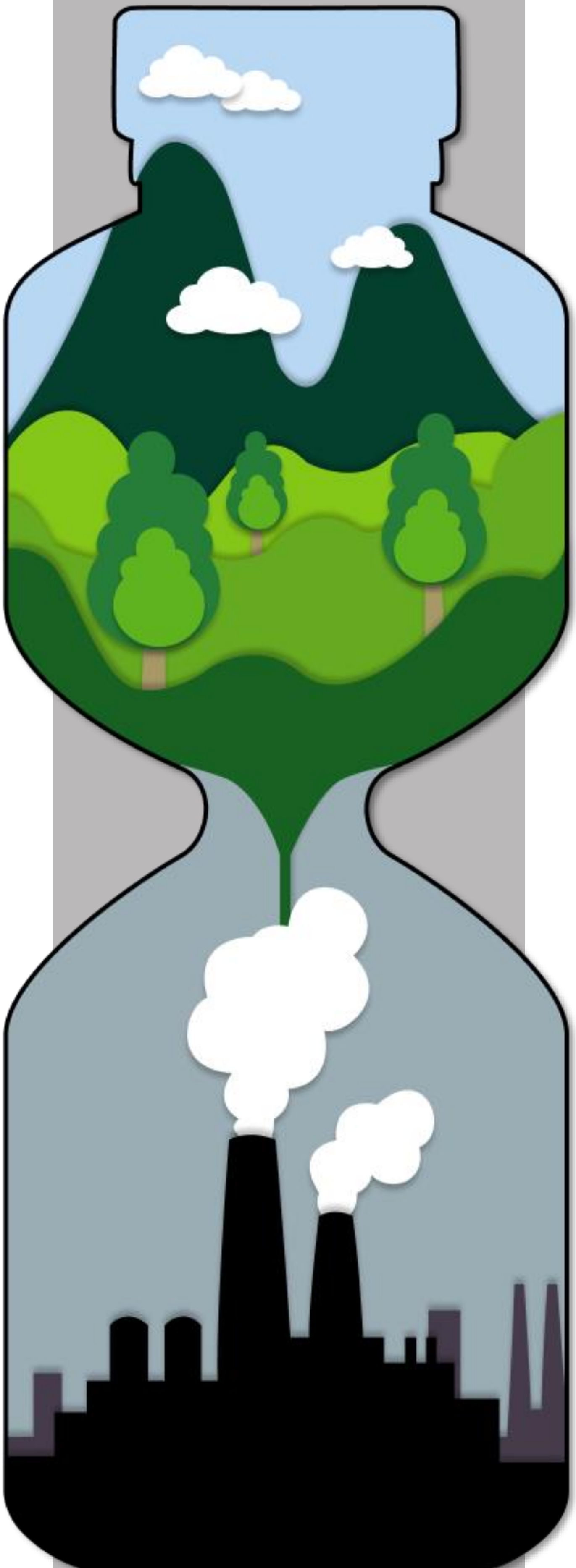

Master's Thesis – Master Sustainable Business and Innovation

Going down the biobased circular (recycling) economy rabbit hole

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Master Thesis – Master Sustainable Business and Innovation

Mandy de Roos, June 2023
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Cover image: Mandy de Roos

Abstract

The plastic petrochemical industry has created a linear economy, leading to global problems such as climate change. To diminish these problems, innovations in the recycling and plastic industry are happening, namely biobased polymers (BBP) and chemical recycling. Shifting to a biobased circular economy leads to the research question: *How can the transition towards a biobased circular (recycling) economy be achieved?* The transition is studied using the Multi-Level Perspective theory, mapping the three levels. For this, interviews are conducted with business associations/scientists for the landscape, novel BBP producers/chemical recyclers for the niche, and mechanical recyclers (including sorters)/petrochemical industry for the regime.

Sub-question 1: *What types of polymers will comprise the future market of biobased polymers?* Drop-ins are made using biobased/recyclate added to crackers containing fossil oil, adding a percentage to create a BBP. On the other hand, novels are entirely and efficiently made from biomass and have added value. Challenges that favour drop-ins include the power of the regime, scale problems, and the high-cost price of biomass. Thus, it is not surprising that drop-ins will comprise the future market of BBP. However, optimally, the market should comprise more novel polyester BBP in the long term.

Sub-question 2: *What barriers and opportunities do (the identified future) BBP encounter when trying to fit into the recycling infrastructure for plastics?* Novels face two main general barriers and opportunities, the barriers of the chicken-egg problem and contamination potential, the opportunities of scaling up recycling for a circular economy, and the recycling target of 40% set in the Dutch Transition Agenda for Plastic. Additionally, novels have three main chemical opportunities due to depolymerisation: low scale, low cost, and low energy usage.

Sub-question 3: *What solutions are (currently) available to overcome the barriers to fitting the future BBP into the recycling industry to create a circular economy?* Five concrete policy suggestions are given: enabling collaboration, instituting CO_2 pricing, investing in reuse, starting sorting/recycling novels, and adding a mandatory percentage of biobased content.

To conclude, policymakers and governments need to use a system perspective to transition towards a biobased circular economy. Novel polyesters should be promoted due to their proven lower energy consumption, low persistence, and added value. Companies should be given the choice of using a mandatory recyclate or BBP by the Extended Producer Responsibility system. This combination has the highest CO_2-saving potential and could stop the chicken-egg problem.

Abbreviations

AP	Acidification Potential
BBC	Biobased Circular
BBP	Biobased Polymers
Bio-PE	Bio-polyethylene
BM	Business Model
CO_2	Carbon dioxide
CR	Chemical Recycling
CR	Chemical Recycling
EMF	Ellen MacArthur Foundation
EOL	End-of-Life
EP	Eutrophication Potential
EPBP	European PET Bottle Platform
EPR	Extended Producer Responsibility (in Dutch: UPV)
ESPR	Eco-design for Sustainable Products Regulation
ETS	Emission Trade System
EU	European Union
GHG	Greenhouse Gases
GWP	Global Warming Potential
IP	Intellectual Property
KIDV	Knowledge Institute Durable Packaging (in Dutch: Kennis Instituut Duurzame Verpakking)
LA	Lactic Acid
LAB	National Waste Management Plan (in Dutch: Landelijk Afvalbeheerplan)
LCA	Life Cycle Analysis
MIS	Mission-driven Innovation system
MIX	Mixed plastics
MLP	Multi-Level Perspective
MR	Mechanical Recycling
NGOs	Non-Governmental Organisations
NIR	Near InfraRed
NPCE	National Plan Circular Economy
ODP	Ozone Depletion Potential
PCPPW	Post-Consumer Plastic Packaging Waste
PE	Polyethylene
PEF	Polyethylene Furanoate
PET	Polyethylene Terephthalate
PHA	Polyhydroxy Alkanoate
PLA	Polylactic Acid
PMD	Plastic, Metal and Beverage cartons (in Dutch: Plastic, Metaal en Drankkartons)
POCP	Photochemical Ozone Creation Potential
PP	Polypropylene
PPWR	Packaging and Packaging Waste Regulation
PWF	Packaging Waste Fund (in Dutch: Afvalfonds Verpakkingen)
RED	Renewable Energy Directive
SAF	Sustainable Aviation Fuels
SER	Social Economic Council (in Dutch: Sociale Economische Raad)
TMC	Transition Model Canvas
TRL	Technological Readiness Level
VNCI	Association of the Dutch Chemical Industry (in Dutch: Vereniging van de Nederlandse Chemische Industrie)
WTE	Waste to Energy Incineration

Contents

1. Introduction

1.1 Research problem and question

In the late 1900s, the first biobased polymers (BBP) were produced, although this term was not used at the time (Endres & Siebert-Raths, 2011). These, as well as current BBP, are made from a natural source (Ibid.). Meanwhile, most of the present polymers in circulation are from a petrochemical source, a 90-billion-pound industry, used for packaging, textiles, coatings, automotive, and more (Hernández et al., 2014). A downside of this industry is that it has created a linear (make, use, dispose) economy, which has led to worldwide (wicked) problems, such as climate change (The Ellen MacArthur Foundation, 2013). Furthermore, the current end-of-life (EOL) of these polymers is not fully regenerative; there is limited closed-loop recycling, and many end up in a landfill, where they degrade and contaminate the ecosystem (Mathalon & Hill, 2014; Butturi et al., 2020). BBP are the way forward due to their ability to tackle the climate crisis, as they have a lower environmental footprint and are better recyclable (European Bioplastics, 2021; Hernández et al., 2014).

Along with climate change and high fossil fuel (oil) prices, the price of petrochemical plastics is expected to rise, creating opportunities for BBP (Soroudi & Jakubowicz, 2013a). Only 2.42 million tonnes of BBP are available on the market, which is expected to grow to 7.59 million tonnes by 2026 (European Bioplastics, 2021). Based on technical feasibility, BBP can replace around 90% of petrochemicals with their technical substitution potential (Shen et al., 2010a). The main barriers to the growth of BBP are the (current) high cost and the (possible) availability of land and water, strengthening the argument for recycling BBP. Current research looks at diverse (ways of making) BBP to lower costs (Hernández et al., 2014). However, these studies do not venture into the future and the repercussions of the transformation from petrochemical polymers to BBP.

A way to gain insight into the future is by using the Multi-Level Perspective (MLP), the dominant framework for studying transitions (van Rijnsoever & Leendertse, 2020). This theory looks at how niches bring in radical innovations and, with the help of an enabling landscape, overthrow the current regime (incumbents) (Geels, 2002). This framework is relevant, as novel BBP can be categorised as a radical innovation (Chadha, 2011) which could overthrow the current regime. This transition has already caused a spillover into another regime, namely the recycling industry.

There are two types of BBP, namely drop-ins and novels. Drop-ins are chemically identical and can be recycled using the current recycling infrastructure (Spierling et al., 2020). Researchers have noticed that novels such as PLA (Polylactic Acid), PHA (Polyhydroxy Alkanoate), and PEF (Polyethylene Furanoate) do not fit in the current recycling industry and can contaminate the quality of the resulting polymers (Endres & Siebert-Raths, 2011). To limit novel contamination potential, separate waste collection, sorting, and recycling streams are needed (Total Corbion PLA bv et al., 2020). However, the PEF producers have anticipated this limitation and claim to be able to incorporate 5% PEF into the petrochemical PET (Polyethylene Terephthalate) fraction while improving the PET fraction quality (Visser, 2020). Due to this advancement, the European PET Bottle Platform (EPBP) has approved a 2% market uptake of PEF (EPBP, 2017; Stegmann, 2022).

PLA and PHA are currently in their take-off phase, meaning their market will expand (Bours et al., 2022), which could cause the reporting of contaminations to rise. Especially with the transition agenda in mind, on the Circular Economy of Plastics, the goal is to have 15% BBP in 2030 on the Dutch market (Total Corbion PLA bv et al., 2020). There may need to be more than the 2% PEF uptake granted by the EPBP. However, this BBP target is vague about the determination of a focus on drop-ins or novels. It could be argued that novels are favourable because conversion from biomass is efficient (Alaerts et al., 2018). On the other hand, the current recycling industry is solely designed for petrochemical polymers (and thus drop-ins).

Although a shift to circularity is described in the literature, scant evidence can be seen (Ellen MacArthur Foundation & McKinsey & Company, 2016). Different Chemical Recycling (CR) technologies are being researched, these can overcome the limitations of Mechanical Recycling (MR) and facilitate the circular economy. However, CR technologies that fit with novels do not fit drop-ins and vice versa. Thus, when shifting to become more circular, the question is whether this shift should focus more on novels, drop-ins, or both, leading to the research question:

How can the transition towards a biobased circular (recycling) economy be achieved?

Answering this research question will grant policymakers insights into how a transition towards a BBP circular economy can be realised with all the benefits and limitations of both types of BBP and the implications on the recycling industry. Supporting this research question are the following sub-questions:

1. *What types of polymers will comprise the future market of biobased polymers?*
2. *What barriers and opportunities do (the identified future) biobased polymers encounter when trying to fit into the recycling infrastructure for plastics?*
3. *What solutions are (currently) available to overcome the barriers to fitting the future biobased polymers into the recycling industry to create a circular economy?*

1.2 Relevance

1.2.1 Scientific relevance

This research contributes to the literature by extending recent publications such as "Biobased Plastics in a Circular Economy" by Odegard et al. (2017) and "Transition to one circular plastic packaging chain" by Bours et al. (2022). The main focus of the former is BBP, whether they fit in a circular economy, and how policy should enhance this. Leading to new research with only a focus on PLA, namely "Exploring the sorting and recycling of bioplastic PLA" by Bergsma et al. (2019). Which explored whether the sorting and recycling of PLA is possible and what the costs, benefits, and environmental benefits would be. Of the latter, their main focus was on the transition to circular plastic packaging in the Netherlands, using a Mission-driven Innovation system (MIS) model. They looked at the network of actors (decided by their involvement in the various points in the plastic packaging production chain, (non) government organisations, and knowledge institutions) and rules that contribute to developing and disseminating innovative solutions and transforming the current production and consumption to fulfil the mission (Hekkert et al., 2020).

The gap which remains, and what was added to in this research, is the focus on the holistic picture, thus not only the plastic industry but also the recycling industry as the plastic industry has spilled over to the recycling industry since the most prominent plastic producers have invested in innovative recycling technologies. The theory of the MLP will enable mapping this landscape with the multiple regimes (and niches). The MLP was carried out using the Transition Model Canvas (TMC) methodology; it enables the combining of existing literature with practical insights on the transition of BBP and the circularity of the recycling industry. Ultimately, this TMC will generate new literary insights as it shows the complete landscape for the first time.

The theory of the MLP has been criticised on multiple fronts, notably for sketching the regime as a black box (Steen & Weaver, 2017; Farla et al., 2012) and for treating transitions as a standalone phenomenon occurring only in a single socio-technical system (Papachristos et al., 2013; Raven & Verbong, 2007). The criticism has caused the MLP to diverge in different directions. This study combines these add-ons to the MLP, namely incumbent diversification and multi-regime/niche interactions, to create a holistic MLP transition map.

1.2.2 Societal relevance

By mapping the future landscape of the BBP and recycling industry, this research provides a holistic view of realising a sustainable transition toward a circular economy. This view will encourage industry actors and policymakers to critically assess and change their business strategies and hindering policies to allow this transition to occur. Furthermore, this research can open the possibility of additional research into the effects of this transition in the Netherlands and the rest of the world. As a result, consumers globally may become more aware, change their attitudes, and take action to combat climate change (Wi & Chang, 2018).

2. Theory

This section will examine the theoretical background of BBP, the recycling technologies and the theory on transitions used: the MLP.

2.1 (Future) Biobased polymer industry

A sustainable replacement for petrochemical polymers is BBP. The definition used is that BBP are "*derived from the biomass or issued from monomers derived from the biomass and which, at some stage in its processing into finished products, can be shaped by flow*" (Vert et al., 2012, p.403). Simply put, BBP are made from biomass, thus biobased. This statement contrasts with European Bioplastics (2021), which defines a BBP as bio-based and/or biodegradable. This definition is disputed because of biodegradability's ambiguity, causing confusion and being viewed as greenwashing since the polymers can still be derived from fossil fuels (Goel et al., 2021; Nandakumar et al., 2021).

This research does classify BBP into four main categories, namely non-biodegradable (e.g., bio-polyethylene (Bio-PE)) versus biodegradables (e.g., PLA) and drop-ins (Bio-PE) versus novels (PLA). As can be seen in Figure 1, there is an overlap between the categories (Spierling et al., 2020).

2.1.1 Biodegradable versus Non-biodegradable

Microbes can break down all polymers (petrochemical and BBP) under certain conditions (Krieger, 2020). However, some polymers take so long to break down that they are not considered biodegradable (Soroudi & Jakubowicz, 2013a). Biodegradable distinguishes between compostable and natural biodegradable. The European Union (EU) has set a definition for compostable in EN13432, which states that these polymers must decompose within three months or less under predetermined conditions (e.g., at home, in an industrial setting) (European Bioplastics, 2015). The absence of a set definition for biodegradable in nature, other than that it should decompose rapidly under environmental conditions (European Environment Information and Observation Network, 2022), creates confusion as there are no ideal environmental conditions, as Albertsson and Hakkarainen (2017) argue. According to them, degradability does not offer an economic or environmental solution (Ibid.). In the recycling industry, the industrial compostable polymer PLA is already causing problems (Endres & Siebert-Raths, 2011; Stegmann, 2022).

Furthermore, an experiment conducted by the German Environmental Aid shows that even under ideal conditions, compostable materials are not degrading (Deutsche Umwelthilfe e.V., 2022). For a truly circular economy, biodegradable BBP will have to be recycled. Although this study focuses on non-biodegradable polymers, biodegradable polymers must be addressed since Europe mainly focuses on these types of BBP, looking at EU patent applications (Endres & Siebert-Raths, 2011). Thus, when findings/trends show that a rise in biodegradable (composting or in nature) polymers should be expected, this research will examine if/how these materials should be incorporated into the recycling system.

2.1.2 Drop-ins versus Novels

According to some literature, BBP aim to replace the current petrochemical polymers (Endres & Siebert-Raths, 2011). However, there is a big difference between drop-ins and novels. Drop-ins are polymers made from biomass but modified chemically to create the same chemical structure, thus EOL, as their petrochemical polymer counterpart (Spierling et al., 2020). Fitting with the behavioural theory of the firm by Cyert and March (1963), firms use heuristics and R&D to find innovations that are as close as possible to existing routines. Drop-ins are as close as possible to the existing routines of the plastic industry. Secondly, the quality of drop-ins is high enough to replace current plastics. Finally, they are beginning to become economically viable to use (Hernández et al., 2014).

On the other hand, novel polymers are polymers without counterparts in the current plastic industry (Spierling et al., 2020). When looking into their building blocks, novels are easier to derive from biomass (Alaerts et al., 2018). A downside of novels is that due to their newness, they will require numerous certifications/regulations before becoming acceptable. According to Freeman et al. (1983), this is called the liability of newness. To enhance the legitimacy of novels and encourage investment, niche actors (inventors of novels) need to heighten their positive discourse (Van Lente, 1993) and enable the changes required to get their uptake in the waste collection, sorting, and recycling infrastructure (Total Corbion PLA bv et al., 2020).

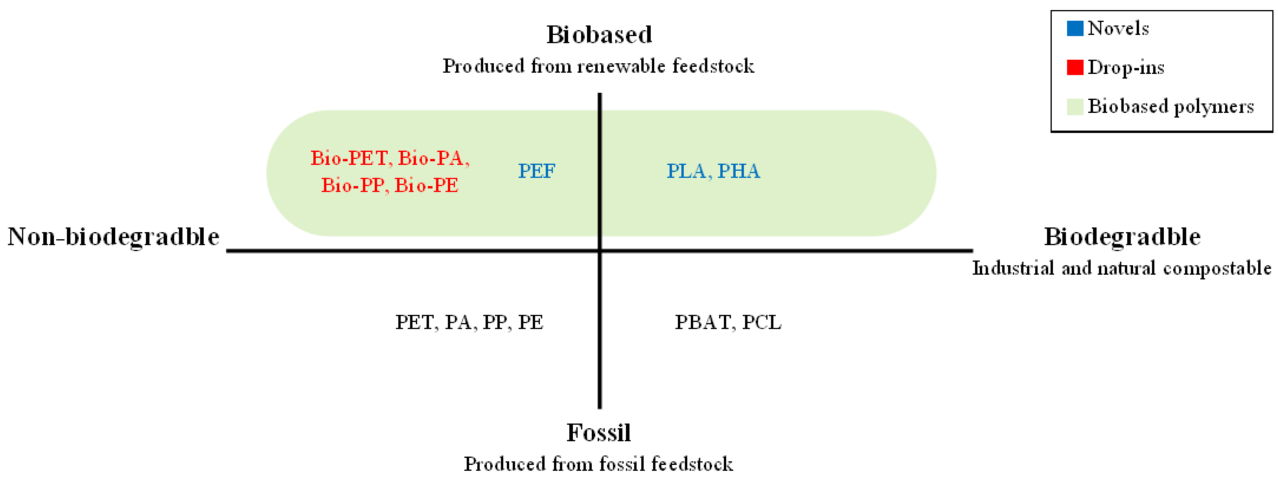

Figure 1. Scope of BBP of this study, inspired by European Bioplastics (n.d.-a)

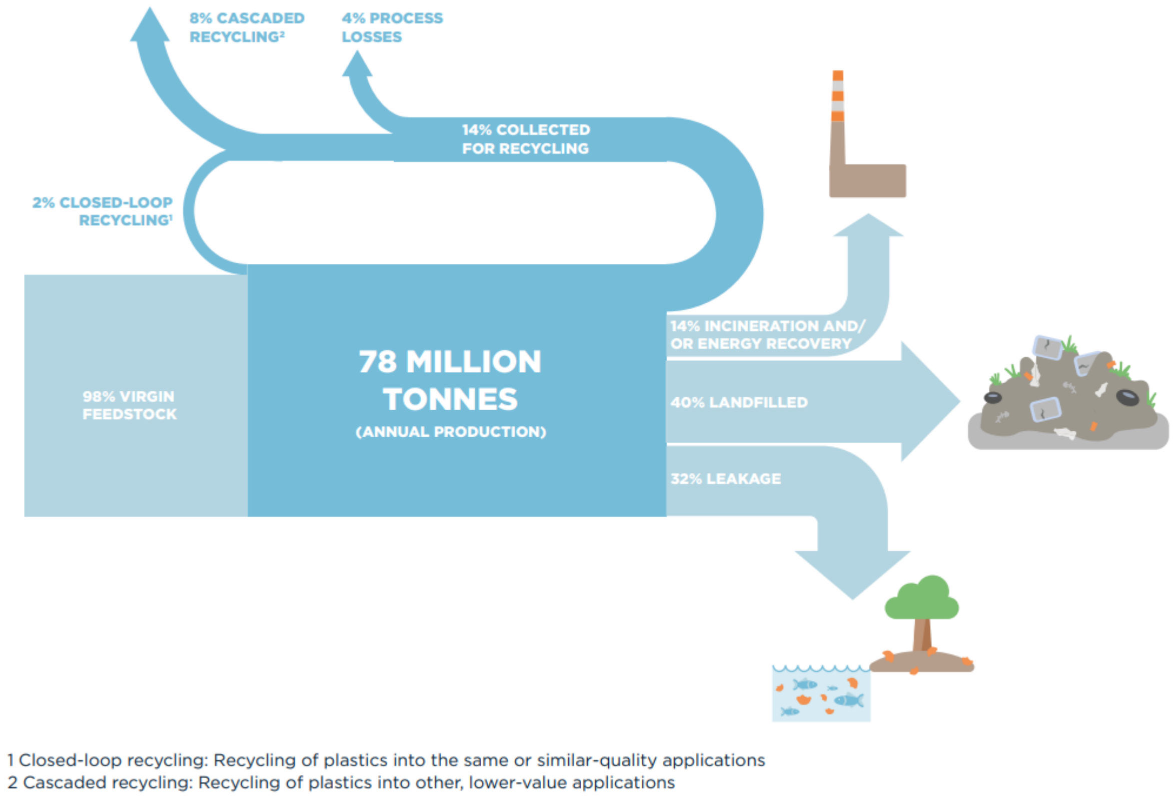

Figure 2. Circularity of plastic packaging (Ellen MacArthur Foundation & McKinsey & Company, 2016)

2.2 Circular (recycling) economy

The definition of a circular economy used is that of the Ellen MacArthur Foundation (EMF), which states that it is "*an industrial system that is restorative or regenerative by intention and design*" (Ellen MacArthur Foundation, 2013, p. 7). In such a system, there is no waste as all materials are reused or recycled. The current plastic economy can be described as less than circular, see Figure 2. Although this figure pertains to plastic packaging, it shows that closed-loop recycling (plastic that retains its value) is only 2% of annually produced plastic packaging. Meanwhile, 72% enter landfills or are leaked into the environment. Plastic packaging is a relevant sector, as it is the dominant user (in the EU) of plastics, using 38% of all plastics (Shen & Worrell, 2014).

Currently, four recycling technologies can be separated, see Figure 3. In this research, the fourth (quaternary) recycling technology is not considered proper, as no material is returned to the value chain. Although energy will be recovered, the material is incinerated, and harmful gases will be emitted into the atmosphere (Al-Salem et al., 2009).

