If somebody puts some legislation out, said every new window must contain at least 10% recycled content. Every new extruded PVC product must have at least, there isn't enough material. There's not enough available. It's not even a matter of capacity in the recycling industry. There wasn't physically enough to put in to give you that’ (#19 PVC windows recycler).

There are contested battles about the right policy approaches to shift the market. Interviewees represent specific stakeholder groups with specific interests, and different stakeholders have their own positions, such as those groups against the mandatory targets, while others advocate setting such targets. Setting up mandatory targets may create a demand-pull and provide incentives to invest in new technologies and infrastructures, but it needs to consider other factors in the system.

Key drivers related to markets and business models

- **Brand value**

Markets have been changing in response to the landscape and consumers’ perceptions regarding plastic pollution. Using secondary plastics can become a business strategy to create positive brand value. An interviewee said:

‘The growing appreciation for the need of recycled content amongst consumers. It's actually creating a value proposition about having recycled content in there’ (#1 Petrochemical producer / Specialist).

Another interviewee also pointed out:

‘It's always reputation’ (#20 Solvent-based recycler).

A manufacturer mentioned:

‘It's like every proportion of recycled plastics is minimising our carbon footprint […] And this can be a major USP (Unique selling proposition) not just in the marketing but as well in the costing’ (#7 Manufacturer).

Clearly, using secondary plastics can be driven by reducing the carbon emission and saving cost of tax payment, and becomes a marketing strategy to respond these pressures from SDGs, circular economy, climate change and plastic pollution. An interviewee also mentioned:

'In the end, there is a lot of marketing behind it. That's also reason why companies work with recycled plastics. It's not because it's always cheaper, but nowadays, the debate about sustainability and carbon emissions so high that companies have a benefit if they use recycled plastics just from a marketing point of view' (#24 Specialist).

Brand owners want to be able to differentiate themselves in terms of recycled content, and limit potential damage to the brand from ocean plastics. An interviewee described,

'I think the other thing that really drives it is to make the thing you want, which if it's more recycled content become a basis for good competition […] If you make it a declared part of the brand value, then, you're probably influencing on the sales director, the marketing director, the product design director' (#18 Mechanical recycler and consultant).

Another example is described by an interviewee:

'[A brand of] Cars have stood out and said we're going to make our cars have 25% recycled plastic by 2025. […] the clever brands have understood that, unless they incorporate some concept of environmental concern and caring about the planet into their brand value, they'll lose the customers' (#18 Mechanical recycler and consultant).

Marketing positive image of recycled content is a key factor to create a successful circular business model (Calvo-Porral and Lévy-Mangin, 2020).

- **Direct customer demand**

Pressure on brand owners created a market distinct from the mainstream market, enabling development and investment. Brand owners play a significant role to create demands to drive the whole value chain to increase the use of secondary plastics. An interviewee explained:

'There are a number of very large brands such as [four names of fast-moving consumer goods company] and many others have signed up the UK Plastics Pact. So, they're looking to put 30% recycled content as an average on the plastic packaging that they put on their shelves by 2025. So, there is a large demand placed on the petrochemical sector, and on the plastics production sector, and the converters to make packaging that's got recycled content' (#21 Chemical recycler).

This shows that market demand is mediated by corporate efforts at sustainability as a result of shifting social norms, although it has clear limits.

For the petrochemical producers, customer demand is from converters, manufacturers, brand owners and retailers. A petrochemical producer said:

> *'We see that our customers are asking for it. They want recycled content' (#4 Petrochemical producer / Chemical recycler).*

Due to the reputation of companies and pledges, the manufacturers and brand owners increase demand for secondary plastics. An interviewee explained:

> *'What's changed is that in the last two years, probably, suddenly, manufacturers and sellers of products which are sustainable or want to impress upon their customers that they've got a product which has some sustainable benefits and started declaring their recycled content […] And right now this is crazy, never been seen before. Virgin PET is trading lower than just flakes of recycled stuff. There's a massive change' (#18 Mechanical recycler and consultant).*

The increasing demand for secondary plastics leads to a change in the market. Some types of plastic polymers are no longer cheaper than virgin plastics. Some recycled plastics are cheaper for certain (typically low-value) applications, while others are more expensive.

- **Searching for competitive advantage in the face of possible disruption**

Dijkstra et al. (2020) highlighted the most prominent drivers to sustainable plastic management for companies are maintaining competitive advantage and accessing green markets. In this transition process, the expected future competitive risks make companies feel the need to avoid losing out. Therefore, companies seek out new relationships and experiments to avoid being victims of emerging disruptive innovations and business models.

Different actors have started to do business model experimentation and 'ecosystem building,' such as partnerships, joint ventures, experiments, and setting up collection points in stores. The joint venture is one of the more popular circular economy business models in this transition process. An interviewee described the case between waste collectors and converters/brand owners:

> *'The business models that seem to work [are when] the inward supply company and the off-take company, they come together and they form a joint venture*

where they are 50-50, and the recycler in the middle, because then [the waste collectors] are locked into supplying the material to the company they own half of, and [the converters/brand owners] are locked into buying the material from them. So that becomes a long-term stable relationship […] in a circular economy, the more that the different individual actor in the chain are all linked together by a binding relationship basically own the shareholding relationship, that becomes a much more stable long-term model' (#18 Mechanical recycler and consultant).

This example also illustrates the circular business model change to value creation and delivery from a merely transactional buyer–supplier relationship to a collaborative relationship across the value chain.

Another example of experimentation is how a chemical recycler established a new business with petrochemical producers / brand owners to use the feedstock to produce new products:

'We collaborate with the petrochemical industry to find commercial outlets for our [name of the product] products […] the chemical companies are experts in looking at material flows and material feedstocks for the processes. And there is now many collaborations in the industry and technical collaborations happening to ensure these new materials, which are plastic waste feedstocks, are suitable for the processes, so that they can close the loop on the plastics value chain' (#21 Chemical recycler).

An interviewee from a waste management company explained how they changed their partnership with brand owners rather than converters:

'So, with [name of waste management company] having the end-to-end control of the material, it was quite a compelling argument for the customer (brand owner). So we found it quite easy to instead of having one converter buy all of the material from [a recycling plant of waste management company], we actually had two customers (brand owners) buying the material, which meant there was a little bit of competition between the customers (brand owners) for purchase, so it meant that they kept the price instead of continually depressing the price, which is what a single customer (converter) can do because you can't go anywhere else (#17 Mechanical recycler).

This is the ecosystem strategy, cutting out other actors by moving into their area. All these new, emerging business model experiments and new ecosystem building initiatives are seeking a balance between cooperation and competition (Hannah and Eisenhardt, 2018).

Market and business model barriers and drivers play out across the value chain

The changes in markets and businesses are largely driven by brand owners, since these actors are facing the strongest consumer pressure. However, they have to work increasingly across the value chain. There are two sets of major changes that can be observed. First, there is an interesting tension between brands trying to pressure their supply chains to produce recycled and recyclable packaging, components, etc., while at the same time brands are sometimes seen as only doing this for communication reasons, which hampers long-term scaling up investment in such solutions across the supply chain. Second, some actors are seeking to capture value from the creation of circular business ecosystems, so they are changing their roles and seeking new ones.

Interviewees provide some examples of the first set of major market and business change. Brand owners not only source the secondary plastics from the suppliers in the upstream, but are also involved in the downstream recycling market. A brand owner explained:

> *'For a long time, we tried to convince our recyclers to improve their recycling processing and get higher recycling rates, but a certain moment, we realised, if we don't use recycled plastics, there's no incentive for recyclers to improve' (#10 Manufacturer / Brand owner).*

This example involved the processes of collaboration and learning.

Pressure on brand owners is influencing business strategies throughout the value chain, so companies are developing business-to-business (B2B) products with high recycled content to differentiate themselves and make themselves attractive to their corporate customers. Also, there is a 'battle of the plastic polymers' developing. An example shows that brand pressure on brand owners is driving primary petrochemical producers to invest in recycling technologies. A petrochemical producer explained:

> *'If we would not deliver [polystyrene] recycling solutions, they (customers – manufacturers/brand owners) will switch to PET or to PE, especially for our dairy [product packaging's customers]. It's a huge investment one because they need to change all their equipment […] [yoghurt pots producers] they want to stay with us because we have very good products, it's also easier to process, it has a lower*

energy use to produce, they have all the equipment' (#3 Petrochemical producer / Mechanical recycler).

It is worth noting the real uncertainty among recyclers about how serious these brand owners' commitments are, when they see companies greenwashing. An interviewee pointed out this concern:

'They (a fast-moving consumer goods company) made, I think, they said, 30,000 [recycled plastic] bottles, but that's nothing, that's not even a pilot run in a bottle blowing facility. So, it really was advertising. I said, "Was this a greenwashing?" And they said, "No, no, because we made it clear it was a demonstration, we wanted to demonstrate that how the technology was becoming available to do this" ' (#17 Mechanical recycler).

If the marketing for secondary plastics is making misleading environmental claims, it may make it problematic for stakeholders to invest in vague brand value commitments. This highlights a tension within the supply chain: suppliers are responding to the consumer pressure and policy pressure faced by brands, but are also exposed to uncertainty about whether brands will respond with real substantive change or only with largely symbolic and communicative strategies. While consumer concerns about the environment are creating change within the regime and in particular the establishment of experiments, pilots and other niche activities, such concerns are not necessarily driving transformative change.

The second major set of observed changes relates to the changing roles and business models of interacting among supply chain actors, as they seek to create and capture value in increasingly circular business ecosystems. Pre-competitive collaboration has been emerging as part of 'ecosystem building' activities. Table 5-1 shows that each actor tends to play multiple roles in a circular economy business model. It is worth mentioning that the intermediaries (distributors, traders and brokers) also play a role in the value chain to help different actors souring specific materials.

Table 5-1 Multiple roles for different actors in a CE business model

Main role	Additional role
Petrochemical producer	Involved in recycling
Manufacturer	Innovate in new grade of recycled plastics Collect the pre-consumer waste from customers
Brand owner	Change the whole supply chain by setting the targets of using secondary plastics and asking the supply chain to work together to achieve the targets
Retailer	Set up collection points at their stores Communicate and educate the consumers to bring their plastic waste to the shops
Recycler, Municipality, EPR organisation	Predominate the innovation of recycling technologies and infrastructures, share data, information and knowledge regarding sorting and recycling to assist designers design for recycling

In transition dynamics, some petrochemical producers have started to play a role as a recycler. A petrochemical producer said:

> '*We have invested and we have started to work in the field of chemical recycling. And next to that, we're also giving it a lot of consideration, what our position in mechanical recycling should be […] we already have a quite substantial compounding base. So, we have all kinds of operations where we take plastics and mix them with certain components and turn them into plastic compounds. And that's, of course, also the operation model for many recyclers. So there, we have some synergies on the business side. And, when it comes to chemical recycling, we hope that we can make our know-how available for that' (#2 Petrochemical producer / Recycler).*

In a circular economy system, the actors not only collaborate with suppliers and their customers, but also start to collaborate with competitors. An example shows that the petrochemical producers, recyclers and their competitors work together to scale up the secondary plastic markets:

> *'We don't only work with [name of chemical recycling company] [...], but we also work together with [another name of chemical recycling company] […] And we're planning to build a plant with them in China and in America, as well in Europe, where we can work together with [name of petrochemical company]. [Name of petrochemical company] is our competitor but we work together for recycling activities' (#3 Petrochemical producer / Recycler).*

Manufacturers play a role in innovating new grades of recycled plastics. A car manufacturer said:

> *'I worked on forcing a different integration of recycled materials with engineers to develop new grades of recycled plastics in cooperation with different partners […] We have these partners […] this [name of advanced recycling company] is not only working with [name of car manufacturing company] [...] this [name of advanced recycling company] is working with different automotive manufacturers, [another name of car manufacturing company], and now we have [the other name of car manufacturing company] that is very enthusiastic because they want to test the different recycled PP on these cars (sic)' (#9 Manufacturer / Brand owner).*

Moreover, manufacturers also collaborate with their customers to collect the pre-consumer waste back to be used in their manufacturing process (#6, #7). This kind of B2B collaboration may not be a new business model. This has been happening for a long time in the market, because pre-consumer plastic waste is cheaper than virgin plastics with high quality and traceability.

Brand owners have more power to conduct supply-chain management, marketing, and improve the traceability of the value chain. Brand owners can change the whole supply chain by setting the targets of secondary plastic use and asking the supply chain to collaborate to achieve the targets. The brand owners' pledges drive supply chain collaboration, and supply chain collaboration can drive the changing business model from a linear one into circular. Therefore, the brand owners need to build up partnerships with both upstream and downstream actors to create a closed/opened loop supply chain. A brand owner said:

'We also have partnerships with waste handlers and with packaging suppliers in terms of exploring new routes for processing materials' (#11 Manufacturer / Brand owner).

Retailers play the role of communicators and educators of consumers in innovative and convenient approaches to waste collection. An interviewee gave an example from the collaboration between a retailer and a chemical recycler:

'[Name of a retailer] is a leading supermarket in the UK, and they put onto the market a large proportion of plastic waste that currently aren't able to be recycled by the householders. So that obviously a lot of pouches, crisp packet bags, films, these types of items. They serve a very important purpose for protecting in the food, ensure shelf life, etc, but when that material is in the home, it's not currently able to be recycled on a large scale. So what [name of a retailer] has done is they were very far reaching in their view, they want to do more to solve the plastic waste problem. And they came to us to sort of say that they would like to collect waste from 10 stores in the [name of a region], they would install bins in store, and they would ask their shoppers come and take, bring back these wastes to the to those 10 stores. And those wastes were then collected, aggregated and then they have been sent to us' (#21 Chemical Recycler).

These collection points in the retail stores can create a higher purity of waste collection stream to help overcome the barriers of collection and sorting.

Many actors are involved in waste management, including recyclers, municipalities, EPR organisations, and brokers. The collective EPR schemes tend to lack collaboration among these actors. The roles, responsibilities of different actors, and operations of EPR schemes vary depending on the provisions of the applicable regulatory framework. For example:

'*Some local authorities are involved in the collection of plastic waste and all wastes from households. And also, they are responsible for the disposal of those wastes […] But sometimes you'd have a district council which will collect, and the county council that will dispose. So it does just depend on the type of structure of the local authority' (#21 Chemical recycler).*

In the case of municipal/local authorities taking responsibility for plastic waste collection, EPR organisations have little direct influence on the quantity and the quality of collected plastic waste (#25) (Bünemann et al., 2021). The collaboration between municipalities, EPR organisations and recyclers still needs to be improved in order to increase the recycling rate and quality of secondary plastics (#25).

In a new circular economy business model, recyclers play a crucial role in predominating recycling technology and infrastructure innovations, sharing data, information, and knowledge regarding sorting and recycling to assist designers in designing for recycling. Through improving the collaboration, recyclers can vertically connect with actors along the supply chain and horizontally connect with brokers, municipalities and the EPR organisers.

Markets and business models across different application areas

The plastic packaging market is much more exposed to consumer pressure, while corporate sustainability pressure diffuses through the supply chain across different application areas. An interviewee gave an example in the construction sector:

> *'I think it's trying to encourage those people (contractors) that do take it more seriously, and we will share this across the company, (using recycled plastics as an alternative or avoid using single-use packaging) will get you really good PR (public relations) for your contracting company that you're doing this great stuff. And you're ahead of the game compared to your competitors and that's why we'll choose you in future. I think that's the message we really want to get across' (#14b Construction manager).*

However, using secondary plastics as a marketing strategy works better for the packaging and visible end-products. Automotive brand owners may advertise the overall percentage of secondary plastics that are used in their vehicles, but face weaker incentives for the invisible parts of components and intermediate products. An interviewee explained:

> *'Anywhere where plastic is used in intermediate products, meaning it is not important for the usage for the user. It is not visible. For instance, in the trunk of your car, there is a board that's made of recycled plastics. Now, nobody pays attention to that. But it's big business. But the only driver there is cost. So, ethical driver, you cannot use them. Nobody's gonna say, "oh, the trunk of my car is made out of recycled products, it is eco-friendly." That doesn't work. If you hold a plastic [name of a brand] bottle in your hand with the green logo on it. That works. So the ethical driver (for invisible parts of intermediate products) is minimal' (#22 Trader / Mechanical recycler).*

Depending on the plastic polymer types and their application areas, price fluctuation and unstable availability may be different. A brand owner shared how they soured on using secondary plastics:

> *‘I think it depends on the products, some of them are easy to find, and in some cases, it's more difficult, it really depends on the type of product that we want to source’ (#13 Retailer / Brand owner).*

In addition to the high cost of recycling and the unstable price of secondary plastics, using them may require additional costs associated with information, certifications, and standards, especially for food contact packaging, automotive and EEE applications.

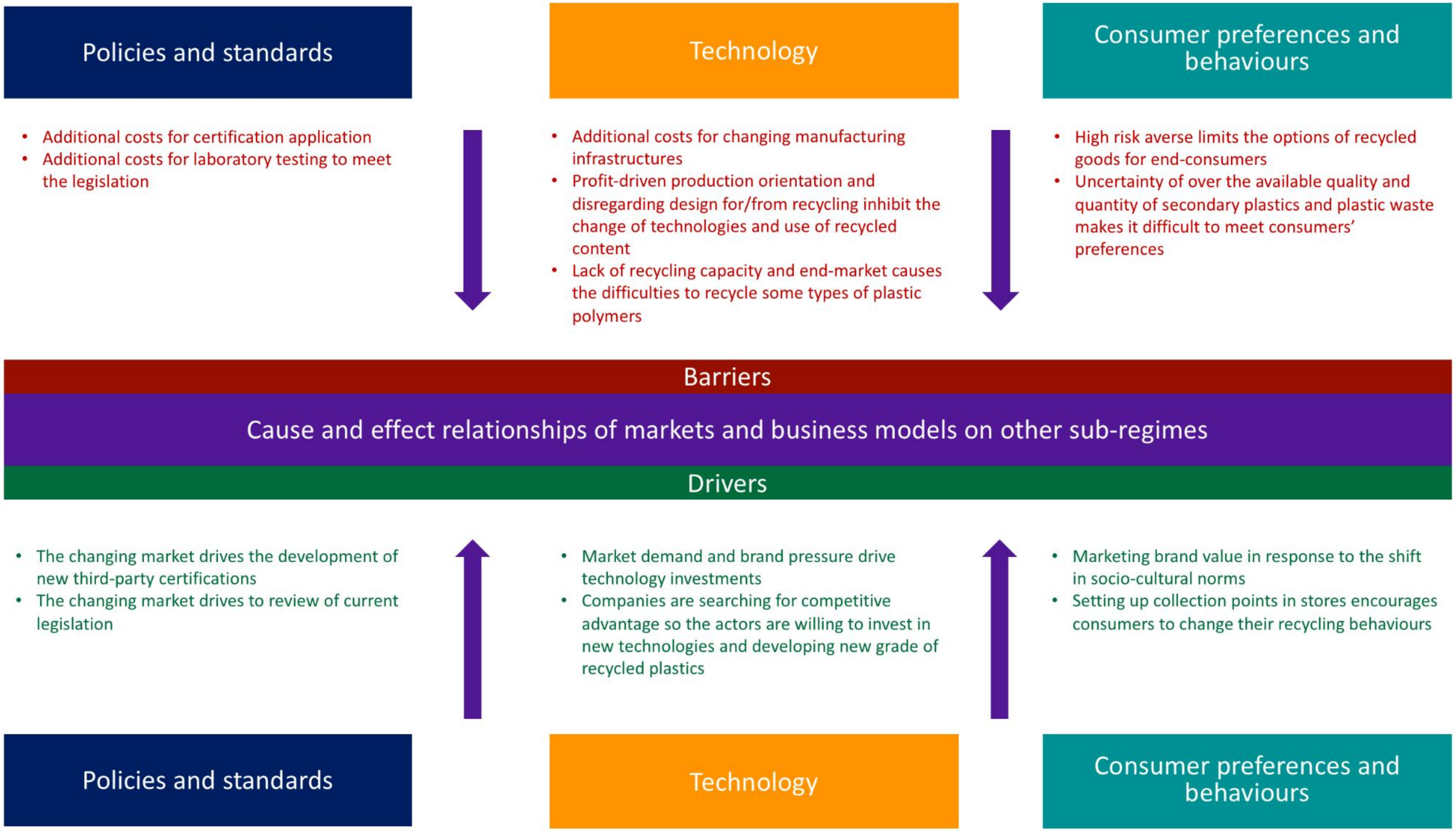


Figure 5-3 Cause and effect relationships of markets and business models on other sub-regimes

Summary of sub-regime of markets and business models

Key dynamics in this sub-regime are the difficult economics of shifting to a circular system, the increasing consumer and brand pressure, and the evolution of business models and strategies to overcome the market barriers. Figure 5-3 shows how the markets and business models have the ability to affect other sub-regimes, using the same method as applied in Figure 5-2.

The changing market drives the development of new third-party certifications, such as the RecyClass recyclability and recycled plastics certifications. In order to shift to a circular market, some relevant legislation has been under review at both the EU level and country levels, such as EPR schemes and the Waste Framework Directive.

Customer demand along the value chain is driven by brand owners and retailers for sustainable marketing, public relations, reputation purpose, and market competition. Market demand and brand pressure drive technology investments. Although sustainable marketing could be a driver, additional costs for changing manufacturing infrastructures, laboratory testing and certification application remain a barrier. The price of secondary plastics can be either a driver or a barrier depending on the demand, recycling cost, and oil price. Some plastic polymers lack recycling capacity and end-markets, while unstable long-term availability of plastic waste and secondary plastics hinder the transition.

Using secondary plastics for marketing brand value becomes a business strategy to respond to the shift in consumer preferences and behaviours. However, high risk aversion limits the options of recycled goods for both the B2B customers and end-consumers. Setting up collection points in retail stores can communicate, educate and encourage consumers to change their recycling behaviours.

5.4.3 Technology

Technologies are fundamental elements for recycling plastic waste and for being able to use secondary plastics. This subsection focuses on analysing the barriers and drivers of the technologies (e.g., digital technologies, sorting, mechanical recycling, chemical recycling and solvent-based recycling) for the transition to increase the use of secondary plastics, as well as their interactions with other sub-regimes.

Key barriers related to technology

- **Technical specifications of different products**

Barriers related to the technical specifications of different products exist across application areas, but in different ways and links to different restrictions from legislation. Packaging and some EEE faces the quality barrier regarding the safety of food contact and human contact.

EEE also needs high-quality secondary plastics that can meet varied and stringent technical specifications. An interviewee gave an example of their products:

> *'If we look at vacuum cleaners, the most challenging requirement is that it needs to withstand a drop test at zero degrees. […] people store them on their balconies every now and then, they get quite cold and they still need to respond to these drops, so it is very challenging for any plastics to drop at zero degrees. […] If we look at coffee makers […] the heat resistance is more important' (#10 Manufacturer / Brand owner).*

Automotive would certainly require higher quality plastics to ensure a long product lifespan. Hence, the higher quality requirement for automotive limits the use of secondary plastics. A car manufacturer explained:

> *'The components that go in the vehicle will use very little recycled material because the technological demands on the product are very, very high. So they have to last for 15 years, they have to stay the same colour, they have to be scratch resistant' (#6 Manufacturer).*

Plastic-containing products in construction also need the high quality of secondary plastics to meet the physical properties and structural reinforcement. An interviewee gave some examples:

> '*In the building construction sector, the issue there is you've got high-performance materials that you don't want to detract from their physical properties […] If you were looking at a scaffolding board, you probably need to be really careful about that; a high-pressure pipe, you're going to be really careful about putting recycled content in there*' *(#1 Petrochemical producer / Specialist).*

Another interviewee mentioned their business faced technical barriers on secondary plastics quality testing of pipe:

> *'Our products go to laboratories to get full specifications. We were in discussion with a big pipe maker in Germany, and we had about 20 different aspects tested.*

And finally, we failed on one, so we couldn't do the business' (#22 Trader / Recycler).

Moreover, plastic polymers have specific physical properties and can be fit into a specific moulding process. Secondary plastics have more technical limitations than virgin plastics, because their quality tends not to be stable. Therefore, sourcing the secondary plastics that can meet the specific quantity and quality for the moulding process applications is a barrier for manufacturers. A manufacturer explained:

'You (need to) have a homogeneous kind of material, and when this is not the case, you have obvious problems in the production process. And that is not acceptable. And that's the reason why a lot of companies are not doing it because they don't have the quality in the cleaning process, or in the recycling process, (and they) are not willing to stop or to disrupt their own production process' (#7 Manufacturer).

The consistency of the quality is highlighted by an interviewee:

'The consistency is really key because very often the tooling to run a recycled material is slightly different. And if you're relying on mechanical recycled material and something that supplies are no longer available, or the properties is changed, that's the last thing they want. And that's what the brand owner is looking for - safety, quality and consistency' (#1 Petrochemical producer / Specialist).

Different batches of secondary plastics do not always have the same properties, thereby requiring a lot of trial and error to meet the consistency, especially when mixing virgin plastics and secondary plastics (Getor et al., 2020).

- **Many technologies are not mature yet**

Both the upstream and downstream of the plastic value faces technical challenges. Many technologies are not mature yet, especially in the downstream, including separation, cleaning and removing contamination and core recycling technologies. These technologies are also costly.

Although adopting digital technologies are recommended as a solution for a plastic circular economy, there are still many barriers to integrate those infant technologies (e.g., blockchain) into the plastic value chain for widely commercial applications (Bhubalan et al., 2022, Steenmans et al., 2021). Bhubalan et al. (2022) pointed out the challenges of applying blockchain to plastic waste management, including many legal issues, since transactions may occur in different places with conflicting jurisdictions. These issues include lack of central governance, money laundering, dependence on third parties, in addition to being a target for fraud and a security risk.

Most of the studies identified specific technical factors (e.g., mainly focusing on blockchain or on mechanical recycling) along the lifecycle stages. However, no previous studies have reported on interactions between different technologies causing barriers and drivers across different sectors and interacting with other sub-regimes. Therefore, this study not only uses the literature as a triangulation, but also provides empirical examples across four applications to add new insights.

Difficulties in collecting widely diverse plastic polymers from complex waste streams were highlighted by an interviewee:

> *'You have to look at how do you get these really largely distributed plastics into the collection and how do we get them back to a recycling facility. For example, […] if you look at a car, you will have a different plastic for the dashboard, and for the passenger seat, and for the tubing for the fuels, and each of these components is different, each of the plastic is designed to fulfil its role exactly in this place. But then how do you bring these all together? And how do you handle such diverse plastics waste streams' (#4 Petrochemical manufacturer / Chemical recycler).*

Traditional plastic waste separation technologies include gravity separation (air classifier, ballistic separator, sink-float separation, jigging, hydrocycloning), electrostatic separation, magnetic density separation, flotation, sensor-based sorting (visible spectroscopy, near-infrared spectroscopy NIR, hyperspectral imaging, X-ray fluorescence, laser-induced breakdown spectroscopy), as well as auxiliary separation technologies (Serranti and Bonifazi, 2019). An interviewee pointed out the immature sorting technologies: *'It's still very difficult to sort all different kinds of plastics, and the better the sorting of the plastics, the better quality of the secondary material will be' (#5 Petrochemical manufacturer / recycler).* Serranti and Bonifazi (2019) highlighted the key challenges: PP-PE separation, LDPE-HDPE separation, black or dark colour polymers, the mixture of biopolymers and conventional plastics, and ocean plastics. The technologies for identifying and sorting plastics, including NIR, chemical tagging, fluorescent tracers, digital watermarking, quick response (QR) and radio frequency identification (RFID) tagging, also have their limitations (Bhubalan et al., 2022). For instance, NIR is not capable of identifying multilayer packaging, and plastic polymers with similar molecular structures (Woidasky et al., 2020). RFID tags, which are made of different types of materials, may cause operational problems (e.g., obstruction of the screens) during the recycling process and losses during the extrusion process (Aliaga et al., 2011). These sorting and recycling processes always have losses which have been estimated in the MFA in Chapter 4.

Hahladakis and Iacovidou (2019) overviewed the technical barriers to the mechanical recycling of plastic waste. Several technical barriers specifically for the mechanical recycling route have been identified: incompatibility between different types of polymers, sorting ability, contamination, degradation at reprocessing, degradation at service life, compatibilization, substitute ability, marketability, feasibility (Hahladakis and Iacovidou, 2019). Many of these barriers were mentioned and confirmed by the interviewees (#1, #3, #4, #5, #6, #7, #10, #11, #16, #17, #18, #19, #21, #22, #23, #24, #25).