2.2.1 Mechanical Recycling; Primary and Secondary recycling

In the current recycling system for plastics, MR is the most frequently used technology (Shen & Worrell, 2014). MR contains four steps, of which the first three coincide with CR. The first three steps are sorting, shredding, and washing the plastic. The fourth step is to melt and reshape the mono-material plastics into pellets or new products using different mechanical

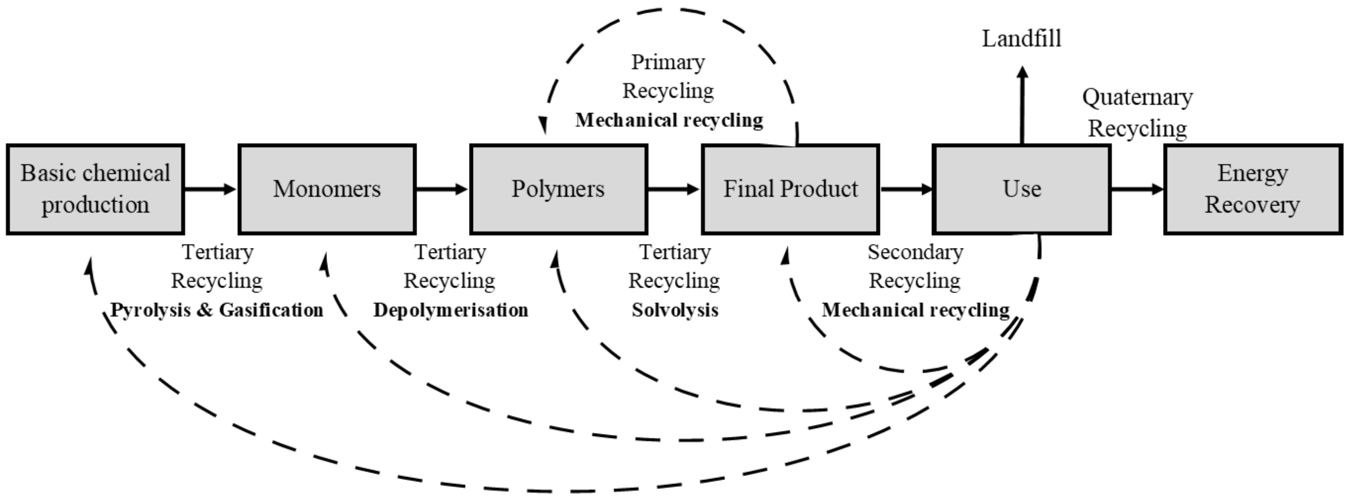

Figure 3. Recycling technologies inspired by (Lamberti et al., 2020) and (Crippa et al., 2019)

means (e.g., injection moulding, screw extrusion) (Ibid.; Al-Salem et al., 2009). MR advantages, compared to CR, are that it has a lower cost for processing, less non-renewable energy is needed, lower global warming potential (GWP), acidification potential (AP), and eutrophication potential (EP) (Shen et al., 2010b).

Primary recycling and Secondary recycling

Primary recycling is closed-loop, producing the highest quality since this material's history is known. Plastic can be reused to produce new high-quality products (Al-Salem et al., 2009). On the other hand, secondary recycling is open-loop, which can also be seen as a downgrading, as diverse plastic backgrounds of a mono-material are combined (Ibid.).

2.2.2 Chemical Recycling; Tertiary recycling

CR is a recycling process in which plastic is brought back to different chemical units, depending on the type of CR. As CR (mainly) brings the polymer back to a smaller building block, more contamination can be removed, and a virgin quality created (Ellen MacArthur Foundation & World Economic Forum, 2016), creating a fully circular economy opportunity. This circularity is also CR's main advantage compared to MR. Recovered monomers can be polymerised into new polymers in infinite cycles (Payne et al., 2019; Hopewell et al., 2009). However, CR is still being developed and limited commercially as few active CR facilities exist in Europe (Shen & Worrell, 2014; Schmidt, 2023). As can be seen in Table 1, solvolysis and depolymerisation Technical Readiness Levels (TRL) are low, and pyrolysis TRL is medium. However, pyrolysis has a lower TRL for challenging plastic waste (Arena & Ardolino, 2022). This low TLR is surprising considering that pyrolysis is not a new idea, as at the start of the millennium, BASF ran the first pyrolysis facility that turned waste plastic into oil (Schmidt, 2023). Nevertheless, these and related plants soon vanished as the oil produced could not compete with the, at the time, low-cost crude oil (Ibid.). The TRL of gasification is comparable to pyrolysis (Schwarz et al., 2021); however, only a limited number of gasification plants use mixed plastic (MIX), and these still suffer from operation problems (Waldheim, 2018).

Table 1. TRL of different CR technologies (Arena & Ardolino, 2022)

CR	TRL
Solvolysis	Low (3-5)
Depolymerisation	Low – Medium (3–6), depending on the polymer and specific process
Pyrolysis	Medium (6–7)
Gasification	Medium-high (6–8)

Solvolysis

Solvolysis, or, in other words, solvent-based purification, is a technique that does not affect the polymer structure itself, which is why it sometimes is not considered a CR process (Broeren et al., 2022). It does dissolve the polymer to remove contaminants and additives from the polymer (Ibid). It can potentially recycle multilayer packaging (Kennisinstituut Duurzaam Verpakken, 2018).

Depolymerisation

Depolymerisation is a group of techniques that bring polymers (only polyesters) back to their monomer units, using different types of catalyst depending on the technique, as seen in Figure 4. From monomers, new virgin quality polymers can be made as complete polymer chains can be restored, and contaminations removed (Broeren et al., 2022).

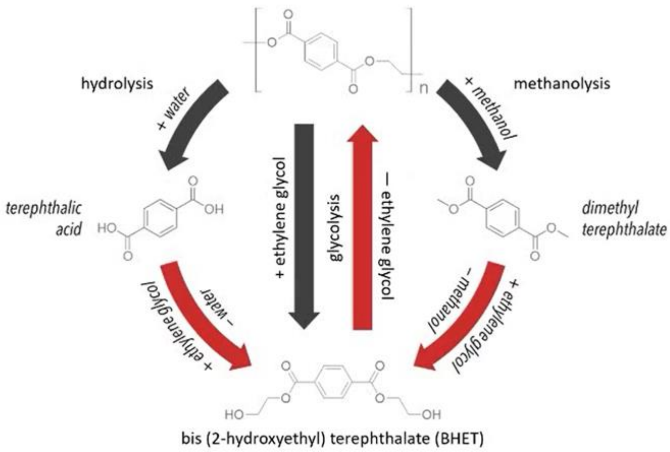

Figure 4. Depolymerisation techniques using PET (Ioniqa, 2023)

Pyrolysis

Pyrolysis is a technique in which a polymer (only non-polyester polyolefins and drop-ins) is brought back to its primary chemical products (naphtha). This technique is done by heating the polymer (at 300 - 900°C) in an inert environment with(out) a catalyst (Kumar et al., 2011; Hann & Connock, 2020). This process transforms the plastic into organic gases (gaseous fraction), which are comelily burned to create energy for this process, and a pyrolysis oil (liquid fraction) which resembles naphtha used in the petrochemical industry (Broeren et al., 2022).

Gasification

Gasification is a technique similar to pyrolysis. The polymer is heated (at 700 - 1500°C) in an environment with a low volume of oxygen (Hann & Connock, 2020). This process transforms the plastic into syngas, a mixture of CO and H_2 (Broeren et al., 2022). This fuel gas can, in turn, be used to create basic chemicals like methanol to produce plastics and non-plastics (Ibid.).

2.2.3 Circular recycling route and risks

According to Lamberti et al., a circular (recycling) economy can be achieved, for BBP, using MR, followed by CR (2020). However, this statement ignores some essential uncertainties. First, the current amount of recycled plastics is low compared to other materials due to the great variety of plastics (Shen & Worrell, 2014), which will only increase with the addition of BBP. Secondly, CR has yet to be proven to work with BBP (Endres & Siebert-Raths, 2011). Thirdly, the CR industry is not linked to the existing waste management system (Lamberti et al., 2020). Finally, BBP that end up in the current recycling process can "contaminate" the quality of the outgoing polymers. This contamination is argued in literature mainly by mixing PLA with PET due to its lower melting temperature (Alaerts et al., 2018). However, the effects of adding other novels (also with lower melting temperatures) on the quality of polymer outputs are unclear (Endres & Siebert-Raths, 2011). No thought has been given to what should happen to biodegradable and novels in the waste stream.

2.3 Multi-Level Perspective

The change from the plastic petrochemical industry to the BBP industry can be described as a socio-technological transformation because it will bring innovative technologies and influence policies, user practices, and the market (Geels, 2004). The MLP theory is effective because it provides a framework/overview of the complete, complex, and changing socio-technical system. In this system, three levels are distinguished, namely, (1) niches, (2) socio-technical regimes (incumbent firms), and (3) exogenous socio-technological landscapes, see Figure 5. According to the MLP, a transition is a regime shift due to interactions between the three levels (Rip & Kemp, 1998; Geels, 2004).

2.3.1 Landscape

In this research, the definition for the landscape used is that a landscape is a backdrop in which a system functions and where the transition occurs (van Rijnsoever & Leendertse, 2020). However, actors in this landscape have little influence over it (Geels & Schot, 2007). BBP and the recycling industries are shaped by several factors, including oil prices, normative values, cultural values, economic growth, and environmental problems (Geels, 2002). As oil prices increase (Hernández et al., 2014), incumbent firms seek cheaper alternatives. Culturally there is higher consumer awareness (Shao & Ünal, 2019), although it remains questionable if this translates into increased consumer demand (Vermeulen, 2013). Environmental problems and current economic (capitalist) growth aspirations can also have negative consequences (Feola, 2020). For a transition to occur, the landscape can put pressure on the regime, creating "windows of opportunity" for novel technologies (BBP) to appear (Geels, 2002).

2.3.2 Niche (radical innovations)

In this research, the definition of a niche system used is a system in which the dominant technology, actors, rules, and interactions are to be determined (van Rijnsoever & Leendertse, 2020). It is generally stated that niche actors can be smaller and more flexible than incumbent systems (Ibid.), but this does not always have to hold true. This openness leads to room for radical innovations (Geels, 2002). Radial innovations mean an innovation that is "*(1) novel; (2) unique; and (3) has an impact on future technology*" (Dahlin & Behrens, 2005, p.717). Using these criteria (novel) BBP can be described as radical, as they are novel and unique compared to current petrochemical polymers (Chadha, 2011). In addition, rising oil prices significantly affect future innovation (Mohanty et al., 2002; Bastioli, 2005). Radical innovations have difficulty breaking through due to the existing infrastructure, regulations, and user practices aligned with current technology (Geels, 2002; Unruh, 2000). In contrast, these radical innovations are designed to solve the problems of the regimes, which is why hybridisation can be seen. Meaning new technologies are added to existing ones to solve bottlenecks. In the end, the process of niche innovation to the regime includes experimentation and adjustments leading to a gradual reconfiguration of the entire system (Geels, 2002). In the end, niche actors hope that their innovations will be used or replace the regime (Geels, 2004).

2.3.3 Regime (incumbent system)

Regimes are defined by Nelson and Winter (1982) as a collection of cognitive and organisational routines/rules that create path dependency and stability—also known as an incumbent system (van Rijnsoever & Leendertse, 2020), consisting of incumbent firms. These heterogeneous actors move along the same trajectory and are externally aligned

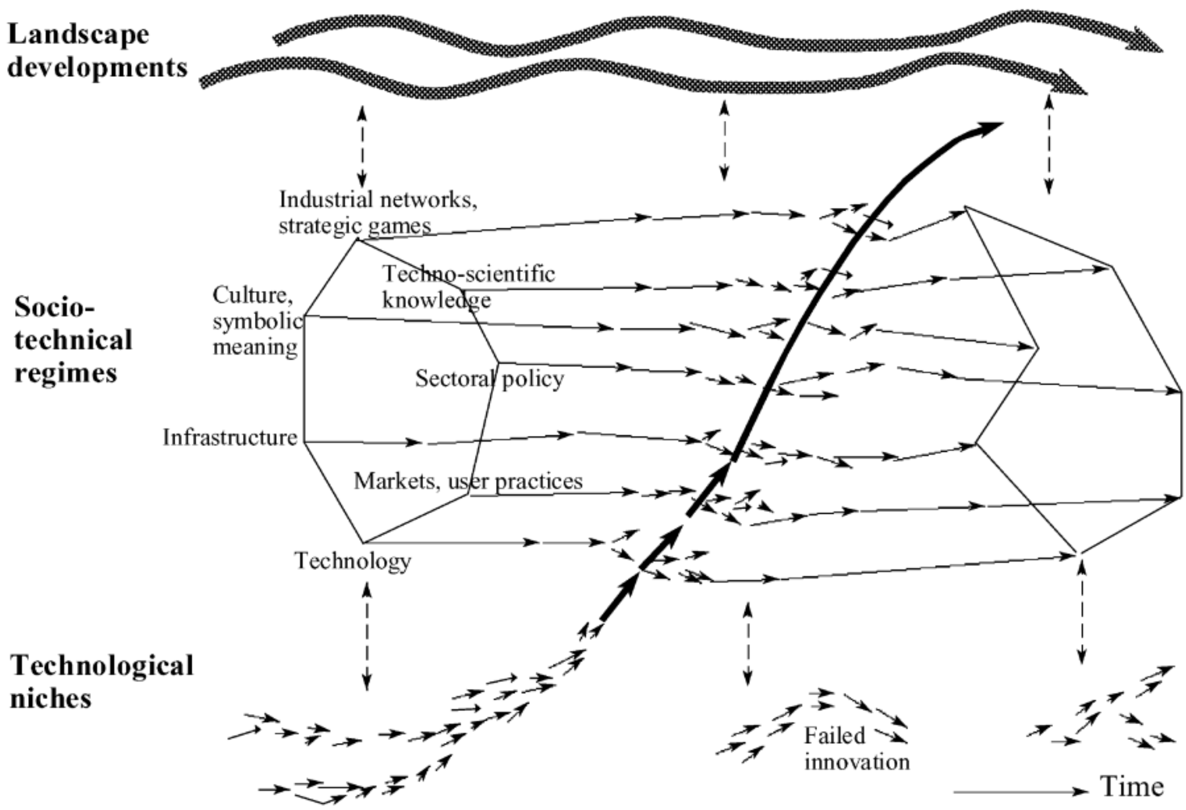

Figure 5. Socio-technical transition in a Multi-Level Perspective (Geels, 2002).

(Geels, 2002). These linkages become lost when a regime faces pressure from the landscape (Callon, 1998). To intercept the landscape, incumbent firms use discursive power to ensure that problems are not put out in the media (Newell, 2009) and maintain their legitimacy. If, however, they sense that change is occurring, they will try to incorporate it through incremental innovation (Geels, 2002) to maintain their historical position.

2.3.4 Add-ons to Multi-level Perspective

As the introduction mentions, the MLP sees transitions as an isolated phenomenon in a single socio-technical system. The theory on incumbent diversification and regime/niche interactions are incorporated to create a holistic version.

Incumbent diversification

The MLP rests on the incumbent's curse, as this curse states that incumbents do not bring in radical innovation, which has been overthrown by Chandy and Tellis (1998). Incumbent firms can diversify, not only in their sector but also in others. These firms have the resources and knowledge to develop radical innovations (Steen & Weaver, 2017). Geels and Schot (2007) further suggest that incumbents can diversify by adopting niche innovations.

Multi-Regime/Niche interactions

Two interactions may create spillovers between systems, namely multi-regime and niche interactions.

Multi-regime interactions

Raven and Verbong (2007) propose four types of multi-regime interactions, i.e., interactions between regime actors in different systems. First is *competition*, when regimes start fulfilling the same functions, thus competing for resources. Second, *symbiosis* occurs when regimes reap the mutual benefits of collaboration. Third is *integration* when regimes become incorporated into each other. Finally, *spillover*, rules transfer from one regime to another.

Niche interactions

Papachristos et al. (2013) proposes four types of niche interactions, i.e., interactions between niche actors in different systems (Geels, 2002). First, *niche transfer*, where a niche in a different regime influences the creation of a new niche. Second, *niche interference* refers to a niche that influences an existing niche in a different regime. Third, *niche autonomy* refers to a niche that is created independently. Finally, *niche emergence* is due to the influences of two or more systems.

3. Methodology / Research design

3.1 Research design

A qualitative research approach is used to research how a transition towards a biobased circular (recycling) economy can be achieved, fitting the explorative nature of this research. The goal is to understand the world through the eyes of actors in the plastic (petrochemical and BBP) and recycling (mechanical and chemical) industries. This comparison led to choosing a *comparative design* for the research design. This design is applicable since this research compares plastic industry innovations (BBP) to the recycling industry at a single point in time (Bryman, 2016). Both industries were incorporated into an adapted Transition Model Canvas (TMC), see Appendix 1, which enables the mapping of the MLP key elements and the comparison.

In this research, the theory of the MLP is tested using the TMC, meaning that the theory was primarily used for deductive reasons. In the final phase, this research became inductive, as an original theory was formed based on the gathered literature, interviews conducted, and the answers to the (sub)questions.

3.2 Operationalisation of the concepts

Operationalisation is based on answering the sub-questions.

Sub-question 1: What types of polymers will comprise the future market of biobased polymers?

The answer to this question was found in the innovations among niche (novel BBP), regime (polyolefin/drop-in BBP), and landscape actors. Mapping the BBP niche focus, strengths, weaknesses, strategies, and strategic resources to destabilise the regime. Due to incumbent diversification and the rise of drop-ins produced by regime actors, they were asked the same questions (to protect the regime). Lastly, landscape actors (scientists/business associations) were questioned about the factors (e.g., oil price) they expected to influence which type(s) of polymer(s) will become dominant.

Sub-question 2: What barriers and opportunities do (the identified future) biobased polymers encounter when trying to fit into the recycling infrastructure for plastics?

A review of the current plastic recycling infrastructure was used to answer this question; this includes the innovations related to CR and the goals of circularity. Recycling regime actors (MR and sorters) were asked how they envision the transition towards circularity, the growth of CR, and the growth of BBP and related (or expected) issues. As the theory explained, novels and PEF can cause issues. The same questions were also asked of chemical recyclers. These questions explore the causes of these issues and lead to the third sub-question.

Sub-question 3: What solutions are (currently) available to overcome the barriers to fitting the future biobased polymers into the recycling industry to create a circular economy?

This question was answered by looking at the total MLP, thus all actors. Landscape and niche (novel BBP) actors can describe their focus, strengths, weaknesses, strategies, and strategic resources to destabilise the recycling (MR) regime. This analysis was extended by looking into the opportunities provided by the niche (CR) recycling actor innovations. Additionally, multi-regime/niche interactions were looked for, as the petrochemical and recycling regimes may influence each other just as the BBP and the CR niche.

3.3 Data collection (incl. Sampling strategy)

Data collection is separated into two steps.

Step 1: Desktop research

First, publications from prominent scientists and reports from niche (BBP and chemical recyclers), incumbent firms (petrochemical and MR), and the landscape (business associations, government) were analysed. This study utilised the Google Scholar database using a range of keywords, e.g., "BBP", "biobased economy", and "BBP recycling", to find articles describing the relationship between BBP and recycling and all nuances. The scope of this research and information gathering will be limited to the Netherlands due to time limitations and the creation of external validity. The desktop research was completed after the inclusion of suggested reports during the interviews; approximately 50 reports and papers were analysed; at this point, no further information was gained, which is a sign that theoretical saturation has occurred. The generated information led to contradictions, questions, and gaps regarding the answers to the main and sub-questions. Here is where step two of the data collection came into play.

Step 2: Interviews

From the data collected in Step 1, the most relevant niche (BBP and CR), incumbent firms (petrochemical and MR), and the landscape (business association/scientist) were interviewed. This selection is a *purposive sampling* technique, as the goal is to sample only information-rich sources that can provide relevant information to the research question (Bryman, 2016). The purposive sampling method is *typical case sampling* since the people selected reflect (in general terms) the viewpoint of that sector. 26 interviews were conducted, resulting in *transcripts*.

The niche system: included four interviews with novel BBP producers and two interviews with chemical recyclers. However, many of the petrochemical (regime) actors were also developing CR plants, meaning that their interviews also contained relevant information.

The incumbent systems: the MR industry (including sorters), accounted for five interviews. In the TMC, MR is described as a Mid-system as the MR system contains only small to medium-sized firms (Vermeulen et al., 2021), meaning that they only fit with the definition of regime actor to a certain extent. On the other hand, the petrochemical industry is a clear regime actor, accounting for four interviews.

The landscape: seven interviews with business associations and five with scientists were conducted. These actors can best describe the landscape factors that influence the actors within the system.

For an overview of the 26 interviews conducted, see Table 2. Due to this high amount of interviews, *data saturation* can be guaranteed, as Guest et al., (2006) state that this happens with a minimum of twelve respondents. The interview method used is *semi-structured interviews*, allowing for the pre-set of questions relevant to the main and sub-questions while providing room for some deviations if necessary. Actors brought forward relevant information, insights, and literature suggestions not considered in Step 1, allowing for iterations. See Appendix 2 for the interview guides used.

After the interviews, the adapted TMC was filled in, incorporating all stakeholders' views and the desktop research. The resulting TMCs will help answer the research question.

Table 2. Interviews conducted.

Sector	Function orientation	Code (#)
Plastic Niche (1)	Business	A
Plastic Niche (2)	Technical	B
Plastic Niche (3)	Technical	C
Plastic Niche (4)	Business/Technical	D
Plastic Regime (1)	Business	E
Plastic Regime (2)	Business	F
Plastic Regime (3)	Business	G
Recycling Niche (1)	Technical	H
Recycling Niche (2)	Business	I
Recycling Regime (1)	Business	J
Recycling Regime (2)	Business	K
Recycling Regime (3)	Business	L
Recycling Regime (4)	Technical	M
Recycling Regime (5)	Business	N
Business association (1)	Business	O
Business association (2)	Business	P
Business association (3)	Business	Q
Business association (4)	Business/Technical	R
Business association (5)	Business/Technical	S
Business association (6)	Business	T
Business association (7)	Business/Technical	U
Scientist (1)	Technical	V
Scientist (2)	Business	W
Scientist (3)	Policy maker	X
Scientist (4)	Business	Y
Scientist (5)	Business	Z

3.4 Data analysis

The data generated is an overview of existing literature, the transcripts, and the TMC. All data was imported into the NVivo software. Due to the deductive focus of this research, a deductive coding scheme was used, namely a *thematic analysis* (Bryman, 2016), which starts with step 1, familiarisation. In step 2, initial coding, the *in vivo coding* method was used, meaning that the codes will remain close to the written text. In step 3, the codes were aggregated into themes based on the theory of MLP, BBP, and the recycling industry. In step 4, these themes are combined to enable answering the sub-questions. In step 5, sub-questions are combined to answer the main research question. The last step, 6, involves using codes and quotations to strengthen the argumentation to answer the research questions (Bryman, 2016).

3.5 Quality indicators of research

The quality of this research can be measured according to Yin's four quality indicators, as these fit well with this qualitative deductive research approach (2009). The first indicator is *construct validity*, guaranteed by the multiple evidence sources used during this research. Using literature and interviews means that the results are not based on a single person's point of view and generate a holistic answer to the research question. Second, NVivo and data analysis methods (*thematic analysis* and *in vivo coding*) are applied to ensure internal validity. By combining these methods, the results are genuinely based on the inputs from the data, and no spurious relationships are found. Third, *external validity* is the main weakness of this study, primarily due to the temporal dimension of the research design. *Comparative designs* focus on a single point in time, but the transition process constantly changes, so the validity of these findings is limited.

On the contrary, generalisations to the Netherlands can be made due to the focus on the Netherlands and the significant amount of data collected and enhanced by interviews. It is possible to conduct additional research to enhance the *external validity*, both geographically and temporarily. The fourth indicator, reliability, will enable this. *Reliability* is high due to the interview guides and the transparent data collection protocol used. Making it possible for future research to find the same articles/publications and interview the same set of actors and thus generate the same results.

3.6 Ethical issues

To minimise ethical issues during data collection, interviews, an informed consent form was filled out online (provided by the University of Utrecht but conveyed digitally). In addition, when participant quotes are used in the results section, these participants was anonymised, with only participant identification visible to the researcher for contact purposes. The interview data (transcripts) will only be stored for the duration of this research. When the research is finalised, this data will be deleted.

4. Results

4.1 Chaos of Transitions

The energy and material transitions are connected (U). The Intergovernmental Panel on Climate Change (IPCC), "*accounting rules aggregating all forestry-related emissions … have created a reward for countries importing biomass since, even though overall emissions are likely to have increased as a result of switching from coal to imported biomass, the country can count them as zero and report a reduction*." (Norton et al., 2019, p. 1260). In other words, biomass burning is carbon dioxide (CO_2) neutral and has a climate advantage. According to actors, this has led to the wrong direction for biomass use (T, Z). This simplicity brought forward by the IPCC has also led to the inclusion of biomass in the definition of renewable energy in the European Commission's Renewable Energy Directive (RED) of 2009 as being a means to reduce greenhouse gas (GHG) (Norton et al., 2019). This challenge is also apparent in the current RED II target for the energy transition (G, D, E). This target states a mandatory minimum of 14% of biomass content in fuels (for road and rail transport) by 2030 (European Commission, 2018). However, this is not the only risk related to RED, as plastic recycled to fuel can also be counted as renewable by member states. Especially with sustainable aviation fuels (SAF), targeting 2% renewable by 2025, which also can include plastic-to-fuel, making it difficult to promote recycling to virgin-quality polymers (Bergsma et al., 2022).

The BBP sector (niche and regime) and the energy sector have increased their demand for biomass. Meanwhile, novel BBP producers complain that the energy sector uses a high amount of the feedstock but escapes the blame for the impact of the increased biomass use (D ; Iffland et al., 2015). Additionally, their increased demand has raised the prices, making BBP more expensive/less competitive compared to fossil-based polymers (D). Meanwhile, biomass in materials has a higher value than in fuel due to its longer life and higher quality input (G, B, T, I). Furthermore, an essential distinction between fuel and polymers is that polymers cannot be decarbonized; fuel and thus energy can, using wind, sun, and water energy (A, B, D, I). On the other hand, these sources are currently not plentiful enough to replace the total energy demand (C). For the energy transition, biofuel is a good temporary solution (Y). We need to be aware that city heating, such as in Breda and Tilburg, has become dependent on waste-to-energy incineration (WTE) as an energy source (U). However, the Social Economical Counsel (SER) pointed out that this should not lead to a lock-in, as this dependency can slow down the transition (Sociaal-Economische Raad, 2020). If we become more circular and start using biomass in polymers, there should be sustainable alternatives for these sources.

In short, it is complex, and everything is connected, which is why it is framed as a transition (A, X, Y). A transition also implies that there is not one solution to tackle this material transition toward BBP (X). It is essential to increase awareness about this interconnectedness. Currently, the focus is on CO_2 reduction, which is more fitting the energy transition than the material transition (Sociaal-Economische Raad, 2020). However, there are also challenges relating to biodiversity and the planetary boundaries. In 2022, a new planetary boundaries figure was released; see Figure 6, in which novel entities' impacts are shown for the first time. This bar shows the chemicals that have been produced and for which we have no idea of their effects (V); as can be seen, this bar is off the chart and should create immediate action to change this impact (Y).

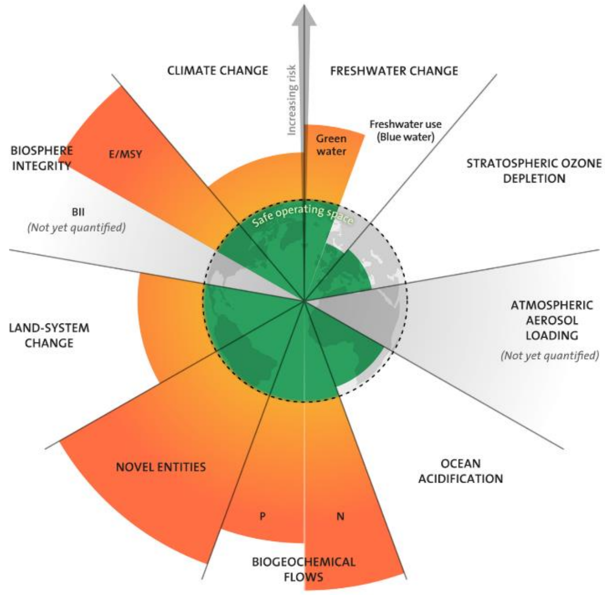

Figure 6. Planetary boundaries 2022 (Planetary Boundaries, 2022)

4.1.1 Change is hard

The most challenging obstacle for the material transition may be social, as people do not like change. The technical development of a novel BBP only took two years. Meanwhile, market development took more than ten years (B). Moreover, while society wants to transition towards a circular system, our behaviour is the opposite. We are increasing our consumption behaviour (P, E, O, S), which is as contractionary as policies that promote green growth (E). We, as consumers, have become accustomed to packaging as a luxury and ease of use (e.g., pre-cut vegetables) (T). Plastic regime actors argue that plastic packaging extends the product's shelf life and state that it should be removed when it brings zero value (G). Arguing that a Life Cycle Analysis (LCA) proves its value, e.g., a cucumber's shelf life will be extended from 1 week to 3 weeks (E). On a critical note, why are those three weeks needed? Cucumbers could be on the shelf within days if produced locally.

An essential first step for this transition is that big firms change, such as McDonald’s, KFC, Mars, and Nestlé (R, M). These firms need intrinsic motivation to make hard choices and be held accountable for those decisions (B). Only these firms themself are stuck with a capitalist mindset, which is understandable in the current economy (S). As the landscape has created a low incentive to change, as it is enough to buy offsets to appease the public (B).

Fitting is the popularity of drop-ins as it creates the same economy and uses the same infrastructure; little to no change is required (V). On the other hand, due to the uncertainty associated with a transition, it is not surprising that both novel and drop-in BBP solutions are exploding at this moment. An actor states, *"in the beginning, it will mainly be drop-ins, but whether the novels can become increasingly dominant later on depends on how the system is set up."* (Q). Others also state that the drop-ins’ market will grow first as they use the existing infrastructure. However, they will never be able to overcome their downside as they can never compete with the additional cost of biomass and being competitive (U), which will give rise to the growth of novel BBP due to their added value, more on this discussion in chapter 4.2.

4.1.2 Plastic aversion

Instead of seeing more clarity on the impact of chemicals, the planetary boundaries results and other publications have created a negative framing of plastics, creating another concerning trend: consumer plastic aversion. One actor states: "*plastic, especially in packaging, you can see that awareness is already relatively high. The knowledge is that we have to be careful with this. Which might have gone too far as to create a kind of plastic aversion."* (T). Researchers concluded in 2020 acknowledged that around 69% of consumers are aware of and worry about the impact of plastic pollution (Johansen et al., 2022). The EMF (2016) also states that the perception of plastic is deuterating in the current society, limiting the industry's licence to operate.

Consumers, strengthened by marketing, feel that polymers are so bad that there is this massive shift to paper. One example in which industry actors state that this has gone too far is the new ban on plastic straws (Ministerie van Infrastructuur en Waterstaat, 2023), creating the hype of paper straws, which is not the right solution due to their lack of ability to hold water (R, G, P, T, E). Furthermore, it is not circular, as these straws cannot be reused and recycled (T, M).

On the other hand, this switch does show that an industry that proclaims to be unable to change (to a paper straw), is able to change after it was made law (Z). Thus, the law is one of the main drivers for this industry to change.

4.1.3 The end of petrochemicals

A social benefit that should be remembered is that, currently, the EU is highly dependent on imports when looking at petrochemicals, creating political and sensitive issues (A). When shifting towards BBP, the focus should be on downsizing this dependency on raw resources. The current situation with the Ukraine war has shown that being independent is very important (Ministerie van Infrastructuur en Waterstaat, 2023).

With the regulations regarding the RED, RED II, and the desire to become independent, it is no surprise that fossil fuels are facing out. However, this comes with its own side effects. Currently, the production of polymers is a side product, making it illogical to keep the infrastructure of polyolefins intact. The facing out is expected to take dozens of years but will give rise to a shift in the source of polymers (S, G, Q, W). Although almost every actor agrees with this statement, one exception states that if fossil fuels stop, there is still enough oil left for polymers for the next hundreds of years (L).

For the rest, everyone agrees there will be a shift towards virgin fossil-free polymers for several reasons. First, due to the global north historical responsibility, meaning we have created enough harmful emissions that we will need to change (E). Secondly, intrinsic motivation, as some regime petrochemical actors claim they want to become more sustainable and circular due to their internal values (G, L). However, they state, "*if you continue to do business as usual, there is no future for you because those days are gone. You need to look at your impact and footprint because the people we work with are also challenging us. Our customers say that I will not buy from you if you do not reduce your carbon footprint."* (G). This quote indicates that big companies and brand owners also demand sustainable materials. Brand owners like Unilever, Nestlé, P&G, Salamon, and Tesco demand recyclable materials (G, U). Thus, regime actors are less intrinsically motivated and more influenced by landscape pressure. Thirdly, the EU climate goals have forced companies to reduce their emissions, for which biobased is one of the solutions (O).

There was a BBP hype in 2007, in which this uptake was already expected; unfortunately, the result is that only 3% of the current polymers are biobased (U, B). In the meantime, there is a new hype, namely CO_2.

4.1.4 CO_2 versus Biomass

There is currently a discussion of CO_2 versus biomass. The Association of the Dutch Chemical Industry (VNCI) just sent a proposal for Future carbon (Z), describing using CO_2 as input instead of biomass as the carbon source for polymers. This proposal has shifted the attention from biomass (V). An advantage of biomass is that nature captures the carbon and reduces the oxygen levels (V). Contradictorily, to convert CO_2 to a material, a lot more energy is needed since CO_2 is very stable (Z, V). It will take a very long time before this becomes a viable production method (A, V). However, as one actor states, "*CO_2, in the end, we need that too, because we do not have enough biomass, but for now, it is mainly a way to be able to think far ahead and not have to do anything now."* (Z). Meaning that CO_2 as a source to produce polymers is inevitable due to the limited amount of biomass. However, this technology should have a secondary focus, as biomass is low-hanging fruit and will incentivise the transition needed in the entire industry.

4.1.5 Limited sustainable biomass

As mentioned above, there is not enough biomass for the entire transition to take place on only sustainable biomass. Humans use 530 PJ/year of fossil resources, and the earth may only have 150 PJ of sustainable biomass (Z). However, research by Leguijt et al. (2020) shows that in the future, the total need for sustainable biomass in the Netherlands will vary between approximately 350-2,000 PJ/year in 2030 and 500-4,200 PJ/year in 2050. The Netherlands will need to become a small to large-scale importer to get this amount of sustainable biomass. When looking into the worldwide biomass availability, importing the needed biomass would be physically possible. However, this does raise the Fair share discussion, thus the size of the claim that the Netherlands can lay on global sustainable biomass since other countries are also entitled to sustainable development and the ability to use biomass (elaborated on in 5.4.2) (Ibid.).

4.1.6 Biobased versus circular economy

Finally, in this transition, some recycling (niche and regime) actors do not believe in a biobased circular economy. They state that polymers should not be made biobased, as they can be made circular, and making biobased circular would require additional sorting streams (I), which is valid for novels. They argue that *"the enormous urge for BBP is also a bit licensed to operate for the big chemical giants to get a green stamp on their plastic"* (L). In other words, they view BBP as a means that regime petrochemical actors can use to produce more BBP without looking into the EOL. This view is partly true, as a biobased economy is focused on keeping the CO_2 stored as long as possible in the material, thus producing as much virgin biobased as possible, as this would heighten the climate gain. Contractionary to a circular economy, which is about minimising virgin polymers (Z). However, this picture is less black-white in real life, as the optimal solution would be a combination of the two. Containing CO_2 in materials and recycling them makes it possible for products with a shorter lifespan, such as packaging, to provide for long-term storage of CO_2 (D, Z).

4.2 Biobased Polymers

The Dutch Action Plan on BBP states that a novel BBP is acceptable if there is an LCA improvement of at least 30% compared to the fossil alternative (Total Corbion PLA bv et al., 2020). Actors state that this 30% improvement is a minimal requirement, but the question is what is included in this LCA scope. Does the LCA only look into the first lifecycle or up to the third or more? Because the more life cycles included, the more uncertainties there are—making this number hard to determine (Z). Other authors state that an LCA comparing novels versus fossils is unfair for several reasons.

First, fossil production has been optimised over the past 50 years (S, D, W), meaning that these methods are well-established and efficient (Walker & Rothman, 2020). This optimisation cannot be said for the (novel) BBP industry. Additionally, the manufacturing phase, compared to other stages, has the highest (around 50%) contribution to LCA impacts due to the process energy required (heat and electricity) and chemicals needed (European Commission, 2019). The potential for efficiency improvements should be incorporated in an LCA (Walker & Rothman, 2020) but is not currently (O). A business association is currently working on an additional standard for this aspect (O).

Secondly, the EOL of the novel BBP has not been developed. Studies show that "*BBP only performed better if they can achieve the same recycling pathway as the fossil alternative.*" (W), meaning novels need to have an EOL equal to or better than their fossil replacement to be able to get an improvement in the LCA impacts. Limiting the design of BBP to drop-ins or novels such as PEF with recycling in mind (W), disregarding other material innovations.

Thirdly, the LCA is dependent on the boundaries set by the researcher. Sometimes the attribution aspect is misused; for example, *"some fossil raw materials are ranked very favourably in terms of LCA. A well-known example is Bitumen. Bitumen is a side product of an oil refinery. Most environmental damage is attributed to the fuels and not the Bitumen. That also means that if you develop an alternative, you take everything into account. Still, if you calculate all that, biobased does not necessarily have to score better than the fossil counterpart*." (Y). In short, for a fair comparison, attribution rules should be stated.

Fourthly, petrochemicals are black boxes when using the ecoinvent databases in an LCA. For a fair comparison, more transparent data is needed for fossil-based polymers (European Commission, 2019).

Finally, LCAs are just numbers (B), meaning that although they give meaningful insights, the dialogue around them is just as important. It would be dangerous if people take the 16 output numbers of an LCA and convert them into one overall score of impact because their weighting factors could differ (B). With an LCA, there are many categories; on some, BBP will score better but worse in others (Y). LCA results should be part of the discussion instead of a single number (B).

4.2.1 Sourcing issues biobased polymers

The source of biomass used for BBP is an essential concern for many actors in the industry looking into drop-ins and novels alike. Nevertheless, it can be stated that novels and drop-ins do not use food sources as biomass.

For drop-ins, the challenge concerns the biomass that needs to go into the crackers, as it cannot contain oxygen. A common biomass source is used cooking oil (G, V, E). However, it is also questionable if enough of this source is available to replace all plastics, as it is also used for the RED standards. Actors using this source expect its availability to grow when fossil fuel car sales are banned in 2035 (European Parliament, 2022), but even then, the question of availability remains (V, E). An actor states, "*the combination of recycling, chemical or mechanical, and biomass. It could be disappointing ... Two-thirds of the Netherlands is full of cows, sheep, and pigs; can we have a small piece of that for biobased. Land use should also be added to the discussion about climate and biodiversity.*" (E). For the transition, a critical look should also be taken into land use which can be used to produce biomass.

As mentioned previously, also for novels, no food source is used; instead, sources such as wood, grass, and different crops (C, B, Y). Another possibility is using residual streams, which is not a 100% solution. It is hard to eliminate contamination within residual streams and thus get competitive BBP (S). *"Residual flow consists of several sugars and may contain some fibre, rubbish, and 95% water. So, it is much more difficult to make a clean lactic acid from that stream than from just pure sugar, which I can buy"* (S), which means that it is cheaper to use a clean stream than a residual (S). Another chain of thought concerns how consumers think about waste streams being used as raw material to contain food (S).

4.2.2 Drop-ins

The petrochemical regime is not only producing polyolefins but is also promoting their production of drop-ins due to landscape pressure, as mentioned earlier, and the regime's vested interest (G). The regime has developed new terms to promote sustainable behaviour to answer the landscape pressure, such as sustainable polymers made from circular and/or bio naphtha. Circular naphtha is made from MR or CR, and bio naphtha is made from biomass (G).

Drop-ins are also known as mass balance polymers because biomass or recyclate is added to a cracker, also containing fossil oil, whereby the method mass balance is used to attribute a percentage of biobased/recyclate to that polymer (Total Corbion PLA bv et al., 2020). Biomass and/or recyclate are blended because these sources cannot fill the cracker completely, as circular naphtha is limited availability (I, G) and the cost of biomass is too high due to the RED II. In the future, the regime actors expect to use more circular and bio naphtha (G). Currently, a regime actor has a demo factory that delivers 1% of circular naphtha and is planning on building one ten times as big in the coming three to four years, but this means only an increase of up to 10% of their feed (E).

Putting these blends on the market requires showing their origin, and biobased naphtha can be measured and shown through the C14 method, which measures the biomass used (G, E, I). Only the circular naphtha part is not measurable (G), making it hard to show that it is being used. However, a bookkeeping method, mass balancing, can keep track of the recycled polymers used in the blends. Some NGOs are critical of this method due to the high amount of freedom in allocating recyclate used, e.g., using "free allocation", as also the recycled content that ends up being used as a gaseous fraction in pyrolysis can be attributed to the polymer produced (Broeren et al., 2022). A fairer way would be the "fuel-exempt" variation, as this would stimulate the use and development of technologies that produce the highest polymer (or precursor) results (Ibid.).

4.2.3 Novels

Only a few new polymers have been introduced in the past years (S). All new novel BBP are polyesters, PLA, PEF, and PHA, bringing benefits and challenges.

Benefits

First, polyesters keep the oxygen from the biomass, meaning that they are very efficient to make from biomass (A, U, B, Z, V). This efficiency can be explained as all biomass contains sugars (glucose); sugar molecules are C6 (carbon), H12 (hydrogen), and O6 (oxygen) atoms, which only need to be rearranged to produce, for example, PLA. Polyethylene (PE), conversely, is very inefficient, as ethylene does not contain oxygen atoms, which need to be removed. When removing O6, C3 will also be removed in the chemical reaction, meaning that only C3 is left to use to produce PE (Iffland et al., 2015). Also explained by an actor: *"you can easily calculate that you need 3.5 kilos of sugar for 1 kilo of ethylene. That is just because you have to get rid of a lot of oxygen. ... But lactic acid, for example, converts 1 kilogram of sugar into 1 kilogram of lactic acid."* (U).

Secondly, polyolefins are very hydrogen and electron intensive to produce from biomass. This intensity is due to thermodynamics, as sugar is a relatively stable molecule (low energetically) and creating a strong (energy-containing) C-C bond in ethylene is hard. Meaning more energy, reactants, or catalysts have to be used. However, even then, 100% conversion is difficult, creating even lower PE yields (Iffland et al., 2015). An added benefit of the low use of hydrogens in polyester is that there is no endless stream of green hydrogen and electrons. Especially in the future, with the energy transition, this could become scarce (V).

Thirdly, polyesters can be recycled using depolymerisation, which requires less energy as the polymer is only brought back to its monomer (A, V); more on the advantage of this technique in chapter 4.4.3.

Fourthly, polyolefins are persistent in nature; polyesters degrade faster (A, V). Actors are concerned that "*if we do not cause a break in the trend, then we will be sorry in 20-30 years because we might have polyolefins from CO_2 or biomass (drop-ins), but we will still not be sustainable, we will still have a plastic soup, due to the problem of persistence."* (V). In short, using drop-ins creates polymers from a sustainable source, but their impact on the environment will be equally bad as the current polyolefins. Polyesters will degrade faster and thus could be a solution.

Fifthly, novels have an added value, as PLA/Solanyl are compostable or can biodegrade (U, R, Q). PEF is lighter and has better barrier properties due to the oxygen inside (A, U, B). Due to this, novel producers can ask for a higher price than drop-ins, as they deliver an added advantage (Y, U).

Finally, novel producers use more sustainable additives, as these producers are more intrinsically sustainable and more flexible regarding industry demands (B) since they are not fixed in the regime.

Challenges

The novels' challenges or the drop-ins' advantages are also plentiful. Firstly, drop-ins can count on the regime's power that produces them and their vested interest (the factories and infrastructure are built). Regime polyolefin actors argue that building new factories for novels is not very sustainable (G, Z, L, E). Additionally, the regime wants to stay, so it will do everything to slow this material transition down (A, V). "*Within a large multinational, you naturally have politics. You also decide where the investments should go. ... they cannot look beyond their own market or their factories. They are busy optimising things within their own system."* (F). In other words, investments in the regime will be in vested interest. This interest is also visible in failed collaborations, such as Avantium with BASF (U) and Nature Works with Dow (B), showing that regimes focus on their own markets.

Secondly, there are scale (chicken-egg) problems. There is currently no alternative for a million tons of, e.g., PE. (S). Novels (and drop-ins) cannot compare in scale to polyolefins (F, U, S, P, Q, W, Y, C, E). Meanwhile, scale is significant in lowering costs. When PE builds a factory, it is for 1 million tons. PLA is building factories for 100-150.000 tons, and PEFs demonstration plant is only for 5.000 tons (U). Additionally, this low scale means that it is not profitable to separate/recycle. Thus, there is no EOL (D, Z). The chicken- egg problem of novels means that because it will not be recycled, there is a low level of adoption, but due to their being a low volume, there is no incentive to create a recycling stream (Total Corbion PLA bv et al., 2020; Odegard et al., 2017). However, a larger scale comes with the previously named problem of limited biomass (A, Z). Additionally, upscaling will harm biodiversity due to extensive single-plant cultivation of the land surrounding the plant needed (B). Nevertheless, on a positive note, novels are growing in scale. *"In the last four years, there have been several announcements of new plants of equal size; maybe we are finally on this upswing on the growth curve. Multiple producers are good, as you do not have to ship so far; you have more price competition" (*B). Thus, the growth of multiple PLA plants is good because it reduces shipment emissions and creates competition.

Thirdly, novels have a high-cost price due to the low scale, as mentioned above, and the high cost of biomass (not only due to RED II). In history, there were not many times that sugar was cheaper than ethane (U). Additionally, novel BBP producers need to fulfil all kinds of sustainability standards; this includes ecological, social, and economic aspects, heightening the end-cost price of novel BBP (O). Currently, this higher price can only be paid by niche products (P, Q, G), such as LEGO trees (S), or in the marketing budget for 1 product (Q).

4.3 Biodegradable or compostable

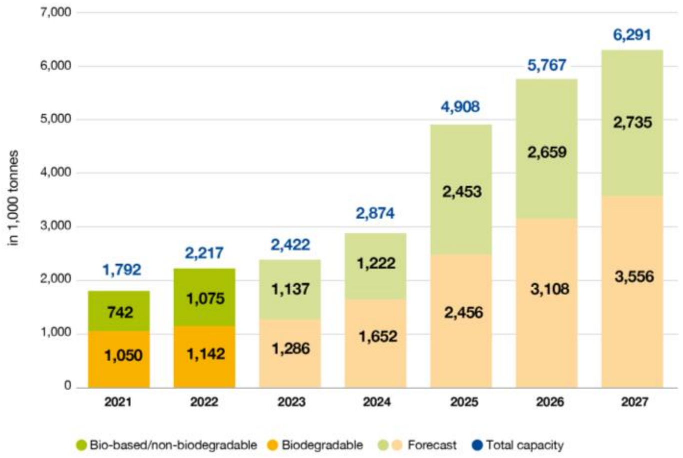

Figure 7. Global production BBP (European Bioplastics, n.d.-b)

A way to go around the vested interest, chicken-egg problem, and create enough added value to overcome the cost is biodegradability, which is expected to grow according to EU bioplastics, see Figure 7. Although growth is predicted, the cause is due to growth in the Asian market, which makes sense due to the lack of recycling infrastructure (O). Still, this solution also makes sense in the EU for several reasons.

First, the solution makes sense when closed-loop recycling is not viable, as some products still end up in nature (W, Z). Unfortunately, most materials are over-dimensioned and stay too long in the environment. Biodegradability offers a shorter solution (R, Y), which means that biodegradable is only for specific applications, namely two categories. First, polymers that cannot be removed from the soil or marine (C, U, D, B), examples of this are in the agricultural sector, such as root protection of plants (D, U, C). Second, food packaging (A, D, G), as there is a cut-off to what costs more energy, making new packaging versus recycling contaminated packaging. When a product contains too much organic waste (contaminations) that are hard to remove, it costs less energy to make a new one (A).

On the other hand, there are ample reasons for not using biodegradables everywhere. First, biodegradable is not energy efficient. Composting is even below burning with energy recovery on the waste pyramid (P, C). Meaning that if it is possible to recycle the material, this is preferable. As EMF states, keeping material in the Technosphere is essential (P).

Secondly, biodegradability is context-specific and will not happen worldwide. Between the different actors, there is confusion between compostable and biodegradable in nature. In nature, it needs to be context-specific (A). However, actors suspect that within the next dozen years, nothing will come on the market that will be degradable worldwide (R). Furthermore, since it is so context-specific, it is particular that there is no certification system in place. It is suspected that this will come, as it is already done in the US and France, where additional information needs to be provided (O). On the other hand, from a biodegradable novel producer's standpoint, it is hard to certify for every environment and is mainly too costly (C). "*If you need a new certification method for each specific variant, which is not possible. On the other hand, in each of the different mediums, your product reacts differently, and you can never meet everything*" (C).