An example from plastic packaging shows the limitation on the number of times the plastic can be mechanically recycled. A mechanical recycler said:

> *‘They have done some analysis on this [limitations of the recyclable packaging]. That has to do with multiple factors. In principle, you could, depending on what types of polymer, somewhere between 5 and 10 times can be possible, but that’s a theoretical assessment. We know that at the moment still at least 50% of virgin material is added every cycle’ (#16 Mechanical recycler and consultant).*

Another example from automotive shows that it is too difficult to replicate primary production from a blend of secondary plastics through mechanical recycling:

> *‘If I just get ABS from all these cars, I just end up with this weird sort of average of all these grades. […] you can't duplicate what the clever polymer chemists do’ (#18 Mechanical recycler and consultant).*

The above quotation indicates that the quality of secondary plastics from mechanical recycling struggles to compete with, the quality of virgin plastics, which inhibits the transition to the use of recycled plastics.

It is worth noting that the cross-contamination of bioplastics can also be a barrier in mechanical recycling. A mechanical recycler pointed out:

> *‘We actually shoot up a PET bottle and when there's a piece of PLA film in front of it, they go along. We can’t make 100% accurate. So, sometimes we pollute the PET stream with PLA, which actually causes yellowing effects and some*

agglomeration issues during the melting process of the PET, so we are actually downgrading the PET by small pieces of PLA. So, that's the risk of PLA being in there' (#16 Mechanical recycler and consultant).

New biomaterials have been emerging in the transition of a plastic circular economy. However, it is important to make sure that these new materials do not create other problems, such as cross-contamination in conventional mechanical recycling, creating more single-use or non-recyclable materials, as well as higher environmental impacts.

The other current barrier to be considered is the technology readiness level. For chemical recycling, currently, many of the cases are still at laboratory- or pilot-scale (Uekert et al., 2023). Solis and Silveira (2020) assessed the Technology Readiness Level (TRL) for the chemical recycling of household plastics. At present, three (pyrolysis, catalytic cracking and conventional gasification) out of nine chemical recycling technologies have higher TRL. The other technologies are still not ready to be commercialised yet. A chemical recycler also mentioned this barrier of lacking technology readiness:

'You have to increase the technology readiness level and really get it to scale. I think that's a very practical and technical obstacle' (#4 Petrochemical producer / Chemical recycler).

To tackle this barrier, more financial investment from the markets, new networks and business models, and support from the regulations are required. Producing secondary feedstock can be a potential complementary strategy to achieve the EU targets of increasing plastic recycling rate and using secondary plastics. Interviewees expected that more cases will achieve the commercial scale in the coming five to ten years (#1, #3, #21).

Key drivers related to technology

- **Better tracing technologies**

Some European businesses have started to apply digital technologies to support the plastic value chain, in order to tackle barriers to plastic waste recycling and secondary plastics use (Chidepatil et al., 2020, Tramutola, 2019). Smart bin collection and segregation with digital technologies, such as blockchain, Internet of Things, artificial intelligence, and big data, enables segregating commingled plastics and monitoring flows (e.g., Chidepatil et al. (2020) Tramutola (2019)). An example can be found in manufacturers and brand owners using digital track-and-trace technology to record and share the product composition information with consumers, collectors and recyclers, as described by a manufacturer:

> *'We think the ability to track and trace all materials […] if you're making composite products, you can embed in the data set […] the material grade, what its properties are, so on and so forth […] So, understanding that key dataset to see what can be combined together and used is an absolute key driver' (#8 Manufacturer).*

A waste management company explained an effective practice in their waste treatment facilities:

> *'We have lots of big data on recycling. So we know on an individual packaging based on the barcode, how it actually ends up at our sorting centre. So we know how it is sorted. And with that, we also know which type of recycler it will go' (#16 Mechanical recycler and consultant).*

These examples demonstrating better tracing technologies drive the use of secondary plastics. In addition, these examples add insights into how the digital technologies enable data and information sharing across the value chain, which is further discussed in the Section 5.5 describing the role of data-information-knowledge. Better digital technologies can not only improve the sorting processes, but also allows consumers to engage in active plastic waste collection (#8) (Gibovic and Bikfalvi, 2021).

- **Emergence of solvent-based and chemical recycling possibilities**

Solvent-based recycling can be a driver to increase the use of secondary plastics, by helping to separate hazardous chemicals from plastic-containing products. Chemical recycling can produce secondary feedstock with quality is as good as virgin feedstock. Plastic waste which cannot be treated by mechanical recycling, such as film packaging, food packaging, and engineering plastics with legacy additives, can be treated through these solvent-based recycling and chemical recycling processes.

An example of chemical recycling for food contact packaging is given by an interviewee:

> *'If you've got non-food contact, plastic is not going to food contact materials, you can't put it back into food packaging […] So, feedstock recycling will enable us to take those plastics, put them through a refinery, and you'll get the virgin quality. That means it can go into food contact or non-food contact applications' (#1 Petrochemical producer / Specialist).*

Another example of engineering plastics with legacy additives is mentioned by the interviewee:

> *'If you've got a plastic with a legacy additive, that you're no longer allowed to recycle and put back on the market. When you put it through a thermally destructive process, you destroy that. And now that feedstock can go into a cracker and you end up with virgin like qualities' (#1 Petrochemical producer / Specialist).*

Some interviewees (#1, #16, #21) and peer-reviewed papers (e.g., Coates and Getzler (2020) and Dogu et al. (2021)) argued that chemical recycling to feedstock and monomer as transformational technologies could contribute to creating a circular plastic system. Kubiczek et al. (2023) also argued that chemical recycling/feedstock recovery of plastic-to-fuel can contribute to the fulfilment of the circular economy model in the EU. However, media and NGOs (see Tabrizi et al. (2020), Rollinson and Oladejo (2020) and Brock et al. (2021)) still have concerns about plastic chemical recycling/feedstock recovery to either fuel or chemicals. The energy-intensive, carbon-intensive, low-yield, fate of waste streams remain unclear, as well as what toxic pollutants are produced that may have adverse environmental impacts. Meys et al. (2020) proposed a life cycle assessment (LCA)-based model to assess trade-offs of environmental impacts across different plastic waste treatment options (refinery feedstock, plastic-to-fuel, plastic-to-monomer, plastic-to-value-added chemicals, mechanical recycling, and energy recovery), highlighting that some chemical recycling routes in some cases may not result in environmental benefits. Uekert et al. (2023) also found that some forms of chemical recycling have higher environmental impacts than mechanical recycling in terms of greenhouse gas emissions and water use, and in some other cases, chemical recycling has even higher environmental impacts than virgin plastic production. According to a study from the European Commission's Joint Research Centre, all forms of plastic waste recycling (mechanical recycling, solvent-based recycling, chemical recycling) result in lower carbon emissions than energy recovery (Garcia-Gutierrez et al., 2023), which implies that these non-mechanical recycling technologies may still be a complementary plastic waste treatment to the mechanical recycling, from a climate change perspective.

Technology barriers and drivers play out across the value chain

Upstream actors face key barriers of quality and quantity of secondary materials, as well as changing manufacturing processes and infrastructures in some cases. However, these upstream actors are willing to invest in new technologies due to the drivers from landscape and other sub-regimes (e.g., policies and customer demand). The downstream actors face key barriers in collection, sorting and mechanical recycling. However, the development of better tracing technologies, advanced sorting technologies, and non-mechanical recycling technologies is becoming a driver to increase the use of secondary plastics.

The life cycle of plastic polymers in a circular economy would heavily rely on technical knowledge and innovation as different plastic polymers have very different material properties and these plastic polymers are widely used in diverse applications. Actors across the value chain have different innovation priorities, making alignment difficult. Also, there is a lot of uncertainty about what other stages of the value chain are doing.

Technology across different application areas

Even though the technical specifications for plastic-containing products across different applications are very different, there are still low-value niches in which secondary materials can currently compete, for example, construction materials that are not visible to consumers (#8). This suggests the possibility that secondary plastics could follow a “disruptive innovation” trajectory, which could be similar to the case of minimills in the steel industry (Christensen, 2013), which entered markets producing low-value rebar used in construction, and gradually moved into higher-grade and higher-value product categories as the technology improved.

Moreover, different application areas have different technical challenges. The selected quotations give some examples. First of all, there are the immature technologies in sorting packaging waste. An example is caps and pumps:

> *‘Lots of things like caps fall through the sorting process, and therefore, don't get back into a pure stream of that material type. So, it can be difficult to get some of those materials back in the same way that you can get large bottles, for instance’ (#11 Manufacturer / Brand owner).*

These caps and pumps are lost without being selected for recycling.

Secondly, plastic waste in construction may contain dirt and mixed demolished waste. An interviewee explained the difficulties:

> *‘It's a very difficult process because especially in the windows sector, it is not just waste from a fabricator, it's a waste from the building site. And when you demolish a window, (from) an existing building, on a building site, you can imagine that’s*

dirt inside, so it has to be very, very important that recycled material that you're taking back or that you are recycling is so clean that you can put it again in an extruder. And for this, you need a very, very good cleaning process. Otherwise, you will have a lot of problems in the production process' (#7 Manufacturer).

Thirdly, an ELV recycler described the barrier to sorting different graded plastic polymers:

'I think there's an issue certainly in the longer life more complicated products like cars and waste electrical equipment, that you end up with these polymers which are essentially a blend of a lot of other grades. So within the plant that I had in [a location], I picked up a handful of polypropylene chips. They might have come from 1000 different cars and be 200 different grades of plastics. So I have no way of knowing the physical properties of every single chip. I have no way really of knowing what additives have been put into each of those compounds when they were originally used 10 or 15 years ago to make the original car. So when I made my polymer, it's a kind of average generic blend of all the grades' (#18 Mechanical recycler and consultant).

This sorting barrier is caused by contamination from additives and mixing of different grades. This further causes a barrier to the quality of secondary plastics at the manufacturing stage. This highlights the importance of the role of data-information-knowledge which is further discussed in Section 5.5.

Fourthly, the complexity of product design causes difficulties with separation. A WEEE example is mentioned by an interviewee:

'*What difficult is that there are more and more interconnections that are not reversible. So there is most parts are glued or there are sticking together because of the high density integration of small household devices, smartphones, for example. So they are very hard to separate, in the end, you don't have a clear recycling waste stream coming out […] If you have 20 different polymer types in one product, it gets harder and harder to separate out of the shredding, if you have 20 different polymer types, you need 20 different sorting steps, separation steps' (#24 Specialist).*

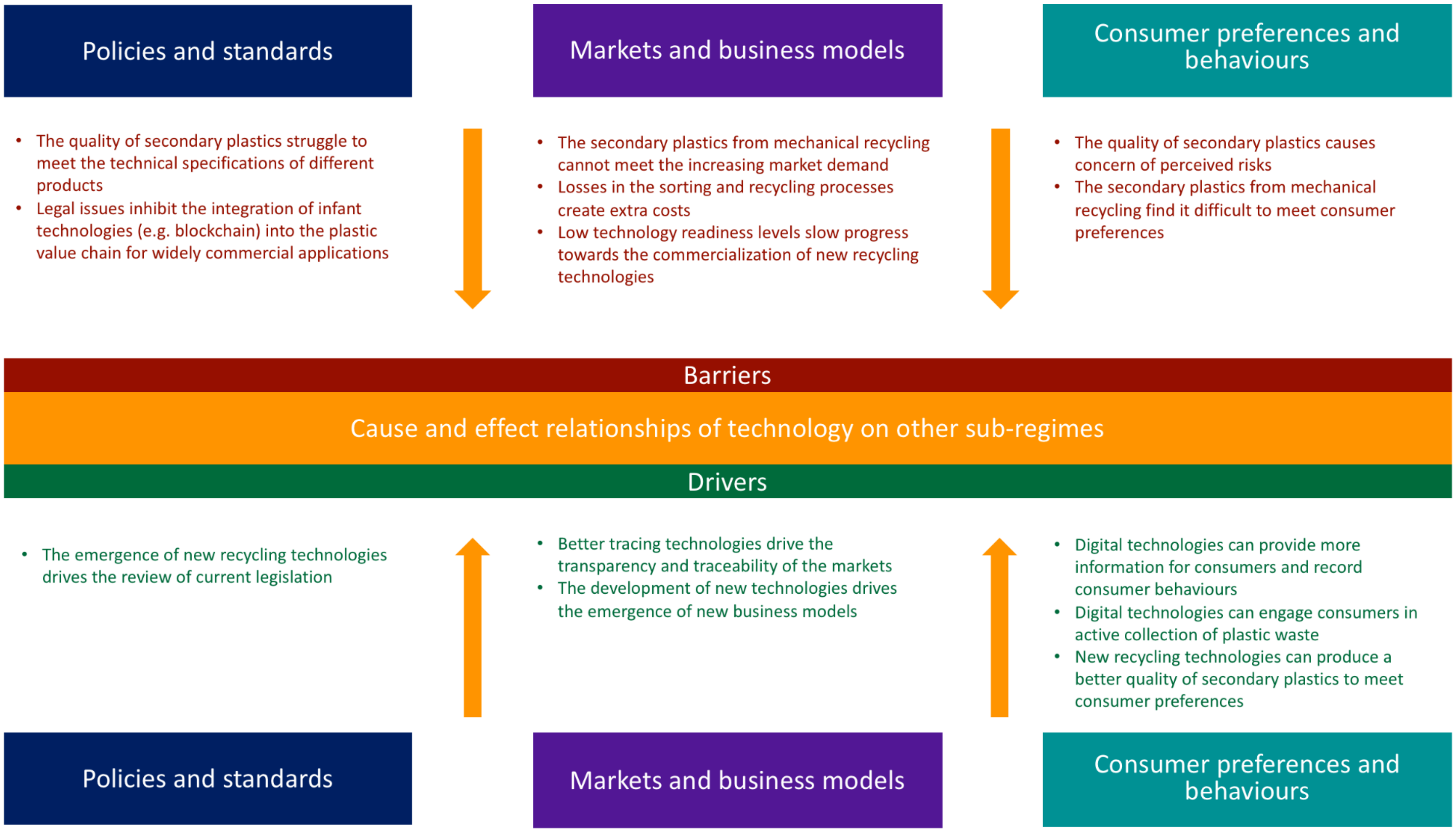


Figure 5-4 Cause and effect relationships of technology on other sub-regimes

Summary of sub-regime of technology

Key dynamics in this sub-regime are the emerging technologies, which are still not mature, and need to be integrated into full systems and into business models. At the same time, there are unhelpful technology trends, such as increased product complexity, and the embedding of electronics in products. Figure 5-4 shows how the technology has the ability to affect other sub-regimes, using the same method as applied in Figure 5-2.

The main technical barriers across the value chain are the quality and quantity of plastic waste and secondary plastics, changing manufacturing processes and infrastructures, and the collection, sorting, and mechanical recycling. The diverse plastic polymer types mixed within plastic-containing products across different waste streams cause technical barriers to plastic waste collection and sorting, especially the longer lifespan products from construction, automotive and WEEE. It is difficult to create a closed loop for engineering and high-performance plastics due to the lack of recycling technology and/or the economies of scale. Also, the recently innovated bioplastics for packaging may risk contaminating the conventional mechanical sorting and recycling systems. These barriers rely on the improvement of regulations and traceability to enable better collection and separation on plastic waste.

Due to the pressure from landscape and drivers from other sub-regimes, the actors along the value chain have been investing in new technologies. These new technologies, including digital technologies, advanced sorting technologies, solvent-based recycling and chemical recycling, can become the drivers to increase the use of secondary plastics and be solutions to tackle some technical barriers from collection, sorting, and mechanical recycling. However, scaling up these non-mechanical recycling technologies and widely applied digital technologies into the plastic system remains a challenge. The technical barriers to collection and sorting, the development of new recycling technologies, and the integration of digital technologies into sustainable plastic management, need support from the markets and regulators.

5.4.4 Consumer preferences and behaviours

This subsection analyses the social practices of consumer preferences and behaviours. In this section, the consumer sub-regime mainly focuses on the end-users, while the B2B consumers are discussed in the sub-regime of markets and business models. Key barriers are consumer habits and routines and perceived risks, while drivers are the shifting social norms around the acceptability of linear practices.

Key barriers related to consumer preferences and behaviours

- **Consumer habits and routines**

Consumer habits and routines developed in the linear economy system are key barriers (#1, #7, #8, #11, #12, #13, #18, #19, #24, #25). The findings from the interviews confirm the importance of consumer behaviours observed by others (e.g., Parajuly et al. (2020)). Consumers are involved in the plastic value chain at the stages of purchase, use, waste sorting and recycling. Consumers' purchasing behaviours related to plastic-containing products are influenced by product perceived value, beliefs, sustainable behaviours, knowledge of the circular economy, social norms, and demographic factors (Núñez-Cacho et al., 2020, Testa et al., 2022). Waste sorting and recycling behaviours are shaped by moral norms, identity and values, social pressure, environmental beliefs, knowledge and experience of recycling, convenience of access to recycling facilities, and the interactions between any of these factors (Saphores et al., 2012, Botetzagias et al., 2015, Thomas and Sharp, 2013). The literature has summarised the general factors that influence consumers' purchasing behaviours and waste sorting and recycling behaviours. Interviewees further reported how consumer habits and routines affect specifically the use of secondary plastics across the value chain and different applications.

Although end-consumer awareness and acceptance of secondary plastics have been increasing, there is still a discrepancy between awareness and buying decisions. Even when there is a label showing the product is made from recycled plastic content, the end-consumers' buying decisions are normally influenced by other factors such as quality, price, and appearance (#12, #13). Furthermore, a survey representative of the Italian and Spanish population conducted by Testa et al. (2022) showed that consumers with higher plastic concerns negatively mediate the positive effect of purchasing secondary plastic products. Namely, consumers with higher plastic concerns would prefer plastic-free options and so are less interested in buying secondary plastic products. It is noteworthy that plastic-related behaviours and products are diverse, so it is difficult to generalise consumer behaviours for all plastic-containing products.

There are differences between consumer awareness and buying decisions, and between consumer awareness and recycling behaviours, as confirmed by the Eurobarometer survey (Dagiliūtė et al., 2023). Nearly a decade ago, Thomas and Sharp (2013) pointed out that not everyone participates in recycling or sees recycling as a consumer responsibility, although recycling has become a social norm in many communities. A retailer highlighted:

> *'There's discrepancy, they (end-customers) criticise producers and retailers for producing too much plastics, but it doesn't mean that everyone who is criticising them, completely recycling everything at home, although they value the products in the supermarket, of course, the customers are responsible for the key of the problem, it plays one role of that' (#12 Retailer / Brand owner).*

This illustrates very slow shifts in consumer habits with regard to the separation and sorting of household plastic packaging waste.

It is worth mentioning that the Covid-19 pandemic, which is identified as a factor on the landscape level, has subdued the continuing formation of social norms regarding environmentally sustainable practices, and has affected the perceptions around recycled alternatives (Makki et al., 2021). From the behavioural science perspective, this could also lead to a 'fresh start' effect in creating new eco-conscious habits to promote a circular economy and ensure safe and hygienic practices at the same time (Makki et al., 2021).

Companies (especially manufacturers / brand owners) feel the pressure to change, but also feel frustrated that consumer activists see companies as responsible rather than consumers. The interviews from this study provide insights into the comprehensive consumer responsibilities for increasing the use of secondary plastics. An interviewee suggested:

> *'It should be ECR, extended consumer responsibility' (#16 Mechanical recycler and consultant).*

Another interviewee highlighted that consumers need to take responsibility for both purchasing decisions and recycling behaviours:

> *'Consumers have significant role on this in terms of purchase preference that is what they want to do or in terms of how they choose to manage the products and plastics that they get […] Consumers will have to do their bit […] I don't think most people will appreciate the costs of recycling or actually what is involved in recycling' (#11 Manufacturer / Brand owner).*

This barrier may be improved by education campaigns, better labelling for recycling instruction, developing user-friendly collection and sorting systems and providing economic incentives. For example, the energy labelling of electrical appliances using ratings between A and G grades ('A' being good, 'G' being poor) (Council Directive 92/75/EEC, Commission Directive 2003/66/EC, Directive 2010/30/EU, Commission Delegated Regulation (EU) No 1060/2010, Regulation (EU) 2017/1369, and Commission Delegated Regulation (EU) 2019/2016). Since these energy efficiency ratings were introduced, they made consumers more aware of energy use, and consumers have shifted towards more energy efficient appliances (Schleich et al., 2021). To maintain sales, the manufacturers then have had to improve the performance of their products. In this case, it was EU legislation that pushed progress. Governments and companies need to agree on regulations that prevent environmental harms from arising from consumer activities, rather than simply risk relying on consumers to change their practices.

- **Perceived risks**

Perceived risks, including reduced quality, reduced functionality, limited attractiveness, value for money, general risks, contamination risks, and perceived safety, are identified as barriers to consumer willingness to pay a price premium for products made of secondary plastics (Magnier et al., 2019, Polyportis et al., 2022, Meng and Leary, 2021, Essoussi and Linton, 2010). Consumers tend to have contamination fears and other negative perceptions especially about secondary plastics used in skin-contact and food-contact products. Meng and Leary (2021) further explored these consumer perceptions, from evolutionary perspectives on contagion, contamination, and the emotion of disgust.

A brand owner / retailer also confirmed and mentioned that end-consumers used to have more concerns about products made from recycled plastics in the past. The following quotation demonstrates that consumer habits are still hard to shift as concerns of perceived risks for particular products are deeply embedded:

> *'We used to have cases. It used to be that recycled bottle, maybe a bit yellow compared to virgin (plastic bottle). And we had cases of a transparent detergent bottle, which one is recycled, maybe, 80% was recycled, and the other one was perhaps 100% virgin, and they were standing next to each other. And it was visible from the sales figures that consumers were distracted and thought something changed. And then, there was one story about water bottle, our customers called (us) and complained that the water is moulded or something and didn't really understand it (is made by recycled plastics) (sic)' (#12 Retailer / Brand owner).*

Key drivers related to consumer preferences and behaviours

- **Shifting social norms around the acceptability of linear practices**

Beyond the existing literature discussing the long-standing barriers from the aspect of consumer habits and routines, the interviews in this study add new insights into the shifts of social meaning of linear plastic consumption and production. Plastic used to mean cheap, durable, plentiful, clean, modern and disposable (Bauer and Fontenit, 2021). Now, the social meaning has shifted, and it also has connotations of pollution and the destruction of nature. These shifts indicate a social disruption (Mah, 2021). Examples from the interviewees demonstrate how the shifting public consciousness and consumer perceptions of plastic destabilise other sub-regimes.

The *Blue Planet II* series produced by the BBC and narrated by David Attenborough shows the devastating threat of plastic waste to the ocean and wildlife (BBC, 2017). Many interviewees mentioned that *Blue Planet II* successfully increased public consciousness of plastic pollution and consumer acceptance of secondary plastics (#1, #5, #7, #11, #14a, #18, #19, #21). Thus, the increasing public consciousness of plastic pollution is one of the key drivers for interviewees and/or their clients to invest in using more secondary plastics. It is interesting that many interviewees took *Blue Planet II* as an example. However, increasing public consciousness of plastic pollution is not only accomplished by one documentary, but it does show that media can contribute to these shifting social norms.

This end-consumers' change in social norms drives the change of business customers along the value chain. An interviewee described:

> *'That movie was so great. David Attenborough, Blue Planet, if you're having a plastic cup with a plastic straw in it, then you see a picture of a turtle with a straw in its nose, it's very direct. So it's very impactful. So, I do think that it's been a massive people and value driven thing. And I think that is probably the driver is people want to work for companies that seem to be doing the right thing. And clients want to make sure that they are choosing supply chain partners that are tackling this issue, and they don't want to be seen as like being part of the problem' (#14a Construction manager).*

Another interviewee further explained how different actors are shifting their actions:

‘The main drivers for this are the demand from customers for a more sustainable and circular economy approach to plastics production and what we've seen in the last maybe two years since the things like Blue Planet II, the raising of profile of the problem of plastic waste in our oceans and in the environment’ (#21 Chemical recycler).

Changing consumer perceptions can drive the changes in business models. An interviewee described this:

‘I think consumers are sometimes more powerful than governments here. So if you're really clever, you convince your loyal customers that not only have you got the best fizzy brown liquid in the world, but actually somehow you're delivering it in a way that is good for the planet […] you start layering on sustainability as part of your overall brand value' (#18 Mechanical recycler and consultant).

The broadcast of the *Blue Planet II* in late 2017 created a broad trending discussion on social media and increased online searches related to plastic waste and plastic pollution (Males and Van Aelst, 2021). Following this sensation, many celebrities and NGOs also continue to advocate for global citizens and politicians to urge action on plastic pollution. In 2018, National Geographic Magazine also published the series, ‘PLANET or PLASTIC?’, to report the facts on plastic pollution worldwide (National Geographic, 2018). Therefore, the widespread influences from the media destabilise and reconfigure the regime to close the plastic loop.

Consumer preferences and behaviours barriers and drivers play out across the value chain

Shifting social norms from the consumers affect the value chain from petrochemical production and product design to recycling systems. As explored under the ‘markets and business models’ sub-regime, this pressure is most acutely felt by brand owners. An interviewee said,

‘I think there’s a big movement within the whole material resource kind of business where people are now kind of starting to realise that we can’t keep on using virgin materials, and sort of making a shift to use more of the materials we’ve already brought to market and aren’t used anymore’ (#13 Retailer / Brand owner).

The brand owner further explained:

'I think the most important drivers for us are kind of making our assortment better for our customers. So we're always looking kind of incremental improvements in product design, to make our designs better, so that the products last longer, but at the same time, also make them from better materials […] And part of that is making sure that it's recycled, make sure that we know that it's recycled' (#13 Retailer / Brand owner).

Increasing concerns about plastic pollution, climate change, circular economy and sustainability from the landscape level and the consumer pressure drive the actors along the value chain to put effort into corporate sustainability, a top-down systems science of environmental, social and governance (ESG) (Sheehy and Farneti, 2021, Bansal and Song, 2017). The socio-culture of measuring the business key performance indicator (KPI) has been shifting in the past few years. Rather than mainly focusing on profits, many firms also start to measure KPI for sustainability. As firms need to publish the annual sustainability reports, using secondary plastics has become one of the circular economy strategies for firms to present their progress on sustainability. People within companies also wish to respond to the changing social norms/values rather than doing corporate sustainability and corporate social responsibility as solely profit-driven responses to consumer pressure, although there are constraints of what is financially viable.

Consumer preferences and behaviours across different application areas

Consumers' awareness and acceptance are focusing on plastic packaging at the moment. An interviewee said:

'In the packaging industry, the end consumers already open to say, "okay, it doesn't matter if this bottle is transparent or not if it's grey or black or whatever, the most important thing is that it's from recycled plastics." So, the next step will be when will it start at the end consumer saying, "for me, it is acceptable that the edge bend (of furniture) is grey because it's from recycled material." I mean, it's a development process that we will see (sic)' (#7 Manufacturer).

This shows that the shifting consumer criteria, but rather limited to specific applications. The end-consumers' acceptance of secondary plastics to be used in different plastic-containing products may shift at different paces.

The consumers' waste sorting habits seem to have a higher impact on plastic packaging, as a high proportion of plastic packaging waste comes from the household waste stream and relies on end-consumers' recycling behaviour to clean, separate the waste and put it into the right recycling bin. It is worth mentioning that WEEE would have another barrier regarding end consumers hoarding the WEEE at home for a long period of time.

With regard to the construction sector, an example from a PVC windows recycler mentioned that the negative social perceptions of the PVC as a pressure pushed PVC windows manufacturers to collaborate with both competitors and recyclers to create a closed-loop recycling system. An interviewee observed:

> *'I think it is pressure. The reason we exist as a company is pressure from the NGOs that wanted to kill off the PVC, […] because it was bad and polluting and manmade and evil, and we should all have wooden windows or metal or aluminium because they're easily recycled. And it was [name of a company] going (to say), "hang on a minute, you can recycle PVC." We built a factory to prove it. It sort of went from there' (#19 PVC windows recycler).*

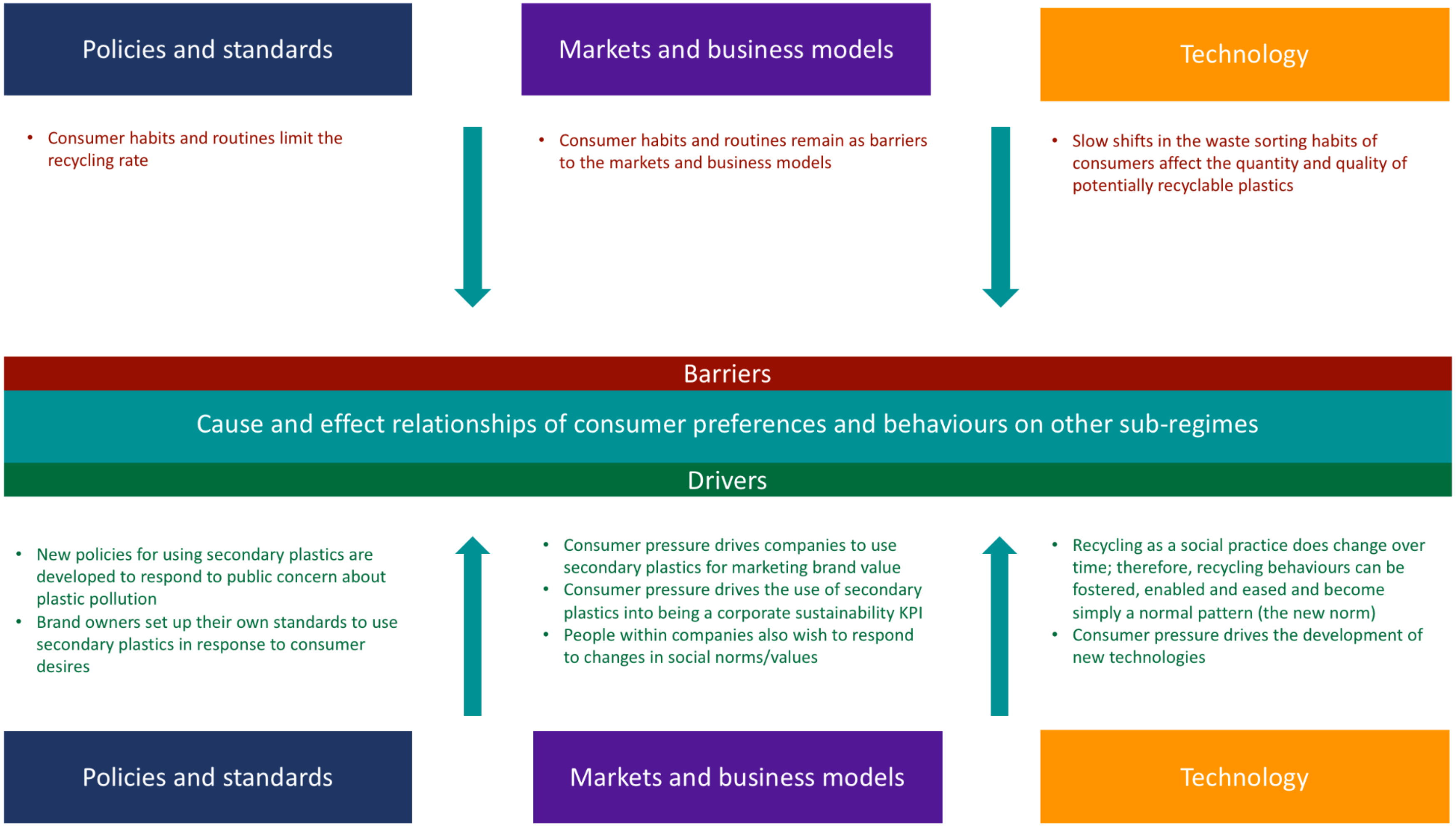


Figure 5-5 Cause and effect relationships of consumer preferences and behaviours on other sub-regimes

Summary of sub-regime of consumer preferences and behaviours

The key dynamics of this sub-regime are that participants observe an ongoing shift in the public consciousness of plastics, but also highlight many ways in which established routines and norms constrain change. Figure 5-5 shows how the consumer preferences and behaviours have the ability to affect other sub-regimes, using the same method as applied in Figure 5-2. The generalised shift in consumer belief about plastics seen as 'bad' has also influenced policies. According to interviewee #16, the Single-Use Plastics Directive is primarily driven by the consumer perception on ocean plastics.

Efforts to close loops could be seen as part of a 'defence' marketing strategy against the generalised consumer 'backlash' against plastics. Interviewees also expressed the notion that value chain stakeholders are modifying their behaviour in response to shifting social norms, such that they, too, want to adopt practices that are socially and morally acceptable, so long as these are business-viable.

Slow shifts in consumer waste sorting and recycling habits affect the quantity and quality of plastic waste. Recycling as a social practice has changed over time due to socio-demographic factors, psychological factors and contextual factors (Varotto and Spagnolli, 2017). The current barriers can be overcome by interventions, such as deposit return schemes or reverse vending machines, which may be seen as convenient waste collection systems with monetary incentives. Clearer labelling of recycling instructions, and information on how to promote plastic recycling behaviour, as well as developing social modelling to create social plastic recycling norms, would likely have additional beneficial effects. Recycling behaviours can be fostered, enabled and eased and become simply a normal pattern (Miliute-Plepiene et al., 2016, Varotto and Spagnolli, 2017, Ofstad et al., 2017).

5.5 The role of data, information and knowledge

While analysing the barriers and drivers of each sub-regime in section 5.4, I observed that data-information-knowledge plays a vital role in the plastic system. The interviewees report limitations of information exchange and knowledge diffusion across actors in the linear system, suggesting that data-information-knowledge dimensions at the socio-technical regime level are critical for the transition towards a circular plastic system. Similarly, several studies have identified the lack of 'traceability' as a barrier to plastic circularity (Milios et al., 2018, European Commission, 2018a, Paletta et al., 2019), but provide little understanding of how this barrier manifests in practice. This section is an expanded and restructured discussion of the role of data, information, and knowledge, which was summarised and published in Hsu et al. (2022). Here, the theme is explored in more detail, thus addressing an important gap in the literature.

Tseng et al. (2021) pointed out the research gap in understanding the barriers and drivers for different firms/actors to integrate a circular economy and data-information-knowledge within a changing socio-technical system in an Industry 4.0 era. This subsection aims to address this gap by investigating barriers related to data-information-knowledge in the transition to a circular plastic system. Jäger-Roschko and Petersen (2022) recommended focusing future research on: circular economy information exchange, access to information, incentives for circular economy information sharing, and differentiation between products. Therefore, this subsection focuses on the role of data-information-knowledge in using secondary plastics in four application areas. The main research question addressed in this subsection is: How do data, information, and knowledge-related issues create barriers to the development of markets for secondary plastics in the EU?

Drawing on the data-information-knowledge-wisdom (DIKW) hierarchy (Ackoff, 1989, Rowley, 2007), I highlight the distinction between data, information and knowledge. Data are elementary parameters derived from observation without context and interpretation. Information is processed data through sorting, classification, aggregation, and interpretation for a specific purpose. Knowledge represents the transformation of data and information with the combination of experience, capability, skills, training, and perception into actionable instructions for decision-making support. Wisdom, as the highest level of the DIKW hierarchy, is more intangible and harder to measure than the other components, and is excluded from this analysis.

Data, information, and knowledge play fundamental roles in the socio-technical system change. Most obviously, innovation is strongly conditioned by learning processes, in which actors develop new knowledge about both technological possibilities and market opportunities, while users need to learn about new innovations if they are to be adopted. Knowledge development and diffusion are thus key elements in the emergence of new technological systems (Hekkert et al., 2007). Knowledge gaps about demands and technological possibilities, and a failure of knowledge diffusion among actors within the system, clearly inhibit change.

The MLP highlights the fact that institutional structures contribute to the stability of existing systems, and this includes institutionalised measurement and data collection processes (such as data collected on material flows), or institutionalised forms of knowledge (such as standards and guidelines). Information and knowledge are subject to many of the forms of lock-in and path dependence that inhibit change in socio-technical systems.

In a linear system, upstream stages of primary extraction and manufacturing are not necessarily connected to the disposal and waste processing. This creates discrepancies between what is expected and prioritised at different stages. In a circular system, actors across the value chain are required to have a greater understanding of the technologies, material properties, and quantity and direction of flows, so that specifications that work at a system level can be defined to ensure product quality and reliability in a circular system.

5.5.1 Barriers at each lifecycle stage

The results summarised below show how data-information-knowledge aspects constrain actions across different lifecycle stages (Figure 5-6), in order to identify the specific barriers for each actor.

Lifecycle stage	Barriers
Petrochemical production	• Difficult to trace if the production processes add feedstocks from chemical recycling • No standards for a mass balance approach
Design	• Lack of understanding about recycling technologies, and how to design for/from recycling
Manufacturing	• Product composition information is not shared to the actors across the value chain • Lack of information about origins, quality, availability and reliability of secondary plastics causes uncertainties regarding performance of plastics for specific applications
Retail and Consumption	• Retailers find it difficult to establish baseline and measure progress over time and against their targets of recycled content and recyclability
Waste collection	• Unclear recycling instructions lead to consumer confusion about disposal • Unclear data and information on material composition increases the difficulty of adequate segregation
Waste treatment	• Lack of traceability to fully understand the provenance of plastic waste • Knowledge gaps with regard to technical aspects of recycling technologies • The absence of standardised composition labelling

Figure 5-6 Barriers of data-information-knowledge at each lifecycle stage

- **Petrochemical production**

Plastic users, including manufacturers of final products, brand owners and retailers, often wish to know whether their plastic contains secondary material, either because the use of recycled plastics is a regulatory requirement, or because of consumer pressure. However, plastic recycling systems generally offer limited traceability of secondary plastics.

A particular traceability challenge emerges in the context of chemical recycling, which enables the recovery of primary chemicals from which plastics can be generated. However, as they go back into the petrochemical production stage, it is impossible to trace the destination of the material derived from plastic waste. As explained by a petrochemical producer:

> *'If [material entering] crackers had a very small quantity of recycled feedstock, […] it gets distributed across the whole network. The question is, where does it end up? […] You don't find [that] today' (#4 Petrochemical Manufacturer / Chemical Recycler).*

The potential solution to this information challenge is to use a 'mass-balance' approach, which requires agreed standards of data collection and reporting, to enable certification (#4, #21). Stakeholders across the European plastic value chain, including petrochemical producers, plastic converters, manufacturers and chemical recyclers, advocated that the European Commission adopt a mass balance chain of custody, to calculate chemically-recycled content in plastics. However, Zero Waste Europe (2021) and Eunomia (2021) pointed out the concern about inflated estimates of recycled content and the inconsistency of current third-party verification without legislation (e.g., International Sustainability and Carbon Certification (ISCC) Plus, ISO 22095 Chain of Custody — General terminology and models). There are still on-going debates on how to improve this mass-balance approach, such as to use more precise units and a batch-level mass balance method.

- **Design**

Designers lack understanding of recycling technologies, including both how to design for recycling and how to design products with recycled plastics. Historically, product designers rarely designed with recycling in mind, nor did they considered how best to design to encourage the use of secondary materials. An interviewee explained:

'If we have this demand coming from the consumer, the manufacturer wants to fulfil the demand, but sometimes he [manufacturer] can't because he doesn't know how to handle recycled materials' (#24 Specialist).

It is important for designers to acquire relevant information and knowledge on recycling technologies from a design perspective. A consultant explained:

'If you understand recycling, then you can actually change your packaging. If you don't know what's happening, then how can you design something that is actually recyclable?' (#16 Mechanical recycler and consultant).

- **Manufacturing**

At the manufacturing stage, a key barrier is that product composition information is not always shared across the value chain. The lack of information about origins of secondary plastics and material composition of products causes uncertainties for manufacturers. Information on quality, availability and reliability of secondary plastics is needed across different application areas. An interviewee said:

'From the production side, we see that […] manufacturing companies don't really know the quality they get, […] [and] the quality is varying all the time' (#24 Specialist).

- **Retail and Consumption**

Circular economy pledges have recently been made by many brand owners or retailers, however, some have found it challenging to access data and information to build a baseline of secondary plastic use and, thus, to measure progress over time and against their targets. Currently, there is no harmonised standard to measure the recycled content, as well as to assess the degree of recyclability of plastic products, which could also lead to the risk of overcounting. This is dependent on institutional frameworks, collection systems, and recycling infrastructures in different countries. A retailer/brand owner explained the case for their firm:

'Every country has a different measuring system, sometimes it is labelled or not, and also standards are not clear' (#12 Retailer / Brand owner).

- **Waste collection**

At the waste collection stage, unclear recycling instructions and differences in segregation and collection systems across regions and countries lead to consumer confusion about disposal, while unclear data and information on material composition increase the difficulty of adequate segregation for waste collectors and sorters in the pre-treatment stage.

Barriers to the labelling are also identified, especially on the packaging. A retailer mentioned:

> *'At the moment, it is always confusing because country by country is different' (#12 Retailer / Brand owner).* Another interviewee said, '*in different countries, recycling works differently. So we don't put any labels on how to dispose of products' (#13 Retailer / Brand owner).*

In the construction, electrical and electronic equipment (EEE) and automotive sectors, it appears that detailed information on secondary plastics and their material composition is rarely provided to end consumers and recyclers. The only data shown to the consumers, if any, may be the percentage of secondary plastic used in the products for marketing purposes. An interviewee pointed out that poor information on material composition for plastic components embedded in products creates difficulties for further segregation and treatment when the plastics enter waste streams:

> *'How do you know what kind of material it is? You don't know. It's not known. And that is a lack of information, and it is lack of communication' (#7 Manufacturer).*

- **Waste treatment**

At the waste treatment stage, the barriers include lack of traceability to understand the provenance of plastic waste, and knowledge gaps regarding technical aspects of recycling technologies. Three key factors were identified by those interviewed: i) the complexity of the material composition of plastic-containing products, ii) the absence of standardised composition labelling, and iii) the cross-contamination issues as a result of the collection of mixed plastic waste streams. A manufacturer said:

> *'So the biggest problem of recycled material is the provenance. So, where it comes from? It's understanding the provenance and then also understanding the mixture of it. If you're post-consumer waste, you have no idea where it's coming from, you don't know what contamination is in there' (#6 Manufacturer).*

5.5.2 Interaction of data-information-knowledge barriers with sub-regimes

Applying the MLP conceptual framework reveals the key strengths needed to highlight the interactions and co-evolutions of heterogeneous elements. It thus directly responds to calls in the literature for analysis examining the interaction of barriers. This subsection explores how the barriers associated with the data-information-knowledge map cross and interact with each of the sub-regimes of the socio-technical regime. This analysis draws on the mapping of barriers across the value chain (Figure 5-6), but now explores how these barriers interact. The interactions are summarised in Figure 5-7. The figure shows that the barriers are mutually reinforcing, creating a ‘web of constraints’ (Domenech et al., 2017).

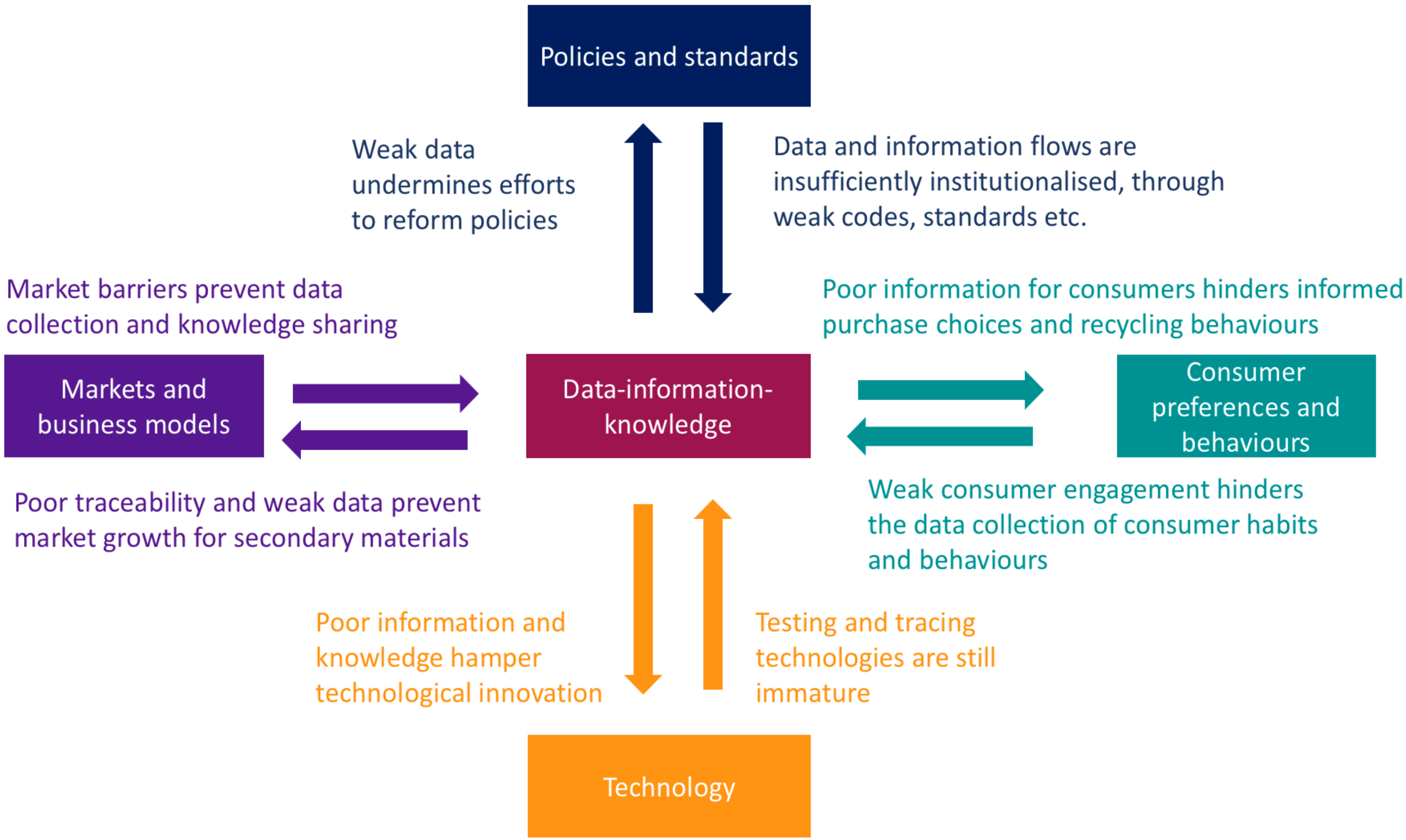


Figure 5-7 Summary of interaction of data-information-knowledge barriers with sub-regimes

- **Policies and standards**

The evidence presented in the previous section highlights that across the value chain there is weak institutionalisation of data and information flows. This includes limited standardisation of rules for information disclosure or standardised ways of measuring secondary plastics. For example, measurement standards are not in place for measuring recycled feedstock from chemical recycling.

> *'At the moment, there is no ISO standard or there's no international standard or European standard on this mass balance approach' (#4 Petrochemical Manufacturer / Chemical Recycler)*.

Codification of data and information flows and knowledge resources through regulations, standards and certification processes are essential for building trust and mutual understanding across the value chain. Obviously, weak data hampers efforts to improve these policies.

- **Markets and business models**

Historically, there has been a lack of collaborative engagement among companies across the supply chain since it was not necessary in a linear system. Market barriers prevent development of data, while concerns about loss of intellectual property inhibit data sharing and knowledge diffusion. An interviewee said:

> *'[A brand of carbonated soft drink] doesn't want (their competitors) to know what is putting in markets […] And I would say like that we have a lack of data regarding traceability of material inside the EU' (#25 Extended producer responsibility organisation).*

Therefore, new business models based on collaboration need to emerge to enable knowledge sharing while overcoming fears about losing intellectual property to competitors. New emerging business models enabling information and knowledge to flow across the supply chain take time to establish.

Data-information-knowledge issues reinforce barriers to markets and business models. Tracing, sensing and testing plastic waste and the performance of secondary plastics add costs and uncertainties to the use of secondary plastics, reducing their market attractiveness. An interviewee mentioned:

> *'When it comes to certified, they need to pay for audits, factory visits, etc, kind of also adds to the price' (#13 Retailer / Brand owner).*

Both the car manufacturer and a recycler participating in the interviews highlighted these costs in relation to end-of-life vehicles:

> *'We had to spend quite a lot of money testing to make sure that the plastic didn't contain unwanted additives like lead or cadmium or banned flame retardants' (#18 Mechanical recycler and consultant).*

Poor traceability and weak data prevent market growth for secondary plastics. Interviewees pointed out these barriers limited the market growth, especially for the online trading platforms (#23 , #22). One of the interviewees said:

> '*If it should work for these online trading platforms, you really need to specify the (technical specifications of) product very clearly. And, that's not so easy when it comes to recycling (trading plastic waste and recycled plastics)' (#23 Broker).*

The need for new knowledge to facilitate circularity is already generating knowledge-based entrepreneurship through the establishment of consulting services providing legal information and recycling technology knowledge to the brand owners, retailers and packaging companies. Access and control over data is likely to be an important source of competitive advantage in a future circular ecosystem, and efforts to secure intellectual property are likely to hamper the open exchange of data that would facilitate greater circularity.

- **Technology**

Testing and tracing technologies are still immature, therefore, many firms are not able to monitor their use of recycled plastics. A retailer explained:

> *'What we are not able to do is to specify the real volume (of recycled plastics), because this is the real challenge there, how much? And how can we increase it?' (#12 Retailer / Brand owner).*

Another retailer also mentioned:

> *'I think for us right now, the most difficult part for us is kind of just monitoring how we can make sure that we know what we're doing in terms of the impact, and the improvement that we're making' (#13 Retailer / Brand owner).*

The construction sector also faces similar difficulties:

'I think it's quite difficult for us to track and measure whether or not it is virgin plastic or recycled plastic […] we don't know what is involved in that plastic' (#14 Construction manager).

Another construction manager further explained:

'We need to get the data on recycled materials from the suppliers, and then, we need to calculate the total recycled material ratio for the building we built, so we need to take the data from every product and calculate how much of such product we put in our building and compile. […] That's not something we do regularly, and it is a very time-consuming process' (#15 Construction manager).

The technical barriers are not only monitoring the quantity of secondary plastics, but also testing the quality of secondary plastics. Using recycled plastics requires extra laboratory testing, either by secondary plastic sellers or buyers, to ensure that it can meet the specific demands of the product. This is especially important for technical plastics and food contact plastics. It is technically challenging to consistently produce same quality of technical plastics, because it needs not only the high purity of recycled content, but also lots of testing to find a mixture of accurate proportions of different monomers and additives to meet specific requirements. An interviewee said:

'I think it's really hard with these complicated technical polymers to deliver a really sustainable model' (#17 Mechanical recycler).

Poor information and knowledge hamper technological innovation (Hekkert et al., 2007). Using recycled plastics requires information and knowledge regarding material science and technologies. An interviewee mentioned:

'Early 20 years ago, when I got involved in setting up [name of a recycled plastic product] […] there was very few people doing it and didn't really understand the knowledge and the science that needs to be put behind this to make it into a commercial opportunity' (#8 Manufacturer).

Another interviewee also pointed out:

'There is obviously a bit of skill in that because you need to understand how much additive is in the mix of virgin and recycled content' (#17 Mechanical recycler).

- **Consumer preferences and behaviours**

Although consumer awareness and perception about plastic issues have changed in the past few years, consumer habits related to purchase decisions and waste disposal behaviours are identified as barriers according to the findings in the previous section. In some cases, it is technically achievable to use a higher percentage of secondary plastics, however, consumers may not accept or be willing to buy the products. An interviewee explained:

> *'There is maybe absolutely no difference to the products, but if consumers perceive it to be dirty or whatever, then you know you have a challenge to communicate some of those things to consumers' (#11 Manufacturer / Brand owner).*

Poor information for consumers also hinders informed recycling behaviours. An interviewee mentioned:

> '*I think part of it (barrier) is constant sort of an information stream. Do you really know where it's going and what you have to put in the box (bin)? As an individual, I haven't got a clue what's going on' (#19 PVC windows recycler).*

Another interviewee highlighted that poor information for consumers creates losses of plastic waste:

> *'There's a massive sorting loss [...] if Mrs. Jones (end consumer) doesn't understand that the ice cream tub can be put in a recycling bin, then there's a huge loss to residual waste' (#18 Mechanical recycler and consultant).*

Moreover, consumers lack understanding about the impact of waste disposal and recycling:

> *'Consumers are not really aware of what is the impact of the sorting […] if I put this waste on the other bin, I don't care if it will be the same results because I don't have any visibility of this sorting' (#25 Extended producer responsibility organisation).*

Weak consumer engagement hinders the data collection of consumer habits and behaviours. An interviewee mentioned:

> *'Currently, at the present moment we only see half of the pattern. Once the manufacturer finishes the product and it's distributed to a retailer, the pattern is*

sort of very very much lost. And then, once it goes to the hands of the consumer, then it goes to the kerbside collection, then to a MRF (Material Recovery Facilities) or the PRF (Plastic Recovery Facilities), we only see 50% of the story really' (#8 Manufacturer).

The interviewee highlighted that consumer engagement helps brand owners and recyclers collect data regarding consumer habits and behaviours to improve their product design and plastic waste collection (#8).

5.5.3 Ongoing development of data, information and knowledge

To tackle these aforementioned barriers, strategies have been suggested to enhance data and information flows, and knowledge development and diffusion, both of which are important in enabling the development of a more circular socio-technical system. In this section, I draw on interviews to highlight progress regarding product composition information from manufacturers, secondary plastics information for manufacturers, developing and diffusing knowledge through R&D and collaboration, and codifying knowledge through purchase and design guidelines. Where relevant, examples across four different plastic application areas (packaging, construction, automotive and EEE) are provided.

- **Developing and institutionalising data and information flows**

Product composition information from manufacturers

Information provided by manufacturers on the content of their products is important for facilitating subsequent recycling. Various international standards and EU policies (e.g., ISO 1043, ISO 11469, SAE J 1344, and various EU Directives) have long regulated labelling of goods to facilitate recycling, and the provision of information to assist dismantlers of EEE and end-of-life vehicles. However, progress in transparent secondary plastic markets has been limited. Emerging digital tracking technologies are creating new opportunities in this area.

The automotive industry requires plastic labelling standards, however, while this has been identified as a key barrier for over ten years (Duval and MacLean, 2007), specific progress has been slow. Several leading car manufacturers established databases such as International Material Data System introduced in 2000, while the EEE manufacturers and brand owners have also followed full material declaration approaches to document product composition information. However, these databases are restricted to the upstream partners who are involved in the collaboration. In recent years, new circular businesses have emerged in both EEE and automotive sectors by applying digital technologies to share the product composition information across the whole value chain (Tramutola, 2019).

One example in packaging has manufacturers and brand owners using digital track-and-trace technology to record and share the product composition information with consumers, collectors and recyclers, as described by a manufacturer:

> *'We think the ability to track and trace all materials […] if you're making composite products, you can embed in the data set […] the material grade, what its properties are, so on and so forth […] So, understanding that key data set to see what can be combined together and used is an absolute key driver' (#8 Manufacturer).*

The construction industry has been discussing materials passports and building information model based (Karki et al.)-based material passports, although these seem to not have made much practical progress yet. Data and information, such as technical datasheets and certificates of regulatory compliance, provide the material traceability and share with actors across the value chain through digital platforms. This kind of best practice will take time to develop and scale up.

Secondary plastic information for manufacturers

Manufacturers using secondary plastics need better information about these materials. In some cases, manufacturers simply wish to demonstrate that they are using secondary materials and need data only on the volumes of secondary materials within their inputs. In other areas, manufacturers need detailed and accurate data on the provenance and composition of secondary materials to ensure that the material meets their quality criteria and regulations. For example, those involved in food packaging must ensure that recyclers can provide information regarding safety and traceability to manufacturers to fulfil the requirements of EU regulations (e.g., REACH (EC No 1907/2006), food contact legislation (EC No 1935/2004, EC No 282/2008)). One solution to enable this is the use of deposit-return schemes or reverse vending machines.

Manufacturers thus look to their suppliers, often recyclers or converters, but also brokers and collectors, to provide data that clarifies origins, quality and quantity of secondary materials. Part of the challenge relates to the collection of data. In order to measure the amount of secondary plastics used in the new products, the Monitoring Recyclates for

Europe platform organised by many plastics associations has been working on secondary plastic data collection since 2018.

Intermediaries in the plastic value chain, including distributors and brokers, help their customers access specific secondary plastics to meet their requirements, however, this ad hoc process tends to lack traceability beyond those involved in it. Work to standardise and institutionalise data, and to ensure comparability, is thus becoming increasingly important. Many certifications have been developed to improve traceability, such as Recycled Plastics Traceability Certification by RecyClass.