Thirdly, biodegradables can cause a littering problem. Especially if an industrial compostable polymer is confused with a biodegradable polymer, it will remain there for a long time. This confusion is common because consumers think they can throw both in nature (A, F, S, W). Companies should not promote biodegradable/compostable packaging to prevent consumers from littering. One actor stated: *"I developed Mars foil which was biodegradable. They purposely never told anyone because if they told the consumer that we have a biodegradable film, everyone would throw their wrapper on the street. And then everyone sees Mars on the street; even if it is good for the environment, it is still bad for their brand."* (R). A downside to not mentioning biodegradability on the packaging is that the investment and sustainability branding of the investment cannot be promoted (R).

Fourthly, biodegradability in nature and composability are too slow. It currently takes 10-12 years for a novel biodegradable (in nature) polymer to degrade. The goal is to

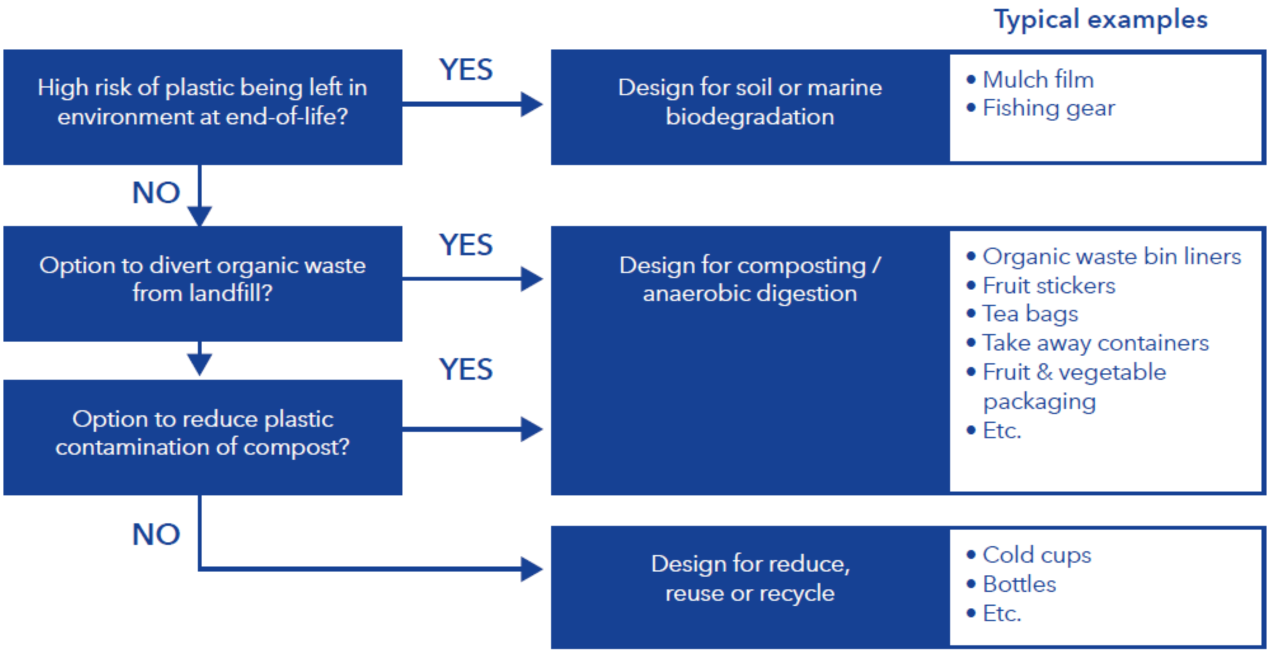

Figure 8. Decision tree PLA (Buijzen et al., 2020). Option 1 includes marine degradation.

reduce this to 3 years (C). Since most biodegradable polymers are blends, the starch is gone relatively quickly, but the other polymer, most commonly PLA, is not (U). As mentioned (in the theory), the composting norm is three months; however, in reality, this is shorter, around 2-4 weeks. This shortening is also why compostable BBP are accused of being too slow to degrade (Buijzen et al., 2020). Although it is unclear why this difference between norm and reality occurred, composters claim that a cycle of 6 weeks would already be too long to be profitable (Bours et al., 2022). Other causes that increase degradation time are the material thickness (A). For example, PLA is certified to a thickness of 3mm; in practice, they are often thinner and would thus decompose quicker. However, the Dutch government stated that compostable packages could not be thrown in GFT. "*PLA has long focused on composability, but that is a route that is not useful in Northwest Europe because packaging is not allowed in the GFT"* (P).

Finally, the supply of PLA waste (post-consumer) currently exceeds the compost demand (Niaounakis, 2019), indicating that having more compostable materials does not make sense from a composter's point of view.

4.3.1 Marine degradable

A new concerning trend is marine degradability; see Figure 8. Although it is already clear that it will not solve the plastic soup problem, new ideas for marine degradability to use for fishing nets and fishing gear to protect marine animals are promoted (O). Producers of marine degradable materials state that if the fishing gear is left in the ocean (be it accidental), it will not persist for hundreds of years. They do end with a critical note that PLA, for example, will not degrade as fast in a marine environment as during industrial composting (Buijzen et al., 2020). This low degrading speed could be an understatement because PLA is heavier than water and will thus sink to a location where it will be cold. One actor even states that it will not degrade (B) as there are areas in the ocean where nothing degrades, as there are no microorganisms (O). This lack of degradation is also why it is hard to develop a standard for marine degradability, as biodegradation at the bottom of the ocean is not likely to happen (Directorate-General for Environment, 2022a).

Novel producers also examine what happens if fish eat their BBP (A). It is already known that "*bio accumulative pesticides and other bad stuff accumulate on hydrophobic polymers*" (B), meaning that these pesticides will get into the diet of fish (B).

A common misconception is that if the material is hydrolysable, it will immediately disappear when discarded in the sea; however, animals will still get stuck in these nets. If the fishnet dissolves immediately, the product will have a short service life (B). In short, marine degradability is not a perfect solution and should be prevented. Prevention of litter, public awareness, and waste management are more important topics to address to prevent marine litter (Van Den Oever et al., 2017).

4.3.2 Misconceptions

There are plentiful misconceptions concerning the term biodegradable. Firstly, BBP is not biodegradable per se (S, T). As there are also fossil biodegradable materials (F), see Figure 1.

Secondly, recyclers proclaim to be against (biodegradable) BBP. A regime recycler stated, "*if you just take a little bit of BBP that sneaks its way into other material, when you want to recycle it, it is devastating for the quality."* (J). Although, it can be argued that they are against all new sorts of plastics (U, O), as every new polymer will increase the complexity of the recycling stream and thus disrupt the process (Crippa et al., 2019). Thus, it is true that every BBP is a source of contamination in the current recycling process (Alaerts et al., 2018). However, it is a misconception that (compostable) BBP cannot be MR (Buijzen et al., 2020). A study performed by Wageningen Food & Biobased Research for the EU Open-Bio project even showed that the contaminants caused by compostable BBP have a similar effect as petrochemical plastics' (Van Den Oever et al., 2017)

Thirdly, the knowledge of the definition of biodegradable (versus compostable) and the implications are limited, which is caused by its complexity. For example, one actor stated, "*PLA is biodegradable… I do not need machines for it… it breaks down outside*" (R). Thus, this actor believes PLA to be biodegradable in nature; this shows that even if the producers claim it is industrial compostable (B), the term has too much room for interpretation.

Fourthly, the term "degradable", used by a non-biodegradable novel plastic actor, can heighten the complexity even more. Their main reasoning for its use is that it does not state biodegradable, but low persistence is meant (A). "*We have shown that the BBP breaks down much faster than PET. It takes about 1 year under industrial composting conditions. Thus, we do not meet the requirements of industrial composting, and cannot say that it is biodegradable"* (A). This actor states the importance of a short biodegradable timeframe; thus, if a polymer ends in nature, it should not remain there long (A).

Finally, some actors state that with biodegradable polymers, there will not be any microplastics remaining (R). However, this depends on multiple aspects. Microplastics are solid particles smaller than 5 millimetres (Urbanus et al., 2022) and state nothing about the environmental impact, whose effects are still unknown (Ibid.). *"Anything that biodegrades will be a microplastic at some point in the product's life cycle. There is no other way."* (C). Meaning all biodegradables will get to this microformat; the question is how long they will remain in this format; this is environment and material-specific (C) as these microplastics can spill over (transfer by wind, runoff in the soil, or being digested) into an environment where they are not intended for (Directorate-General for Environment, 2022a). However, polyolefins will also break down into microplastics and remain in this format for a long time, independent of the environment (U, P).

4.4 Recycling infrastructure for plastics

There are rules for all MR, as every recycler/sorter needs to follow the National Waste Management Plan (in Dutch: Landelijk Afvalbeheerplan) (LAB), which contains a Waste hierarchy see Figure 9, in which sorters have to strife for the highest tier. Nevertheless, there is a minimum they must reach, which means that for recyclable material, this is the norm. If sorters do not comply with this norm, they can lose their permit (N).

Waste hierarchy

a. Prevention;
b. Preparation for reuse;
c1. Recycling of the original material in an equal or as to the requirement material quality comparable application, including mechanical recycling and chemical recycling in the form of "monomer chemical recycling" and "solvolysis" but not as "chemical recycling via base chemicals";
c2. Recycling of the original material in a non-equal or as required material quality not comparable through application and/or chemical recycling base chemicals;

d. Other recovery, including energy recovery;
e1. Burning as a form of disposal;
e2. Dump or discharge.

Figure 9. Waste hierargy, (Rijkswaterstaat, 2021)

Due to the LAB waste hierarchy, the most common method of recycling is MR (c1, in Figure 9). As described in theory, it is easy, low on energy and costs (J, P), and can be small-scale (P). MR is mainly known for open-loop recycling, downcycling, but it is also used for high-quality products, e.g., Quality Circle Polymers, which make the raw materials for Samsonite suitcases (E). However, this association is due to the physical and thermal stress inflicted on the polymer chain during the melt and extrusion steps, leading to the degradation of the polymer chain (Ragaert et al., 2017; Hann & Connock, 2020). Due to this, adding 20 to 40% virgin polymer is common to upgrade the properties (G).

However, there is one exception, sorters/recyclers can be excluded from following the LAB when the processing (according to the minimum standard) costs more than € 205/ton (Rijkswaterstaat, 2021). In short, to MR plastics they cannot contain too many contaminants. Whereby recyclers use the more straightforward calculation that at 15% (based on weight) contamination, the plastic packaging will be burned. Both methods rely on weight, which creates an unfairness compared to glass (Q) and means that foil will be burned especially quickly (M).

4.4.1 Packaging recycling

As mentioned in the theory section, plastic is predominantly used in the EU in packaging. However, with MR, due to possible contaminations, its recyclate cannot be used for food-grade packaging (G, H), making it hard to create a circular economy.

On the other hand, the recycling rate for post-consumer plastic packaging waste (PCPPW) is low. PCPPW recycling is 50%, which is lower than the 90% for glass, paper, and metal (Afvalfonds verpakkingen, 2022). The lower collection rate partly causes this lower recycling rate, as people find it challenging to place the PCPPW in the correct bin, whether it is Plastic, Metal and Beverage cartons (in Dutch: Plastic, Metal en Drankkartons) (PMD) or residual waste (Q). Additionally, after sorting, around 65% of the plastic remains; the remainder, 35%, are bonded, black-coloured, and large labelled products (N, J). This 35% is due to the limitations of the current sorting Near InfraRed (NIR) technology, which uses an Infrared scanner to detect the material and separate a preselected plastic sort. Some of these products even proclaim to be recyclable but will not get through the sorting system (M, L).

The low percentage of PCPPW recycling is also due to the chain deficit (L). "*If you look at the business model, to get waste in, you have to be cheaper than the incineration plant, and at the end, after making a nice raw material, you have to be cheaper than a virgin plastic*" (K). In short, the MR industry is stuck between two walls; the price must be lower than WTE initially and, in the end, lower than virgin polymers. The price is also influenced by the amount of recycled content out there, making the price highly variable (K, Q, H). Getting a positive value on PET, PE, and PP is possible. However, the value of foil, MIX, and pet tray fractions are negative (N). This negative value is due to it not being a mono-material, explained later. Although the recycling industry tries to sort into more mono-materials, for example, colours, there is a low market adoption (K). To overcome this chain deficit, for PCPPW, an extended producer responsibility (EPR) system is set up (L).

4.4.2 Extended producer responsibility

Material	% NL 2018 achieved	% NL 2018 target	% EU 2025 target	% EU 2030 target
All packaging	79%	70%	65%	70%
Plastic	52%	48%	50% (+70%)	55%

Figure 10. Recycling goals of the government (Bruijnes et al., 2020)

An EPR means that packaging producers and importers are legally responsible for their PCPPW; thus, its prevention, collection, and recycling in The Netherlands (Cevikarslan et al., 2022). As a response, big packaging companies have set up the Packaging Waste Fund (PWF) (X; Bruijnes et al., 2020). The main task of the PWF is to obtain the recycling goals set out by the government, see Figure 10. To achieve this, the PWF has taken complete control over the post-consumer packaging sector (L, M), which is debatable if this is a good direction, as it can also hold back innovation (C). It compensates the municipality for picking up PCPPW €800/ton. (P), of which two-thirds is needed to cover collection costs and the remaining one-third for transport and other costs. The goal is that this incentivises municipalities to choose recycling instead of WTE, although this is also incentivised by incineration fees (Cevikarslan et al., 2022). Furthermore, the PWF also pays a fee per ton of well-sorted waste to sorters (M) and processing fees to recyclers (Cevikarslan et al., 2022).

The PWF has created two instruments (which overlap). Firstly, the waste management fee (in Dutch: Afvalbeheersbijdrage), which producers/importers must pay when producing/using more than 50t of packaging per year. The rate used by the PWF in 2022 was €700/ ton (Cevikarslan et al., 2022). This fee pays for all the costs mentioned above. It is a polluter pays system, as one can imagine that the costs set out by the PWF will be calculated back to the consumer, meaning if consumers think they need to buy products, they will also need to pay for the PCPPW they create (X). It is a system that costs money to set up (K), but it explains why more plastic gets picked up in the Netherlands and not in Spain, Italy, and Greece (M). However, it is not implemented for all plastics, as "*the core of*

EPR is aimed at product groups that lend themselves for that instrument, and that is, for example, not plastic in general. Because then you would have to organise it for everything that contains plastic, it is easier for plastic packaging alone" (X).

The second instrument is tariff differentiation. Producers using excellent recyclable material pay less for the waste management fee. They use the Recycle Check made by the KIDV (Knowledge Institute Durable Packaging), which includes suggestions on mono-material (P). The Recycle Check is based on the current system of collecting, sorting, and recycling PCPPW in the Netherlands (Kennisinstituut duurzaam verpakken, 2022). Only currently, tariff differentiation is a sham, as the difference is minimal (L). The question if biobased should be promoted using this tool, was met with mixed emotions, as the line of thought was that their tasks should remain focused on post-consumer plastic waste, thus stimulating using recycled content fits, but stimulating a renewable source as feedstock should be stimulated in a different manner (P).

Improvements required

Manny actors state that the PWF is a good tool; it is very efficient, as small organisations with a limited number of employees (10-20) can arrange collection and recycling at a low cost, 0.15-2% of the original sales price of the packaging on the market (Vermeulen et al., 2021). However, many also agree that it needs improvement (T).

First, it is responsible for all PMD, so this waste collection system was generated without considering cross-contamination (L). Furthermore, it is only responsible for post-consumer PMD, meaning that a company's PMD waste will not be collected but burned (K). However, this has changed as of 2023, as schools and companies can separate their PMD packaging free of charge and have it collected by the PWF (Stichting EPR, 2022), only this is not mandatory yet.

Secondly, PWF steers on low-cost and high-volume recycling. PWF is responsible for all PMD but will only pay sorters for a selection of plastics, namely PET, PET trays, High-Density Polyethylene, PE, PP, Polystyrene, Foil (DKR 310), and Mix (DKR 350) (N), meaning that all new materials (residual) will be sent to the burning industry (M, L, E). This focus is on the highest % of materials in the stream, not the highest value (J), such as novel BBP and highly recyclable polymers. However, there should also be a recycling solution for these materials (J, C). Sorters report that they are willing to invest if the PWF rewards the sorting of new material. However, the realisation will take approximately two years due to the longer delivery time of the sorting machine (M).

Third, it does not define what type of recycling quality is needed, thus incentivising low quality as this requires less investment (T, L). Also, according to the R hierarchy, the most sustainable options are not the cheapest. Current policy practice focuses on choosing "affordable options" with an agreed price limit, the €205/ton mentioned earlier. There is no obligation to systematically assess the sustainability of existing and innovative recycling options to determine which recycling choices should be made. With the price limits given, that decision is left to the market (Vermeulen et al., 2021). PWF has targets to promote the quality, which state that the foil and PET should be 90% pure, PE, and Polypropylene (PP) 94%, and a precondition of a maximum of 55% MIX (Verrips et al., 2019). However, when looking at a PET bottle, if it has a non-PET cap, label, or food contamination, this is not seen as an impurity but as something outside of the sorter's control (M). This example shows that even if a stream is 90% pure (according to PWF), it will contain more than 10% contamination.

Fourth, there is only a stick and no carrot; sorters will get less money if they are below the purity target but will not get rewarded if they score above the target, meaning there is no drive to improve (M; Verrips et al., 2019)). Contradictory, it is not profitable to be above the recycling target; being below will result in a minimal fine but less cost for disposing of the residual (M). Sorter states: "*if you sort something very carefully, you will have more residual waste. Otherwise, we can just insert 10% waste into the foil because that is allowed. But we said we are going for quality. Only we received a lot of negative comments from the PWF, that we had too much residue, 5% more residue than the average colleague.*" (M). So, sorters get negative attention from PWF if they have more residual and higher-quality sorting.

Finally, there is no focus on minimising or reusing packaging. The basic idea of the EPR has led to the assumption that producers are incentivised to design their products with minimal waste. However, in the case of the current EPR schemes, this assumption is not correct because the incentive is too weak: collective recycling is organised at rates of less than 2% and sometimes even 0.1% of the product price, and this does not lead to a strong incentive for eco-design (Vermeulen et al., 2021). Nevertheless, the government is also looking into the possibility of putting this in an EPR (T; Ministerie van Infrastructuur en Waterstaat, 2023).

4.4.3 Chemical recycling

A downside of CR is that it is a container concept; actors even use a new term, advanced recycling. The upside of CR is that it promotes solving the shortcomings of MR. Thus, it focuses on stricter grades, such as food and medicinal products (E, F). This focus is possible, as CR will get the same properties and quality performance as virgin polymers since all additives and contaminants will be removed (F, G). Furthermore, this technology saves CO_2 compared to making a new polymer (H).

Depolymerisation

According to some actors, depolymerisation is better than pyrolysis when looking into all the CR methods. Firstly, it saves energy and cost, as the material will only be returned to the monomer, not to naphtha (A). Depolymerisation CR actor included in this study focused on Aromatic polyesters. However, Aliphatic polyesters like PLA can also be depolymerised, which is now done by the producer Corbion itself (D, U) but not on an industrial scale.

Although pyrolysis is being promoted as being farther in development (F), depolymerisation is also getting ready for production, "*I would say that within two or three years, we will have PET bottles with the recycled BHET content."* (H).

Pyrolysis

Polyolefins, on the other hand, can only be CR using pyrolysis (A, H). On the other hand, pyrolysis cannot handle polyesters (V) because they contain oxygen. Meaning the two methods (pyrolysis and depolymerisation) and their materials are mutually exclusive. As polyolefins have no oxygen in them (there is no oxygen in fossil naphtha), meaning that for the recyclate to be put into the cracker, it needs pre-treatments to lose all the oxygen; in other words, you are trying to fit a square peg into a round hole. All these pretreatment processes cost resources and energy (V). One of the main parts of this pre-treatment is sorting. Currently, one actor has a site of a cracker which is the size of 5 football fields; only four out of those five are for separation (E) as the plastic waste brought forwards can contain small parts of, e.g., PVC, which contains halogens which, during their breakdown, will lead to acidic halogen gases such as hydrogen chloride to be produced, which cause thermal decomposition of the equipment and are toxic (Hann & Connock, 2020).

Furthermore, these crackers cost billions of dollars, the industry's most expensive part, meaning that the owners do not want to risk them degrading (G). This risk is the main reason why the purification of pyrolysis oil is essential and that it meets strict specifications. Even with this in place, the ratio of pyrolysis oil to (fossil) naphtha will be relatively low as a security measure, making it unlikely that a cracker will run solely on pyrolysis oil (Hann & Connock, 2020). As of today, no limit in this ratio has been published by a petrochemical regime actor (Ibid.).

Downsides

CR has downsides. Firstly, with pyrolysis, the material (and biomass) is brought back to naphtha and can thus be sold as fuel, which pyrolysis is mainly used for currently (Ellen MacArthur Foundation & World Economic Forum, 2016). Selling recyclate as fuel has created some concern with actors as this is not a positive direction for a circular economy (P, M, L). Although some actors expect this conversion will be banned by law at some point in time (I). Only it raises the issue of what should happen to the formed gaseous fraction, a fixed by-product of pyrolysis (Hann & Connock, 2020).

Secondly, actors fear it can create a new lock-in instead of a temporary solution (V). According to the polyolefins regime, there is a high demand for circular naphtha in polymers on the market, and this demand will create a circular economy (I). Others state that this is using status quo thinking, looking at the existing infrastructure/assets, such as production lines, very much drives pyrolysis. As the polyolefins regime is promoting pyrolysis, it gives them a licence to operate (A).

Thirdly, critics are concerned that CR will use mechanical recyclable materials for CR since continuous pyrolysis inputs are required for this technology to function and be profitable (H). These continuous inputs could come at the cost of MR material (Q) already being used. However, this is argued to be done due to the technology's learning curve; when it develops further, it should be able to handle non-mechanical recyclable materials (U, X). Not much is done in policy since this industry is still in its infancy (T). However, this process has been developing for over 20 years (L, J). Questions remain if stringent regulations preventing MR material usage will prevail and if there will be enough residual streams to fill these enormous pyrolysis factories (K). The KIDV states that pyrolysis will require the current collection systems to be optimised or PCPPW to be imported from neighbouring countries. Otherwise, plastic streams other than PCPPW will also be needed as feedstock (Kennisinstituut Duurzaam Verpakken, 2018).

Finally, slowly it is being realised that CR is not the promised holy grail, in which everything can be recycled (M). Chemical recyclers complain that in residual streams, there is too little PP, too much PVC, or contamination (K). "*Pyrolysis is not the holy grail, but it is a way to recycle endlessly, and you cannot do that with mechanical*" (I). This actor is not the only one claiming the endless loops for CR. Also, the EMF claims that CR could enable "infinite" loops (Ellen MacArthur Foundation & World Economic Forum, 2016). Unfortunately, this is not true; in an LCA calculation done by an actor, they showed that its efficiency is almost equal to burning with energy recovery (T). Pyrolysis is not 100% efficient; rough calculations show a loss of 40%, and a circle of 60% is not very circular (T, V).

4.4.4 Mono-materials

While discussing getting higher recycling quality output, both MR and CR proclaimed that mono-materials are preferable. Mono-materials mean no additives, like flame-retardant, and different colours because mixing colours will result in a grey recyclate. (N, H, L). Colours are used mainly for marketing; consumers want and recognize products due to their specific colour (P).

Mono-material also means no multilayers, such as PET trays, which are used to meet product requirements and barrier quality. There have been recent attempts to get rid of PET trays; for example, the PET trays containing chicken breast have been replaced with a PP foil, a mono-material, which sounds preferable. However, in practice, the PP foil went into the foil sorting system, which means it ended up in a mixed stream and decreased its quality (M).

"*Like the Crocs, ideally, I want to put that in the CR. It is a mono-material shoe….you could do MR. But the thing is, grinding it back, you would not get the same performance*" (G). According to this polyolefin regime actor mono-materials should be sent to CR; the only question is, if the chemical also wants mono-material, what is the added value of CR if it could also be mechanically recycled (P).