A number of technologies have been developed to mechanically segregate plastic and track polymer composition of specific materials and recycled contents. Schyns et al. (2022) developed a fluorescence-based analytical technique to mark the recycled content of plastic packaging. A waste management company also explained a good practice in their waste treatment facilities:

> *'We have lots of big data on recycling. So we know on an individual packaging based on the barcode, how it actually ends up at our sorting centre. So we know how it is sorted. And with that, we also know which type of recycler it will go' (#16 Mechanical recycler and consultant).*

This could potentially be mainstreamed in the future, easing the problems associated with traceability. Better traceability through consistent data and information flows can be enabled through regulations, new digital and tracking technologies, better coordination across the supply networks and new business models.

Regarding the quality of secondary plastics, many ISO/EN standards for recycled plastics have existed since 2007 (Villanueva and Eder, 2014). However, these generic technical characteristics of different recycled plastic polymer types are difficult to fit the different specifications of diverse applications in actual practice. As secondary plastic information regarding quantity, quality, availability and reliability still contains numerous gaps, actors in different areas of applications have been developing labels and/or platforms for information sharing. Some examples are selected from the interviews:

In packaging, some products indicate the percentage of secondary plastics used, using labelling schemes such as the global recycled standard (GRS) and Blue Angel ecolabel. EPR schemes are also driving data collection around secondary materials in packaging.

In EEE, application-specific technical requirements may generate additional challenges for manufacturers using secondary materials, with important implications for information flows. An interviewee described their project working on developing a trading platform:

> *'If you want to produce a smartphone and you're looking for material out there for a second material, you are never really sure about the quality of the material specifications [...] We really want to put all the numbers on the material specifications online […] If a seller has a material to offer, he should specify how much he has to offer and how long he can offer this material and with this quality [...] also, we want to indicate the reliability of the seller' (#24 Specialist).*

Some car manufacturers have developed their own grading system for recycled plastics to provide quality information codifying material properties of secondary plastics. An interviewee described:

> '*From the beginning, when I worked inside the [automotive manufacturing] group, everybody from engineering department said to me that, 'you have to take the same specification like virgin plastic' […] That's the reason that [ELV recycling] company and my company want to assure every time for each recycling grades have the same performance' (#9 Manufacturer / Brand owner).*

This example also shows the process of transformation from data and information into knowledge through codification of know-how experience.

- **Knowledge development and diffusion**

In addition to the developments in data and information previously explored, there are ongoing efforts to develop, diffuse and codify new knowledge required for greater circularity.

Developing and diffusing knowledge: Research and development (R&D)

The development of new knowledge depends on formal R&D, as well as learning by doing, and learning by interacting with suppliers, customers and others (Malerba, 1992). Formal R&D is important because it increases technical knowledge specific to particular problems, and also builds skills and capacity that enable research active organisations to absorb new ideas developed elsewhere (Cohen and Levinthal, 1990). Both private and public R&D on circularity for plastics has increased in recent years, with the creation of new public funding streams specific to the circular economy from the European Commission and many European member states (Circular Plastics Alliance, 2021).

Codifying knowledge: purchase and design guidelines

An important mechanism for facilitating the diffusion of knowledge required for greater circularity is the codification of knowledge in the form of guidelines, instruction manuals, and so on. This includes guidelines within firms that help to co-ordinate design criteria, input purchase decisions, and so on, the guidelines firms use to manage their own supply chains, and the public guidelines produced to communicate to the entire supply chain. Interviewees described a range of examples, including:

- Procurement guidelines to overcome knowledge gaps about the opportunities to use secondary materials *(#15 Construction manager)*.
- Brand owners codified knowledge to manage their supply chains. An interviewee described their experience: *'The guidelines are out there based on our experiences. So, when we started the programme, we learned that it's not easy to use recycled plastic, so we have a lot of problems in the beginning […] and then, quite often the final product didn't meet the requirements […] So, we decided to be much more structured about how we do this […] with guidelines' (#10 Manufacturer / Brand owner).*
- Guidelines for product designers to help them understand the characteristics of secondary materials*: 'And that's why we have design guidelines. […] We have to show companies and manufacturers how they can use actually recycled plastics, what are the processes and production requirements for recycled plastics' (#24 Specialist).*
- Efforts by recyclers to develop guidelines for packaging designers, something that has been supported by the Plastics Recyclers Europe and Circular Plastics Alliance. For example, one recycler familiar with such guidelines explained: *'We're mainly looking at […] Can your packaging be recycled? So, try to use mono-material, try to use the standard types of plastic that are used a lot, and recycled a lot. Don't choose sleeves or labels, all that kind of thing' (#16 Mechanical recycler and consultant).*

Both the packaging and EEE have developed industry-level design guidelines specifically for plastics. Public guidelines in the EEE sector not only focus on design for recycling but also design from recycling (Berwald et al., 2021). Industry-level guidelines for automotive and construction products are still developing.

Summary of the role of data-information-knowledge

In summary, a circular economy is much more data- and knowledge-intensive than a linear economy, since it requires actors to access data, information, and knowledge from across the entire value chain. Some recommendations for stakeholders involved in the plastics value chain are offered below.

Designers, plastic producers, and manufacturers need to share information on quantity, quality, availability and reliability of product composition and secondary plastics, recycling instructions, and environmental impacts to their customers, end-consumers and recyclers. The upstream actors are encouraged to codify and diffuse knowledge on how to integrate secondary plastics within products. Brand owners, retailers and NGOs need to inform end-consumers about plastic recycling and the safety and environmental sustainability of secondary plastics. Recyclers need to educate the designers, plastic producers, manufacturers on how to design for recycling. Solutions to overcome the barriers regarding the traceability for both plastic waste and secondary plastics rely on digital technologies, business networks, labelling and certification. Technology support relies on technical startups, machinists, producers, manufacturers. Financial support relies on brand owners and governments, whilst the harmonised legislation, labelling and certification regarding recycling and secondary plastics rely on policymakers and third-party authorities.

5.6 Networks across different actors

The previous section on the role of data-information-knowledge shows that part of the reason for weak knowledge is the historical lack of collaboration and networking across the value chain. Networks link actors within and between the sub-regimes, and networks are essential for enabling the knowledge flows on which innovation and transition depend (Weber and Rohracher, 2012, Hekkert et al., 2007). The existing linear business models, as part of the socio-technical sub-regime using virgin plastics and lack of collaboration, reinforce the persistence of the current linear economy system. In recent years, companies across the plastic value chain have established collaborations and networks that facilitate learning-by-interacting (Alhusen et al., 2021), which helps to overcome knowledge gaps created by the historical absence of collaboration across the value chain.

Several interviewees described their collaborative activities specifically in terms of addressing knowledge gaps. For example:

'We work together with third partners, R&D groups, technology developers, recyclers to develop chemical recycling of polystyrene […] The recycling activities […] required chemical producers because you need know-how to handle styrene' (#3 Petrochemical producer / Mechanical recycler).

Many of these emerging networks and linkages are informal and relate to specific collaborative projects or initiatives. However, some companies have also developed formal collaborative networks. For example, a co-operative organisation across the value chain is developed in order to generate and share understanding about collection methods and tolerances for impurities in secondary plastics (PolystyreneLoop, 2019) (#20).This section highlights the way that actors are seeking to develop new formalised collaborative networks that facilitate overcoming barriers. New emerging supply chain alliance networks can be classified into five domains: the Circular Plastics Alliance; Joint Industry Value Chain Initiatives; Plastics Pacts; EU-funded projects; and the Alliance to End Plastic Waste.

- **The Circular Plastics Alliance**

Due to the European Strategy for Plastics, the Circular Plastics Alliance (CPA), a policy initiative collaboration between European Commission and the plastic industry, was launched in 2018. This network drives the voluntary pledges to use 10 million tonnes of secondary plastics by 2025. The industry representers in the CPA explained the benefits of this new collaboration:

'The Circular Plastics Alliance, it's an opportunity for the industry to step forward and make the change. […] So, there, you see, waste management companies, converters, recyclers, plastics producers […] all looking to work together to help achieve the targets for reuse and recycling […] So I think trying to build collaboration is really important, and that's a new policy measure from the European Commission' (#1 Petrochemical producer / Specialist).

Through the policy initiative, the CPA creates a platform for different actors in industry and policymakers to share knowledge and communicate with each other to discuss how to work together to overcome the barriers.

- **Joint industry value chain initiatives**

Except for the existing associations based on the role of actors, such as Plastics Europe, European Plastics Converters (EuPC), European Plastics Distributors Association

(EPDA), Plastics Recyclers Europe (PRE), another frame of the networks has emerged. This network focuses on improving the circularity of specific plastic polymer types through the collaboration with actors across the value chain. Namely, joint industry value chain initiatives, including PET Container Recycling Europe (Petcore), Polyolefin Circular Economy (PCEP), Vinyl Circular Solutions (VCS), VinylPlus and Styrene Circular Solution (SCS). A specialist described:

> *'We have to work together, we can't work in our side. To that end, we set up some platforms […] The whole idea is that you get all of the value chain together in those. So those platforms represent a material specific interest' (#1 Petrochemical producer / Specialist).*

This type of network helps to consider the circularity of polymers from the lifecycle perspective and engage the actors along the value chain to develop industry-level solutions. These joint industry value chain initiatives drive the voluntary pledges to enhance collection, sorting and recycling and develop the end market for recycled plastic polymers. It is worth noting that these joint industry value chain initiatives are focusing on the widely used plastic polymers, however, there are many other high-end used engineering plastic polymers that are not commonly considered in the discussion and collaboration of plastic circular economy due to lack of economic scale.

- **Plastics Pacts**

The other networks are the Plastics Pacts with global, regional or country-level initiatives. Under the umbrella of the EMF's Plastic Pact, Europe has the European Plastics Pact, and the UK (which is the first Plastic Pact launched in 2018), the Netherlands, France, Portugal, and Poland also have their own national Plastic Pacts. These Pacts set up voluntary targets in the plastic circular economy strategies, which also include increasing the use of recycled content, but mainly focus on single-use plastic products and packaging. The construction, automotive and EEE applications are involved in the CPA, but are not involved in these kinds of networks and pledges.

- **EU-funded projects**

EU-funded projects provide financial support for research and innovation, which helps to tackle economic barriers in a set period of time and establish consortiums of University-Industry-Government-Institute to improve the value chain communication and build up reliable relationships. The EU-funded projects benefit packaging, construction, automotive and EEE application areas.

An interviewee involved in the EU-funded project relevant to EEE applications described how the project enables different actors to understand the needs between each other:

> *'We work all along the supply chain with start from the collection to the pre-processing to the compounders and manufacturers in the end […] From what we've seen, everyone is really surprised how big the progress that we had, because usually, two or four years (ago), nobody was really collaborating, nobody was really talking to each other. So, one big problem that we saw is communication, the collaboration along the entire value chain. And that's the biggest benefit that we see. So, we have manufacturers, they can tell the collecting industry and the sorting industry, what they need their specifications. So, all this collaboration is now summing up and delivering very good results' (#24 Specialist).*

The risk in investment new technology is one of the barriers, especially for SMEs (small and medium-sized enterprises). The EU-funding helps to ease this barrier and build up trust between different actors for long-term partnerships. An interviewee who coordinated an EU-funded project relevant to the construction waste explained:

> *'In Europe, no one wants to take the risk. So, small companies cannot take the risk. That's the reason why I have established a cooperative and I have 70 members [70 firms], all the big polystyrene producers […] We have different block groups from recyclers, plastic producers, additive users, and machinery. And they are all having representatives and we work together. So, we have a great network' (#20 Solvent-based Recycler).*

This experimental case has made progress in developing new sorting and recycling technology. However, this experimental case fell into bankruptcy in early 2022, due to the soaring energy prices and Covid-related impacts.

Each EU-funded project focuses on a specific area, including designs for recycling, collection and sorting, recycled content, R&D, and investments and monitoring. The Plastics Circularity Multiplier initiative further developed a database to synergise relevant projects to collaborate together. Through alleviating economic barriers, the EU-funded projects demonstrated the technical feasibility to use secondary plastics in different application areas and improved the collaboration across the value chain.

- **Alliance to End Plastic Waste**

Since the EU produced the second largest amount of plastics in the world and also is a pioneer in the plastic circular economy, it is important for the EU actors to contribute to tackling the global plastic pollution. A group of global companies across the value chain gathered together to establish an alliance to end plastic waste. Europe's End Plastic Waste Innovation Platform, based in Paris, aims to collaborate with startups to find innovative solutions for plastic waste. This alliance also aims to create the value of secondary plastics, thus, it has the potential to contribute to the future secondary plastic market in the EU. A European multinational petrochemical company explained the reasons why they became involved in this alliance:

> *'There is also the question of how do you deal with waste more efficiently, and especially how do you utilise plastic waste. [Name of the company] is also a founding member of the Alliance to End Plastic Waste. So, this is also something that we deal with also on a high management level' (#4 Petrochemical Manufacturer / Chemical Recycler).*

Another interviewee described the active collaboration:

> *'We're also one of the founding members of the Alliance to End Plastic Waste, which is very active in Asia. We do a lot of projects at the moment with the Alliance to End Plastic Waste. It's a lot of companies, our competitors, but also downstream users of our products, combined in companies like [names of brand owners], they are all combined into this Alliance to End Plastic Waste and looking for solutions to recycle polymers' (#5 Petrochemical producer / recycler).*

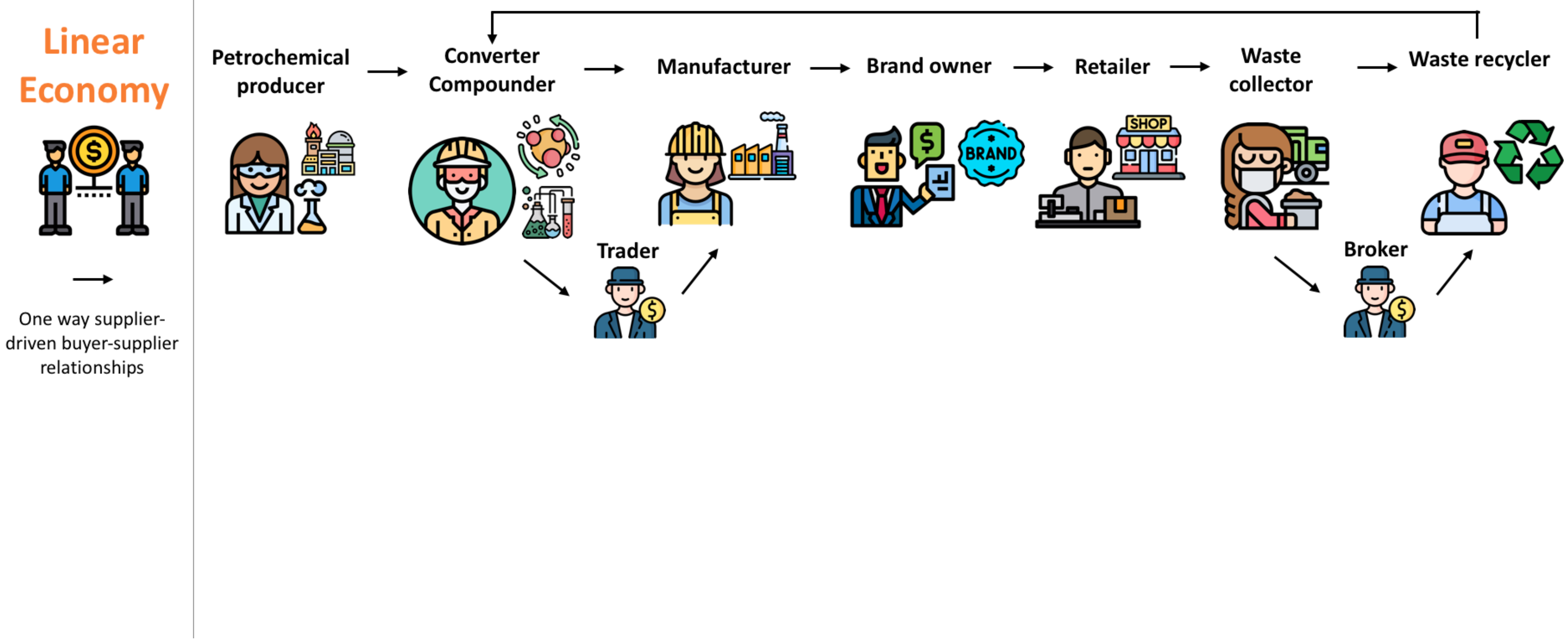


Figure 5-8 Networks operating in a linear economy

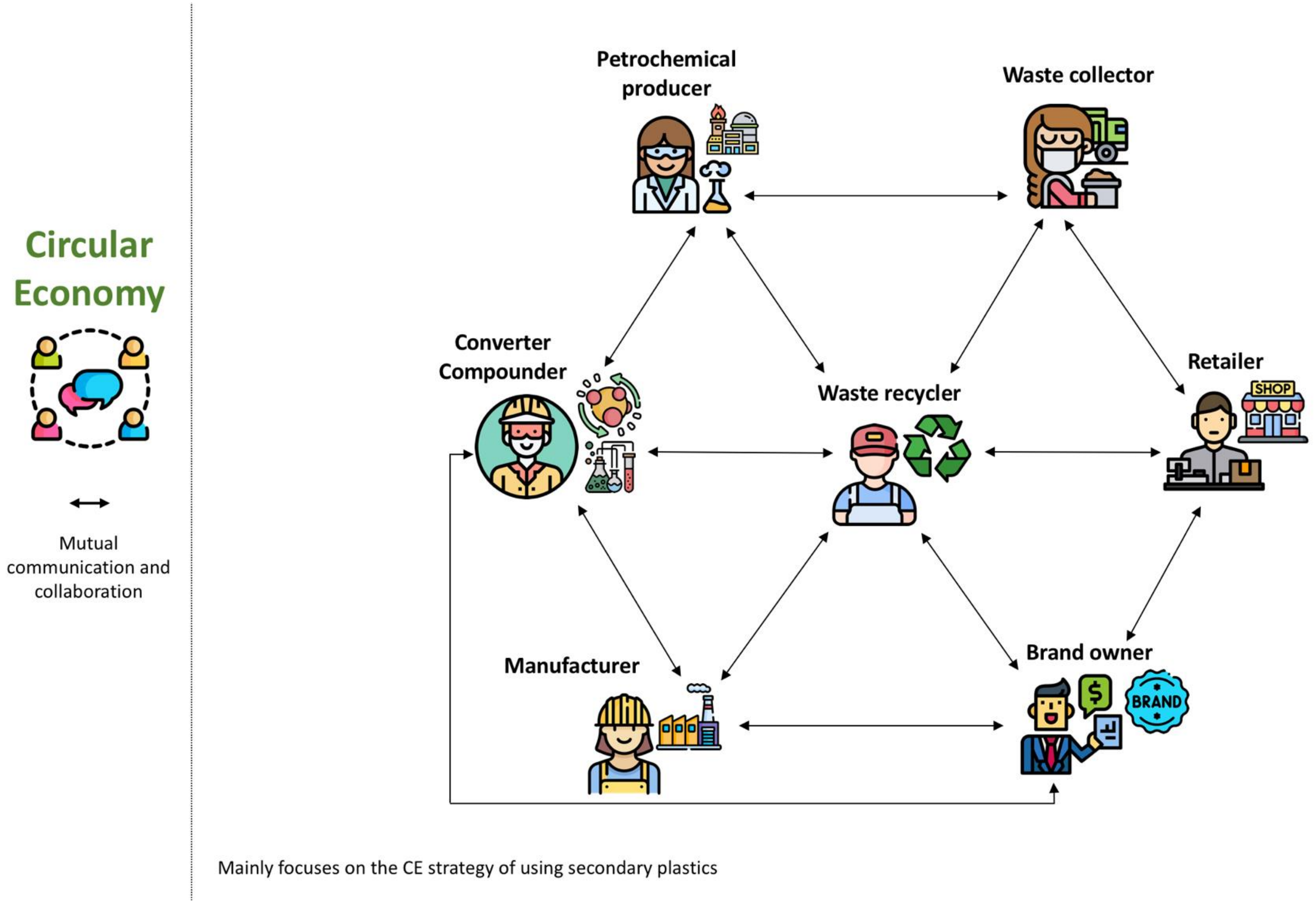


Figure 5-9 Networks operating in a circular economy

Summary of the networks across different actors

Figure 5-8 and Figure 5-9 illustrate the various networks operating in a linear economy system and a circular economy system in a simplified manner, only representing the stakeholders in the plastic value chain. In a linear economy system, the network linkages were weak across the value chain, and between governments and industry. This inhibits learning and knowledge exchange. The lack of long-term partnerships also makes it difficult to invest. Therefore, the lack of secure material supplies, the high cost of waste treatment, and the high price of secondary plastics lock in business decisions. It is supplier-driven delivery with buyer–supplier relationships. The sellers may produce secondary plastics according to the recycled granules they get, however, the secondary plastics tend not to meet the needs of buyers' on the market, unless it is a customised request.

In recent years, a variety of factors, including changing policies, increasing consumer awareness, and new technologies, have driven the development of new emerging initiatives and formalised networks. New circular economy systems facilitate different actors along the value chain to collaborate with recyclers directly as waste recyclers are the secondary plastic producers. The waste recycler is central to the circular economy system in Figure 5-9 because this study mainly focuses on the circular strategy of using secondary plastics. In other cases of circular economy systems, the figure may be represented differently. In a circular economy system focused on using secondary plastic, actors start to collaborate horizontally with competitors and vertically with other actors across the supply chain. Policy, civil-society and business-led forums provide opportunities for networking and knowledge exchange. These networks help to find solutions for plastic pollution; innovate high-quality grade recycled plastics; create demand; improve the plastic material traceability; and share data, information and knowledge to assist in the re-design of products and systems. Technology and business opportunities are driving network formation and collaboration and the actors are learning by doing through these networks and collaboration. Some cases will continue to support the transition, while some cases may fail in the transition dynamics.

5.7 Web of constraints and web of drivers

Previous sections have discussed the barriers and drivers to the use of secondary plastics across different sub-regimes and their dynamics. Based on the interviews and the findings presented in the previous sections, it is clear that the interactions among these factors are complex. The main purpose of this thesis is to answer the research question: What are the barriers and drivers reconfiguring the regime to increase the use of secondary plastics? To simplify the diagrams and make them readable, the variables of barriers and drivers separated into two diagrams. The variable 'demand of secondary plastics' is used to understand the factors that increase the use of secondary plastics. This section highlights the key interconnections between barriers that characterise the 'web of constraints' (Domenech et al., 2017). On the other hand, this section also looks at the interconnections between drivers to characterise the 'web of drivers' (Dijk et al., 2019) to articulate 'motors of change,' which opens up the regime for change.

This analysis offers insights into the interrelatedness of barriers and drivers of the demand for secondary plastics within these transition dynamics, rather than providing a new set of policy measures. The CLDs can serve as a visual aid to understand the complex interrelationships within the system's structure more explicitly. Different colours of the variables in Figure 5-10 and Figure 5-11 present different sub-regimes. The colours are aligned with the colours of each sub-regime from the previous section. Namely, the sub-regime of policies and standards is in dark blue; the sub-regime of markets and business models is in purple; the sub-regime of technology is in orange; and the sub-regime of consumer preferences and behaviours is in green. The variables generalised the factors across different application areas.

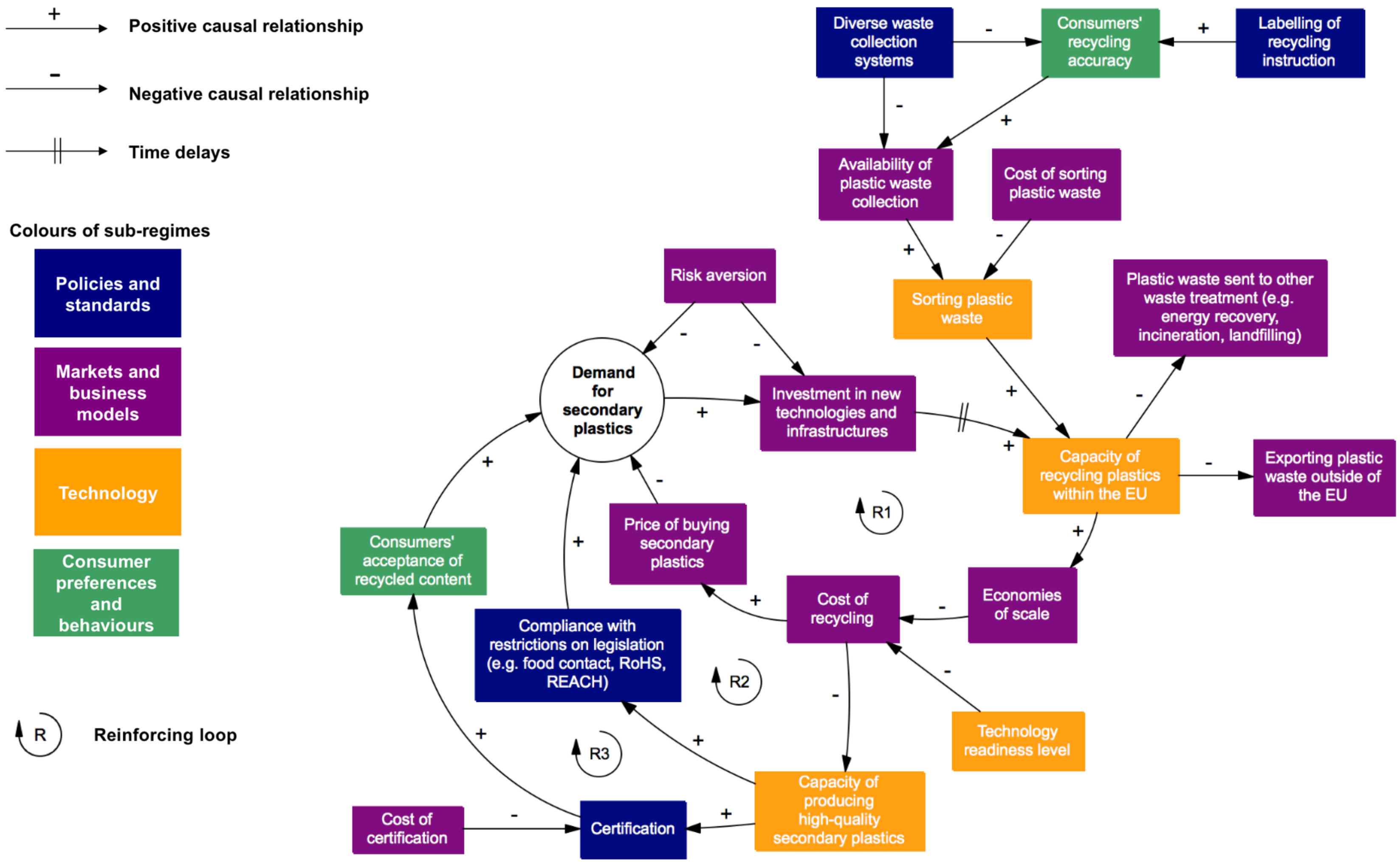


Figure 5-10 Web of constraints

- **Web of constraints**

Figure 5-10 depicts the CLD of the web of constraints. The higher diversity of waste collection systems across different regions influences the lower consumers' recycling accuracy. The less clear the labelling is for recycling instructions, the worse the consumer recycling accuracy. This lower accuracy leads to lower availability of plastic waste collection.

The availability of plastic waste collection and the cost of sorting plastic waste also affect the sorting rate. The less plastic waste is sorted, the less can plastic waste be recycled. Due to the lack of capacity for recycling plastics within the EU, plastic waste is either exported outside of the EU or sent to other waste treatment (e.g., energy recovery, incineration, landfilling). A reinforcing loop (R1) indicates that less investment in new technologies and infrastructures causes low capacity of recycling plastics within the EU; the lower capacity of recycling plastics within the EU, the smaller the economies of scale of recycling; smaller economies of scale of recycling causes the higher cost of recycling; higher cost of recycling leads to higher prices for buying secondary plastics; higher prices of secondary plastics cause a lower demand for secondary plastics; lower demand for secondary plastics causes less investment in new technologies and infrastructures. The lower technology readiness level also results in the higher cost of recycling.

Reinforcing loop 2 (R2) and reinforcing loop 3 (R3) follow the same causal relationships in R1 between the variable of 'investment in new technologies and infrastructures' and the variable of 'capacity of producing high-quality secondary plastics.' This shows that investment in new technologies and infrastructures always takes several years until it achieves commercial operation. Lack of recycling capacity, economies of scale, and the high cost of recycling, amplify the difficulty to increase the demand of secondary plastics, especially for the cases of specific high-end plastic polymers or high-end applications.

R2 shows that the higher cost of recycling, the lower capacity of producing high-quality secondary plastics; the lower capacity of producing high-quality secondary plastics, the fewer secondary plastics that can meet legislation requirements; the fewer secondary plastics that can meet legislation requirements, the less demand there is for secondary plastics. R2 reveals the quality of secondary plastics is the key to triggering change, as legislation restrictions play a vital role in safety control, which needs to be considered as a priority rather than relaxed. R3 shows that the lower capacity of producing high-quality secondary plastics, the fewer secondary plastic-containing products are able to be certified. The fewer acquired certifications may potentially reduce the consumers' acceptance of recycled content and eventually decrease the demand of secondary plastics. The cost of certificate applications can affect the willingness to certify applications, while risk aversion would affect both the demand of secondary plastics and investment in new technologies and infrastructures.

Feedback loops in the CLD of the web of constraints include:

Reinforcing loop 1: Investment in new technologies and infrastructures → Capacity of recycling plastics within the EU → Economies of scale → Cost of recycling → Price of buying secondary plastics → Demand of secondary plastics → Investment in new technologies and infrastructures.

Reinforcing loop 2: Investment in new technologies and infrastructures → Capacity of recycling plastics within the EU → Economies of scale → Cost of recycling → Capacity of producing high-quality secondary plastics → Compliance with restrictions on legislation → Demand of secondary plastics → Investment in new technologies and infrastructures.

Reinforcing loop 3: Investment in new technologies and infrastructures → Capacity of recycling plastics within the EU → Economies of scale → Cost of recycling → Capacity of producing high-quality secondary plastics → Certification → Consumers' acceptance of recycled content → Demand of secondary plastics → Investment in new technologies and infrastructures.

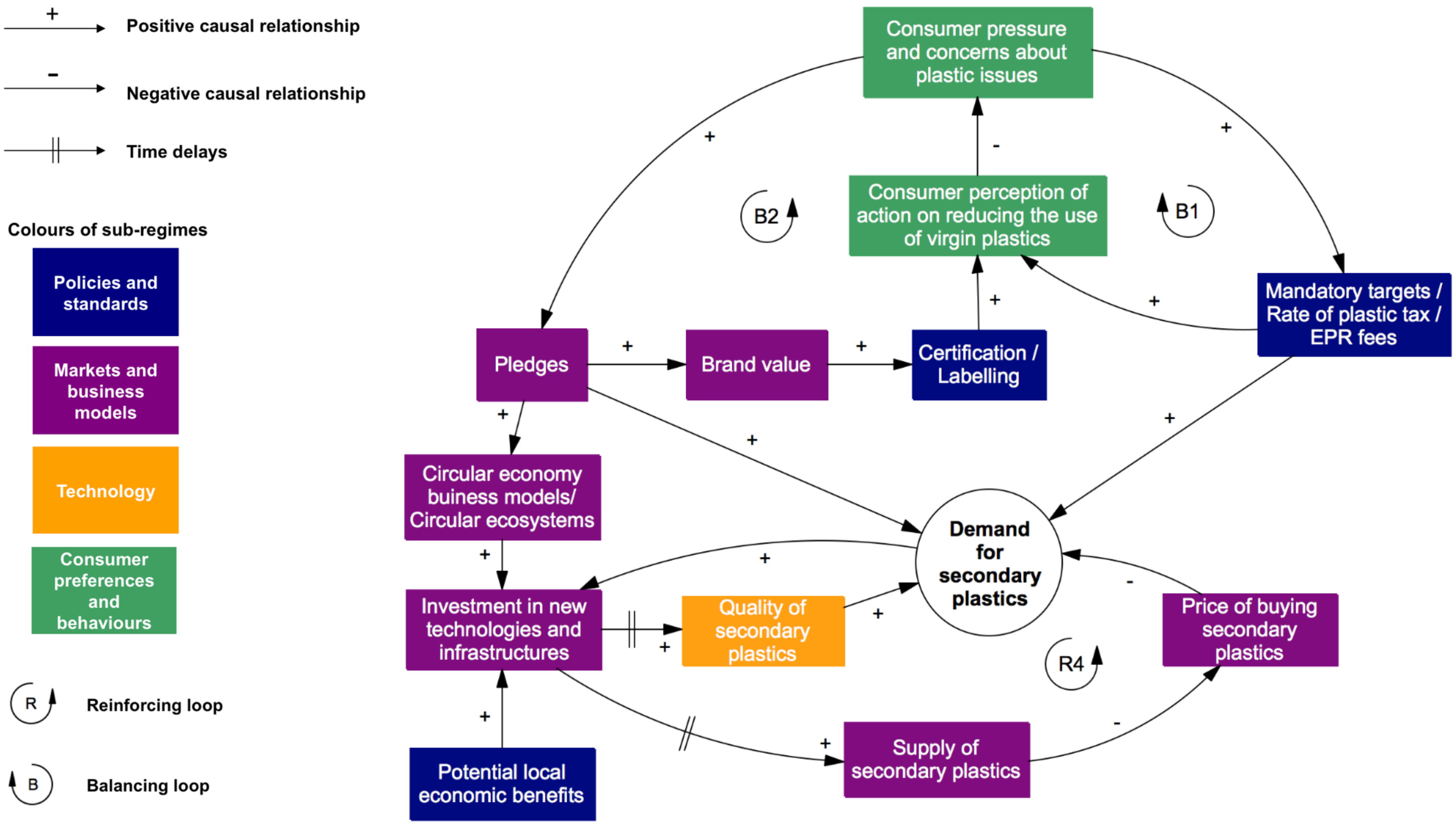


Figure 5-11 Web of drivers

- **Web of drivers**

Figure 5-11 depicts the CLD of the web of drivers. A reinforcing loop (R4) here is that a lower price for buying secondary plastics is a driver in some cases, which leads to increase in the demand for secondary plastics. The higher demand for secondary plastics would increase the investment in new technologies and infrastructures. More investment in new technologies and infrastructures can increase the supply of secondary plastics. When the supply of secondary plastics is increased, the price of buying secondary plastics can be lower. More potential local economic benefits can lead to more investment in new technologies and infrastructures. More investment in new technologies and infrastructures can increase the quality of secondary plastics. The higher the quality of secondary plastics, the greater the increase in the demand for secondary plastics.

Mandatory targets/plastic taxes/EPR fees and pledges are the main drivers to increase the demand for secondary plastics. Consumer pressure and concerns about plastic issues leads to the introduction of new policies on mandatory targets/plastic taxes/EPR fees. These new policies on mandatory targets/plastic taxes/EPR fees increase the consumer perception of action on reducing the use of virgin plastics. The higher consumer perception of action on reducing the use of virgin plastics can reduce consumer pressure and concerns about plastic issues, creating a balancing loop (B1).

Another balancing loop (B2) is that consumer pressure and concerns about plastic issues leads the actors across the value chain to make voluntary pledges. More pledges can increase the brand value. In order to increase the brand value, the firms may apply for more third-party certifications or put more labelling for recycled content as evidence of the safety and quality of the recycled plastics. More certification/labelling for recycled content and recyclability may increase the consumer perception of action on reducing the use of virgin plastics. However, the effects of certification/labelling will vary for different consumers (#12, #13) (Starr and Brodie, 2016). Again, the higher consumer perception of action on reducing the use of virgin plastics can reduce consumer pressure and concerns about plastic issues. These increasing pledges may enhance the emergency of circular economy business models and/or circular ecosystems. The more development of circular economy business models and/or circular ecosystems, the greater the increase in the investment in new technologies and infrastructures.

The CLD of the web of drivers in Figure 5-11 shows that B1 and B2 are connected with each other. If mandatory targets are introduced, it can eventually reduce consumer pressure and concerns about plastic issues, thus reducing the need for actors to continue to make voluntary pledges. In this case, however, the overall demand for secondary plastics may not increase, which means the mandatory targets may not be an effective policy. The CLD of the web of drivers shows this possibility, however, this requires further investigation and modelling tests.

Feedback loops in the CLD of the web of drivers include:

Reinforcing loop 4: Price of buying secondary plastics → Demand of secondary plastics → Investment in new technologies and infrastructures → Supply of secondary plastics → Price of buying secondary plastics.

Balancing loop 1: Consumer pressure and concerns on plastic issues → Mandatory targets/ Rate of plastic tax / EPR fees → Consumer perception of action on reducing the use of virgin plastics → Consumer pressure and concerns on plastic issues.

Balancing loop 2: Consumer pressure and concerns on plastic issues → Pledges→ Brand value → Certification/Labelling → Consumer perception of action on reducing the use of virgin plastics → Consumer pressure and concerns on plastic issues.

Summary of web of constraints and web of drivers

The CLDs provide a system perspective to help visualise the interrelatedness between the factors across different sub-regimes. I gathered evidence on the casual relationships of using secondary plastics from the actors across the value chain to explore the feedback loops. The results of reinforcing loops highlight the interconnected factors that show how the snowballing effect destabilises the system. Namely, the reinforcing loops leverage the changes through smaller investments and make big effects. The balancing loops represent the interconnected factors that attempt to bring conditions into equilibrium. In this study, this means the consumer may not continue to put more pressure on policymakers and brand owners or have more concerns about plastic issues once the voluntary pledges, mandatory targets, and economic instruments (e.g., plastic taxes, EPR fees) are made. The strength of these feedback loops could change over time.

The web of drivers reveals that the power from the consumers leads the actors along the value chain to make pledges, as well as push the change of legislation. Voluntary pledges, mandatory targets, and economic instruments (e.g., plastic taxes, EPR fees) create demand-pull. However, consumer acceptance of recycled content and recycling accuracy remain barriers within the web of constraints.

Increasing the demand for secondary plastics still faces a multitude of constraints and path dependencies. The availability and purity of plastic waste, the recycling capacity, lack of economies of scale, the quality of secondary plastics together with the high costs for sorting plastic waste, recycling, and high price of purchasing high-quality secondary plastics inhibit the demand for secondary plastics.

The results thus reveal the co-evolution of policies and standards, markets and business models, technology, and consumer preferences and behaviours. Multiple journeys (Grubb et al., 2017) have been emerging in the plastic circular economy transition. The consistent and systematic policy mixes (e.g., harmonised labelling, waste collection system and legislation, improving standards, establishing product passports, developing user-friendly and smart collection systems, expanding recycling capacity, financing new digital, sorting and recycling technologies, providing economic incentives for redesigning products and using recycled content, and education campaigns) can potentially break these vicious circles. Through diffusion and codification of knowledge to create technology-push, different actors across the value chain have been developing new networks and playing multiple roles in engaging with the co-evolutionary dynamics.

It is worth noting that the CLDs are limited to interviews and literature. The information from the interviewees is employed to represent a collective voice from the actors along the plastic value chain in the EU and the literature is combined as a triangulation. Therefore, further empirical studies are needed to validate the developed CLDs. Due to the complexity of social-economic-technological interactions, some causal relationships are likely to be false due to the limitations of the evidence gathered. Validation will require conventional statistical analysis to establish relationships (e.g., Bayesian statistics, regression analysis). The developed CLDs can serve as a blueprint to decide how best to collect quantitative data to further validate the casual relationships and feedback loops. For example, designing policies for mandatory targets and/or plastic tax will require conducting surveys on the consumer perception of action on reducing the use of virgin plastics, and consumer pressure and concerns about plastics, and collecting the data on voluntary pledges, demand for secondary plastics, investment in new technologies and infrastructures, supply of secondary plastics etc. Modelling the system dynamic can help to assess the effectiveness of the policy interventions.

6 Discussion

6.1 Overall discussion of the integrated MFA and TA

MFA is a powerful tool for describing the flows within the system. However, it cannot tell us why the flows are as they are. The qualitative TA provides an attempt to explain the observed patterns, and to put them in the context of the socio-technical regime that is producing the flows. Chapter 6 integrates MFA and TA, by bringing the results of quantitative MFA and qualitative TA together for discussion, thus building a more comprehensive understanding of the plastic system in the EU. Qualitative TA helps to validate the amount within the plastic flows and further explains the reasons why the results of quantitative MFA show that the existing plastic system in the EU is non-circular. Qualitative TA also explores the existing and emerging drivers, as well as the interactions across different sub-regimes in dynamic transition. Hence, integrated interpretation of MFA and TA can achieve greater insight into the dynamic transition of plastic system. This study presents the findings within the EU as a whole, but each European country may face similar, though different, outcomes from the identified barriers and drivers. For example, evidence indicates that member states with landfill restrictions have higher plastic recycling rates (Plastics Europe, 2017).

The pressure from the landscape and the scale of plastic pollution shows the need for radical transformation in the European plastics system. Both parts of the analysis in this thesis respond in different ways to the challenges. The material flow analysis (MFA) results show the scale of current plastic flows entering ten end-of-life routes. The majority of this plastic waste enters non-circular routes including landfills, incineration, exports and losses to the environment. Among these ten routes, only 4 Mt out of 37 Mt of plastic waste returns to the plastic manufacturing process in Europe.

The MFA results link to transition analysis (TA) results to further understanding the barriers and drivers that would constrain or to increase the use of secondary plastics along the value chain and across four main application areas. The TA results show that barriers interacting with different sub-regimes create a web of constraints. On the other hand, the pressure from the landscape and niche innovations creates windows of opportunity to destabilise and restructure the regime, resulting in a web of drivers. The findings respond to the call from the literature for further analysis of the interactions among different factors inhabiting the plastic circular economy transition. The emerging networks and business models show how different actors participate in this co-evolution dynamic to direct plastic waste to circular pathways. MFA and TA provide complementary perspectives for a more comprehensive picture of a plastic circular economy transition (see Table 6-1).

Table 6-1 Summary of the findings of MFA and TA

Landscape		**Sustainable Development Goals (SDGs) | Climate change | Circular economy | Plastic pollution | China's plastic waste import ban | Covid-19 pandemic**				
Lifecycle stage		**Polymers and fibres production and consumption**	**Product manufacturing**	**Product consumption**	**Waste generation**	**Waste treatment**
Actors		Petrochemical producer Converter | Compounder Distributor | Trader	Manufacturer	Brand owner Retailer End-consumer	Municipality EPR organisation Waste management company	Mechanical recycler Chemical/Solvent-based recycler Broker
Material flows		Total production 66,786 kt Total consumption 66,623 kt	Total products production 67,834 kt	Total production consumption 73,481 kt	Total plastic waste generation 37,068 kt	10 End-of-Life routes Secondary plastics used in the EU 4,025 kt
Policies and standards	B	Lack of standards and clarity in definitions	Compliance with restrictions of legislation	Lack of standardisation to measure progress	Diverse waste collection systems Labelling of recycling instruction	Problems of the collective EPR scheme
	D	Guidelines and definitions of recyclability and recycled plastics	Mandatory targets Green public procurement Plastic tax, EPR fees	Anticipated future policy Certification/Labelling	EPR scheme DRS (Deposit Return Scheme) RVM (Reverse Vending Machines)	Recycling targets Potential local economic benefits to develop recycling capacity
Markets and business models	B	Uncertainty over the available quality and quantity of secondary plastics and plastic waste	Established norms and routines Additional costs to change infrastructures in some cases Uncertainty of long-term secondary plastics availability	High risk aversion Uncertainty over the available quality and quantity of secondary plastics	Availability of plastic waste collection High costs of sorting plastic waste	High costs and lack of economies of scale Exporting plastic waste outside of the EU Plastic waste sent to other waste treatment Uncertainty of the demand from brand owners' commitments
	D	Direct consumer demand Searching for competitive advantage in the face of possible disruption	Direct consumer demand Searching for competitive advantage in the face of possible disruption	Brand value Pledges New emerging business model experimentation and ecosystem building	New emerging business model experimentation and ecosystem building	Direct consumer demand New emerging business model experimentation and ecosystem building
Technology	B	Technical specifications of different plastic polymers	Technical specifications of different products	Quality of secondary plastics	Cross-contamination Immature sorting technologies	Plastic waste with legacy additives Lack of plastic recycling capacity in the EU Technology readiness level
	D	Better tracing technologies	Better tracing technologies	Better tracing technologies	Better tracing technologies	Emergence of solvent-based and chemical recycling possibilities
Consumer preferences & behaviours	B			Consumers' acceptance of recycled content	Consumers' recycling accuracy	
	D	Consumer pressure and concerns on plastic issues				
Data-information-knowledge		Origins, quality, availability and reliability of plastic polymers/feedstocks Technical knowledge of secondary plastic composition	Design for/from recycling Product composition	Measuring progress towards the targets of recycled content and recyclability	Recycling instructions Material composition	Provenance of plastic waste Knowledge of recycling technologies
Research gaps for MFA		Flows of recycled feedstock from plastic waste	Plastic-containing product composition analysis Flows of intermediate products	Dynamic stock modelling to predict the potential secondary plastics supply	Plastic-containing waste composition analysis Individual plastic-containing waste flows from different collection systems	Fate of the plastic waste Flows of secondary plastics
Networks		**Circular Plastics Alliance | Joint industry value chain initiative | Plastic Pact | EU funded projects | Alliance to End Plastic Waste**				
Niches		**Radical technical innovation | Infrastructural innovation | Business model innovation | Grassroots and social innovation**				

B Barriers D Drivers

- **Significant data gaps for a plastic circular economy transition**

Both the MFA and TA findings reveal significant data gaps in the plastic system, highlighting that data, information and knowledge are key factors in the transition. The MFA, with over 400 categories of plastic-containing products, showed significant data gaps regarding plastic composition because of the different types of plastic polymers widely used in products across different application areas. The same product categories manufactured by different firms have different product compositions, which makes it difficult for individual plastic polymers to be tracked across the value chains. Most of the data for the MFA are collated from statistical databases such as UN Comtrade and Eurostat database. This study shows that in the case of plastics data, both virgin and secondary plastics data are aggregated within the same product categories, making it challenging to track highly aggregated semi-finished plastic-containing products on the upstream in the statistical database.

On the downstream, the plastic waste data is highly aggregated as much plastic waste is either collected in the mixed waste stream or embedded in WEEE, ELV, and construction waste streams. The MFA shows the data gaps for tracking quantities of both plastic materials and plastic waste. Improving data is important to improve the understanding of material flows, and thus inform better policy, and reveal opportunities for secondary plastic markets.

When promoting a circular economy, both the quantity and quality of secondary plastics are important. The TA further explored the barriers related to data gaps for tracking the qualities of both plastic materials and plastic waste. It showed that efforts to improve data are constrained by a wide set of barriers. TA highlights the role of data-information-knowledge along the value chain and across different sub-regimes creating a web of constraints. Several practical cases show how different actors across the value chain build up new networks and play multiple roles to share the data, information and exchange knowledge to create a circular economy system.

- **MFA-based knowledge is needed to inform policies for addressing the barriers at the regime level**

Both the MFA and TA identified research gaps related to material flows at each lifecycle stage. This highlights the value of combining these methodologies, which would identify a set of research gaps for future MFA (see **Error! Reference source not found.**). MFA itself is critical for gauging the relative importance of different flows, and hence the relative importance of barriers to circularity related to those flows, as identified by the TA.

At the production and consumption stages of plastic polymers and fibres, there is a need to develop MFA models that can track flows of recycled feedstocks. This can help address the uncertainty over the availability of secondary plastics and plastic waste. Technical knowledge of secondary plastic composition and chemical formulations is needed to overcome the technical barriers.

At the product manufacturing stage, flows of intermediate plastic-containing products need to be further investigated, as they are highly aggregated in the current statistical datasets. It is necessary to investigate plastic-containing product composition, which can inform the labelling of recycling instructions and improve waste sorting and collection systems.

At the product consumption stage, developing dynamic stock modelling can help to forecast future waste flows for the potential secondary plastic supply. Eriksen et al. (2020), Ciacci et al. (2017) have done the dynamic material analysis of the PET, PE, PP and PVC flows in Europe to evaluate the potential for a circular economy. As PS and other plastics are facing barriers regarding lack of economies of scale to recycling, developing dynamic stock modelling of PS and other plastics is suggested. Modelling stocks of PS and other plastics can provide knowledge to better understand future waste flows and explore the potential solutions for moving towards a circular economy.

At the waste generation stage, a plastic-containing waste composition analysis is needed to develop new sorting and recycling technologies, inform how to design for/from recycling, and inform the policymaking regarding the problems of legacy additives. There are diverse waste collection systems and highly aggregated waste generation statistical datasets. Antonopoulos et al. (2021) measured the flows of plastic packaging waste by collecting primary data from material recovery facilities and recycling plants in the EU. Further studies are needed to track individual plastic-containing waste flows across different collection systems (e.g., kerbside-sorted waste collection, kerbside-commingled waste collection, central waste collection stations, commercial and business waste collection, deposit return scheme, WEEE collection points, plastic packaging collection points at retail stores).

At the waste treatment stage, tracking the flows of secondary plastics and the fate of the plastic-containing waste generated from the EU are recommended. Lase et al. (2023)

project different scenarios for plastic MFA in the EU27+3, accounting for different recycling routes in 2018 and 2030. Further research is recommended to collect primary data to monitor the current flows of secondary plastics along different recycling routes. This will allow the establishment of indicators that can measure the progress toward the targets of recycled content. Navarre et al. (2022) mapped the fate of the plastic food packaging waste generated by the Netherlands and exported to Asia, which revealed that the fate of this plastic food packaging waste is leaked to the marine environment. Further studies are needed to better understand the fate of different plastic-containing wastes generated within the EU, as well as tracking the flows of secondary plastics used in the EU. Understanding these flows will provide scientific evidence to aid the formulation of plastic circular economy policy.

Improving the MFA at the waste treatment stage will also inform policymakers what the needs are for investments in new infrastructures and increase the recycling capacity within the EU. This will prevent plastic waste from being sent to other waste treatment or exports outside the EU.

- **Potential socio-technical changes can reshape plastic flows**

Integrated MFA and TA can provide more insights into how the potential socio-technical changes on different levels might contribute to reshaping plastic flows in the future. The following paragraphs provide a narrative discussion, which can serve as a blueprint to develop a quantitative scenario analysis.

Landscape level

At the landscape level, the main factors include the circular economy, oil prices, China's plastic waste import ban, SDGs, climate change, plastic pollution, and the pandemic. The political salience of the circular economy and SDGs generates the policy pressure at the regime level that can lead to increasing the number of circular flows such as reduce, reuse, repair, remanufacture, and recycle. These circular flows need to be tracked and included in a future MFA. The fluctuation of oil prices affects the price of virgin plastics, and the changes in monetary flows between virgin plastics and secondary plastics affect the material flows. China's plastic waste import ban affected the flows of plastic waste exports, although most of the plastic waste was sent to other countries outside of the EU in the past few years. However, if this plastic waste can be recycled within the EU in the future, the plastic waste export flows can be reduced, while recycling and/or energy recovery flows can be increased. Due to the pandemic, the overall production of plastics has temporarily decreased, while consumption of some plastic products has increased, such as single-use face masks, personal protective equipment, and packaging for delivery. Thus, the pandemic has affected the flows of plastic production and consumption.

Plastic pollution also increases the flows of plastic waste entering into the environment. Driven bottom-up by citizen and NGO initiatives, very few amounts of ocean plastics have been collected and recycled into new products for marketing purposes. However, this new flow is normally omitted on the MFA due to its less quantitative impact and lack of data.

It is important to note that the use of plastics and shifts towards the use of secondary plastics are affected by many other different possible factors on the landscape level. These factors, beyond the influence of actors within the European plastic system, include demographics, food poverty, trade agreements, and regulations in other systems. These external conditions can also have long-term effects on the changes in plastic flows.

Regime level

At the regime level, institutional and political mechanisms, social and cognitive mechanisms, and techno-economic mechanisms have the potential to change future plastic flows and shift to a plastic circular economy.

For the institutional and political mechanisms, action driven top-down by governments to expand EPR schemes, strengthen regulations to prevent plastic waste from entering non-circular destinations (e.g., landfill bans) and strengthen regulations to force the waste to be treated within Europe. Such actions can help to reduce the plastic waste flows to landfills, exports outside of Europe, and losses to the environment, as well as increase the flows of recycling and energy recovery.

Although mandatory targets as a demand-pull policy are not suitable for all plastic and plastic-containing products, setting mandatory targets for some specific plastic products can increase the secondary plastic flows. The mandatory targets, including at least 30% recycled content in plastic bottles by 2030, and the requirement of a construction and building tender with recycled content in PVC window frames in some regions, will help to increase the amount of secondary plastic flows and the proportion of recycled plastic consumption. Economic incentives (e.g., plastic taxes) can also play an important role.

Improving collection systems is the key intervention to reduce the discrepancy between flows of waste collection and flows of recycling, as well as reduce the flows to non-circular destinations. Clarifying chemical legislation, definitions of waste and products, and harmonising standards and certifications are the other relevant top-down institutional and political mechanisms required to develop information and knowledge flows, which can indirectly support to reshape plastic flows.

Social and cognitive mechanisms involve educating actors, changing mindsets and behaviours, and strengthening stakeholder collaboration. These actions can influence the whole plastic system, especially on the plastic flows of production and consumption, as well as the flows to waste collection. The changes of flows affected by social and cognitive mechanisms may be hard to quantify.

For the techno-economic mechanisms, enhancing design not only changes the proportion of production flows between virgin plastics and secondary plastics, but also improves the plastic flows at the waste collection and treatment stages and directs them towards circular destinations. Destabilising the existing path dependencies of the waste treatment system would rely on investing in collection, sorting and recycling infrastructures. Investment in advanced technologies and infrastructures can help to increase the recycling capacity and quality, and eventually reshape the plastic flows.

Niche level

The niche innovations, including innovative manufacturing, collection, sorting and recycling technologies, innovative plastic manufacturing factories and recycling facilities, business model innovation, and grassroots and social innovation, clearly supports the development of infrastructures and changes the actors' behaviours to reshape the plastic flows in the long-term. These innovations, however, may not bring about changes to the plastic flows in the beginning of transition process. Reshaping the plastic flows would depend on whether the niche innovations succeed or not and will require more time to investigate.

6.2 Comparison with other studies

6.2.1 Comparison with other plastic material flow analysis studies

Building on previous studies, this study provides a more exhaustive examination of plastic flows with detail for over 400 product categories and a comprehensive analysis of waste treatment and EoL flows within the EU in 2016. The findings of the study are largely aligned with previous work. The estimation of 66 Mt total production in this study is higher than 60 Mt reported by Plastics Europe (2017), which may be explained by the inclusion of some different plastic polymers and fibres. Kawecki et al. (2018) estimated the order of consumption as PP> LDPE > PET > HDPE > PVC > PS > EPS. This study estimated the order of consumption as PP> LDPE> HDPE> PVC> PET> PS. The consumption of PET is lower in this study because the production, trade and consumption flows of fibres are separated from the flows of PET polymers and entered into the process at the same point, while the plastic system defined by Kawecki et al. (2018) considered PET polymer production first, followed by fibre production, and they separated the textile manufacturing and non-textile manufacturing.

For the potential leakage, this study estimates 3,380 kt of mismanaged plastic waste, which is consistent with the estimation by Lebreton and Andrady (2019). Lebreton and Andrady (2019) suggest 3.3 (1.3–9.1) Mt mismanaged municipal plastic waste in Europe, defined as unsound disposal, including urban litter and open dumps, based on population density, GDP distributions, per capita municipal solid waste generation and an estimate of the mismanaged fraction. This study estimates of losses of microfibres from washing clothes are aligned with that of Hann et al. (2018), however, this study shows losses from manufacturing are lower than Hann et al. (2018). This may be because the transfer coefficient applied in this study originally came from a survey of firms operating in the best practices (Lassen et al., 2015) and, as a consequence, the estimation of this study may be more optimistic. Despite the inherent uncertainty of estimates of losses, this study and others point to the flows of losses being a major area of concern with associated environmental implications.

6.2.2 Comparison with other plastic circular economy transition studies

Although plastic waste has been mechanically recycled for many years, the year 2018 was a turning point to accelerate the transition towards a plastic circular economy. Many drivers occurred in 2018, but most of the relevant studies were conducted before 2018, and this research has attempted to assess the drivers and barriers of the ongoing transition to close the loop of plastics in the EU.

The findings of barriers are mostly aligned with previous studies, but many drivers have emerged and led to new changes in the system. Technical barriers to mechanical recycling remain the same as the found in study from Hahladakis and Iacovidou (2019), but more investments and development in mechanical recycling, solvent-based recycling and chemical recycling have emerged. Other regulations and market barriers for new recycling technologies have also appeared. The price of secondary plastics is a key factor, but no longer the single factor that businesses have used to decide on or decline the use of secondary plastics anymore. This is due to the pressure from the landscape, concerned consumers and EU legislation. As the demand increases, secondary plastics may be even more expensive than virgin plastics.