4.4.5 Circularity recycling gap

Recycling is needed to reach a circular economy, but it is not a 100% fit. In the past years came the realisation that from every viewpoint, recycling will always need virgin feedstock (O, V). Even if we could close the loop 100%, there would always be a higher demand due to population growth and the growing demand for more products (I, K). One actor even estimates that between now and 2050, the polymer demand will triple (K).

As the KIDV explains, we are now only at the beginning of the recycling economy and need to transition to the circular economy to reach intrinsic sustainability, meaning that sustainability comes from within, and no regulation needs to be set up (P; Bruijnes et al., 2020). Multiple solutions are available to grow into the recycling economy; one proposed by a plastic niche actor is to start sorting and recycling the few upcoming BBP. They argue that is what the subsidies are for and should trigger the market to change (D). According to some actors, the most important takeaway is that to fill the gap to 100% circular, the virgin produced is from a renewable source like biobased and not fossil (O, T).

4.5 Initiatives happening in the recycling and plastic industry.

4.5.1 Funds and collaboration

During this research, most actors acknowledged that they frequently collaborated for private gains, e.g., funding. One of the most used fund applications to get innovations starting in these sectors is the Dutch Groeifonds (Grow fund). The Groeifonds is a funding program to prepare the Netherlands for 2050 (A). Two funding applications were frequently mentioned. First, the Biobased Circular (BBC), in which 120 actors collaborate, actors from the industry up to the knowledge institute. They are currently in the process of applying for a fund of 300 million. If granted, the program promises to support projects such as a lactic acid (LA) factory for Corbion and a Glycol factory for PET and PEF production for Avantium (A).

Second, Brightlands Circular Space was granted 25 million euros, a collaboration project between 4 founding partners: The University of Maastricht, TNO, Sabic, and Brightlands. Its program is about the sharing of knowledge to support a circular economy. Focussing on recycling of post-consumer plastic, from MR to gasification (E). Only a petrochemical regime actor states that using these funding programs results in getting criticised, as people fear it is used as state support (E). On the other hand, this actor also complains about the large hoops and papers required to get these funds (E), making it unlikely that smaller firms have the capacity to acquire them on their own. These hoops and papers thus create a barrier in the current funding structure and may minimise the needed collaborations.

A trend within the industry, also with the last application, is sharing knowledge and mainly partnering with knowledge institutes (E, C, J). Although this sounds promising, sharing knowledge is limited, as companies point out that they still fear the loss of their Intellectual Property (IP) and need to make a profit (H, J, F). What is lacking is the incentive to create unity, an infrastructure that could benefit all. However, this type of overall system collaboration seems to be the setup of the BBC but is uncommon industry-wide (F).

4.5.2 EU or Dutch regulations.

Many actors see a lot of opportunities and limitations in (upcoming) EU or Dutch regulations. One of the most named is the upcoming Packaging and Packaging Waste Regulation (PPWR), which requires 30% recyclate to be included in the packaging material. Some state that this is a positive movement, as this stimulates the use of recyclate and investment in this industry (D, H, T, L, K). The question is whether there is enough waste/recyclate for the whole sector (H, K). Additionally, using it for food-grade packaging and only being able to use mechanical could cause problems. Unwanted multilayers would be created to protect food against contamination (I). That is why some state CR should be included (Q, I). However, the type of recyclate is undefined. To prevent the overuse of CR, as it would be the easiest source, different values need to be given to different types of recycling (T).

Secondly, the implementation of the CO_2 tax caused mixed reactions. Actors favour this solution as it promotes the least CO_2-producing solution without forcing the industry in one direction; the most sustainable option will win (D, T, W, J, K). This solution is also something that the government is trying to achieve (X). The CO_2 tax is also already implemented in the UK, combined with a PPWR (K). Alternatively, some actors feel they already pay the CO_2 tax for their factory emissions (F). Or state that they view it as one-dimensional since it would unfairly promote biomass and not promote looking into microplastics, biodiversity, and other circular challenges (L). Lastly, some believe it is insufficient and state that we should stop fossil resources entirely (Z).

Third, the National Plan Circular Economy (NPCE) contains 287 improvement points, including the CO_2 tax (T). The downside of this report is that approximately 100 of these points are plans to research the potential impact of the suggestions. As stated in the report, the Dutch government still lacks insight into the possible effects and the feasibility of interim objectives. This gap needs to be worked out in more detail; this is why the national targets cannot be set. The concrete details will be examined in 2023, and a decision will be made in 2024 (Ministerie van Infrastructuur en Waterstaat, 2023). However, for the other points, the actual impact of the policy on the sector will take multiple years (X). The SER is even of the opinion that the NPCE does not generate enough action that the materials transition requires (Sociaal-Economische Raad, 2023).

Fourth, the Dutch Action Plan suggests creating a shortlist for (novel) BBP. Which also causes mixed reactions. Actors in favour state that there are already more than 150.000 polymers, meaning that any new polymer will contaminate the recycling infrastructure (L). Limiting, standardising, and reducing the amount of plastic will improve recyclability (Z). Unilever is already decreasing their plastics to 100 kinds of plastic for their packaging (F). Other arguments in favour are that it incentivises the government to take more control and create a safe environment for developing novel polymers. Only polymers not on the list will receive less focus (Q), which reduces innovation (C). To prevent this, some argue for a flexible list that moves with the innovations happening. However, how materials can get on this list (Q) and how many fractions can be on the list (J) remain unanswered. A recycling regime actor has conducted private research showing that five polymers could replace 85% of the polymers in use today (L). However, this research has remained unpublished and thus unverifiable.

Finally, create the same mandatory requirements for polymers as for the energy sector (RED II). There has been a skew growth due to the previously named preference for biofuels. There should be a mandate to include a fixed percentage of biomass in polymers. This way, brand owners will be forced to accept the raised price of the polymers (U, E).

4.5.3 Getting to a circular recycling system

There are multiple suggestions for heightening the recycling system's circularity. One frequently mentioned problem is consumers' confusion about where to put their waste, into which bin (P). *"Labelling for the consumers, not what the material is, but where they could put it because this counts for the consumer. Then we will start going into a circular economy because we will get good material sorting"* (O). In other words, the recycling bin should be standardised to be stated on the label instead of the material. Although sometimes done on packaging in the Netherlands, consumers are still confused. This confusion can be traced back to the high effort asked of consumers, such as removing the lid or the label to be placed in a different bin (L).

Secondly, the sorting of PMD separated it into food and non-food. Food source PMD waste can be reused in packaging, while non-food waste cannot. This distinction is not made, meaning nothing can be used for food grade (L, P). The question is, who should separate it? Actors state that it would be easy to do for sorters (P), but when looking back at the section regarding the NIR technology, this is not 100% true.

Thirdly, design for recycling. The EMF states that 80% of the circularity is determined in the design phase. What is important is that designers not only consider recycling but also sorting. If a product is not correctly sorted, it will not be recycled (L). Moreover, when looking into the material options, consider the chance that the material will end up in nature (C, V, Z); a good example is the decision tree from Corbion, see Figure 8. This figure shows that the more likely the change that it ends up in nature, the less persistent the material used should be.

Finally, traceability can also heighten the recycling percentage, as it will show the gaps in the recyclate stream (W). The question is whether this tracking should happen on the product or stream level (J). Products that cannot be sorted are currently recognized with their barcode to communicate to their producers. However, this communication is a Business Model (BM) for sorters; they sell this information (L). A new start-up for product traceability, frequently mentioned as promising, is the Holy Grail project, which uses a watermark printable on hard plastics (F, P, W). However, markers such as these or barcodes will not gather information about the use phase (Crippa et al., 2019). Furthermore, the high cost and the company's sensitive information, which will need to be shared, make this unlikely to succeed (J). This limitation makes relying on stream-level tracing a more feasible solution, as it will not need standardised codes and can be done already (J).

4.5.4 Changing the BM

Another option is to change the BM to create a circular economy. Such as leasing materials or offering products as a service, such as Philips Lights as a service (Services | Philips, n.d.). As shown in Figure 11, Philips Lights as a service includes electricity and closes many of the circularity loops. Although not yet done for materials, this could be a future option (F). The brand owner owns the packaging material to be cleaned or remade into new products (A, F). One of the first signs of this change is that more big firms are investing in recycling their materials (A, M).

Another option is buyback; actors could buy back their materials from sorters; thus, instead of being paid by the PWF, they will get money from the producers themselves. Although in the past, this was unsuccessful with PLA due to its low amount in the waste stream, making it not viable to invest in a new NIR machine (B).

A third option is to increase the deposit system, a suitable carrot-stick method, as people who do not bring back the product pay for it, motivating others to bring it back for the reward (A, F, Z, T, E, J). It is also a system that can guarantee food-grade quality (R, P, J). Although the CO_2 balance for this system is questionable, depending on the locations of the cleaning and refilling installation (J). Additionally, this system requires at least 80% of the products to be returned, as this would mean that the packing will be recycled five times (T). Although current deposit systems have a higher yield (T), making this a promising direction.

A final option is to reuse the plastic packaging. This trend is seen in the Albert Heijn and Eco Plaza with their reusable tubs. However, the system around these packages could be improved, being less reliable on consumers returning them (T). Reuse is better than recycling, as it is higher on Lansink's ladder. On the other hand, it requires a supply chain approach with more collaboration (P). One of the risks with reuse, which is also true for the deposit system, is the risk of contamination, as people could use the packaging to store toxic chemicals. For reusable packaging, it must resist high-quality cleaning to remove all contaminants (P). However, one of the most promising reusable trends is using BBP (T, A, B). Novel BBP producers are looking into a broader reusable system than the current single-use system (A, B), this is a win-win for them as this would mean they would get more out of the limited available biomass. Additionally, this would make the higher price of the material more viable and means a big plant is not needed (B).

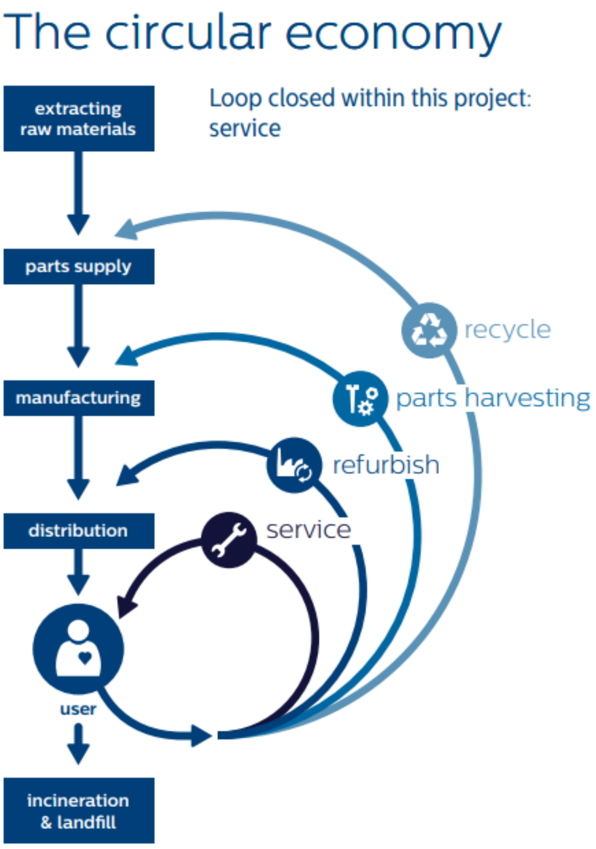

Figure 11. Circularity of Philips lights as a service (Koninklijke Philips N.V., 2015)

4.6 Transition Model Canvas

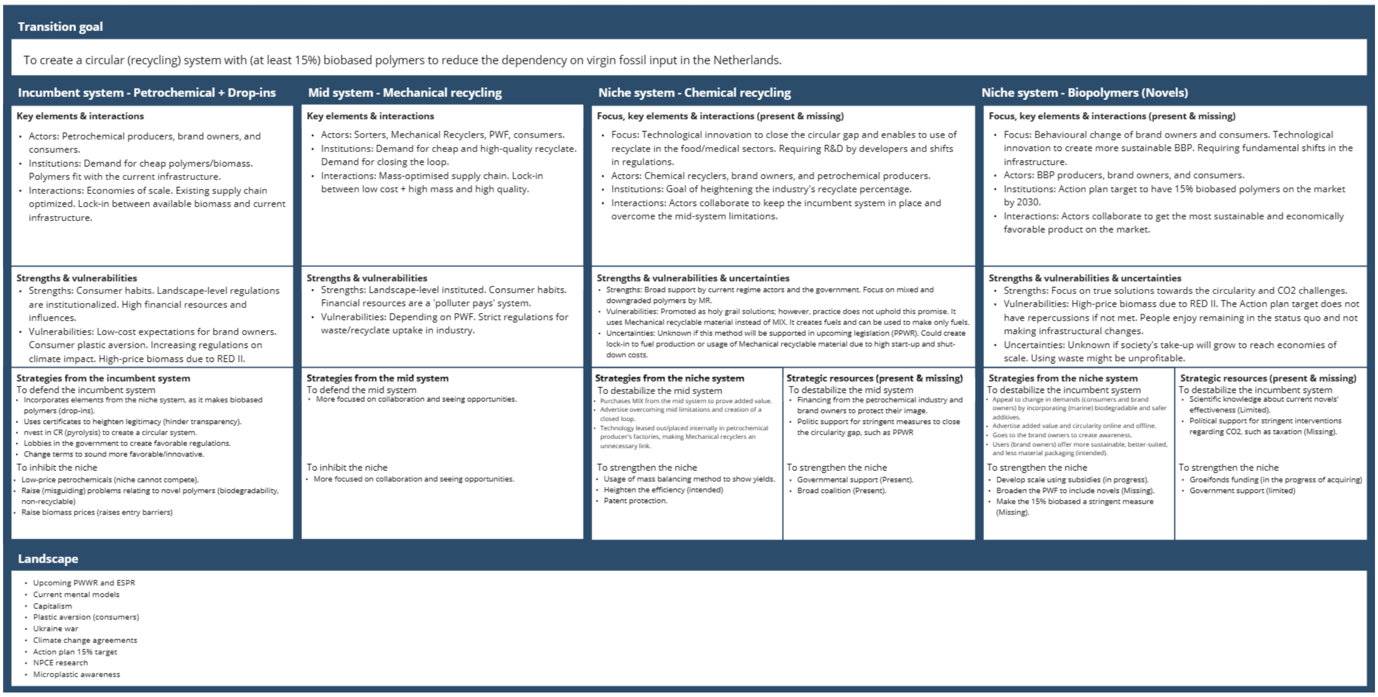

Figure 12. Transition Model Canvas on the plastic and recycling industry. See Appendix 3 for a larger version.

The TMC in Figure 12 creates an overview of all the points discussed in this chapter. Looking into the TMC, the incumbent petrochemical regime is presented in the left section. In this section, it can be stated that the regime has overcome its lock-in and performs incumbent diversification due to the production of drop-ins. It uses its strengths of consumer habits and resources to incentivise policies that strengthen its core business. However, the multi-regime interaction competition for the same resources as the RED II is their main difficulty. Moreover, these regime actors are stuck with brand owners' high-quality and low-price expectations.

The following section presents the mid system, or the MR (including sorting) recycling industry. What can be seen is that MR is entirely dependent on the PWF. As the PWF creates the incentive for the high-volume, low-cost system. The producers and municipalities rely on this system as well. Due to this, they do not see CR as a threat but only as an opportunity to help with the fractions of mix or residual, which this sector currently cannot recycle. This addition, if successful, could break the lock-in of high mass and low cost versus high quality.

The niche system of CR (with a focus on pyrolysis) can be seen in section one from the right. What is fundamental is that the niche interaction used is niche emergence, as the influence of the recycling system and the polyolefin system has created this niche. This dependency is visible when looking into the actors involved and their stakeholders. Due to this niche relying on the weakness of the current mid system and the resources of the polyolefins regime, it has generated enough awareness to be generally accepted as a good solution despite the low efficiency. However, it is still unsure if and how this niche will be supported in upcoming regulations.

The niche system of BBP (novels) can be seen in the right section. What is striking is that according to the niche interactions, this is a niche autonomy, as the niche is created independently. This independence is apparent when looking at the structural changes that need to be made, as introducing BBP novels would start as contamination. However, the power exerted by the current regime (incumbent actors) from the polyolefins and recycling is holding it back, even though it could be beneficial for other reasons (Alaerts et al., 2018). Therefore, the niche relies on its target of reducing CO_2 emissions and creating circularity, hoping to win consumers and governments over in the long haul, with the first step being the Groeifonds application.

Finally, in the box at the bottom, there is the landscape. In the upcoming regulations like the PWWR, the Action plan, and the NPCE can be found. As well as the desire for the Dutch government to be independent due to the Ukraine war, thus being a driving force for improving recycling (Deloitte et al., 2015). However, more important is the awareness that needs to be created that reaching the target set out by the IPCC for the 2°C-circular economy will require a paradigm shift (Stegmann, 2022). This paradigm shift means not only looking into sorting and recycling, as this will not close the loop 100%. More people have become aware that there needs to be a change in the feedstock. A limit should be set to the continuous economic growth targets, as biomass (in BBP) could result in an unintended rebound effect (Ibid.).

5. Discussion

In the discussion, the three sub-questions will be answered, followed by a short reflection on the added value and limitations of this research.

5.1 Sub-question 1: What types of polymers will comprise the future market of biobased polymers?

In the transition agenda on the circular economy of polymers, the goal is to have a 15% share of BBP on the Dutch market in 2030 (Total Corbion PLA bv et al., 2020). In research conducted by the University of Delft, two shifts are seen as necessary to include BBP in the circular economy. The first shift is the optimisation of the recycling system (Odegard et al., 2017) as it is not 100% closable. The second shift will be towards renewable feedstock, thus BBP from a sustainable source (Ibid.). With the shifts completed, recycling of BBP, sustainably sourced, and a low carbon footprint, the circular economy will be linked to a biobased economy (Ibid.). However, even in this system, energy inputs will also be needed to produce these polymers, and as renewable energy is currently scarce, as mentioned in the results section 4.1, efficient use of energy is preferred. Other authors agree that BBP fit into a circular economy, in which their EOL must include a high recycling rate (CE Delft, 2017a; Bergsma et al., 2019; Odegard et al., 2017), also called a circular bioeconomy (Stegmann, 2022), this combination will lighten the burden on the biomass resources (Ministerie van Infrastructuur en Milieu & Ministerie van Economische Zaken, 2016), and can serve as a (temporary) carbon sink (Odegard et al., 2017).

However, the current management of the material transition in the Netherlands is low compared to the set targets and ambitions of realising a circular economy in 2050 (Sociaal-Economische Raad, 2022). A cause of this low uptake may be the four main barriers identified in the Action plan of the Dutch government to promote biobased.

First, BBP is more expensive than their fossil counterparts, with the additional costs ranging from € 167 (PE by bio-PE) to € 4,000 per tonne (LDPE by PHA) (Total Corbion PLA bv et al. 2020). On the other hand, this is based on a weight basis, which does not account for the following discrepancies:

- BBP, on average, have a higher density;
- On a product level, BBP allows for material savings; e.g., a 0,89 mm thick Danone dairy cup made of HIPS could be slimmed down to 0,66 mm thickness in PLA (Schut, 2016);
- CO_2 or other externality costs are not included (Stegmann, 2022).

Second, there is an incomplete insight into the sustainability benefits of biobased compared to fossil polymers (Total Corbion PLA bv et al., 2020), and measures such as the LCA are not fair (explained in the result section 4.2). Other authors also mention the dependency of the sustainability of BBP on their production (the environmental, health, and safety hazards such as exposure to pesticides) (Álvarez-Chávez et al., 2012), the location where the biomass is grown, and the biomass used (Verrips et al., 2019). At the same time, others argue that there is a potential CO_2 saving equivalent of $241e^{316}$ million tonnes of CO_2 (Walker & Rothman, 2020). The leading cause for these diverse arguments is the misconception that BBP is one kind of material. One way to distinguish and promote the lowest CO_2 emissions is by using harmonised quality or sustainability criteria/standards (Verrips et al., 2019; Odegard et al., 2017; Crippa et al., 2019). However, currently, many certification standards are misused and confuse consumers. Current standards, identified by Niaounakis, e.g., (2019) for biodegradable: ISO 17088:2012, EN 13432:2000, EN 14995:2006, ASTM D6400-12, AS 4736, ASTM D5338- 15, ISO 14855-2:2018, and for BBP, (biodegradable or non-biodegradable): EN 16640:2015, ISO 16620- 4:2016, ASTM 6866-18 and EN 16785-1:2015. Furthermore, certification claims such as OK biodegradable SOIL and OK biodegradable MARINE raise the discussion (mentioned in the results section 4.3) if these claims should be mentioned to consumers (Van Den Oever et al., 2017). European standards are being developed regarding communication on EOL of BBP for B2B and B2C (Ibid.).

Third, the EOL exists for the drop-ins but is still underdeveloped for novels.

Fourth, unfamiliarity (Ibid.), as mentioned in the result section 4.1.1, change is hard. This unfamiliarity is arguably the main reason most BBP today are drop-ins (Álvarez-Chávez et al., 2012). Their identicalness to their fossil-based counterparts makes them reliable (Bours et al., 2022). Furthermore, the Dutch Action plan states that drop-ins are low-hanging fruit, thus will enable the realisation of the highest percentage of BBP (Bours et al., 2022; Total Corbion PLA bv et al., 2020). Although using a critical perspective, it could be stated that this Action plan and other steering documents are written with the help of (branch) organisations whose members are predominantly fossil-based, thus, have an interest in drop-ins (Bours et al., 2022). For a plastic circular economy transition, the fossil-based incumbent industries' role should be made clear and reinforced in policies (Crippa et al., 2019). However, their role is still undefined, and power struggles remain, as can be seen in the attempt of the Ministry of Infrastructure & Water Management and Economic Affairs & Climate in collaboration with the sector to create a covenant around the composting/processing of PLA, for which refuted argumentation was used (Bours et al., 2022). As mentioned in the result section 4.3.2, there are a lot of misconceptions about biodegradables and novels, including the low awareness of the recyclability of novels which has environmental benefits in most cases (Bergsma et al., 2019). The only thing holding this EOL back is the PWF, as they do not reward its separation, as seen in the results section 4.4.2.

Short-term drop-ins will comprise the future market of BBP. However, long term, optimally, the market should comprise of more novel polyester BBP, with their market share expected to grow (Alaerts et al., 2018); this is due to four reasons (for a more detailed description, see results section 4.2.3).

First, polyester persistence is lower than drop-ins. This low persistence is beneficial, as research shows that even with advanced collection infrastructure, around 5% of the polymers will leak into the environment. On a global scale, if the leakage of 32% could be reduced to 1%, this would mean around 1 million tonnes of polymers would leak and accumulate in nature every year (Ellen MacArthur Foundation & World Economic Forum, 2016). Meaning that it would be beneficial to have a lower persistent polymer, which would degrade in 1-13 years (A; C) compared to over 100 years (Liu et al., 2014).