In contrast to Milios et al. (2018), which identified a 'lack of demand' as a barrier, the interviews I conducted suggested that the demand for secondary plastics has become a driver. Paletta et al. (2019) identified the barriers of low consciousness on single-use packaging consumption and customers' disinterest toward secondary plastics, while the findings of this study show that the consumers' awareness and interest in secondary plastics have become a driver in recent years. This shows that factors identified as barriers in other studies could be both barriers and drivers in different situations according to the findings in Section 5.

As with Milios et al. (2018), Paletta et al. (2019), Gong et al. (2020), the analysis presented here identifies collaboration as an enabler of a plastic circular economy transition. Additionally, this study identifies, in detail, that many new collaborations have been developed in the past few years, especially across the value chain and application areas, including: the Circular Plastics Alliance; Plastics Pacts (EMF's Plastic Pact, European Plastics Pact, and the UK, the Netherlands, France, Portugal, and Poland Plastic Pacts); EU funded projects; and the Alliance to End Plastic Waste. These networks and changing business models drive the demand for secondary plastics, for use by companies who have pledged to use these materials. The networks and changing business models also help to overcome the barriers from the sub-regimes of market and technology, plus they improve the development of data-information-knowledge.

Aligned with Milios et al. (2018), European Commission (2018a), Paletta et al. (2019), this empirical work identified the barrier 'lack of traceability and transparency'. To be more specific, this study has specifically identified the types of data, information and knowledge that are needed at each lifecycle stage along the plastic value chain. The work also explored the data-information-knowledge that has been developing across four application areas (packaging, construction, automotive, electrical and electronic equipment). The findings regarding the barriers of data-information-knowledge highlight that shifting to a circular system is much more data-information-knowledge-intensive than a linear economy. This imposes real costs, such as companies needing to perform additional laboratory testing etc., but these costs could be reduced through standardisation and better tracing data on product composition. Overcoming the barrier regarding the traceability for both plastic waste and secondary plastics would rely on technologies, business networks and certification.

6.3 Research limitations

The present study posed limitations on flow-quantitative, transition-qualitative research and integrated MFA and TA discussion.

For flow-quantitative research, different references and databases have different definitions of plastics, thus creating a challenge in conducting an MFA, especially in ensuring the data collated from different sources and at different lifecycle stages have the same scopes of plastics.

Most of the production and trade data are secondary data extracted from the Eurostat and UN Comtrade databases. These production and trade data have some outliers or missing values, because the original data relies on reporters, and different reporters may have different reporting standards and processes (Chen et al., 2022). Moreover, Eurostat aggregated the EU28 level data based on the arithmetic sum of 28 member states at national levels, and the member states updated their data at different times. I have contacted the Eurostat user support team several times, because the data had been changing over time when I did the data collection. Eurostat explained that they previously had a bug in the aggregation process, which they had addressed after I contacted them. However, small differences in the data are probable and normal due to updates of the member states' national values. Corrections to the arithmetic aggregation of the values of national levels shall continue to be made at each update until a permanent fix is in place.

Data quality is another limitation, especially the flows of intermediary products into final product categories, the plastic fraction in products, mixed plastic waste categories (as in other plastic waste shown in the MFA), plastic waste in different polymer types, flows of reuse, and the estimation of losses. To enhance the robustness of the MFA results and to further expand the analysis of polymer flows, the data availability around these aforementioned areas would need to be improved. Another limitation is that, while the MFA results mainly address the hotspots of non-circular pathways based on the material quantity, they can hardly represent the material quality/grades and their environmental, economic, and social impacts. The MFA results can therefore serve as a basis for further assessment, such as life cycle assessment.

For transition-qualitative research, a weakness is that policymakers and end-consumers were not direct participants in the interviews, although the relevant factors were included in the study, since consumer and policy issues were discussed by participants. The sample size was limited by the actors across Europe who agreed to take part in this study. In total, 142 potential interviewees/companies were contacted, however, only 26 interviewees agreed to participate in this study. This study is a self-funded project, therefore, it has several limitations regarding financial support and networking, such as not being able to recruit more participants and hold workshops for further discussion on developing CLDs. A greater number of interviewees would be needed to further compare the barriers and drivers between different geographical regions. As the field is a commercial market, the interviewees may have been wary of disclosing information that they felt might have an effect on their position in the market, or on the application of more onerous regulations and operating procedures. Because the EU target is to use 10 million tonnes of secondary plastic in the market by 2025, this study concentrated on identifying the different types of barriers and drivers to using secondary plastics. Nevertheless, I acknowledge the importance of other circular strategies in a plastic circular economy transition and recommend addressing the barriers and drivers of the other circular strategies in a more holistic way.

For integrated MFA and TA discussion, not all the barriers and drivers across three levels of the MLP can be quantified, as most of the barriers and drivers are qualitative data from interviews and literature. Therefore, the discussion brings two parts of the results together through a narrative description. These limitations point to potential avenues for future research, which are listed in the next chapter.

7 Conclusion

7.1 Summary of research findings and contribution

This PhD research conducted material flow and transition analyses to investigate the current flows of plastics in the EU and the barriers and drivers to the use of secondary plastics. A comprehensive plastic MFA for the EU shows more than 66 Mt of plastic polymers and fibres were produced, 73 Mt plastic-containing products were consumed, and more than 37 Mt plastic waste were generated. However, only around 4 Mt of secondary plastics were returned to the EU market. The detailed examination of plastic waste destinations in this study shows that plastics in the EU are still far from being circular.

The analysis has also highlighted profound data gaps, especially for plastic fraction estimation of complex products. Such data are not routinely collected, and the available data are outdated. Further research is needed to update data on the plastic fraction of products. The movements of the market towards blockchain and big data applications with details of product composition have the potential to improve the traceability of plastics throughout the whole system. The requirements of improving data quality and availability allow for reliable monitoring of plastic management, and for more accurate assessment of opportunities and infrastructural gaps.

Based on the findings, six strategies, combining a range of policy instruments, and behavioural and technological interventions, are recommended to move towards more circular pathways. This MFA study can help to monitor the progress of ongoing plastic circular economy policy strategies and point to areas of future development.

Through a MLP, the findings show that the barriers and drivers to secondary plastics use are complicated interactions rather than linear cause-and-effect. The year 2018 was a turning point for accelerating the transition, as many drivers emerged, including adopting A European Strategy for Plastics in a Circular Economy, amending the Circular Economy Package, launching the Circular Plastics Alliance, the proposal of Green New Deal, China's plastic waste import ban, and increased consumer awareness and acceptance increased.

This transition analysis (TA) provides an overview of the ongoing transition to a plastic circular economy especially focusing on the strategy of increasing the use of secondary plastics, and analysing the barriers and drivers along the value chain and across four application areas. The results show that the pressures from the landscape create the windows of opportunities to destabilise the linear economy system. The main drivers for the adoption of secondary plastics come from EU legislation and consumer pressure, especially in packaging applications. In light of consumer pressure, marketing and reputation management have emerged as relevant drivers to adopt secondary plastics, however, the findings also point to the persistence of barriers that limit the use of secondary plastics. Policies and standards, technological, and consumer preference and behaviour barriers linked to the quantity and quality of recycled plastics, especially in the EEE and automotive sectors, have limited the uptake of secondary plastics. From a market perspective, this study identifies barriers associated with the high costs of producing secondary plastics, and investment risks in light of uncertain consumer demand and future policy. Across all applications, the study highlights the importance of, and challenges with, networking and new business model development. The plastic system transition is further hampered by a lack of data, poor traceability of material origins, and historically weak knowledge diffusion across the value chain. This study highlights efforts to overcome these barriers, such as attempts to codify knowledge through the development of guidelines for eco-design of products, and the establishment of certifications and labels to increase traceability.

The main contributions of this PhD research can be listed. Firstly, this study applies a comprehensive MFA to quantify plastic flows in the EU. It is based on a more detailed product-by-product analysis of plastic products and plastics contained in other products than has hitherto been published (covering over 400 product categories), and provides a detailed exploration of end-of-life destinations of plastic waste and an estimation of losses from the system. Secondly, this study contributes to understanding the transition dynamics towards a plastic circular economy in the field of transition studies, using the multi-level perspective theoretical framework. Specifically, this study reveals the interactions between barriers and drivers, affecting the use of secondary plastics, for a number of sub-regimes. The work covers the whole value chain analysis with new insights into the role of data-information-knowledge and networks. Last but not least, the material flow and transition analyses have demonstrated the value of bringing together two typically separate bodies of theory (industrial ecology and transition theory). This thesis has thus made a contribution to the development of interdisciplinarity across these fields. The findings allowed systemic understanding of transformation processes, which interconnect the material flows, actors, data-information-knowledge, and other factors (policies and standards, markets and business models, technology, consumer preferences and behaviours) in a sociotechnical transition.

7.2 Avenues for future research

This study has shed the light on the comprehensive plastic flows in Europe, the factors lock-in the use of secondary plastics and proposed the circular pathways with mechanisms to stimulate the use of secondary plastics. Building on this thesis, further research is encouraged as this topic is rapidly evolving and will need more pieces of scientific evidence to support the policymaking.

Further MFA research would benefit from surveys of value chain stakeholders about plastic product composition, to fill the data gaps. This opens up many avenues for research and the dissemination of knowledge, as plastics have been widely used in numerous sectors. Surveys will be needed to investigate the composition of products that use different types of virgin plastics, secondary plastics, and additives in different applications. This would enable/enhance the segregation of plastic waste, the setting of standards for the use of secondary plastics and redesign of products. The combination of material flows and monetary flows for future work is recommended, as the circular economy tends to provide economic benefits, but secondary plastics may not always be the cheapest option. Based on this MFA, further environmental impact and social impact assessments and evidence, comparing virgin plastics, secondary plastics, and new alternative materials (e.g., bioplastics), could be provided. A study over a longer timeframe could also help to investigate the change in plastic flows throughout the plastic circular economy transition processes.

Further MLP research of the plastic circular economy can analyse the other circular economy strategies, including slowing the loop and narrowing the loop, such as repair, product-service systems, and alternative bio-materials. Most of the existing studies have focused on the barriers of legislation, technology and economy. This study further analysed the network and business model, and the role of data-information-knowledge. Future studies can further investigate the socio-cultural norms, especially how to reduce the discrepancies between consumer awareness and consumer purchasing decisions and disposal behaviours. Moreover, plastic packaging has drawn more attention, therefore, this study attempts to compare the differences across packaging, construction, EEE, and automotive at the regime level. Future studies analysing barriers and drivers of a plastic circular economy in other applications (e.g., textiles), are suggested. Last but not least in terms of MLP research, further work is recommended to show whether innovations at the niche level in Europe affect the transformation of the plastic system.

Further research on the combination of MFA and TA could be conducted by linking the MFA with the proposed CLDs to develop simulation models using system dynamics. However, such research will require more quantitative data and a scenario analysis to explore, more deeply, how socio-technical development can change plastic flows and quantitatively evaluate potential pathways that may be better in transitioning towards a more circular plastic future.

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Appendices

Appendix A List of plastic polymers and fibres

Polymers
PET (1)
20164062 - Polyethylene terephthalate in primary forms having a viscosity number of >= 78 ml/g
20164064 - Other polyethylene terephthalate in primary forms
HDPE (2)
20161050 - Polyethylene having a specific gravity of >= 0,94, in primary forms
PVC (3)
20163010 - Polyvinyl chloride, not mixed with any other substances, in primary forms
20163023 - Non-plasticised polyvinyl chloride mixed with any other substance, in primary forms (70% (Kawecki et al., 2018))
20163025 - Plasticised polyvinyl chloride mixed with any other substance, in primary forms (70% (Kawecki et al., 2018))
LDPE (4)
20161035 - Linear polyethylene having a specific gravity < 0,94, in primary forms
20161039 - Polyethylene having a specific gravity < 0,94, in primary forms (excluding linear)
PP (5)
20165130 - Polypropylene, in primary forms
PS (6)
20162035 - Expansible polystyrene, in primary forms
20162039 - Polystyrene, in primary forms (excluding expansible polystyrene)
Other thermoplastics
20161070 - Ethylene-vinyl acetate copolymers, in primary forms
20161090 - Polymers of ethylene, in primary forms (excluding polyethylene, ethylene-vinyl acetate copolymers)
20162050 - Styrene-acrylonitrile (SAN) copolymers, in primary forms
20162070 - Acrylonitrile-butadiene-styrene (ABS) copolymers, in primary forms
20162090 - Polymers of styrene, in primary forms (excluding polystyrene, styrene-acrylonitrile (SAN) copolymers, acrylonitrile-butadiene-styrene (ABS) copolymers)
20163040 - Vinyl chloride-vinyl acetate copolymers and other vinyl chloride copolymers, in primary forms
20163060 - Fluoropolymers
20163090 - Polymers of halogenated olefins, in primary forms, n.e.c.
20164013 - Polyacetals, in primary forms
20164020 - Polyethers, in primary forms (excluding polyacetals, polyether alcohols)
20164040 - Polycarbonates, in primary forms
20164050 - Alkyd resins, in primary forms
20164090 - Polyesters, in primary forms (excluding polyacetals, polyethers, epoxide resins, polycarbonates, alkyd resins, polyethylene terephthalate, other unsaturated polyesters)
20165150 - Polymers of propylene or of other olefins, in primary forms (excluding polypropylene)
20165230 - Polymers of vinyl acetate, in aqueous dispersion, in primary forms

20165250 - Polymers of vinyl acetate, in primary forms (excluding in aqueous dispersion)
20165350 - Polymethyl methacrylate, in primary forms
20165390 - Acrylic polymers, in primary forms (excluding polymethyl methacrylate)
20165450 - Polyamide -6, -11, -12, -6,6, -6,9, -6,10 or -6,12, in primary forms
20165490 - Polyamides, in primary forms (excluding polyamide -6, -11, -12, -6,6, -6,9, -6,10 or -6,12)
20165920 - Petroleum resins, coumarone-indene resins, polyterpenes, polysulphides, polysulphones, etc., n.e.c., in primary forms
Thermosets
20164030 - Epoxide resins, in primary forms
20164070 - Unsaturated liquid polyesters, in primary forms (excluding polyacetals, polyethers, epoxide resins, polycarbonates, alkyd resins, polyethylene terephthalate)
20164080 - Unsaturated polyesters, in primary forms (excluding liquid polyesters, polyacetals, polyethers, epoxide resins, polycarbonates, alkyd resins, polyethylene terephthalate)
20165270 - Polymers of vinyl esters or other vinyl polymers, in primary forms (excluding vinyl acetate)
20165550 - Urea resins and thiourea resins, in primary forms
20165570 - Melamine resins, in primary forms
20165630 - Amino resins, in primary forms (excluding urea and thiourea resins, melamine resins)
20165650 - Phenolic resins, in primary forms
20165670 - Polyurethanes, in primary forms
Fibres
20601110 - Aramids staple, not carded, combed or otherwise processed for spinning
20601120 - Other polyamide tow and staple, not carded, combed or otherwise processed for spinning
20601130 - Polyester tow and staple, not carded, combed or otherwise processed for spinning
20601140 - Acrylic tow and staple, not carded, combed or otherwise processed for spinning
20601150 - Polypropylene synthetic tow and staple not carded, combed or otherwise processed for spinning
20601220 - High-tenacity filament yarn of aramids (excluding sewing thread and yarn put up for retail sale)
20601240 - High-tenacity filament yarn of nylon or other polyamides (excluding sewing thread, yarn put up for retail sale and high-tenacity filament yarn of aramids)
20601260 - High-tenacity filament yarn of polyesters (excluding that put up for retail sale)
20601310 - Polyamide textile filament yarn, n.p.r.s. (excluding sewing thread)
20601320 - Polyamide carpet filament yarn, n.p.r.s. (excluding sewing thread)
20601330 - Polyester textile filament yarn, n.p.r.s. (excluding sewing thread)
20601340 - Polypropylene filament yarn, n.p.r.s. (excluding sewing thread)
20601350 - Elastomeric filament yarn, n.p.r.s.
20601420 - Polypropylene monofilament of >= 67 decitex and with a cross-sectional dimension of <= 1 mm (excluding elastomers)

Appendix B List of plastic-containing products

Product category	Plastic fraction (%)
22 Manufacture of rubber and plastic products	
22.21 Manufacture of plastic plates, sheets, tubes and profiles	
22211050 - Monofilament with any cross-sectional dimension > 1 mm, rods, sticks, profile shapes, of polymers of ethylene (including surface worked but not otherwise worked)	100%
22211070 - Monofilament with any cross-sectional dimension > 1 mm, rods, sticks, profile shapes, of polymers of vinyl chloride (including surface worked but not otherwise worked)	100%
22211090 - Monofilament with any cross-sectional dimension > 1 mm; rods; sticks and profile shapes of plastics (excluding of polymers of ethylene, of polymers of vinyl chloride)	100%
22212153 - Rigid tubes, pipes and hoses of polymers of ethylene	100%
22212155 - Rigid tubes, pipes and hoses of polymers of propylene	100%
22212157 - Rigid tubes, pipes and hoses of polymers of vinyl chloride	100%
22212170 - Rigid tubes, pipes and hoses of plastics (excluding of polymers of ethylene, of polymers of propylene, of polymers of vinyl chloride)	100%
22212920 - Flexible tubes, pipes and hoses of plastics, with a burst pressure >= 27,6 MPa	100%
22212935 - Flexible tubes, pipes and hoses of plastics, not reinforced or otherwise combined with other materials, without fittings	100%
22212937 - Flexible tubes, pipes and hoses of plastics, not reinforced or otherwise combined with other materials, with fittings, seals or connectors	100%
22212950 - Plastic tubes, pipes and hoses (excluding artificial guts, sausage skins, rigid, flexible tubes and pipes having a minimum burst pressure of 27,6 MPa)	100%
22212970 - Fittings, e.g. joints, elbows, flanges, of plastics, for tubes, pipes and hoses	100%
22213010 - Other plates..., of polymers of ethylene, not reinforced, thickness <= 0,125 mm	100%
22213017 - Other plates..., of polymers of ethylene, not reinforced, etc., thickness > 0,125 mm	100%
22213021 - Other plates..., of biaxially orientated polymers of propylene, thickness <= 0,10 mm	100%
22213023 - Other plates..., of polymers of propylene, thickness <= 0,10 mm, others	100%
22213026 - Other plates..., of non-cellular polymers of propylene, thickness > 0,10 mm, n.e.c.	100%
22213030 - Other plates..., of polymers of styrene, not reinforced, etc.	100%
22213035 - Other plates, sheets, film, foil and strip, of polymers of vinyl chloride, containing >= 6 % of plasticisers, thickness <= 1 mm	100%
22213036 - Other plates, sheets, film, foil and strip, of polymers of vinyl chloride, containing >= 6 % of plasticisers, thickness > 1 mm	100%
22213037 - Other plates, sheets, film, foil and strip, of polymers of vinyl chloride, containing < 6 % of plasticisers, thickness <= 1 mm	100%
22213038 - Other plates, sheets, film, foil and strip, of polymers of vinyl chloride, containing < 6 % of plasticisers, thickness > 1 mm	100%
22213053 - Plates..., of polymethyl methacrylate, not reinforced, etc.	100%
22213059 - Plates..., of other acrylic polymers, not reinforced, etc., n.e.c.	100%

22213061 - Plates, sheets, film, foil, strip of polycarbonates, non-cellular excluding floor, wall, ceiling coverings - self-adhesive, reinforced, laminated, supported/similarly combined with other materials	100%
22213063 - Plates..., of unsaturated polyesters, not reinforced, etc.	100%
22213065 - Plates, sheets, film, foil, strip, of polyethylene terephthalate, not reinforced, etc., of a thickness <= 0,35 mm	100%
22213067 - Plates, sheets, film, foil, strip, of polyethylene terephthalate, not reinforced, etc., of a thickness > 0,35 mm	100%
22213069 - Plates, sheets, film, foil, strip of polyesters, non-cellular excluding floor, wall, ceiling coverings, self-adhesive - of polycarbonates, polyethylene terephthalate, unsaturated polyesters	100%
22213082 - Plates, sheets, film, foil, strip of polyamides, non-cellular (excluding floor, wall, ceiling coverings, self-adhesive, reinforced, laminated, supported/similarly combined with other materials)	100%
22213086 - Plates, sheets, film, foil and strip, of non-cellular poly(vinyl butyral), amino-resins, phenolic resins or polymerisation products, not reinforced, laminated, supported or similarly combined with other materials (excluding self-adhesive products as well as and floor, wall and ceiling coverings of H	100%
22213090 - Plates, sheets, film, foil and strip, of non-cellular plastics, n.e.c., not reinforced, laminated, supported or similarly combined with other materials (excluding self-adhesive products, floor, wall and ceiling coverings of HS 3918 and sterile surgical or dental adhesion barriers of CN 3006 10 30)	100%
22214120 - Plates, sheet, film, foil and strip of cellular polymers of styrene	100%
22214130 - Plates, sheets, film, foil and strip of cellular polymers of vinyl chloride	100%
22214150 - Plates, sheets, film, foil and strip of cellular polyurethanes	100%
22214180 - Plates, sheets, film, foil and strip of cellular plastics (excluding of polymers of styrene, of polymers of vinyl chloride, of polyurethanes, of regenerated cellulose)	100%
22214230 - Non-cellular plates, sheets, film, foil, strip of condensation or rearrangement polymerisation products, polyesters, reinforced, laminated, supported/similarly comb. with other materials)	100%
22214250 - Non-cellular plates, strips..., of phenolic resins	100%
22214275 - Non-cellular plates, sheets, film, foil, strip of condensation or rearrangement polymerisation products, amino-resins (high pressure laminates, decorative surface one/both sides)	100%
22214279 - Other plates, sheets, films, foil and strip, of polymerisation products	100%
22214280 - Other plates..., non-cellular of plastics other than made by polymerisation	100%
22.22 Manufacture of plastic packing goods	
22221100 - Sacks and bags of polymers of ethylene (including cones)	100%
22221200 - Plastic sacks and bags (including cones) (excluding of polymers of ethylene)	100%
22221300 - Plastic boxes, cases, crates and similar articles for the conveyance or packing of goods	100%
22221450 - Plastic carboys, bottles, flasks and similar articles for the conveyance or packing of goods, of a capacity <= 2 litres	100%
22221470 - Plastic carboys, bottles, flasks and similar articles for the conveyance or packing of goods, of a capacity > 2 litres	100%
22221910 - Spools, cops, bobbins and similar supports, of plastics	100%
22221925 - Plastic stoppers, lids, caps, capsules and other closures	100%
22221950 - Articles for the conveyance or packaging of goods, of plastics (excluding boxes, cases, crates and similar articles; sacks and bags, including	100%

cones; carboys, bottles, flasks and similar articles; spools, spindles, bobbins and similar supports; stoppers, lids, caps and other closures)	
22.23 Manufacture of builders' ware of plastic	
22231155 - Floor coverings in rolls or in tiles and wall or ceiling coverings consisting of a support impregnated, coated or covered with polyvinyl chloride	74%
22231159 - Other floor, wall, ceiling... coverings of polymers of vinyl chloride	74%
22231190 - Floor coverings in rolls or in tiles; and wall or ceiling coverings of plastics (excluding of polymers of vinyl chloride)	74%
22231250 - Plastic baths, shower-baths, sinks and wash-basins	81%
22231270 - Plastic lavatory seats and covers	75%
22231290 - Plastic bidets, lavatory pans, flushing cisterns and similar sanitary ware (excluding baths, showers-baths, sinks and wash-basins, lavatory seats and covers)	81%
22231300 - Plastic reservoirs, tanks, vats, intermediate bulk and similar containers, of a capacity > 300 litres	87%
22231450 - Plastic doors, windows and their frames and thresholds for doors	61%
22231470 - Plastic shutters, blinds and similar articles and parts thereof	66%
22231950 - Builder's fittings and mountings intended for permanent installation of plastics	95%
22231990 - Builders' ware for the manufacture of flooring, walls, partition walls, ceilings, roofing, etc., guttering and accessories, banisters, fences and the like, fitted shelving for shops, factories, warehouses, storerooms, etc., architectural ornaments such as fluting, vaulting and friezes, of plastics,	100%
22.29 Manufacture of other plastic products	
22291000 - Plastic articles of apparel and clothing accessories (including gloves, raincoats, aprons, belts and babies' bibs) (excluding headgear)	85%
22292130 - Self-adhesive strips of plastic with a coating consisting of unvulcanised natural or synthetic rubber, in rolls of a width <= 20 cm	60%
22292140 - Self-adhesive plates, sheets, film, foil, tape, strip and other flat shapes, of plastics, in rolls <= 20 cm wide (excluding plastic strips coated with unvulcanised natural or synthetic rubber)	60%
22292240 - Self-adhesive plates, sheets, film, foil, tape, strip and other flat shapes, of plastics, whether or not in rolls > 20 cm wide (excluding floor, wall and ceiling coverings of HS 3918)	60%
22292320 - Tableware and kitchenware of plastic	95%
22292340 - Household articles and toilet articles, of plastics (excluding tableware, kitchenware, baths, shower-baths, washbasins, bidets, lavatory pans, seats and covers, flushing cisterns and similar sanitary ware)	55%
22292500 - Office or school supplies of plastic (including paperweights, paper-knives, blotting pads, pen-rests and book marks)	54%
22292610 - Plastic fittings for furniture, coachwork or the like	95%
22292620 - Statuettes and other ornamental articles of plastic (including photograph, picture and similar frames)	100%
22292630 - Perforated buckets and similar articles used to filter water at the entrance to drains, of plastic	100%
22292910 - Hard rubber or plastic combs, hair-slides and the like (excluding electro-thermic hairdressing apparatus)	100%
22292915 - Hairpins, curling pins, curling grips, hair-curlers and the like, and parts thereof, of plastic (excluding electro-thermic hairdressing apparatus)	100%
22292920 - Outer soles and heels of plastics	100%
22292950 - Other articles made from sheet	100%
13 Manufacture of textiles	

13103100 - Synthetic staple fibres, carded, combed or otherwise processed for spinning	15%
13103200 - Artificial staple fibres, carded, combed or otherwise processed for spinning	15%
13108210 - Yarn (other than sewing thread) containing >= 85 % by weight of synthetic staple fibres, n.p.r.s.	96%
13108250 - Yarn (other than sewing thread) containing >= 85 % by weight of synthetic staple fibres, p.r.s.	96%
13108320 - Yarn containing < 85 % by weight of polyester staple fibres (other than sewing thread), mixed with artificial fibres, n.p.r.s.	50%
13108333 - Yarn containing < 85 % by weight of synthetic staple fibres (other than sewing thread) mixed with carded wool or fine animal hair, n.p.r.s.	50%
13108336 - Yarn containing < 85 % by weight of synthetic staple fibres, mixed with combed wool or fine animal hair, n.p.r.s.	50%
13108340 - Yarn containing < 85 % by weight of synthetic staple fibres (other than sewing thread), mixed with cotton, n.p.r.s.	50%
13108380 - Other yarns, containing < 85 % by weight of synthetic staple fibres (other than sewing thread), n.p.r.s., n.e.c.	50%
13108390 - Yarn containing < 85 % by weight of synthetic staple fibres (other than sewing thread), p.r.s.	50%
131083Z0 - Yarn of synthetic staple fibres mixed with wool, n.p.r.s	50%
13108410 - Yarn (other than sewing thread) of artificial staple fibres, n.p.r.s.	96%
13108430 - Yarn (other than sewing thread) of artificial staple fibres, p.r.s.	96%
13108510 - Sewing thread of man-made filaments	96%
13108550 - Sewing thread of man-made staple fibres	96%
13203130 - Woven fabrics of man-made filament yarns obtained from high tenacity yarn, strip or the like (including nylon, other polyamides, polyester, viscose rayon)	15%
13203150 - Woven fabrics of synthetic filament yarns (excluding those obtained from high tenacity yarn or strip and the like)	15%
13203170 - Woven fabrics of artificial filament yarns (excluding those obtained from high tenacity yarn)	15%
13203210 - Woven fabrics of synthetic staple fibres, containing 85 % or more by weight of synthetic staple fibres	15%
13203220 - Woven fabrics of synthetic staple fibres, containing less than 85 % by weight of such fibres, mixed mainly or solely with cotton (excluding fabrics of yarns of different colours)	21%
13203230 - Woven fabrics of synthetic staple fibres, containing less than 85 % by weight of such fibres, mixed mainly or solely with cotton, of yarns of different colours	21%
13203240 - Woven fabrics of synthetic staple fibres mixed mainly or solely with carded wool or fine animal hair	15%
13203250 - Woven fabrics of synthetic staple fibres mixed mainly or solely with combed wool or fine animal hair	15%
13203290 - Woven fabrics of synthetic staple fibres mixed other than with wool, fine animal hair or cotton	15%
13203330 - Woven fabrics of artificial staple fibres, not of yarns of different colours	15%
13203350 - Woven fabrics of artificial staple fibres, of yarns of different colours	15%
13921150 - Blankets and travelling rugs of synthetic fibres (excluding electric blankets)	45%
13921359 - Table linen of woven man-made fibres and of other woven or non-woven textiles (excluding of cotton, of flax)	66%
13921370 - Table linen of non-woven man-made fibres	66%