Secondly, polyester novels have added value. Thus, they can compete with polyolefins in their performance (Alaerts et al., 2018). For example, PEF has superior gas barrier properties to PET (Stegmann, 2022), and PLA can help food stay fresh longer (Van Den Oever et al., 2017). Also, biodegradability is

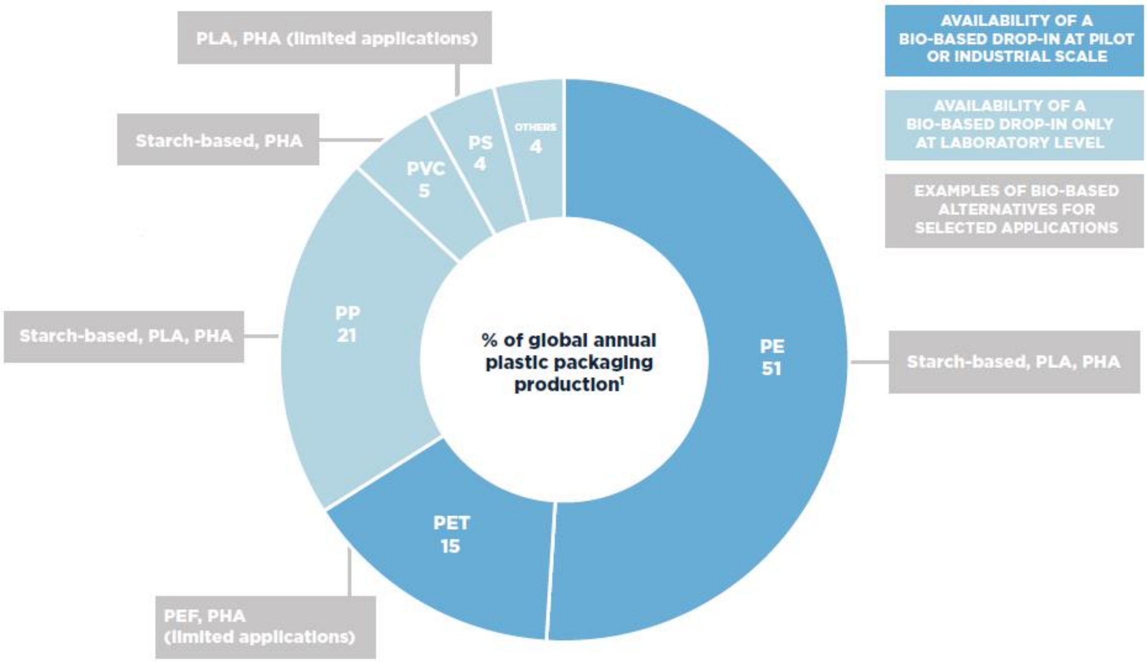

Figure 13. Technical feasibility (Ellen MacArthur Foundation & World Economic Forum, 2016)

an added value for selected applications, such as when combined with organic waste (Crippa et al., 2019; Odegard et al., 2017) or hard recoverable agricultural products. In this case, it can help lower the microplastics in the soil or water. Awareness needs to be raised that biodegradability in nature is different from composability. Some researchers even proclaim that it should be forbidden to label polymers as biodegradable; the term "industrially compostable" should only be used for PCPPW that ends up in GFT waste in the first place (Odegard et al., 2017). The term persistence instead of degradability, used by some novel producers, could diminish the misconceptions and create the clarity needed for consumers. The term persistence in a specific environment would not have the association of being degradable in any environment. As polyester novels are not the "bio-benign" polymers as described ideally by the EMF, they are an excellent first step. They fulfil the targets of being recyclable, competitive in functionality, and able to reduce negative impacts when leaked into the environment. Only, they are not able to disintegrate within a short time frame within a natural environment (Ellen MacArthur Foundation & World Economic Forum, 2016). Although the question should be raised about the definition of a short timeframe and if this would be preferable as this would also influence the product lifetime.

Thirdly, novel polyesters have the best energy balance at the beginning and EOL. As mentioned in the results section 4.1.5, only a limited amount of sustainable biomass is available. When switching towards a higher percentage BBP, technologies should be prioritised that make the most efficient use of these limited biomass sources (Winter et al., 2022). Research shows that the efficiency increases with the oxygen content contained in the polymer (Ibid.); as mentioned in the results section 4.2.3, polyolefins do not contain oxygen, while biomass contains a lot of oxygen. The removal of oxygen goes hand in hand with cost, energy use, and CO_2 emissions (Bours et al., 2022). In other words, reducing complex natural polymers into polyolefins is disadvantageous (Crippa et al., 2019). Furthermore, it is questionable if there is enough sustainable biomass to produce drop-ins (Bours et al., 2022).

In the EOL, as elaborated on in the next sub-question, polyesters fit with the EOL of MR and CR technology depolymerisation. Depolymerisation is one of the most efficient methods of all CR technologies, without the risks of creating a potential lock-in to the current industry.

Fourthly, as can be seen in Figure 13, and mentioned in the introduction, from a technical viewpoint, it is viable to replace the polyolefins with novels (in grey).

However, for these novel polyesters, policymakers must overcome thinking and investing in the vested interest. Research done by the Central Planning Bureau has shown that when using a social welfare viewpoint, markets are not sufficiently investing in innovative sustainable technologies compared to innovative solutions (Verrips et al., 2019). As Crippa et al. state, "*the market entry of novel non-fossil-based plastics requires a paradigm shift reminiscent of the change from coal to oil, which took decades to complete"* (2019, p.63). In short, a paradigm shift is needed; otherwise, this transition will take a long time to complete.

5.2 Sub-question 2: What barriers and opportunities do (the identified future) BBP encounter when trying to fit into the recycling infrastructure for plastics?

The answer to the question of which barriers and opportunities the novel polyesters encounter when trying to fit into the recycling infrastructure are threefold; general, MR, and CR barriers and opportunities.

5.2.1 General barriers and opportunities

Barriers

There are two main general barriers that novels encounter. First, there is the chicken-egg problem (result section 4.2.3). Due to its low volume, there are critical challenges regarding regulations, policies, and costs to implement circular strategies (Stegmann, 2022). The need for a higher volume, and the currently low projections, are described by many researchers as being a problem (Cornell, 2007; Soroudi & Jakubowicz, 2013b; Crippa et al., 2019; Bours et al., 2022). The question then becomes what volume is needed; research has shown different numbers; Cornell states that a minimum of 4.500.000 kg, but preferably 18.000.000 kg, are needed to be sustainable (2007). On the other hand, this research also states that the BBP need a sufficient value to overcome the cost of separation (Ibid). This value is also an opportunity, as most novels have a higher value than their polyolefin counterparts, meaning that the buyback strategy by novel producers could become interesting.

For PLA specifically, it is profitable to sort 3D-PLA if the percentage of PLA in PMD is 1-5%. Currently, it is only 0,4%, but it is expected to grow to 1-5% in 2030 (Bergsma et al., 2019). Others state that this volume should be 5-10% of one kind of novel, as this would be similar to the volume of current recyclable polymers (Odegard et al., 2017). On the other hand, knowing how high the volume needs to be will not solve the chicken-egg problem; thus, Bours et al. state that the way forward is to build the recycling infrastructure (2022). This building is hindered, according to sorters, as they and recyclers are not financially compensated for working on BBP (Odegard et al., 2017). Nevertheless, it could already be profitable today as the most significant volume of polymers is sorted from the waste stream, meaning that the remaining volume contains a higher volume of BBP (De Bie et al., 2021).

The second main general barrier is the contamination potential. A benefit of the low volume described above is that in the current recycling stream novels are not a concern (European Bioplastics, 2015). However, this will change with the desired growth of BBP to 15% and the potential growth of novels. In the literature, a large amount of research has been conducted on the contamination of PLA in the PET stream. As concluded in the results section 4.3.2, the effect of BBP is similar to any new polymer (De Bie et al., 2021). Nevertheless, the growth of PLA and PEF above the threshold of 5% (with which it can be mixed favourably with PET) should not have a detrimental effect on another recycling stream. In Table 3, concentrations of PLA causing contaminations in PET quality differentiates from 0,005% up to 5%. Solutions call for successfully using a NIR installation, already existing in the current recycling infrastructure, to sort PLA out (Bergsma et al., 2019). Literary research conducted by Alaerts et al. (2018) shows that the efficiency of this method differentiates per research; some state an efficiency of 86-95%, while others argue 99.6%. The highest efficiency will not be able to sort to the extent of the lowest concentration of contamination.

Table 3. Concentration PLA in PET causing contamination (Alaerts et al., 2018)

Concentration %	Concentration ppm	Impact
0.05	453	"No visual deviations in terms of colour and transparency"
0.05	453	"Not any significant difference in colour and haze"
<0.1	<1000	"Makes any rPET resin unsuitable"
0.1	1000	significant opacification of recycled PET
0.1	1000	PET recyclate unusable for many end-products
0.3	3000	"Lowers the onset of crystallization and retards recondensation"
>0.3	>3000	PLA causes yellowing of PET
2	20,000	Besides lower quality resin, also agglomeration and sticking to dryer walls
5	50,000	Besides lower quality resin, also agglomeration and sticking to dryer walls

Looking into the history of contamination of the recycling stream, PVC is reminiscent in its contamination quality, as the combination of PVC with PET will accelerate one another's degradation (Awaja & Pavel, 2005) at 0,005% PVC (Bergsma et al., 2019). In the current infrastructure, this is removed using a NIR, meaning that PLA or any other novel should not be a problem either (Bergsma et al., 2019). Otherwise, other standard methods used to remove PVC, such as a hot conveyor belt or rotating drums, would allow the separation due to the lower softening temperature of PVC as well as PLA compared to PET (Alaerts et al., 2018). However, due to the low volume, investing in a new NIR or other technology is costly, returning to the chicken-and-egg problem.

Opportunities

There are two main general opportunities that novels encounter. First, there always will be a gap when scaling up recycling for a circular economy (see results section 4.4.5); many actors state that BBP will provide the new virgin inputs (Bours et al., 2022). Additionally, there is a high likelihood that for the high food-safety regulations regarding food packaging, there will be a need for virgin inputs, and luckily the focus of BBP is on (food)packaging (Van Den Oever et al., 2017). The EMF (2016) even states that recycling and reuse are needed to decouple from the polyolefins but are insufficient on their own. Current global recycling rates are 14%, and even if this would rise to more than 55% (higher than the rates achieved by advanced countries today), the EMF suspects that the annual virgin feedstock in 2050 will still have doubled (Ellen MacArthur Foundation & World Economic Forum, 2016).

The second opportunity is the recycling target of 40% (to be recycled) set in the Dutch Transition Agenda for Plastic, in which the 40% is split up into 30% for MR and 10% for CR. To realise this recycling target, 94% of the polymers discarded as waste in the Netherlands will need to be sorted by 2030 (Bergsma et al., 2022). Since BBP will need to increase to 15% of the total polymers on the market, their sorting is also guaranteed.

5.2.2 MR barriers and opportunities

Barriers

There are two main mechanical barriers that novels encounter. The MR process currently is unfavourable for generating a usable recyclate for three reasons. First, many BBP are hygroscopic, causing hydrothermal degradation as polymers are not dried before melting (Cronell, 2007; Soroudi & Jakubowicz, 2013b). Secondly, the chain scission mentioned in results section 4.4 decreases the impact strength of the recyclate with each extrusion up to 20,2% at ten times (Soroudi & Jakubowicz, 2013b). Thirdly, if BBP were separated, mixing additives and grades of one type would make more than one recycling loop unlikely (Crippa et al., 2019).

The second barrier that novels encounter can be found in the LCA impact categories. Research conducted by Spierling et al. shows that contradictory to the result mentioned in theory by Shen et al. (2010b), looking into the EOL options for BBP MR has the lowest GWP but the highest AP, EP, photochemical ozone creation potential (POCP), and ozone depletion potential (ODP). Meanwhile, CR scores lower on all these impact categories. The only downside of this study is that these results are only based on the material PLA and is thus limited (Spierling et al., 2020). These results would be a barrier if they also hold true for other BBP novels, as currently, MR is preferred.

Opportunities

There are two main mechanical opportunities that novels encounter. First, building on the abovementioned barrier, BBP MR can negatively impact the climate. However, the benefit of avoiding novel BBP production has a more significant impact than recycling itself. Depending on whether, e.g., PLA produced is included for 100% or 49%, the climate impact will be -0.3 or 0.0 kg CO2-eq./kg PLA, respectively (Bergsma et al., 2019).

The second opportunity is relatable to the 40% recyclable target, as currently, the MR infrastructure in the EU is small, with around 1000 SMEs. This small scale means the sector does not have economies of scale or R&D capabilities (Crippa et al., 2019). Thus, to meet the 40% target, upscaling is needed. Upscaling will also benefit society by increasing employment and reducing dependency on raw material imports (Deloitte et al., 2015). This upscaling is the moment to realise the recycling of novel polymers (Odegard et al., 2017).

5.2.3 CR barriers and opportunities

Barriers

There are two main chemical barriers that novels encounter. First, if the choice is made to invest heavily in pyrolysis, a lock-in (excluding the BBP novel) could happen for several reasons. First, it is logical to invest in pyrolysis in combination with the low-hanging fruit of drop-ins. However, using a long-term perspective, novel polyesters are not suitable for pyrolysis but for depolymerisation (Crippa et al., 2019). Secondly, this investment could lead to a "lock-in", which is not unimaginable as countries that have heavily invested in WTE are also locked into this technology (Hann & Connock, 2020). Third, as mentioned in the theory section 2.2.2, the outputs of pyrolysis are gas and naphtha and can and are used as fuels. Also, this is equivalent to WTE, creating a "plastic-to-fuel" pathway that could be preferred in the market, thus creating this "linear lock-in" (Crippa et al., 2019).

The second barrier is related to depolymerisation, as depolymerisation can include catalysts to improve the chemical reaction. Unfortunately, in current published information, there is little regard for toxic in and by-products (Hann & Connock, 2020).

Opportunities

There are three main chemical opportunities that novels encounter, as they fit with depolymerisation. First, depolymerisation can be performed relatively easily in a small-scale setting for polyesters (De Bie et al., 2021). Making it a feasible method to start already without risks of lock-in.

Secondly, compared to pyrolysis, which is viewed as being expensive, depolymerisation could take place without additional costs (as it saves in production and incineration costs) (Bergsma et al., 2022).

Finally, as the material will only be returned to the monomer and not to naphtha (A), depolymerisation saves both energy and money.

5.3 Sub-question 3: What solutions are (currently) available to overcome the barriers to fitting the future BBP into the recycling industry to create a circular economy?

In this analysis, suggestions of potential policies that would overcome the barriers to fitting the novel BBP into the recycling industry are not exhaustive. Additional research containing the benefits and costs of these suggestions is needed. However, policies are needed as the increase in biobased and recycling will not happen on their own. Both are more expensive than polyolefins over the whole supply chain; thus, without government policy, there is no incentive to change (Bergsma et al., 2022).

With the creation of policies, there should be the realisation that there is no "silver bullet", no one solution, to solve this complex problem due to the ever-changing environmental and social challenges. Various activities, actions, cooperative, and legislative approaches will be needed to overcome the tragedy of the commons (Vince & Hardesty, 2018). Implementing a change on the part of this system will have impacts (unanticipated) on other parts. This realisation needs to be raised as current policies rarely consider these impacts (on the system) (Crippa et al., 2019). An example of this effect is the implementation of RED (II), as mentioned in the results section 4.1. To create a circular economy in which the use of biomass is of high value, many policies and business models will need to be adjusted (Sociaal-Economische Raad, 2020). Research conducted by Coronado, Lerpiniere & Velis (2015) shows that a business-as-usual scenario will not only not solve the problem but increase the complexity, current challenges, and cross contaminations of material flows. Crippa et al. (2019) states that disruption of products, activities, and BM innovation will be needed.

5.3.1 Develop vision European Union

A holistic vision regarding the future of the EU is needed to enable systematic change. Even on the topic of recycling, there is no vision of including CR adjacent to MR (Crippa et al., 2019). Researchers suggest that a roadmap to 2050 is needed, which includes the types and applications for BBP. A crucial precondition is comparing the application level of materials using a standardised value-chain-based method (such as an LCA), which the whole sector should recognise. Which is something that the EU is working on (Bours et al., 2022).

To enable a sustainable economy, the research conducted by Leipold & Petit-Boix (2018) shows the need to explore the relations between the bioeconomy and the circular economy to define which cycles contribute most towards creating a biobased circular economy. This competition between these economies is heightened by the butterfly model of the EMF, which only shows the distinction and not the collaboration of these economies (technosphere versus biosphere) (Ibid.). Due to the lack of definition (of the collaboration) in existing standards and guidelines, there has been much criticism. Setting this distinction, such as the examples in Figure 14, would create the need to prioritise actions (Ibid.). This vagueness is also present in the scope of the circular economy, which ranges from polyolefins to BBP. Looking into the EU Action plan for the circular economy, the practical implications are not always clear, especially regarding the biobased sector. The 2017 Action Plan only contains a small article on biobased relating actions (European Commission, 2017; Leipold & Petit-Boix, 2018)

Two examples of the biobased economies can be seen in the EU. Italy has a bottom-up strategy due to pressure from the private sector. Contrary, Germany had a top-down strategy due to supply-side policies. What can be learned is that both countries mention that what hampers the development of the market is the lack of long-term supportive policies and regulations (Imbert et al., 2019).

Current developments in the Netherlands show various upcoming directions to link circularity with the bioeconomy. Such as the four buttons which need to be turned for a circular

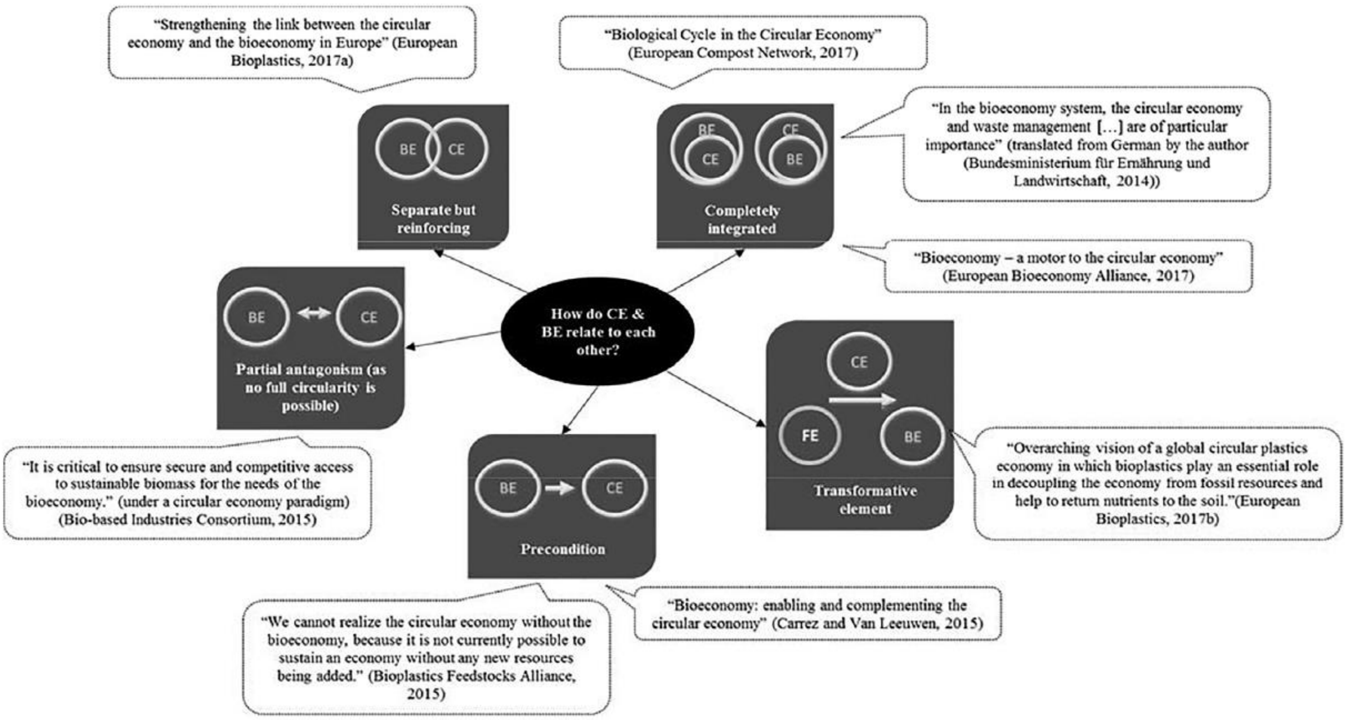

Figure 14. Relationship options between bio and circular economy (Leipold & Petit-Boix, 2018). BE: bioeconomy; CE: circular economy; FE: fossil economy.

economy; one of them is Substitution, replacing finite raw materials with renewable raw materials with a lower environmental footprint (Ministerie van Infrastructuur en Waterstaat, 2021). The Plastics Transition Agenda developed the direction of more supply and demand of recyclate and BBP (Total Corbion PLA bv et al., 2020). However, there is a lack of policy commitment to the high-quality use of BBP (Sociaal-Economische Raad, 2022), as the worldwide availability of sustainable biobased materials is limited (see results section 4.1.5).

In literature, there are multiple solutions to this limited biomass; one from a system perspective is the expansion of the RED II to include other sectors like chemical, industry, and construction (Ibid). Expansion of RED II would be an essential first step in showing that the materials and energy transition are equally important as the materials transition is equally drastic and urgent as the energy transition. An energy transition without raw materials transition creates tensions and risks. While an energy transition with attention towards the material transition results in opportunities, as they are linked.

From a technical point of view, other suggestions to overcome the biomass shortage include the Trias Bio-Logical. Trias Bio-Logical states, first, to reduce the need for sustainable biomass (circularity, demand reduction). Secondly, increase the availability of sustainable biomass (improved agricultural and forestry techniques). Third, use biomass where there is no sustainable alternative yet (steering with policy, developing conversion routes) (Leguijt et al., 2020).

The following sections will contain five concrete policy suggestions: enabling collaboration, instituting CO_2 pricing, investing in reuse, starting sorting/recycling novels, and adding a mandatory percentage of biobased content.

5.3.2 Enabling collaboration

The EMF (2016) describes the circular economy as gaining traction and needs a systematic approach for which collaboration mechanisms must be developed. Crippa et al. (2019) describe the need for policy innovations, thus, removing legal and regulatory barriers to enable collaboration.

In the results section 4.5.1, it was described that current collaborations are only focused on knowledge sharing to a certain extent. The literature also identifies the IP barrier as one of the main limitations of collaborations (Castaldi, 2021). The EU should facilitate collaboration, using digital tools to foster innovations and research, enabling systematic solutions and shared risk-taking, which could enable the faster uptake and implementation of novel BBP (Crippa et al., 2019).

The Dutch government is trying to create cooperation and commitment, as they state that mutual trust is an essential point of attention for closing the cycle in the product chain (Ministerie van Infrastructuur en Milieu & Ministerie van Economische Zaken, 2016). With mutual trust, there should be a rise in transparency. This transparency is essential in the CR industry. Sub-question two shows that depolymerisation has promise. However, details about the chemicals used and the technology's viability in industrial waste management are incomplete, and the mass flows are unknown. Hann & Connock (2020) state that to get investment; these details should be freely given to heighten the understanding of these technologies. The same could be stated for the LCA information concerning polyolefins (see results section 4.2).

Other researchers state that collaboration is needed in the first place to steer away from the linear economy (Johansen et al., 2022), to overcome the current plastic value chain fragmentation (Ellen MacArthur Foundation & World Economic Forum, 2016), creating a shared responsibility (Sociaal-Economische Raad, 2022), creating a more circular product, process, and service or BM (Ministerie van Infrastructuur en Waterstaat, 2023), and supply security of feedstock (Kennisinstituut Duurzaam Verpakken, 2018).

5.3.3 Institute CO_2 pricing

As already suggested in the results section 4.5.2, the institution of CO_2 prices should encourage the most promising technology, which could be BBP. Research shows that the current system taxes labour heavily but rarely energy or material use, meaning that circularity is hardly stimulated as this would contain more labour, less energy, and fewer materials (Ministerie van Infrastructuur en Milieu & Ministerie van Economische Zaken, 2016). Currently, the Dutch government and the EU are looking into the option of a primary fossil raw materials tax to stimulate the market for secondary raw materials (Ministerie van Infrastructuur en Waterstaat, 2023). This primary fossil raw materials tax to promote a secondary material market sounds like progress; however, there are three risks.

First, producers who want to process secondary raw materials in their products run into legal walls when obtaining permits due to the "waste or raw material" assessment. This assessment could also jeopardise the financing of these activities. The system of granting permits, their supervision, and enforcement are not equipped for the (high-quality) reuse of raw materials that have already been used in our economy and for the specific risk assessment - including for the safety of employees - that goes with it (Sociaal-Economische Raad, 2022).

Second, this taxation may increase plastic aversion and stimulate the substitution of plastics (Verrips et al., 2019). Which, in the end, just like the shift to paper straws, will not lead to the desired outcomes.

Third, suppose the taxation of the emissions is constructed using the same scheme as the EU Emission Trade System (ETS). In that case, their impact will be limited in incentivising the circular use of plastics. The main problem with the current CO_2 ETS is that individual countries (member states) have an interest in their national industry. Research conducted by Clò (2011) shows that member states have over-allocated carbon credits, which has dramatically lowered the value of CO_2. Similar problems could arise if this system is extended to include materials.

On the other hand, circular companies and products have a hard time finding launching customers. To which the primary cause is attributed to the missing fair game rules, as without the calculation of the true cost (which can be obtained by this tax), a circular BM will never succeed (Ministerie van Infrastructuur en Waterstaat, 2021).

5.3.4 Investing in reuse

As mentioned in the results section 4.5.4, investing in a reuse system also makes sense from a BBP novel producers' standpoint, as they will avoid the investment and competition with the high economies of scale of the polyolefins. Moreover, it will limit unwanted effects regarding climate, biodiversity, environmental, and social aspects (Sociaal-Economische Raad, 2020). Additionally, it heightens their fit with the vision of Resource Efficient Europe (Deloitte et al., 2015).

Current estimates have shown that at least 20% of plastic packaging on the market today can be reused, which should be promoted by a well-working EPR (Crippa et al., 2019). In the review of the "EU Packaging Directive", one of the targets is to focus on reuse, with the Dutch government supporting reuse targets at the European level. Additionally, they are looking at how the EPR should be used/implemented to make optimal use of the potential of reusable packaging. The government wants to encourage reusable packaging in various sectors, such as supermarkets and retail, catering and home delivery, e-commerce, and B2B. They do this through sector-wide agreements/cooperation and (if necessary) legal obligations (Ministerie van Infrastructuur en Waterstaat, 2023). This encouragement could be increasingly relevant, given the retail, logistics, and e-commerce trends. There is a precondition for this to succeed: the distance between supply and usage needs to be short enough, or there will need to be a reverse logistic system (Ellen MacArthur Foundation & World Economic Forum, 2016).

One of the most known reverse logistic systems is the deposit system. This system has been very successful in the history of PCPPW (Meys et al., 2021). Plastic litter consists of 90% packaging; expanding the deposit system could heighten the incentivisation for the consumer to bring the material back instead of littering (Verrips et al., 2019), although this is not risk-free (see results 4.5.4).

5.3.5 Start sorting/recycling novels

The Dutch Action plan states that for the current chicken-egg problem (see sub-question 1) to be solved, the ministry should take a more direct role in determining the added value of new polymers in the plastics supply chain. If found valuable and thus stimulated, there should be legislation on their recycling, as their climate impact depends on their EOL. The addition of a new fraction to the sorting will therefore have to be agreed upon by all the parties involved. The recent addition of the PET trays as a mono-stream to be sorted out is an example of how this can be organised (Total Corbion PLA bv et al., 2020). One of the steps in the Action plan is to start the process with the PWF and KIDV to get sorting specifications for novel BBP that pass the sustainability criteria positively (Ibid).

Bergsma et al. state that to realise the 15% biobased target, stimulating BBP development will be needed, including sorting and recycling (2019). This stimulation should happen with compensation for the sorting and recycling of BBP, e.g., PLA and PEF, are mentioned (Odegard et al., 2017).

It should be realised that every new material introduction starts as a contamination. However, the government should be aware that the power exerted by the incumbent recyclers could inhibit novel plastics even if they are beneficial (Alaerts et al., 2018). Expectations are that more abrupt changes will happen in the recycling landscape due to the changes in plastic types. Meaning the blocking of desirable plastics will not persist for an unnecessarily long time (Ibid).

The same Action plan states that the government should take control of novel BBP by making a shortlist (Total Corbion PLA bv et al., 2020). This way, the sorting and recycling industry can provide purer recyclate, and the residual fraction will decrease, allowing for the recycling industries' growth (Odegard et al., 2017). Alternatively, as the EMF describes it, "*convergence towards a set of global collection and sorting archetypes, allowing for regional variation but building upon a set of common principles, would offer packaging designers a common system to work towards, create clarity for citizens, and enable the capture of economies of scale*" (Ellen MacArthur Foundation & World Economic Forum, 2016, p. 53). This system will promote economies of scale, giving designers direction to work with and creating a more comprehensive EOL for consumers. On the other hand, the concerns stated in the result section 4.5.2 hold true. Compared to current polyolefins, innovative material should be stimulated (Total Corbion PLA bv et al., 2020). This stimulation is why the suggestion of a living list is preferable. However, this means there needs to be a guidance system to help businesses when introducing or developing new material to limit recycling system disruption (Crippa et al., 2019).

5.3.6 Adding a mandatory percentage biobased content

One actor states that banning polyolefins is the only way forward (Z), as this would be the only way to promote the uptake of BBP. It could be built upon several single-use plastic bans. However, a general ban on all polyolefins is questionable if legally feasible (Total Corbion PLA bv et al., 2020). What would be feasible is the requirement of a mandatory percentage of biobased content, which is also suggested in the Action plan Biobased Plastics, to set the same standards as the RED II (Bergsma et al., 2022). The added benefit of this requirement would be that for the additional cost, it would be a 'polluter pays' system (Ibid.). There are two different levels on which the mandatory requirement can be expressed, on a national level or a European level.

On a national level, the PWF could stimulate the use of biobased content. However, the PWF could not make it mandatory to use biobased content as binding requirements for the design of circular products, as it cannot be laid down in national legislation, as this would amount to quantitative restrictions on imports (Vermeulen et al., 2021). They can extend the tariff differentiation of good recyclable material to include biobased. Actors working for the PWF stated that they did not think this was a good solution as the PWF is focused on waste and not the beginning of life (P). However, when looking into Art. 6, paragraph 4 of the Dutch Extended Producer Responsibility Regulations Decree, calls for the entire life cycle to be included in the differentiated rates. According to this provision, "*the producers' financial contributions to the producer organisation … shall be differentiated where possible, taking into account the entire life cycle, durability, reparability, reusability and recyclability of the substances, mixtures or products and the presence of hazardous substances therein*" (Wet - Besluit Regeling Voor Uitgebreide Producentenverantwoordelijkheid - BWBR0044197, 2020). This law is not the only legal basis for using differentiation. The European legislation Art. 8a(4) of the Waste Framework Directive obliges Member States as well to include tariffs that "*are differentiated, where possible, for individual products or groups of similar products, in particular by taking into account sustainability, reparability, reusability and recyclability and the presence of hazardous substances, based on the entire life cycle*" ((Europees Parlement & De Raad, 2008). This provision was introduced in 2018, encouraging differentiated rates to include sustainable solutions (Vermeulen et al., 2021).

When the government would (temporarily) finance a lower waste management fee for bioplastics, this could stimulate bioplastics in the packaging market with little implementation costs (Bergsma et al., 2019). In addition, it is stated that combining biobased with recyclate would generate greater business support than if implemented in different requirements (bodies) (Ibid.).

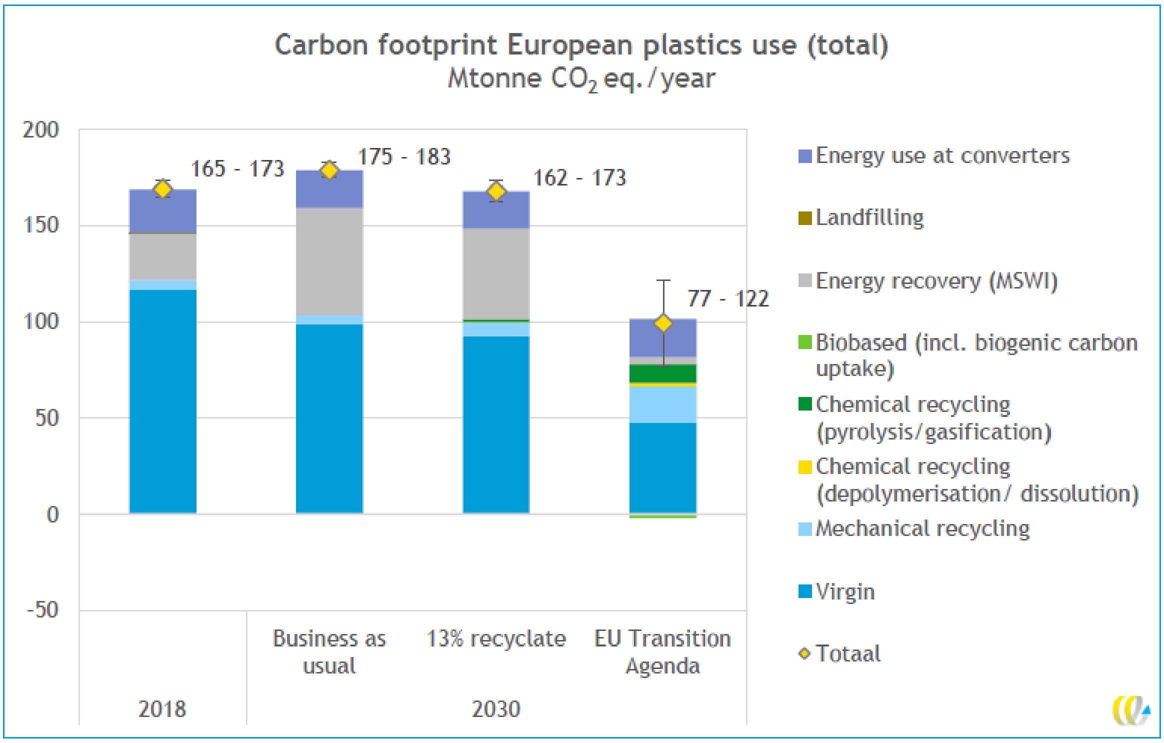

Figure 15. Relationship options between bio and circular economy (Bergsma et al., 2022)

Starting this requirement on a European level would make sense, as this would create and maintain an equal playing field, as legal (design) product requirements can only be taken at an international level (Ministerie van Infrastructuur en Waterstaat, 2023). Practically, it would require changing the EPR EU-wide, after which the national EPRs should follow; thus, the PWF in the Netherlands, to make it mandatory to include 30-55% recyclate or BBP by 2030 (Bergsma et al., 2022). As the EPR would apply to a small number of companies, the (administrative) burden would be relatively low (Ibid.). This combination of recyclate or BBP is preferred as it gives producers the freedom of choice, thus choosing the best suitable option for their product group (Ibid.). See Figure 15; this shows that the EU Transition Agenda scenario of using 55% circular polymers (meaning 15% BBP and 40% recycling) saves 80 Mton CO_2 compared to business-as-usual and 64 Mton CO_2 compared to only focusing on recyclate (Ibid.). However, these results (of the EU Transition Agenda) rely on negative carbon due to biogenic carbon uptake, which implies that the landscape may not change, as this would diminish the biogenic carbon uptake. However, research shows that this change will likely happen, as Southeast Brazil has experienced land use and land cover changes due to using biofuels to reduce carbon emissions (Thomaz et al., 2019). For the results of Figure 15 to be accurate, land use change should be guarded.

On a European level, two upcoming regulations could include the mandatory inclusion of BBP and recyclate: the Proposal for Eco-design for Sustainable Products Regulation (ESPR) and the PPWR. The ESPR is currently for many energy-related products; a new proposal is broadening and deepening to include almost all physical products. The prescription of a certain content of recyclate or biobased materials for new products will also become possible, according to the Ministerie van Infrastructuur en Waterstaat (2023). However, it is more likely to be included in the PPWR, as mentioned by actors in the results section 4.5.2. In the revision of the PPWR, published on 30 November 2022, the Dutch government wants to include the use of at least 40 percent recyclate and/or BBP in all packaging by 2030; they will strongly advocate this during the negotiations on the revision of the PPWR (Ministerie van Infrastructuur en Waterstaat, 2023). However, the current PPWR proposal does not contain this objective, as it only focuses on reduction, circular economy, and using a recyclate content (Directorate-General for Environment, 2022b). Currently, the PPWR is only a proposal, and more steps must be taken. During the negotiations, this could be added; the next step will be the publication of a draft report, after which votes from the committee and planetary still need to happen before it is adopted (Ragonnaud, 2023).

5.4 Reflection

5.4.1 Theoretical implications

This research's innovative contribution to literature, as argued in the Scientific relevance, is the provision of a complete landscape that includes both the regime of the plastic industry, the recycling industry, and both niches which influence the uptake of the novel and/or the drop-in BBP. The current gap is seen when looking at the promotion of BBP by the government, as they only state that 15% BBP will be needed in 2030. However, the practical definition is left up to the industry to formulate what materials fall under BBP. This lack of definition could also mean that drop-ins containing only a (limited) percentage of biobased could be used. The same can be said for the PPWR; it states the use of recyclate, but the technology used for recycling is left up in the air. Also, the recent publication of the NPCE states to focus on researching the impacts and leaves the decision up to 2024. Something that is more discouraging is that even if the implications of the NPCE or PPWR are implemented, it will take a long time to realise. Meanwhile all the risks and linkages hold these two (recycling and plastic) systems intact.

This research has added to the literature that it should be made clear which BBP should be promoted and why and that leaving it up to the market with its vested interests will only lead to lock-ins. Due to the multiple actors (including the recycling industry) involved in this research, it has created a holistic view of the current order of business happening in the BBP sector and the chemical industry. It has shown why novels should be promoted (persistence, energy balance in the beginning and EOL, added value) and depolymerisation (energy usage, no lock-in to fuel, measurable efficiency, low cost). Policymakers and governments can use this overview to concretise the roadmap to 2050, as it shows that a systemic transition is needed. In which the government has to step up and take control over the transition, as critical assessments and changes to hindering policies are needed to allow this transition to occur. For example, the strict regulations on waste and the ban on single-use plastics promote the faulty use of paper.

This research can be an important first step in heightening consumer awareness, as current transitions leave room for their own interpretation by actors. Such as the use of the word degradation, used by an actor to describe a time frame longer than industrial compostable but shorter than a polyolefin. This research promotes the use of the word persistence. Other confusions are due to the terms around CR, an umbrella term, also called advanced recycling, which raises concerns as different technologies with different results are meant. These diverse results also show that the myth of CR being a holy grail and a circular solution is rejected.

Finally, the research methodology of the TMC was too narrowly defined to work for this research and thus adapted to include combining two regimes/niches. This combination is also a contribution to theory. The MLP theory is used to investigate a system as a whole, but the definitions of the landscape, niche, and regime are vague. This vagueness is why researchers primarily identify one regime actor and one niche actor to focus their research on. This research shows that focusing only on one regime and niche actor will not show the entire system and can lead to the wrong conclusions.

5.4.2 Future research

Future research could look more into extending the MLP by incorporating two or more regimes/niches and using the created TMC (used by this study). To show how valid the extension of this method is in other sectors or if a new theory should be written.

Secondly, this research had only focused on the Netherlands; more on this in the limitations. This research found that the Netherlands has multiple rules/organisations, such as PWF, to enable recycling. However, other countries may differ, and conducting comparative research may give a more holistic overview of the industry on an EU or even global scale.

Third, within a regime, the consumer plays an important role and can influence change with their behaviour, such as "voting with their wallet". This research has mainly focused on the firms and scientists within this field. However, future research could extend this by examining the consumer perspective and awareness. Such as the consumer aversion to plastic, how far along this is, and whether it can be changed.

Fourth, in the future a second similar research can be conducted with the same methodology to heighten this research's validity. It can also show how the transition has changed or how scientific breakthroughs or mental models have altered the direction of the transitions.

Fifth, future research should look at regulations regarding limited sustainable biomass use as the growing material and energy transition will heighten the risk of its depletion. The Netherlands, and other countries, will become an importer of this resource, raising the Fair share discussion. In current international justice, industrialised nations (such as the Netherlands) have historically been the main drivers of climate change, but developing nations were negatively impacted (Burch et al., 2019). Similarly, wealthy nations often start the policies and processes for combating climate change, but those policies and mechanisms significantly impact people in developing nations. This disregard for international justice can also be seen in the Paris Agreement of December 2015, as the concept of an international equitable burden-sharing arrangement to control and reduce carbon emissions was officially abandoned (Clémençon, 2016). As a result, equity and environmental justice concerns have been effectively disregarded. The poorest and most vulnerable nations are left exposed to the threat presented by steadily rising greenhouse gas emissions for which they bear little responsibility (Ibid.). Instead, developing countries are being pressured to restrict their future emissions (Ibid.). Future researchers will need to find a way to overcome this (historical and international) injustice and include it in a solution for the Fair share distribution of sustainable biomass sources.

Finally, there is research conducted by SUSTCERT4BIOBASED, an EU-funded project of 3 years, investigating the harmonisation of sustainable BBP labels to support tracing the products along international and EU value chains (Infoscope Hellas, 2023). This investigation on sustainable labels for BBP could heighten the positive association needed to overcome the chicken-egg problem associated with novel BBP.

5.4.3 Limitations

When looking into the main limitations of this research, as discussed in paragraph 3.5 Quality indicators of research, the first limitation is external validity due to the focus on a single point in time while looking at a transition. The results could be outdated in a relatively short period due to technological changes that can happen influenced by the dynamic system. The technologies in question are the CR technologies, the BBP, and the technology to produce polymers with CO_2. Current research is even looking into using genetically modified organisms (crops) to make BBP. The dynamics influencing these technologies are the climate debates, the energy and material transition, and even the awareness and knowledge about microplastics that may come about—making it hard to predict which direction each of these technologies will go into on their own or may even influence each other. Even the publication of a paper, even this publication, could change the direction of the transition. This flexibility means that the findings of this research have to be seen in the light of the current systems and need to be repeated when there are any changes in the plastic or recycling industry.

The second is the focus and limited generalisability to the Netherlands. This generalisation is a limitation, as mentioned in the discussion, as most significant decisions will be made on the EU level, as strict regulations on a national level are not legal and would make the Netherlands unfavourable for the industry. However, this focus on the Netherlands has also brought some benefits, as mentioned the Netherlands has some stringent regulations, such as a landfill ban on recycled materials, the PWF, and a government looking into ways to improve. These findings are hard to generalise to other countries in the EU but can enable other countries to leapfrog.

The third limitation is the focus of this research on the industry. This focus can be attributed to the theory of the MLP used, which is known for its excessive focus on market and state-based actors, and a disregard for actors operating in civil society settings (Hargreaves et al., 2011). This MLP-based analysis needs to be expanded to consider civic society group viewpoints that transcend already-in-place systems and regimes. This expansion could have been done by including the Social Practice Theory, which focuses on practices (Ibid.). The focus of the MLP has led to the result that non-governmental organisations (NGOs) were not an important stakeholder group during the interviews. Although this research focused on business associations and scientists looking into and having the power to influence policies, they do not write them. Interviewing more policymakers or NGOs, such as The Ocean Clean-up, would have given this research a more holistic view of the landscape and its challenges. For example, in 4.1.4 CO_2 versus Biomass, the switch towards CO_2 could imply that the chemical industry can maximise fossil fuel usage, as they will need a stable, continuous supply of CO_2. This viewpoint is more likely to be argued for by NGOs than industry actors or business associations.

The fourth and final limitation is the exclusion of the effects of methane leakages by biodegradable polymers. One regime actor mentioned during the interviews the importance of raising the awareness that the use of biodegradable polymers in landfills would only heighten global warming, as methane (which has 25 more impacts than CO_2) would be emitted (Spierling et al., 2020) a concern which is also raised in the literature. However, not everyone agrees with this statement; Kolstad et al. (2012) research states that PLA in landfills will not lead to more methane formation. On the other hand, although globally, 50% of the plastic waste will end up in a landfill (Organisation for Economic Cooperation and Development, 2022), in the Netherlands, it is prohibited to landfill recyclable materials (Plastics Europe NL, 2021). Furthermore, on a European scale, methane is captured in landfill installations (Buijzen et al., 2020).

6. Conclusion

This research aims to answer the following research question: *How can the transition towards a biobased circular (recycling) economy be achieved?* To come to the answer, a combination of desk research containing roughly 50 published works, including scientific research, firm, and EU publications, and 26 interviews with different actors in the recycling, plastic, and knowledge sectors were conducted. The combination of these data sets provided different points of view on the transition.

To achieve a transition towards a biobased circular (recycling) economy, policymakers and governments need to use a system perspective. Using this perspective, multiple transitions and, thus, a holistic MLP can be linked. As stated by the SER, energy and the material transition are linked and can be used to reinforce each other positively. However, the attention given to the energy transition by the RED II has created an imbalance and holds back the material transition. This imbalance is felt throughout the whole MLP system of the material transition. Niche and regime actors state that they are unable to cover the higher cost of biomass due to fuel uptake and have been given the negative attention associated with its use. Meanwhile, literature and actors agree that the polymer sector must move away from fossil to biobased resources to achieve a circular economy.

It is possible to have a low uptake of biomass to produce polymers, already discussed by novel producers, as they lack economies of scale and are unable to take up much biomass without having detrimental effects on biodiversity, namely focussing on reuse (reusable packaging). Promoting reusable plastic packaging is the first thing that should be promoted and will speed up the transition towards a biobased circular economy, due to the following reasons:

- It solves the problem of recycling as this is avoided;
- It tackles the largest sector of plastic, namely packaging;
- It lowers virgin feedstock uptake dramatically;
- It makes the added cost of biomass redundant.

More novel polyesters should be promoted to enable a sustainable biobased circular economy. The current policy mentioned in the Action plan to pick the low-hanging fruit of drop-ins is an easy way to get to the required 15% BBP stated in the Transition Agenda. However, using the MLP, it can be seen that drop-ins are created by the regime due to the pressure of the landscape but are bound by the current vested interest. Promoting and scaling up drop-ins will enable the CR method of pyrolysis to rise (for packaging) with the risk of lock-in to the recycling of polymers to fuel. Limiting the realisation of a circular economy, even if recycling polymers is promoted during pyrolysis, a percentage of inputs will always be turned into energy. What should be recognized is that a circle of 60% is not circular.

Scale-up will need to happen when using polyesters, but not to the scale of polyolefins (due to the point mentioned above). Their feedstock can range from biomass to side products or even waste. Although the use of waste sounds the most promising for a circular economy, current legislation prohibits its use, especially in combination with packaging. Another benefit of polyesters, if promoted, is that it will limit the dependency on other countries, as more local production will be promoted, which means more competition and thus reinforcing higher quality; it will incentive a race to the top. Furthermore, polyesters have added benefits when looking into their beginning and EOL. Initially, their inclusion of the oxygen atom means their creation is less energy intensive, more resource efficient, and thus more sustainable as there is a limited amount of sustainable biomass. In the EOL, polyesters can use the CR method of depolymerisation. This method uses less energy, has higher efficiency, and creates monomers that cannot be used for anything other than polymers.

When focussing on the use phase of polymers, packaging novel polyesters are more sustainable due to two reasons. Firstly, their persistence is lower compared to polyolefins. When the packaging does end up in nature, the time to degrade is shorter, as polyolefins take hundreds of years compared to the ten years needed for a novel polyester. Although this timeframe can be made shorter, this will only be beneficial for specific applications. Following this statement, polymers can have an added value, such as biodegradable in nature, industrial compostable, or oxygen content. PEF has better barrier properties making it better suitable for holding CO_2-containing beverages than PET. Additionally, it will be a mono-material and thus even better recyclable. Conversely, PLA lets through more oxygen and is thus better suited to hold bread and fruits to extend their shelf life.

The policy recommendation following this research is to generate a holistic view (a roadmap) of the transition toward a circular economy in 2050 using a system perspective. An important first step can be the incentivisation of the current EPR system to include a mandatory recyclate or BBP in the tariff differentiation, as this combination has the highest CO_2-saving potential. Additional standards should be set to ensure that this system does not focus on profit but on sustainability. With recycling, MR will result in the highest discount, followed by depolymerisation, and little to none with pyrolysis and gasification. For BBP, the Action plans 30% improvement based on their polyolefins counterpart can be used on a few preconditions:

- There should be room to account for the optimisation that still needs to happen with novels production;
- The EOL of novels should consider the possibility of being recycled;
- A critical look should be taken at the data on polyolefins.

With the uptake of BBP, the sorting/recycling of novels should be more economically viable, thus solving the chicken-egg problem.

For this step, the government will have to step up, as the current EPR system, the PWF, thinks biobased uptake is outside their scope. However, as the EPR formation states, their creation is to promote sustainable development, and the PWF should be held to this standard. Expanding the PWF to include BBP will make it a system that promotes sustainability throughout the supply chain and can lead to overcoming some of its shortcomings.