13921470 - Toilet linen and kitchen linen, of non-woven man-made fibres	66%
13921640 - Bedspreads (excluding eiderdowns)	77%
13922150 - Sacks and bags, of knitted or crocheted polyethylene or polypropylene strip, used for packing goods	62%
13922170 - Sacks and bags, of polyethylene or polypropylene strip, used for packing goods (excluding knitted or crocheted)	62%
13922210 - Tarpaulins, awnings and sunblinds (excluding caravan awnings)	73%
13922230 - Tents (including caravan awnings)	53%
13922270 - Pneumatic mattresses and other camping goods (excluding caravan awnings, tents, sleeping bags)	80%
13922430 - Sleeping bags	31%
13922499 - Articles of bedding filled other than with feathers or down (including quilts and eiderdowns, cushions, pouffes, pillows) (excluding mattresses, sleeping bags)	31%
13922993 - Sanitary towels, tampons and similar article of textile materials (excluding wadding)	18%
13922997 - Napkins and napkin liners for babies and similar article of textile materials (excluding wadding)	18%
13922999 - Floor-cloths, dish-cloths, dusters and similar cleaning cloths, knitted or crocheted; life-jackets, life-belts and other made up articles (excluding sanitary towels and napkins and similar articles)	27%
13931200 - Woven carpets and other woven textile coverings (excluding tufted or flocked)	90%
13931300 - Tufted carpets and other tufted textile floor coverings	29%
13931990 - Carpets and other textile floor coverings (excluding knotted, woven, tufted, needlefelt)	41%
13941155 - Polyethylene or polypropylene binder or baler (agricultural) twines	85%
13941160 - Cordage, ropes or cables of polyethylene, polypropylene, nylon or other polyamides or of polyesters measuring > 50 000 decitex, of other synthetic fibres (excluding binder or baler twine)	85%
13941170 - Twines of polyethylene or polypropylene, of nylon or other polyamides or polyesters measuring <= 50 000 decitex (5 g/m) (excluding binder or baler twine)	85%
13941233 - Made-up fishing nets from twine, cordage or rope of man-made fibres (excluding fish landing nets)	93%
13941235 - Made-up fishing nets from yarn of man-made fibres (excluding fish landing nets)	93%
13941253 - Made-up nets from twine, cable or rope of nylon or other polyamides (excluding netting in the piece produced by crochet, hairnets, sports and fishing nets)	93%
13941255 - Made-up nets of nylon or other polyamides (excluding netting in the piece produced by crochet, hairnets, sports and fishing nets, those made from twine, cable or rope)	93%
13951010 - Non-wovens of a weight <= 25 g/m² (including articles made from non-wovens) (excluding articles of apparel, coated or covered)	98%
13951020 - Non-wovens of a weight of > 25 g/m² but <= 70 g/m² (including articles made from non-wovens) (excluding articles of apparel, coated or covered)	98%
13951030 - Non-wovens of a weight of > 70 g/m² but <= 150 g/m² (including articles made from non-wovens) (excluding articles of apparel, coated or covered)	98%
13951050 - Non-wovens of a weight of > 150 g/m² (including articles made from non-wovens) (excluding articles of apparel, coated or covered)	98%
13961500 - Tyre cord fabrics of high tenacity yarn, of nylon, other polyamides, polyesters or viscose rayon	85%

14 Manufacture of wearing apparel	
14121120 - Men’s or boys’ ensembles, of cotton or man-made fibres, for industrial and occupational wear	46%
14121130 - Men’s or boys’ jackets and blazers, of cotton or man-made fibres, for industrial and occupational wear	48%
14121240 - Men’s or boys’ trousers and breeches, of cotton or man-made fibres, for industrial or occupational wear	24%
14121250 - Men’s or boys’ bib and brace overalls, of cotton or man-made fibres, for industrial or occupational wear	59%
14122120 - Women’s or girls’ ensembles, of cotton or man-made fibres, for industrial or occupational wear	46%
14122130 - Women’s or girls’ jackets and blazers, of cotton or man-made fibres, for industrial or occupational wear	70%
14122240 - Women’s or girls’ trousers and breeches, of cotton or man-made fibres, for industrial or occupational wear	65%
14122250 - Women’s or girls’ bib and brace overalls, of cotton or man-made fibres, for industrial or occupational wear	44%
14123013 - Men’s or boys’ other garments, of cotton or man-made fibres, for industrial or occupational wear	59%
14123023 - Women’s or girls’ other garments, of cotton or man-made fibres, for industrial or occupational wear	80%
14131110 - Men’s or boys’ overcoats, car-coats, capes, cloaks and similar articles, of knitted or crocheted textiles (excluding jackets and blazers, anoraks, wind-cheaters and wind-jackets)	47%
14131120 - Men’s or boys’ waistcoats, anoraks, ski-jackets, wind-cheaters, wind-jackets and similar articles, of knitted or crocheted textiles (excluding jackets and blazers)	52%
14131230 - Men’s or boys’ jackets and blazers, of knitted or crocheted textiles	48%
14131260 - Men’s or boys’ suits and ensembles, of knitted or crocheted textiles	15%
14131270 - Men’s or boys’ trousers, breeches, shorts, bib and brace overalls, of knitted or crocheted textiles	24%
14131310 - Women’s or girls’ overcoats, car-coats, capes, cloaks and similar articles, of knitted or crocheted textiles (excluding jackets and blazers)	47%
14131320 - Women’s or girls’ waistcoats, anoraks, ski-jackets, wind-cheaters, wind-jackets and similar articles, of knitted or crocheted textiles (excluding jackets and blazers)	52%
14131430 - Women’s or girls’ jackets and blazers, of knitted or crocheted textiles	70%
14131460 - Women’s or girls’ suits and ensembles, of knitted or crocheted textiles	15%
14131470 - Women’s or girls’ dresses, of knitted or crocheted textiles	32%
14131480 - Women’s or girls’ skirts and divided skirts, of knitted or crocheted textiles	14%
14131490 - Women’s or girls’ trousers, breeches, shorts, bib and brace overalls, of knitted or crocheted textiles	30%
14132115 - Men’s or boys’ raincoats, overcoats, car-coats, capes, etc.	47%
14132130 - Men’s or boys’ waistcoats, anoraks, ski-jackets, wind-jackets and similar articles (excluding jackets and blazers, knitted or crocheted, impregnated, coated, covered, laminated or rubberised)	52%
14132300 - Men’s or boys’ jackets and blazers (excluding knitted or crocheted)	48%
14132445 - Men’s or boys’ trousers and breeches, of man-made fibres (excluding knitted or crocheted, for industrial or occupational wear)	24%
14132460 - Men’s or boys’ shorts, of cotton or man-made fibres (excluding knitted or crocheted)	24%

14133115 - Woman’s or girls’ raincoats and overcoats, etc	47%
14133130 - Women’s or girls’ waistcoats, anoraks, ski-jackets, wind-jackets and similar articles (excluding jackets and blazers, knitted or crocheted, impregnated, coated, covered, laminated or rubberised)	52%
14133200 - Women’s or girls’ suits & ensembles (excluding knitted or crocheted)	50%
14133330 - Women’s or girls’ jackets and blazers (excluding knitted or crocheted)	70%
14133470 - Women’s or girls’ dresses (excluding knitted or crocheted)	43%
14133480 - Women’s or girls’ skirts and divided skirts (excluding knitted or crocheted)	62%
14133549 - Women’s or girls’ trousers and breeches, of wool or fine animal hair or man-made fibres (excluding knitted or crocheted and for industrial and occupational wear)	65%
14133563 - Women's or girls' bib and brace overalls, of wool or fine animal hair and man-made fibres (excluding cotton, knitted or crocheted, for industrial or occupational wear) and women's or girls' shorts, of wool or fine animal hair (excluding knitted or crocheted)	44%
14133565 - Women’s or girls’ shorts, of man-made fibres (excluding knitted or crocheted)	61%
14141100 - Men's or boys' shirts, knitted or crocheted	29%
14141230 - Men’s or boys’ nightshirts and pyjamas, of knitted or crocheted textiles	12%
14141310 - Women’s or girls’ blouses, shirts and shirt-blouses, of knitted or crocheted textiles	27%
14141430 - Women’s or girls’ nighties and pyjamas, of knitted or crocheted textiles	12%
14141450 - Women’s or girls’ slips and petticoats, of knitted or crocheted textiles	15%
14142100 - Men’s or boys’ shirts (excluding knitted or crocheted)	19%
14142230 - Men’s or boys’ nightshirts and pyjamas (excluding knitted or crocheted)	12%
14142300 - Women’s or girls’ blouses, shirts and shirt-blouses (excluding knitted or crocheted)	27%
14142430 - Women’s or girls’ nightdresses and pyjamas (excluding knitted or crocheted)	12%
14142450 - Women’s or girls’ slips and petticoats (excluding knitted or crocheted)	15%
14191210 - Track-suits, of knitted or crocheted textiles	48%
14191240 - Men’s or boys’ swimwear, of knitted or crocheted textiles	80%
14191250 - Women’s or girls’ swimwear, of knitted or crocheted textiles	80%
14191300 - Gloves, mittens and mitts, of knitted or crocheted textiles	30%
14192210 - Other men’s or boys’ apparel n.e.c., including tracksuits and jogging suits (excluding waistcoats, ski-suits, knitted or crocheted)	48%
14192220 - Other women’s or girls’ apparel n.e.c., including tracksuits and jogging suits (excluding waistcoats, ski-suits, knitted or crocheted)	48%
14192230 - Ski-suits (excluding of knitted or crocheted textiles)	63%
14192240 - Men’s or boys’ swimwear (excluding of knitted or crocheted textiles)	80%
14192250 - Women’s or girls’ swimwear (excluding of knitted or crocheted textiles)	80%
15 Manufacture of leather and related products	

15121210 - Trunks, suitcases, vanity cases, briefcases, school satchels and similar containers of leather, composition leather, patent leather, plastics, textile materials, aluminium or other materials	84%
15121220 - Handbags of leather, composition leather, patent leather, plastic sheeting, textile materials or other materials (including those without a handle)	78%
15201100 - Waterproof footwear, with uppers in rubber or plastics (excluding incorporating a protective metal toecap)	85%
15201210 - Sandals with rubber or plastic outer soles and uppers (including thong-type sandals, flip flops)	57%
15201231 - Town footwear with rubber or plastic uppers	57%
15201237 - Slippers and other indoor footwear with rubber or plastic outer soles and plastic uppers (including bedroom and dancing slippers, mules)	55%
15201370 - Slippers and other indoor footwear with rubber, plastic or leather outer soles and leather uppers (including dancing and bedroom slippers, mules)	55%
15201445 - Footwear with rubber, plastic or leather outer soles and textile uppers (excluding slippers and other indoor footwear, sports footwear)	47%
15202100 - Sports footwear with rubber or plastic outer soles and textile uppers (including tennis shoes, basketball shoes, gym shoes, training shoes and the like)	57%
15203120 - Footwear (including waterproof footwear), incorporating a protective metal toecap, with outer soles and uppers of rubber or of plastics	85%
15203150 - Footwear with rubber, plastic or leather outer soles and leather uppers, and with a protective metal toe-cap	45%
15203200 - Wooden footwear, miscellaneous special footwear and other footwear n.e.c.	21%
17 Manufacture of paper and paper products	
17127755 - Bleached paper and paperboard in rolls or sheets, coated, impregnated or covered with plastics weighing > 150 g/m² (excluding adhesives)	20%
17127759 - Paper and paperboard in rolls or sheets, coated, impregnated or covered with plastics (excluding adhesives, bleached and weighing > 150 g/m²)	20%
17221210 - Sanitary towels and tampons, napkins and napkin liners for babies and similar sanitary articles, of wadding	29%
17221220 - Sanitary towels, tampons and similar articles of paper pulp, paper, cellulose wadding or webs of cellulose fibres	29%
17221230 - Napkins and napkin liners for babies and similar sanitary articles of paper pulp, paper, cellulose wadding or webs of cellulose fibers, (excluding toilet paper, sanitary towels, tampons and similar articles)	29%
17221300 - Trays, dishes, plates, cups and the like of paper or paperboard	11%
20 Manufacture of chemicals and chemical products	
20.30 Manufacture of paints, varnishes and similar coatings, printing ink and mastics	26%
20301150 - Paints and varnishes, based on acrylic or vinyl polymers dispersed or dissolved in an aqueous medium (including enamels and lacquers)	26%
20301225 - Paints and varnishes, based on polyesters dispersed/dissolved in a non-aqueous medium, weight of the solvent > 50 % of the weight of the solution including enamels and lacquers	26%
20301229 - Paints and varnishes, based on polyesters dispersed/dissolved in a non-aqueous medium including enamels and lacquers excluding weight of the solvent > 50 % of the weight of the solution	26%
20301230 - Paints and varnishes, based on acrylic or vinyl polymers dispersed/dissolved in non-aqueous medium, weight of the solvent > 50 % of the solution weight including enamels and lacquers	26%
20301250 - Other paints and varnishes based on acrylic or vinyl polymers	26%
20301290 - Other paints and varnishes based on synthetic polymers n.e.c.	26%

25 Manufacture of fabricated metal products, except machinery and equipment	
25733063 - Screwdrivers	34%
26 Manufacture of computer, electronic and optical products	
26121080 - Passive networks (including networks of resistors and/or capacitors) (excluding resistor chip arrays, capacitor chip arrays, boards containing active components, hybrids)	24%
26201100 - Laptop PCs and palm-top organisers	30%
26201300 - Desk top PCs	30%
26201640 - Printers, copying machines and facsimile machines, capable of connecting to an automatic data processing machine or to a network (excluding printing machinery used for printing by means of plates, cylinders and other components, and machines performing two or more of the functions of printing, copying or facsimile transmission)	30%
26201650 - Keyboards	30%
26201700 - Monitors and projectors, principally used in an automatic data processing system	30%
26201800 - Machines which perform two or more of the functions of printing, copying or facsimile transmission, capable of connecting to an automatic data processing machine or to a network	30%
26301300 - Television cameras (including closed circuit TV cameras) (excluding camcorders)	24%
26302100 - Line telephone sets with cordless handsets	54%
26302200 - Telephones for cellular networks or for other wireless networks	54%
26302330 - Telephone sets (excluding line telephone sets with cordless handsets and telephones for cellular networks or for other wireless networks); videophones	54%
26305020 - Electrical burglar or fire alarms and similar apparatus (excluding of a kind used for motor vehicles or buildings)	30%
26305080 - Electric burglar or fire alarms and similar apparatus for buildings	30%
26401100 - Radio broadcast receivers (except for cars), capable of operating without an external source of power	35%
26401250 - Radio broadcast receivers, only mains-operated (excl. these of a kind used in motor vehicles)	35%
26401270 - Radio broadcast receivers for motor vehicles with sound recording or reproducing apparatus	35%
26401290 - Radio broadcast receivers for motor vehicles, n.e.c.	35%
26402040 - Colour television projection equipment	29%
26402090 - Other television receivers, whether or not combined with radio-broadcast receivers or sound or video recording or reproduction apparatus n.e.c.	29%
26403100 - Turntables, record-players, cassette-players and other sound reproducing apparatus	29%
26403200 - Magnetic tape recorders and other sound recording apparatus	28%
26403300 - Video camera recorders	29%
26403420 - Video projectors	29%
26403460 - Flat panel video monitor, LCD or plasma, etc., without tuner (colour video monitors) (excluding with cathode-ray tube)	29%
26404270 - Headphones and earphones, even with microphone, and sets consisting of microphone and one or more loudspeakers (excluding airmen’s headgear with headphones, telephone sets, cordless microphones with transmitter, hearing aids)	29%

26404355 - Telephonic and measurement amplifiers (excluding high or intermediate frequency amplifiers)	29%
26404370 - Electric sound amplifier sets (including public address systems with microphone and speaker)	29%
26512050 - Radio navigational aid apparatus (including radio beacons and radio buoys, receivers, radio compasses equipped with multiple aerials or with a directional frame aerial)	24%
26512080 - Radio remote control apparatus (including for ships, pilotless aircraft, rockets, missiles, toys, and model ships or aircraft, for machines, for the detonation of mines)	24%
26517015 - Electronic thermostats	34%
26701300 - Digital cameras	48%
26701400 - Instant print cameras and other cameras (excluding digital cameras, cameras of a kind used for preparing printing plates or cylinders as well as cameras specially designed for underwater use, for aerial survey or for medical or surgical examination of internal organs; comparison cameras for forensic	48%
26801100 - Magnetic tapes and magnetic discs, unrecorded, for the recording of sound or of other phenomena	92%
26801200 - Optical media for the recording of sound or of other phenomena (excluding goods of HS 37), unrecorded	49%
26801300 - Other recording media, including matrices and masters for the production of disks	93%
26801400 - Cards incorporating a magnetic stripe*	95%*
27 Manufacture of electrical equipment	
27121020 - Automatic circuit breakers >1kV	31%
27121030 - Isolating switches and make-and-break switches >1kV	31%
27121090 - Other apparatus for switching... electrical circuits > 1 000 V	47%
27122230 - Automatic circuit breakers for a voltage <= 1 kV and for a current <= 63 A	31%
27122250 - Automatic circuit breakers for a voltage <= 1 kV and for a current > 63 A	31%
27122330 - Electrical apparatus for protecting electrical circuits for a voltage <= 1 kV and a current <= 16 A (excluding fuses, automatic circuit breakers)	31%
27122350 - Electrical apparatus for protecting electrical circuits for a voltage <= 1 kV and for a current > 16 A but <= 125 A (excluding fuses, automatic circuit breakers)	31%
27122370 - Electrical apparatus for protecting electrical circuits for a voltage <= 1 kV and for a current > 125 A (excluding fuses, automatic circuit breakers)	31%
27122433 - Relays for a voltage <= 60 V and for a current <= 2 A	94%
27122435 - Relays for a voltage <= 60 V and for a current > 2 A	94%
27122450 - Relays for a voltage > 60 V but <= 1 kV	94%
27123130 - Numerical control panels with built-in automatic data-processing machine for a voltage <= 1 kV	27%
27123150 - Programmable memory controllers for a voltage <= 1 kV	27%
27123170 - Other bases for electric control, distribution of electricity, voltage <= 1 000 V	27%
27123203 - Boards, cabinets and similar combinations of apparatus for electric control or the distribution of electricity, for a voltage > 1.000 V but <= 72,5 kV	27%
27123205 - Boards, cabinets and similar combinations of apparatus for electric control or the distribution of electricity, for a voltage > 72,5 kV	27%
27124030 - Boards, panels, consoles, desks, cabinets and other bases for apparatus for electric control or the distribution of electricity (excluding those equipped with their apparatus)	27%

27202100 - Lead-acid accumulators for starting piston engines	11%
27202300 - Nickel-cadmium, nickel metal hydride, lithium-ion, lithium polymer, nickel-iron and other electric accumulators	15%
27311100 - Optical fibre cables made up of individually sheathed fibres whether or not assembled with electric conductors or fitted with connectors	75%
27311200 - Optical fibres and optical fibre bundles; optical fibre cables (except those made up of individually sheathed fibres)	75%
27321100 - Winding wire for electrical purposes	64%
27321200 - Insulated coaxial cables and other coaxial electric conductors for data and control purposes whether or not fitted with connectors	64%
27321400 - Insulated electric conductors for voltage >1 000 V (excluding winding wire, coaxial cable and other coaxial electric conductors, ignition and other wiring sets used in vehicles, aircraft, ships)	64%
27331100 - Electrical apparatus for switching electrical circuits for a voltage <= 1 kV (including push-button and rotary switches) (excluding relays)	31%
27331200 - Lamp-holders for a voltage <= 1 kV	94%
27331310 - Plugs and sockets for coaxial cables for a voltage <= 1 kV	94%
27331330 - Plugs and sockets for printed circuits for a voltage <= 1 kV	94%
27331350 - Plugs and sockets for a voltage <= 1 kV (excluding for coaxial cables, for printed circuits)	94%
27331380 - Other apparatus for connections to or in electrical circuit, voltage <= 1 000 V	31%
27331410 - Trunking, ducting and cable trays for electrical circuits, of plastics	47%
27331430 - Insulating fittings of plastic, for electrical machines, appliances or equipment (excluding electrical insulators)	97%
27401510 - Fluorescent hot cathode discharge lamps, with double ended cap (excluding ultraviolet lamps)	14%
27401530 - Fluorescent hot cathode discharge lamps (excluding ultraviolet lamps, with double ended cap)	14%
27401550 - Other discharge lamps (excluding ultraviolet lamps)	14%
27401570 - Ultraviolet or infrared lamps, arc lamps	14%
27402100 - Portable electric lamps worked by dry batteries, accumulators or magnetos (excluding for cycles or motor vehicles)	23%
27511110 - Combined refrigerators-freezers, with separate external doors	26%
27511133 - Household-type refrigerators (including compression-type, electrical absorption-type) (excluding built-in)	26%
27511135 - Compression-type built-in refrigerators	26%
27511150 - Chest freezers of a capacity <= 800 litres	26%
27511170 - Upright freezers of a capacity <= 900 litres	26%
27511200 - Household dishwashing machines	16%
27511300 - Cloth washing and drying machines, of the household type	22%
27511530 - Table, floor, wall, window, ceiling or roof fans, with a self-contained electric motor of an output <= 125 W	16%
27511580 - Ventilating or recycling hoods incorporating a fan, with a maximum horizontal side <= 120 cm	16%
27512123 - Vacuum cleaners with a self-contained electric motor of a power <= 1 500 W and having a dust bag or other receptable capacity <= 20 l	41%
27512125 - Other vacuum cleaners with a self-contained electric motor	41%
27512170 - Domestic food grinders, mixers and fruit or vegetable juice extractors, with a self-contained electric motor	48%
27512190 - Other electromechanical appliances	43%

27512200 - Shavers, hair-removing appliances and hair clippers, with self-contained electric motor	46%
27512310 - Electric hair dryers	30%
27512330 - Electric hairdressing apparatus (including hair curlers, curling tongs) (excluding hair drying hoods, hair dryers)	32%
27512350 - Electric hand-drying apparatus	32%
27512370 - Electric smoothing irons	21%
27512410 - Vacuum cleaners, including dry cleaners and wet vacuum cleaners (excluding with self-contained electric motor)	41%
27512430 - Domestic electric coffee or tea makers (including percolators)	26%
27512450 - Domestic electric toasters (including toaster ovens for toasting bread, potatoes or other small items)	30%
27512700 - Domestic microwave ovens	18%
27512900 - Electric heating resistors (excluding of carbon)	39%
27901230 - Electrical insulators (excluding of glass or ceramics)	97%
27905100 - Fixed capacitors for 50/60 Hz circuits having a reactive power handling capacity >= 0,5 kvar	37%
27905220 - Fixed electrical capacitors, tantalum or aluminium electrolytic (excluding power capacitors)	37%
27905240 - Other fixed electrical capacitors n.e.c.	37%
27905300 - Variable capacitors (including pre-sets)	37%
27907030 - Electrical signalling, safety or traffic control equipment for roads, inland waterways, parking facilities, port installations or airfields	64%
28 Manufacture of machinery and equipment n.e.c.	
28112400 - Generating sets, wind-powered	15%
28121420 - Pressure-reducing valves combined with filters or lubricators	15%
28121450 - Valves for the control of oleohydraulic power transmission	15%
28121480 - Valves for the control of pneumatic power transmission	15%
28132200 - Hand or foot-operated air pumps	45%
28132800 - Air pumps and ventilating or recycling hoods incorporating a fan, whether or not fitted with filters, with a maximum horizontal side > 120 cm (excl. vacuum pumps, hand- or foot-operated air pumps and compressors)	45%
28141120 - Pressure-reducing valves of cast iron or steel, for pipes, boiler shells, tanks, vats and the like (excluding those combined with lubricators or filters)	15%
28141140 - Pressure-reducing valves for pipes, boiler shells, tanks, vats and the like (excluding of cast iron or steel, those combined with filters or lubricators)	15%
28141160 - Check valves for pipes, boiler shells, tanks, vats and the like	15%
28141170 - Valves for pneumatic tyres and inner-tubes	15%
28141180 - Safety or relief valves for pipes, boiler shells, tanks, vats and the like	15%
28141233 - Mixing valves for sinks, wash basins, bidets, water cisterns etc. excluding valves for pressure-reducing or oleohydraulic/pneumatic power transmissions, check valves, safety/relief valves	15%
28141235 - Taps, cocks and valves for sinks, wash basins, bidets, water cisterns etc. excluding valves for pressure-reducing/oleohydraulic transmissions, check, safety, relief and mixing valves	15%
28141253 - Central heating radiator thermostatic valves	15%
28141255 - Central heating radiator valves (excl. thermostatic valves)	15%

28141315 - Process control valves for pipes, boiler shells, tanks etc. excluding valves for pressure-reducing or oleohydraulic/pneumatic power transmissions, check, safety/relief valves, temp. regulators	15%
28141373 - Ball and plug valves	15%
28141375 - Butterfly valves	15%
28141377 - Diaphragm valves	15%
28241113 - Electromechanical hand drills operated without an external source of power	13%
28241115 - Electropneumatic drills of all kinds for working in the hand	13%
28241117 - Electromechanical hand drills of all kinds (excluding those operated without an external source of power, electropneumatic)	13%
28241120 - Electromechanical hand tools operated without an external source of power (excluding drills, saws)	13%
28241123 - Electromechanical chainsaws	13%
28241125 - Electromechanical circular saws	13%
28241127 - Electromechanical handsaws (excluding chainsaws, circular saws)	13%
28241150 - Grinders, sanders and planers, for working in the hand, with self-contained electric motor, operating with an external source of power	13%
28241180 - Electromechanical hedge trimmers and lawn edge cutters	13%
28241185 - Electromechanical hand tools, with self-contained electric motor operating with an external source of power (excluding saws, drills, grinders, sanders, planers, hedge trimmers and lawn edge cutters)	13%
28241240 - Tools for working in the hand, pneumatic, including combined rotary-percussion	13%
28241260 - Chainsaws with a self-contained non-electric motor	13%
28241280 - Handtools, hydraulic or with a self-contained non-electric motor (excluding chainsaws)	13%
28251333 - Refrigerated show-cases and counters incorporating a refrigerating unit or evaporator for frozen food storage	18%
28251335 - Refrigerated show-cases and counters incorporating a refrigerating unit or evaporator (excluding for frozen food storage)	18%
28251360 - Refrigerating furniture with a refrigerating unit or evaporator (excluding combined refrigerator-freezers, with separate external doors, household refrigerators, refrigerated show-cases and counters)	18%
28251390 - Other refrigerating or freezing equipment	23%
28252030 - Axial fans (excluding table, floor, wall, window, ceiling or roof fans with a self-contained electric motor of an output <= 125 W)	16%
28252050 - Centrifugal fans (excluding table, floor, wall, window, ceiling or roof fans with a self-contained electric motor of an output <= 125 W)	16%
28252070 - Fans (excluding table, floor, wall, ceiling or roof fans with a self-contained electric motor of an output <= 125 W, axial fans, centrifugal fans)	16%
28291230 - Machinery and apparatus for filtering or purifying water	15%
28291250 - Machinery and apparatus for filtering and purifying beverages (excluding water)	15%
28292220 - Spray guns and similar appliances	28%
29 Manufacture of motor vehicles, trailers and semi-trailers	
29102100 - Vehicles with only spark-ignition engine of a cylinder capacity <= 1 500 cm³	10%
29102230 - Motor vehicles with only petrol engine > 1 500 cm³ (including motor caravans of a capacity > 3 000 cm³) (excluding vehicles for transporting >= 10 persons, snowmobiles, golf cars and similar vehicles)	10%
29102250 - Motor caravans with only spark-ignition internal combustion reciprocating piston engine of a cylinder capacity > 1 500 cm³ but <= 3 000 cm³	10%