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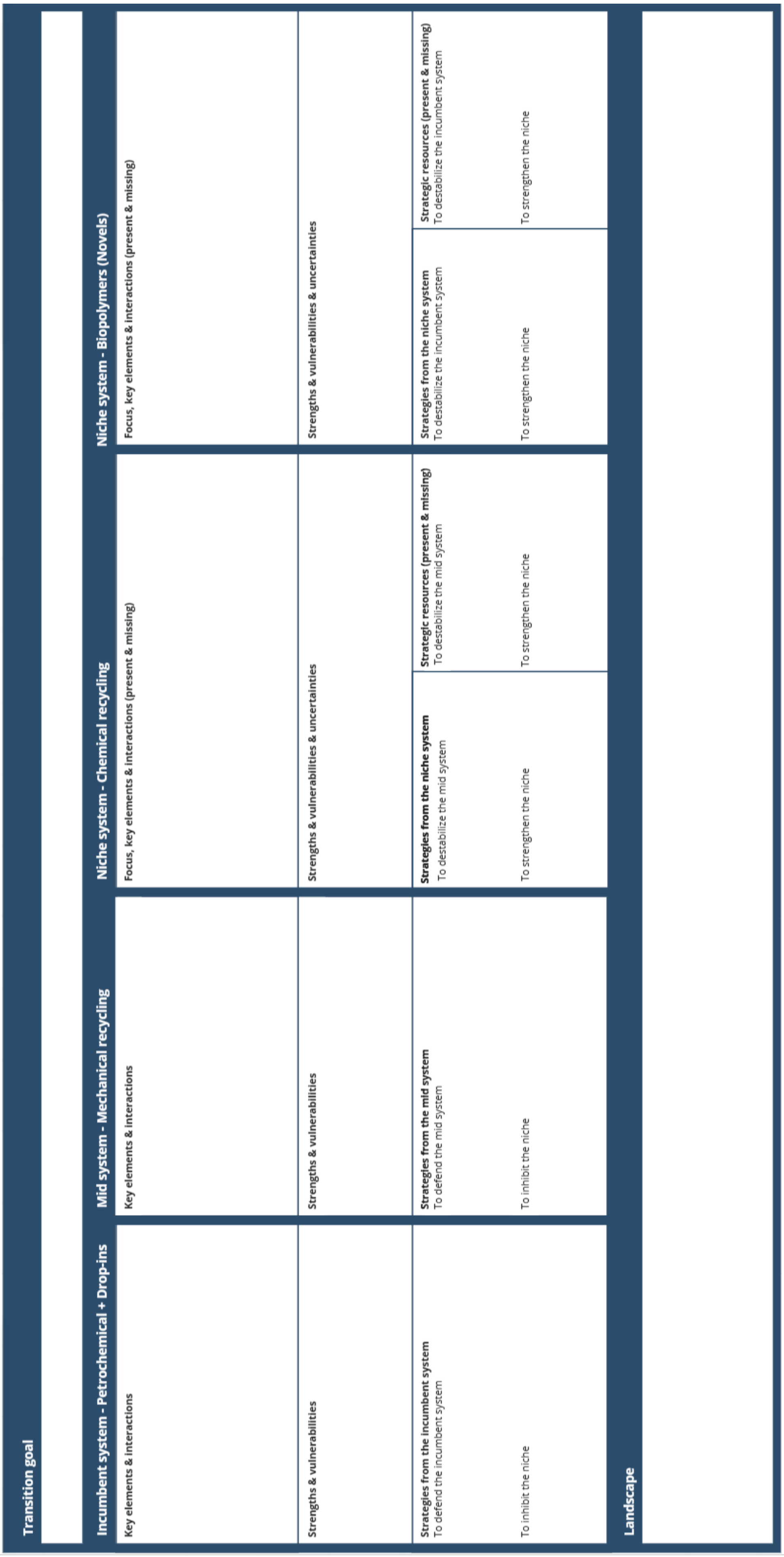
Appendix 1. Transition Model Canvas Adapted



Appendix 2. Interview Guides

Plastic industry, niche actors

Name interviewer: ______________
Name interviewee: ______________
Company: ______________
Function/Speciality: ______________
Date: ______________

Thank you for taking part in this interview about biopolymers and circularity. Before we start with this interview: Do you have any questions? To confirm, did you accept the terms in the online form with information on privacy and recording procedures? Ok, then let us begin.

1) I would describe the polymer you produce as a novel, Bio-PP etc. as drop-ins and then there are the petrochemical plastics, how would you describe the current plastic industry ratios?
    a. What direction do you think this industry is moving towards in the coming years? Why?
    b. How is (fill in company) enabled to grow? Is this by the changes in awareness, or regulations, or…?
    c. I have some suggestions for (company) to grow, and I like to know what you think of them, and whether they should only count for novels and/or drop-ins:
        i. Subsidise the making of biopolymers if used for the Dutch market.
        ii. Decrease the cost if producers choose to use biobased polymer (for packaging materials).
        iii. Making it mandatory to add a percentage of biomass material.
        iv. CO2 cost should be added to the product costs.
        v. Consumers need to pay for the amount of waste that they throw away.

2) Do you think there is a chicken-egg problem, thus due to there being a low amount of (fill in novel) on the market there is no EOL solution, but due to there being no EOL solution there is low adoption?
    a. Do you think this problem is heightened by the petrochemical industries?
    b. I read that novel producers (except PLA) feel excluded from important meetings regarding how the plastic industry should transform, would you agree? Why?
    c. In the Actieplan from the Dutch government, it mentions creating a short list for novel biodegradable biopolymers, do you think this is appropriate?
        i. Should one also be created for all novels?

3) What, in your opinion, is the added value of (fill in novel)?
    a. Do you think all novels should have an added value compared to petrochemicals?
    b. What is your opinion on the added value biodegradability?
        i. (Avantium: Why do you mention that PEF is degradable?)
        ii. Do you think this term has generated bad publicity/associations with (novel)?
        iii. How does biodegradability influence the recycling of the polymer? As I imagine that with water it degrades, but this is standard practise in recycling to remove contaminations.

4) Do you think novels are more sustainable than drop-ins/petrochemical plastics? Why?
    a. How is (company) working on improving the sustainability of (novel)?

5) What is your opinion on the importance of additives?
    a. Some suggest using additives to heighten the recycling potential of novels. Do you think this is needed?

6) What would the ideal EOL of (fill in novel)?
    a. I believe your currently investing in chemically recycling your own material from production waste. Why did you choose chemical recycling?
        i. Do you think this technology will become more sustainable in the future? (Less energy intensive, material consuming)
        ii. How would and should this technology translate to the after-consumer market of the Netherlands?
    b. Would you be willing to recycle your own after-consumer produced polymer from the Netherlands?
        i. If so, a recyclate market should be promoted, would (company) be willing to be part of this?
        ii. What would be good recycling behaviour of a consumer according to you? How are you working on improving it?

7) Do you collaborate with other firms to optimize your innovations? Which firm(s)?
    a. Do you also cooperate with your competitors?
    b. And with the recycling industry to create a closed loop?
    c. Would (company) be willing to join an ‘’open innovation network’’?
        i. What barriers would there be for you to enter? (e.g., IP protection)?

8) In a circular economy, reduce and reuse are promoted, in such an economy what would be you function/role?
   a. Do you think for (company) to be a frontrunner in circularity, it should start is a smaller selected market? Why?
      i. Which market would you prefer? Single use plastics? Schools?
   b. To measure circularity, (novel) should be traceable from biomass to EOL, do you think this is feasible?
      i. Would (company) be open to share this information?

9) Before we end this interview, do you feel like we missed anything? Something you want to add?

Plastic industry, regime actors

Name interviewer: ______________
Name interviewee: ______________
Company: ______________
Function/Speciality: ______________
Date: ______________

Thank you for taking part in this interview about biopolymers and circularity. Before we start with this interview: Do you have any questions? To confirm, did you accept the terms in the online form with information on privacy and recording procedures? Ok, then let us begin.

1) I would describe the polymers PLA, PEF as a novel, Bio-PP, Bio-PE as drop-ins and then there are the petrochemical plastics, What direction do you think this industry is moving towards in the coming years? Why?
   a. How is (fill in company) enabled or hindered to grow? Is this by the changes in awareness, or regulations, or…?

2) Why did (company) choose to invest in (drop-in) and not in novels?
   a. Do you think novels have potential?
   b. In the Actieplan from the Dutch government, it mentions creating a short list for novel biodegradable biopolymers, do you think this is appropriate?
      i. Should one also be created for all novels?
      ii. And for drop-ins?
   c. How are you as a company responding to these novels? (Adopting innovations?)
   d. Do you think drop-ins are more sustainable than novels? Why?
   e. How is (company) working on improving the sustainability of (drop-in)?
      i. Is (drop-in) becoming 100% bio-based in the short term?
3) What, in your opinion, is the added value of (drop-in)?
   a. Do you think all drop-ins should have an added value compared to petrochemicals?
   b. What is your opinion on the added value biodegradability?

4) What is your opinion on the importance of additives?

5) What would the ideal EOL of (drop-in)?
   a. I believe your currently investing in chemically recycling your own material (from production waste). Why did you choose chemical recycling?
      i. There are different types of chemical recycling, why do you think Pyrolysis is the most likely to be successful?

ii. What is currently holding back the growth of this technology? Is this only regulations or …?
iii. Is the technology ready to be implemented on an industrial scale?
iv. Do you think this technology will become more sustainable in the future? (Less energy intensive, material consuming)
v. How would and should this technology translate to the after-consumer market in the Netherlands?

b. Would you be willing to recycle your own after-consumer produced polymer from the Netherlands?
   i. If so, a recyclate market should be promoted, would (company) be willing to be part of this?
   ii. What would be good recycling behaviour of a consumer according to you? How are you working on improving it?

6) Do you collaborate with other firms to optimize your innovations? Which firm(s)?
   a. Do you also cooperate with your competitors?
   b. And with the recycling industry to create a closed loop?
   c. Would (company) be willing to join an ‘’open innovation network’’?
      i. What barriers would there be for you to enter? (e.g., IP protection)?

7) In a circular economy, reduce and reuse are promoted, in such an economy what would be you function/role?
   a. To measure circularity, (drop-in) should be traceable from biomass to EOL, do you think this is feasible?
      i. Would (company) be open to share this information?

8) I have some suggestions for (company) to grow, and I like to know what you think of them, and whether they should only count for novels and/or drop-ins:
   i. Subsidise the making of biopolymers if used for the Dutch market.
   ii. Decrease the cost if producers choose to use biobased polymer (for packaging materials).
   iii. Making it mandatory to add a percentage of biomass material.
   iv. CO2 cost should be added to the product costs.
   v. Consumers need to pay for the amount of waste that they throw away.

9) Before we end this interview, do you feel like we missed anything? Something you want to add?

Recycling industry, niche actors

Name interviewer: ______________
Name interviewee: ______________
Company: ______________
Function/Speciality: ______________
Date: ______________

Thank you for taking part in this interview about biopolymers and circularity. Before we start with this interview: Do you have any questions? To confirm, did you accept the terms in the online form with information on privacy and recording procedures? Ok, then let us begin.

1) How would you describe the current recycling industry? What is the scale of chemical recycling?
   a. What direction do you think this industry is moving towards in the coming years? Why?
   b. How is (fill in company) enabled to grow? Is this by the changes in awareness, or regulations, or…?
   c. I have some suggestions for (company) to grow, and I like to know what you think of them, and whether they should only count for novels and/or drop-ins:
      i. Decrease the cost if producers choose to use biomass/recyclate material (for packaging materials).
      ii. Making it mandatory to add a percentage of biomass/recyclate material.
      iii. CO2 cost should be added to the product costs.
      iv. Consumers need to pay for the amount of waste that they throw away.
      v. Higher rates of collection of waste for waste treatment
      vi. Subside the recycling of plastics, to enable growth of the recycling sector.

2) Would you need to invest in more/new technologies if more novel plastics enter the market? (e.g., for sorting)
   a. Does the purity/contaminations/additives of the stream matter with chemical recycling?
      i. Or only for condensation polymers?
      ii. And biodegradable polymers?

3) There are different types of chemical recycling, why do you think Pyrolysis is the most likely to be successful? (BASF: Why don’t you own a Pyrolysis factory? How will you influence its growth?)
   a. What is currently holding back the growth of this technology? Is this only regulations or …?
      i. Is the technology ready to be implemented on an industrial scale?

4) Do you think chemical recycling will always remain as a compliment to mechanical recycling?

a. Do you think chemical recycling in potential is more sustainable than mechanical recycling? Why?
b. How is (company) working on improving the sustainability of chemical recycling? (Less energy intensive, material consuming)

5) Do you think it's likely that the growth in chemical recycling will lead to a lock-in to produce oil for other purposes than plastic?

6) Many plastic producing companies are also working on chemical recycling of their polymers, what is your opinion on this transition?
   a. Do you see them as competition?
   b. And what about new recycling innovations, such as plastic degrading micro-organism?
   c. Do you collaborate with other firms to optimize your innovations? Which firm(s)?
   d. Do you also cooperate with your competitors?
   e. Would (company) be willing to join an ''open innovation network''?
      i. What barriers would there be for you to enter? (e.g., IP protection)?

7) In a circular economy, reduce and reuse are promoted, in such an economy what would be you function/role?
   a. If so, a recyclate market would be promoted, would this pose a risk for your company?
      i. And what about a switch from bulk collection of waste towards more separate collection streams with a deposit system?
      ii. Do you think this is likely?
   b. To measure circularity, plastics should be traceable from biomass to EOL, do you think this is feasible?
      i. Would (company) be open to share this information?

8) Before we end this interview, do you feel like we missed anything? Something you want to add?

Recycling industry, regime actors

Name interviewer: ______________
Name interviewee: ______________
Company: ______________
Function/Speciality: ______________
Date: ______________

Thank you for taking part in this interview about biopolymers and circularity. Before we start with this interview: Do you have any questions? To confirm, did you accept the terms in the online form with information on privacy and recording procedures? Ok, then let us begin.

1) How would you describe the current recycling industry? What is the scale of mechanical versus chemical recycling?
   a. What direction do you think this industry is moving towards in the coming years? Why?
   b. How is (fill in company) enabled or hindered to grow? Is this by the changes in awareness, or regulations, or…?
   c. I have some suggestions for (company) to grow, and I like to know what you think of them:
      i. Decrease the cost if producers choose to use biomass/recyclate material (for packaging materials)..
      ii. Making it mandatory to add a percentage of biomass/recyclate material.
      iii. CO_2 cost should be added to the product costs.
      iv. Consumers need to pay for the amount of waste that they throw away.
      v. Higher rates of collection of waste for waste treatment
      vi. Subside the recycling of plastics, to enable growth of the recycling sector.

2) The post-consumer plastic market is currently the smallest market, what is currently holding back this growth? Is this only regulations or …?

3) I would describe plastics that are chemical similar to current plastics as drop-ins, such as Bio-PP and Bio-PE, and those that are not similar as novels, such as PLA and PEF. What category do you think will become dominant? Or both? Why?
   a. What is your opinion about novels being a contamination to the waste stream?
      i. And what about biodegradable plastics?
   b. Wat is your opinion on the importance of additives?
      i. Some say due to the additives it's impossible to recycle plastics more than 1 time, is this true?
      ii. Mechanical recycling has its limits, as a plastic can only be recycled for a few cycles. How do you make this estimation?

   iii. How can this problem be solved? Should plastics become traceable?

4) Do you think mechanical recycling should be complemented by chemical recycling?
   a. How is (company) working on improving the sustainability of recycling?

5) Should an additional recycling stream be introduced, for example for PLA, in your opinion? Or more than one?
   a. What would be the biggest barrier for you to recycle it? The cost, or the space of a new NIR, or…?
   b. What amount/kg would a point-source need to be to profitable recycle it?
6) Many plastic producing companies are also working on chemical recycling of their polymers, what is your opinion on this transition?
   a. And what about new recycling innovations, such as plastic degrading micro-organism?
   b. Do you collaborate with other firms to optimize your recycling streams? Which firm(s)?
      i. The plastic industry?
   c. Do you also cooperate with your competitors?
   d. Would (company) be willing to join an ‘’open innovation network’’?
      i. What barriers would there be for you to enter? (e.g., IP protection)?

7) In a circular economy, reduce and reuse are promoted, in such an economy what would be you function/role?
   a. If so, the recyclate market should be expanded, would this benefit your company?
      i. How do you think the recyclate market can be increased/promoted?
      ii. Do you think the purity of recyclate should be 95% or should this standard be lowered?
      iii. And what about a switch from bulk collection of waste towards more separate collection streams with a deposit system?
      iv. Do you think this transition is likely?
   b. Do you think, for good consumer recycling behaviour, the public needs to be further educated on biobased polymers? If so, how?
   c. To measure circularity, plastics should be traceable from biomass to EOL, do you think this is feasible?
      i. Would (company) be open to share this information?

8) Before we end this interview, do you feel like we missed anything? Something you want to add?

Business associations and scientists, landscape actors

Name interviewer: ______________
Name interviewee: ______________
Company: ______________
Function/Speciality: ______________
Date: ______________

Thank you for taking part in this interview about biopolymers and circularity. Before we start with this interview: Do you have any questions? To confirm, did you accept the terms in the online form with information on privacy and recording procedures? Ok, then let us begin.

I would describe the polymers PLA, PEF as a novel, Bio-PP, Bio-PE as drop-ins and then there are the petrochemical plastics, how would you describe the current plastic industry ratios?
   a. What direction do you think this industry is moving towards in the coming years? Why?
      i. Is this by the changes in awareness, or regulations, or…?

2) Do you think there is a chicken-egg problem, thus due to there being a low amount of novels on the market there is no EOL solution, but due to there being no EOL solution there is low adoption?
   a. I read that novel producers (except PLA) feel excluded from important meetings regarding how the plastic industry should transform, would you agree? Why?
   b. In the Actieplan from the Dutch government, it mentions creating a short list for novel biodegradable biopolymers, do you think this is appropriate?
      i. Should one also be created for all novels?

3) What, in your opinion, is the added value of novels?
   a. Do you think all novels should have an added value compared to petrochemicals?
      i. In the Dutch Action Plan, it is argued that bioplastics are justified if they can achieve a climate gain of 30% compared to conventional plastics based on scope 1 emissions (with an LCA), do you think this is fair and measurable?
   b. What is your opinion on the added value biodegradability?
      i. How does biodegradability influence the recycling of the polymer? As I imagine that with water it degrades, but this is standard practise in recycling to remove contaminations.
      ii. Do you think this term has generated bad publicity/associations with (novel)?

4) I read that when producing bio-based materials, the production of oxygen-containing polymers such as polyesters are the more sustainable choice. Thus, the production of the novel PEF is better than the production of drop-in Bio-PP and Bio-PE, do you agree?
   a. And are polyesters also generally more recyclable than polyolefins? Why?
   b. And what about condensation polymers (polyesters) being more sensitive to contaminations?

5) What would be the ideal EOL of biobased polymers?
   a. What direction do you think the recycling industry is moving towards in the coming years? Why?
   b. The post-consumer plastic market is currently the smallest market, what is currently holding back this growth? Is this only regulations or …?

6) What is your opinion on the importance of additives?
   a. Some suggest using additives to heighten the recycling potential of novels. Do you think this is needed?

7) What would be the ideal EOL of biobased polymers?
   a. Should mechanical recycling be complemented by chemical recycling?
      i. There are different types of chemical recycling, do you think Pyrolysis is the most likely to be successful?
      ii. What is currently holding back the growth of this technology? Is this only regulations or …?

8) In a circular economy, reduce and reuse are promoted, do you think biobased polymers are key with this economy?
   a. If so, the recyclate market should be expanded, how should this be done?
      i. Do you think the purity of recyclate should be 95% or should this standard be lowered?
   b. To measure circularity, novels should be traceable from biomass to EOL, do you think this is feasible?
   c. Do you think, for good consumer recycling behaviour, the public needs to be further educated on biobased polymers? If so, how?
   d. I have some suggestions for the growth of biobased polymers and the circular economy, and I like to know what you think of them, and whether they should only count for novels and/or drop-ins:
      i. Subsidise the making of biobased polymers if used for the Dutch market.
      ii. Decrease the cost if producers choose to use biobased polymer (for packaging materials).
      iii. Making it mandatory to add a percentage of biomass material.
      iv. CO_2 cost should be added to the product costs.
      v. Consumers need to pay for the amount of waste that they throw away.

9) Before we end this interview, do you feel like we missed anything? Something you want to add?

Appendix 3. Transition Model Canvas enlarged

Transition goal

To create a circular (recycling) system with (at least 15%) biobased polymers to reduce the dependency on virgin fossil input in the Netherlands.

Incumbent system - Petrochemical + Drop-ins

Key elements & interactions

- Actors: Petrochemical producers, brand owners, and consumers.
- Institutions: Demand for cheap polymers/biomass. Polymers fit with the current infrastructure.
- Interactions: Economies of scale. Existing supply chain optimized. Lock-in between available biomass and current infrastructure.

Strengths & vulnerabilities

- Strengths: Consumer habits. Landscape-level regulations are institutionalized. High financial resources and influences.
- Vulnerabilities: Low-cost expectations for brand owners. Consumer plastic aversion. Increasing regulations on climate impact. High-price biomass due to RED II.

Strategies from the incumbent system

To defend the incumbent system

- Incorporates elements from the niche system, as it makes biobased polymers (drop-ins).
- Uses certificates to heighten legitimacy (hinder transparency).
- nvest in CR (pyrolysis) to create a circular system.
- Lobbies in the government to create favorable regulations.
- Change terms to sound more favorable/innovative.

To inhibit the niche

- Low-price petrochemicals (niche cannot compete).
- Raise (misguiding) problems relating to novel polymers (biodegradability, non-recyclable)
- Raise biomass prices (raises entry barriers)

Mid system - Mechanical recycling

Key elements & interactions

- Actors: Sorters, Mechanical Recyclers, PWF, consumers.
- Institutions: Demand for cheap and high-quality recyclate. Demand for closing the loop.
- Interactions: Mass-optimised supply chain. Lock-in between low cost + high mass and high quality.

Strengths & vulnerabilities

- Strengths: Landscape-level instituted. Consumer habits. Financial resources are a 'polluter pays' system.
- Vulnerabilities: Depending on PWF. Strict regulations for waste/recyclate uptake in industry.

Strategies from the mid system

To defend the mid system

- More focused on collaboration and seeing opportunities.

To inhibit the niche

- More focused on collaboration and seeing opportunities.

Niche system - Chemical recycling

Focus, key elements & interactions (present & missing)

- Focus: Technological innovation to close the circular gap and enables to use of recyclate in the food/medical sectors. Requiring R&D by developers and shifts in regulations.
- Actors: Chemical recyclers, brand owners, and petrochemical producers.
- Institutions: Goal of heightening the industry's recyclate percentage.
- Interactions: Actors collaborate to keep the incumbent system in place and overcome the mid-system limitations.

Strengths & vulnerabilities & uncertainties

- Strengths: Broad support by current regime actors and the government. Focus on mixed and downgraded polymers by MR.
- Vulnerabilities: Promoted as holy grail solutions; however, practice does not uphold this promise. It uses Mechanical recyclable material instead of MIX. It creates fuels and can be used to make only fuels.
- Uncertainties: Unknown if this method will be supported in upcoming legislation (PPWR). Could create lock-in to fuel production or usage of Mechanical recyclable material due to high start-up and shut-down costs.

Strategies from the niche system

To destabilize the mid system

- Purchases MIX from the mid system to prove added value.
- Advertise overcoming mid limitations and creation of a closed loop.
- Technology leased out/placed internally in petrochemical producer's factories, making Mechanical recyclers an unnecessary link.

To strengthen the niche

- Usage of mass balancing method to show yields.
- Heighten the efficiency (intended)
- Patent protection.

Strategic resources (present & missing)

To destabilize the mid system

- Financing from the petrochemical industry and brand owners to protect their image.
- Politic support for stringent measures to close the circularity gap, such as PPWR

To strengthen the niche

- Governmental support (Present).
- Broad coalition (Present).

Niche system - Biopolymers (Novels)

Focus, key elements & interactions (present & missing)

- Focus: Behavioural change of brand owners and consumers. Technological innovation to create more sustainable BBP. Requiring fundamental shifts in the infrastructure.
- Actors: BBP producers, brand owners, and consumers.
- Institutions: Action plan target to have 15% biobased polymers on the market by 2030.
- Interactions: Actors collaborate to get the most sustainable and economically favorable product on the market.

Strengths & vulnerabilities & uncertainties

- Strengths: Focus on true solutions towards the circularity and CO2 challenges.
- Vulnerabilities: High-price biomass due to RED II. The Action plan target does not have repercussions if not met. People enjoy remaining in the status quo and not making infrastructural changes.
- Uncertainties: Unknown if society's take-up will grow to reach economies of scale. Using waste might be unprofitable.

Strategies from the niche system

To destabilize the incumbent system

- Appeal to change in demands (consumers and brand owners) by incorporating (marine) biodegradable and safer additives.
- Advertise added value and circularity online and offline.
- Goes to the brand owners to create awareness.
- Users (brand owners) offer more sustainable, better-suited, and less material packaging (intended).

To strengthen the niche

- Develop scale using subsidies (in progress).
- Broaden the PWF to include novels (Missing).
- Make the 15% biobased a stringent measure (Missing).

Strategic resources (present & missing)

To destabilize the incumbent system

- Scientific knowledge about current novels' effectiveness (Limited).
- Political support for stringent interventions regarding CO2, such as taxation (Missing).

To strengthen the niche

- Groeifonds funding (in the progress of acquiring)
- Government support (limited)

Landscape

- Upcoming PWWR and ESPR
- Current mental models
- Capitalism
- Plastic aversion (consumers)
- Ukraine war
- Climate change agreements
- Action plan 15% target
- NPCE research
- Microplastic awareness