29102310 - Motor vehicles with only diesel or semi-diesel engine <= 1 500 cm³ (excluding vehicles for transporting >= 10 persons, snowmobiles, golf cars and similar vehicles)	10%
29102330 - Motor vehicles with only diesel or semi-diesel engine > 1 500 cm³ but <= 2 500 cm³ (excluding vehicles for transporting >= 10 persons, motor caravans, snowmobiles, golf cars and similar vehicles)	10%
29102340 - Motor vehicles with only diesel or semi-diesel engine > 2 500 cm³ (excluding vehicles for transporting >= 10 persons, motor caravans, snowmobiles, golf cars and similar vehicles)	10%
29311000 - Insulated ignition wiring sets and other wiring sets of a kind used in vehicles, aircraft or ships	64%
29312310 - Electrical or battery operated lighting or visual signalling of a kind used on bicycles	64%
29312330 - Sound signalling burglar alarms, electrical, of a kind used for motor vehicles	64%
29312350 - Electrical sound signalling equipment for cycles or motor vehicles (excl. burglar alarms for motor vehicles)	64%
29312370 - Windscreen wipers, defrosters and demisters for motorcycles or motor vehicles	64%
29321000 - Seats for motor vehicles	17%
29322030 - Safety seat belts*	70%*
29323010 - Bumpers and parts thereof (including plastic bumpers)	10%
30 Manufacture of other transport equipment	
30121100 - Sailboats (except inflatable) for pleasure or sports, with or without auxiliary motor	29%
30924030 - Baby carriages	11%
31 Seats and parts thereof; parts of furniture	
31001150 - Swivel seats with variable height adjustments (excluding medical, surgical, dental or veterinary, and barbers' chairs)	17%
31001170 - Upholstered seats with metal frames (excluding swivel seats, medical, surgical, dental or veterinary seats, barbers' or similar chairs, for motor vehicles, for aircraft)	17%
31001210 - Seats convertible into beds (excluding garden seats or camping equipment)	27%
31001250 - Upholstered seats with wooden frames (including three piece suites) (excluding swivel seats)	17%
31031250 - Mattresses of cellular plastics (including with a metal frame) (excluding water-mattresses, pneumatic mattresses)	27%
31091430 - Furniture of plastics (excluding medical, surgical, dental or veterinary furniture - cases and cabinets specially designed for hi-fi systems, videos and televisions)	79%
32 Other manufacturing	
32301131 - Skis, for winter sports	39%
32301200 - Snow-ski footwear	39%
32301510 - Leather sports gloves, mittens and mitts	30%
32301560 - Tennis, badminton or similar rackets, whether or not strung	62%
32301580 - Balls (excluding golf balls, table-tennis balls, medicine balls and punch balls)	62%
32401100 - Dolls representing only human beings	71%
32401200 - Toys representing animals or non-human creatures	91%
32403100 - Wheeled toys designed to be ridden by children (excluding bicycles); dolls' carriages	43%

32403920 - Toy musical instruments and apparatus; toys put up in sets or outfits (excluding electric trains, scale model assembly kits, construction sets and constructional toys, and puzzles); toys and models incorporating a motor; toy weapons	59%
32501311 - Syringes, with or without needles, used in medical, surgical, dental or veterinary sciences	36%
32501317 - Needles, catheters, cannulae and the like used in medical, surgical, dental or veterinary sciences (excluding tubular metal needles and needles for sutures)	36%
32501333 - Instruments and apparatus for measuring blood-pressure (including sphygmomanometers, tensiometers, oscillometers)	17%
32501335 - Endoscopes for medical purposes	17%
32501363 - Transfusion apparatus (excluding special blood storage glass bottles)*	95%*
32502130 - Mechano-therapy appliances, massage apparatus, psychological aptitude-testing apparatus (excluding wholly stationary mechano-therapy apparatus)	17%
32502253 - Individual artificial teeth of plastics (including metal posts for fixing) (excluding dentures or part dentures)	31%
32504130 - Contact lenses	42%
32504250 - Sunglasses	85%
32504350 - Plastic frames and mountings for spectacles, goggles or the like	85%
32911140 - Non-motorised, hand-operated mechanical floor sweepers and other brushes for road, household or animals	47%
32911190 - Brushes, n.e.c.	47%
32911210 - Tooth brushes	78%
32911235 - Hair brushes	47%
32911237 - Shaving and toilet brushes for personal use (excluding toothbrushes and hair brushes)	47%
32911250 - Artists' brushes and writing brushes	47%
32911270 - Brushes for the application of cosmetics	47%
32911930 - Paint brushes, distempering brushes, paper-hanging brushes and varnishing brushes	47%
32911950 - Paint pads and rollers	40%
32911970 - Brushes constituting parts of machines, appliances or vehicles (excluding for road-sweepers)	18%
32991150 - Safety headgear	36%
32991190 - Headgear of rubber or plastic (excluding safety headgear)	36%
32991210 - Ball-point pens	66%
32991230 - Felt-tipped and other porous-tipped pens and markers	58%
32991250 - Propelling or sliding pencils	11%
32991430 - Refills for ball-point pens, comprising the ball-point and ink-reservoir	66%
32991670 - Typewriter or similar ribbons, inked or otherwise prepared for giving impressions (excluding rolls of carbon or other copying paper strip)	65%
32992130 - Umbrellas, sun umbrellas, walking-stick umbrellas, garden umbrellas and similar umbrellas (excluding umbrella cases)	35%
32994110 - Cigarette lighters and other lighters (including mechanical lighters, electrical lighters, chemical lighters, non-mechanical lighters, vehicle lighters)	59%
32995960 - Vacuum flasks and other vacuum vessels, complete with cases, and parts thereof (excluding separate glass inners)	30%
Personal care and cosmetics products (PCCP) (Scudo et al., 2017)	-

* : Assumption
Note: There is no plastic fraction data can be found for the product category, so the assumption is based on the authors' judgement.

Appendix C List of plastic products in categories of other

22.21 Manufacture of plastic plates, sheets, tubes and profiles
22.29 Manufacture of other plastic products
22291000 - Plastic articles of apparel and clothing accessories (including gloves, raincoats, aprons, belts and babies' bibs) (excluding headgear)
22292130 - Self-adhesive strips of plastic with a coating consisting of unvulcanised natural or synthetic rubber, in rolls of a width <= 20 cm
22292140 - Self-adhesive plates, sheets, film, foil, tape, strip and other flat shapes, of plastics, in rolls <= 20 cm wide (excluding plastic strips coated with unvulcanised natural or synthetic rubber)
22292240 - Self-adhesive plates, sheets, film, foil, tape, strip and other flat shapes, of plastics, whether or not in rolls > 20 cm wide (excluding floor, wall and ceiling coverings of HS 3918)
22292320 - Tableware and kitchenware of plastic
22292340 - Household articles and toilet articles, of plastics (excluding tableware, kitchenware, baths, shower-baths, washbasins, bidets, lavatory pans, seats and covers, flushing cisterns and similar sanitary ware)
22292500 - Office or school supplies of plastic (including paperweights, paper-knives, blotting pads, pen-rests and book marks)
22292610 - Plastic fittings for furniture, coachwork or the like
22292620 - Statuettes and other ornamental articles of plastic (including photograph, picture and similar frames)
22292630 - Perforated buckets and similar articles used to filter water at the entrance to drains, of plastic
22292910 - Hard rubber or plastic combs, hair-slides and the like (excluding electro-thermic hairdressing apparatus)
22292915 - Hairpins, curling pins, curling grips, hair-curlers and the like, and parts thereof, of plastic (excluding electro-thermic hairdressing apparatus)
22292920 - Outer soles and heels of plastics
22292950 - Other articles made from sheet
15 Manufacture of leather and related products
15121210 - Trunks, suitcases, vanity cases, briefcases, school satchels and similar containers of leather, composition leather, patent leather, plastics, textile materials, aluminium or other materials
15121220 - Handbags of leather, composition leather, patent leather, plastic sheeting, textile materials or other materials (including those without a handle)
15201100 - Waterproof footwear, with uppers in rubber or plastics (excluding incorporating a protective metal toecap)
15201210 - Sandals with rubber or plastic outer soles and uppers (including thong-type sandals, flip flops)
15201231 - Town footwear with rubber or plastic uppers
15201237 - Slippers and other indoor footwear with rubber or plastic outer soles and plastic uppers (including bedroom and dancing slippers, mules)
15201370 - Slippers and other indoor footwear with rubber, plastic or leather outer soles and leather uppers (including dancing and bedroom slippers, mules)
15201445 - Footwear with rubber, plastic or leather outer soles and textile uppers (excluding slippers and other indoor footwear, sports footwear)
15202100 - Sports footwear with rubber or plastic outer soles and textile uppers (including tennis shoes, basketball shoes, gym shoes, training shoes and the like)
15203120 - Footwear (including waterproof footwear), incorporating a protective metal toecap, with outer soles and uppers of rubber or of plastics
15203150 - Footwear with rubber, plastic or leather outer soles and leather uppers, and with a protective metal toe-cap
15203200 - Wooden footwear, miscellaneous special footwear and other footwear n.e.c.
17 Manufacture of paper and paper products

17127755 - Bleached paper and paperboard in rolls or sheets, coated, impregnated or covered with plastics weighing > 150 g/m² (excluding adhesives)
17127759 - Paper and paperboard in rolls or sheets, coated, impregnated or covered with plastics (excluding adhesives, bleached and weighing > 150 g/m²)
17221210 - Sanitary towels and tampons, napkins and napkin liners for babies and similar sanitary articles, of wadding
17221220 - Sanitary towels, tampons and similar articles of paper pulp, paper, cellulose wadding or webs of cellulose fibres
17221230 - Napkins and napkin liners for babies and similar sanitary articles of paper pulp, paper, cellulose wadding or webs of cellulose fibers, (excluding toilet paper, sanitary towels, tampons and similar articles)
17221300 - Trays, dishes, plates, cups and the like of paper or paperboard
25 Manufacture of fabricated metal products, except machinery and equipment
25733063 - Screwdrivers
28 Manufacture of machinery and equipment n.e.c.
28112400 - Generating sets, wind-powered
28121420 - Pressure-reducing valves combined with filters or lubricators
28121450 - Valves for the control of oleohydraulic power transmission
28121480 - Valves for the control of pneumatic power transmission
28132200 - Hand or foot-operated air pumps
28132800 - Air pumps and ventilating or recycling hoods incorporating a fan, whether or not fitted with filters, with a maximum horizontal side > 120 cm (excl. vacuum pumps, hand- or foot-operated air pumps and compressors)
28141120 - Pressure-reducing valves of cast iron or steel, for pipes, boiler shells, tanks, vats and the like (excluding those combined with lubricators or filters)
28141140 - Pressure-reducing valves for pipes, boiler shells, tanks, vats and the like (excluding of cast iron or steel, those combined with filters or lubricators)
28141160 - Check valves for pipes, boiler shells, tanks, vats and the like
28141170 - Valves for pneumatic tyres and inner-tubes
28141180 - Safety or relief valves for pipes, boiler shells, tanks, vats and the like
28141233 - Mixing valves for sinks, wash basins, bidets, water cisterns etc. excluding valves for pressure-reducing or oleohydraulic/pneumatic power transmissions, check valves, safety/relief valves
28141235 - Taps, cocks and valves for sinks, wash basins, bidets, water cisterns etc. excluding valves for pressure-reducing/oleohydraulic transmissions, check, safety, relief and mixing valves
28141253 - Central heating radiator thermostatic valves
28141255 - Central heating radiator valves (excl. thermostatic valves)
28141315 - Process control valves for pipes, boiler shells, tanks etc. excluding valves for pressure-reducing or oleohydraulic/pneumatic power transmissions, check, safety/relief valves, temp. regulators
28141373 - Ball and plug valves
28141375 - Butterfly valves
28141377 - Diaphragm valves
28241113 - Electromechanical hand drills operated without an external source of power
28241115 - Electropneumatic drills of all kinds for working in the hand
28241117 - Electromechanical hand drills of all kinds (excluding those operated without an external source of power, electropneumatic)
28241120 - Electromechanical hand tools operated without an external source of power (excluding drills, saws)
28241123 - Electromechanical chainsaws
28241125 - Electromechanical circular saws
28241127 - Electromechanical handsaws (excluding chainsaws, circular saws)
28241150 - Grinders, sanders and planers, for working in the hand, with self-contained electric motor, operating with an external source of power
28241180 - Electromechanical hedge trimmers and lawn edge cutters

28241185 - Electromechanical hand tools, with self-contained electric motor operating with an external source of power (excluding saws, drills, grinders, sanders, planers, hedge trimmers and lawn edge cutters)

28241240 - Tools for working in the hand, pneumatic, including combined rotary-percussion

28241260 - Chainsaws with a self-contained non-electric motor

28241280 - Handtools, hydraulic or with a self-contained non-electric motor (excluding chainsaws)

28251333 - Refrigerated show-cases and counters incorporating a refrigerating unit or evaporator for frozen food storage

28251335 - Refrigerated show-cases and counters incorporating a refrigerating unit or evaporator (excluding for frozen food storage)

28251360 - Refrigerating furniture with a refrigerating unit or evaporator (excluding combined refrigerator-freezers, with separate external doors, household refrigerators, refrigerated show-cases and counters)

28251390 - Other refrigerating or freezing equipment

28252030 - Axial fans (excluding table, floor, wall, window, ceiling or roof fans with a self-contained electric motor of an output <= 125 W)

28252050 - Centrifugal fans (excluding table, floor, wall, window, ceiling or roof fans with a self-contained electric motor of an output <= 125 W)

28252070 - Fans (excluding table, floor, wall, ceiling or roof fans with a self-contained electric motor of an output <= 125 W, axial fans, centrifugal fans)

28291230 - Machinery and apparatus for filtering or purifying water

28291250 - Machinery and apparatus for filtering and purifying beverages (excluding water)

28292220 - Spray guns and similar appliances

31 Seats and parts thereof; parts of furniture

31001150 - Swivel seats with variable height adjustments (excluding medical, surgical, dental or veterinary, and barbers' chairs)

31001170 - Upholstered seats with metal frames (excluding swivel seats, medical, surgical, dental or veterinary seats, barbers' or similar chairs, for motor vehicles, for aircraft)

31001210 - Seats convertible into beds (excluding garden seats or camping equipment)

31001250 - Upholstered seats with wooden frames (including three piece suites) (excluding swivel seats)

31031250 - Mattresses of cellular plastics (including with a metal frame) (excluding water-mattresses, pneumatic mattresses)

31091430 - Furniture of plastics (excluding medical, surgical, dental or veterinary furniture - cases and cabinets specially designed for hi-fi systems, videos and televisions)

32 Other manufacturing

32301131 - Skis, for winter sports

32301200 - Snow-ski footwear

32301510 - Leather sports gloves, mittens and mitts

32301560 - Tennis, badminton or similar rackets, whether or not strung

32301580 - Balls (excluding golf balls, table-tennis balls, medicine balls and punch balls)

32401100 - Dolls representing only human beings

32401200 - Toys representing animals or non-human creatures

32403100 - Wheeled toys designed to be ridden by children (excluding bicycles); dolls' carriages

32403920 - Toy musical instruments and apparatus; toys put up in sets or outfits (excluding electric trains, scale model assembly kits, construction sets and constructional toys, and puzzles); toys and models incorporating a motor; toy weapons

32501333 - Instruments and apparatus for measuring blood-pressure (including sphygmomanometers, tensiometers, oscillometers)

32501335 - Endoscopes for medical purposes

32502130 - Mechano-therapy appliances, massage apparatus, psychological aptitude-testing apparatus (excluding wholly stationary mechano-therapy apparatus)

32502253 - Individual artificial teeth of plastics (including metal posts for fixing) (excluding dentures or part dentures)

32504130 - Contact lenses
32504250 - Sunglasses
32504350 - Plastic frames and mountings for spectacles, goggles or the like
32911140 - Non-motorised, hand-operated mechanical floor sweepers and other brushes for road, household or animals
32911190 - Brushes, n.e.c.
32911210 - Tooth brushes
32911235 - Hair brushes
32911237 - Shaving and toilet brushes for personal use (excluding tooth brushes and hair brushes)
32911250 - Artists' brushes and writing brushes
32911270 - Brushes for the application of cosmetics
32911930 - Paint brushes, distempering brushes, paper-hanging brushes and varnishing brushes
32911950 - Paint pads and rollers
32911970 - Brushes constituting parts of machines, appliances or vehicles (excluding for road-sweepers)
32991150 - Safety headgear
32991190 - Headgear of rubber or plastic (excluding safety headgear)
32991210 - Ball-point pens
32991230 - Felt-tipped and other porous-tipped pens and markers
32991250 - Propelling or sliding pencils
32991430 - Refills for ball-point pens, comprising the ball-point and ink-reservoir
32991670 - Typewriter or similar ribbons, inked or otherwise prepared for giving impressions (excluding rolls of carbon or other copying paper strip)
32992130 - Umbrellas, sun umbrellas, walking-stick umbrellas, garden umbrellas and similar umbrellas (excluding umbrella cases)
32994110 - Cigarette lighters and other lighters (including mechanical lighters, electrical lighters, chemical lighters, non-mechanical lighters, vehicle lighters)
32995960 - Vacuum flasks and other vacuum vessels, complete with cases, and parts thereof (excluding separate glass inners)
PCCP

Appendix D Interview guide

Interview guide

General questions to all actors:

1. Can you briefly describe [the plastic manufacturing process/ business/ plastic use/ recycling process] in [the company]?
2. Can you talk more about the [specific plastic circular economy projects] in [the company]?
3. How do you collaborate with [your partners/ suppliers/ waste management partners/ clients] to enable recycled plastics to be used in [packaging/construction/automotive/electrical and electronic equipment] sectors?
4. What are the main obstacles in producing and selling recycled plastics?
5. What are the key reasons/factors that determine your use/your clients use of secondary plastics?
6. What are your clients' opinions of using recycled plastics? And how you communicate with them?
7. What kinds of innovation are needed along the value chain in order to increase the use of recycled plastics?
8. What would be, according to you, crucial interventions to expand a stable secondary plastic market?
9. Is there anything you would like to add? Or anything further we need to know on the topic?
10. Is there any [plastic producers/manufacturers/recyclers/ intermediaries] in [packaging/construction/automotive/electrical and electronic equipment] sectors in Europe that you can suggest us to get in touch with?

Specific questions to different actors:

Petrochemical producers

- What are the main reasons for [the company] to invest in plastic recycling and producing recycled plastics?
- How do plastic producers deal with the future expansion of the secondary market? Any impacts/opportunities for [the company]?

Manufacturers / Construction managers/ Brand owners / Retailers

- What kind of products are currently made from recycled plastics in [the company]?
- What is the share of recycled plastic used in your business compared to virgin plastic?
- Could you talk about the requirements for using recycled plastic in your business/from your clients?
- Do your clients have any concerns about using recycled plastics (e.g., colour, olfactory performance)?
- Have any of your products made from recycled plastics applied to any certifications? Why?
- Do your products have any labels regarding recycled plastics?
- Do you know where the recycled plastics used in [your company's] products come from?
- Do you track plastic waste and recycled plastics along the supply chain?

Recyclers

- What is the average share of plastic waste, recycled to actually produce recycled plastics? Any limitation?
- How do you deal with these losses and by-products in the recycling process?
- What are the waste specifications for procurement and material specifications for selling?
- Which types of plastics are more available to recycle? Which one is more difficult to recycle in the [packaging/construction/automotive/electrical and electronic equipment] sector?
- How do you see feedstock/chemical recycling contributing to the EU target of using recycled plastics set by the Circular Plastics Alliance?

Intermediaries (Traders and Brokers)

- What are the main obstacles to finding these plastic waste/recycled plastics to meet your client's requirements?
- Do you track plastic waste and recycled plastics?
- How do you see the roles of intermediaries and online trading platforms in the EU recycled plastics market?

Extended producer responsibility organisation

- Do you see any changes in business from your clients to tackle obstacles in the past few years?
- Do you see any problems regarding the information transparency of the plastic packaging along the value chain?
- How can EPR schemes be improved to increase the use of recycled plastics?

Appendix E Information sheet for participants

Participant Information Sheet For *Stakeholders of European Plastic Value Chain*
UCL Research Ethics Committee Approval ID Number: **14181/001**

YOU WILL BE GIVEN A COPY OF THIS INFORMATION SHEET

Title of Study: How circular is European plastic? Measuring plastic flows toward a plastic circular economy in the EU
Department: Institute for Sustainable Resources
Name and Contact Details of the Researcher(s):
Wan-Ting Hsu email: wan-ting.hsu.16@ucl.ac.uk
Name and Contact Details of the Principal Researcher:
Will McDowall email: w.mcdowall@ucl.ac.uk

1. **Invitation Paragraph**
You are being invited to take part in a PhD research project. Before you decide it is important for you to understand why the research is being done and what participation will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask me if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part. Thank you for reading this.

2. **What is the project's purpose?**
In 2018 the European Commission launched the European Strategy for Plastics in a Circular Economy (CE), which highlights the need to increase plastic recycling and better harness CE potential. According to this, by 2030 recycled plastics should increase four-fold. Therefore, a better knowledge of the end-of-life of plastic in Europe is needed, including accurate understanding of current main destinations of plastic waste, recycling efficiencies and, importantly, flows of secondary materials that may substitute primary plastic production.

   This study aims to contribute to a more accurate of secondary flows of plastic by addressing two main questions: What is the scale and composition of recycled plastic flows in the EU? And; How can we further increase the circularity of plastics?

   This study will be conducting a material flow analysis (MFA) and analysis of the plastic recycling value chain in order to investigate different opportunities to increase plastic circularity. This study will collect both primary (through interviews) and secondary data to estimate physical flows from industrial and post-consumer plastic waste, estimate recycling efficiency and outputs and calculate use of secondary plastics for production and export.

3. **Why have I been chosen?**
This study uses convenience sampling and snowballing from the members of European plastics-related associations (e.g., the Circular Plastics Alliance, Plastics Recyclers Europe and the European Plastics Converters Association) due to its accessibility and time efficiency. Prospective interviewees are those involved in the plastic value chain, especially those involved in promoting recycled plastic materials and circular loops in plastic packaging, construction, waste electrical and electronic equipment (WEEE), and end-of-life vehicles (ELV). The sample will also focus on

pioneers or best-practice professionals, which will enable sufficient qualitative data for the research questions to be met.

4. **Do I have to take part?**
   It is up to you to decide whether or not you want to take part. If you do decide to take part, you will be given this information sheet to keep, and asked to sign a consent form. You can withdraw at any time without giving a reason and without it affecting any benefits to which you are entitled. If you decide to withdraw you will be asked what you wish to happen to the data you have provided up that point.

5. **What will happen to me if I take part?**
   Participants are involved in the research through one-to-one interviews with the researcher. Interview are not expected to exceed one hour each time.

6. **Will I be recorded and how will the recorded media be used?**
   The interviews will be recorded and subsequently transcribed. The written notes and audio recordings of your activities made during this research will be used only for analysis. No other use will be made of them without your written permission, and no one outside the project will be allowed access to the original recordings.

7. **What are the possible disadvantages and risks of taking part?**
   The risks would be the possibility of disclosure of information to a third party. To mitigate this risk, the information would only be disclosed with the agreement of the participants.

8. **What are the possible benefits of taking part?**
   While there are no immediate benefits for anyone participating in the project, it is hoped that this work will provide a better view of the plastic material flows and the opportunities to apply circular economy strategies by cooperating stakeholders across the plastic value chain in the EU to increase the circularity of European plastic flows.

9. **What if something goes wrong?**
   If something goes wrong, the participants can contact the researcher's supervisor, Dr Will McDowall [Lecturer, Energy Institute, 14 Upper Woburn Place, London WC1H 0NN, England] to raise a complaint. However, if the participants feel your complaint has not been handled to your satisfaction, you can contact the Chair of the UCL Research Ethics Committee – ethics@ucl.ac.uk

10. **Will my taking part in this project be kept confidential?**
    All the information that I collect about you during the course of the research will be kept strictly confidential. You will not be able to be identified in any ensuing reports or publications. All the information from the interview will be held. Only I and my supervisors will have access to it.

11. **Limits to confidentiality**
    - Please note that assurances on confidentiality will be strictly adhered to unless evidence of wrongdoing or potential harm is uncovered. In such cases the University may be obliged to contact relevant statutory bodies/agencies.

- Confidentiality will be respected subject to legal constraints and professional guidelines.
- Confidentiality will be respected unless there are compelling and legitimate reasons for this to be breached. In this case, we would inform you of any decisions that might limit your confidentiality.

12. What will happen to the results of the research project?

The results of the research will be presented in my PhD thesis, which will be finished in 2021, and likely be published in conference or journal articles. You will not be identified in any report or publication without your permission. The participants will obtain a copy of the published results from researcher. Data collected during the course of the project will be stored in the UCL archiving system and might be used for additional or subsequent research until 2021.

13. Local Data Protection Privacy Notice

Notice:

The data controller for this project will be University College London (Lazarevic et al.). The UCL Data Protection Office provides oversight of UCL activities involving the processing of personal data, and can be contacted at data-protection@ucl.ac.uk. UCL's Data Protection Officer can also be contacted at data-protection@ucl.ac.uk.

Further information on how UCL uses participant information can be found here:

www.ucl.ac.uk/legal-services/privacy/participants-health-and-care-research-privacy-notice

Your personal data will be used for the purposes outlined in this notice. The categories of personal data used will be as follows:

Name
Organisation
Position
Address
Email

The legal basis that would be used to process your *personal data* will be performance of a task in the public interest.

Your personal data will be processed so long as it is required for the research project. If I am able to anonymise or pseudonymise the personal data you provide I will undertake this and will endeavour to minimise the processing of personal data wherever possible.

You have certain rights under data protection legislation in relation to the personal information that we hold about you. These rights apply only in particular circumstances and are subject to certain exemptions such as public interest (for example the prevention of crime). They include:

- The right to access your personal information;
- The right to rectification of your personal information;

- The right to erasure of your personal data;
- The right to restrict or object to the processing of your personal data;
- The right to object to the use of your data for direct marketing purposes;
- The right to data portability;
- Where the justification for processing is based on your consent, the right to withdraw such consent at any time; and
- The right to complain to the Information Commissioner's Office (ICO) about the use of your personal data.

If you are concerned about how your personal data is being processed, or if you would like to contact us about your rights, please contact UCL in the first instance at data-protection@ucl.ac.uk.

If you remain unsatisfied, you may wish to contact the ICO. Contact details, and further details of data subject rights, are available on the ICO website at: https://ico.org.uk/for-organisations/data-protection-reform/overview-of-the-gdpr/individuals-rights/

14. Who is organising and funding the research?

This PhD research project is self-funded with a summer studentships from the UCL Plastic Waste Innovation Hub.

16. Contact for further information

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Thank you for reading this information sheet and for considering taking part in this research study.

Appendix F List of publications

Journal paper

Wan-Ting Hsu*, Teresa Domenech, Will McDowall. (2022) Closing the loop on plastics in Europe: The role of data, information and knowledge. Sustainable Production and Consumption, volume 33 pp. 942-951. https://doi.org/10.1016/j.spc.2022.08.019

Wan-Ting Hsu*, Teresa Domenech, Will McDowall. (2021) How circular are plastics in the EU?: MFA of plastics in the EU and pathways to circularity. Cleaner Environmental Systems, volume 2, 100004. https://doi.org/10.1016/j.cesys.2020.100004

Conferences

Domenech Aparisi*, T; Casas Arredondo, J; **Hsu, WT**; (2020) How circular are plastics in the UK? Findings from Material Flow Analysis. In: Plastics Research and Innovation Fund Conference, Creative Circular Economy Approaches to Eliminate Plastic Waste. UK Circular Plastics Network.

Wan-Ting Hsu*, Teresa Domenech, Will McDowall. (2021) Closing the loop on plastics in Europe: opportunities and challenges in different sectors. International Conference on Resource Sustainability. July 19-23, 2021 University College Dublin, Ireland.

Wan-Ting Hsu*, Teresa Domenech, Will McDowall. (2019) Circular economy of plastics: analysis of plastic flows and stocks in Europe. PLATE: Product Lifetimes And The Environment.

Wan-Ting Hsu*, Teresa Domenech, Will McDowall. (2019) Closing the loop on plastics: insights into the recycled plastic flows in the EU. International Society for Industrial Ecology Conference. July 7– 11, 2019 Tsinghua University, Beijing, China.

Wan-Ting Hsu*, Will McDowall, Teresa Domenech. (2018) A review of circular economy indicators from the micro to the macro level. Science to support Circular Economy International Symposium. September 19, 2018 TU Wien, Vienna, Austria.