Navigating the Post-Industrial Recyclate Landscape

Policy Implications, Market Dynamics, and Allocation Methodologies in Life Cycle Assessment

Master's thesis in Industrial Ecology

GRETA GASCON RUDIN
DANIEL BRANTEBÄCK

DEPARTMENT OF TECHNOLOGY MANAGEMENT AND ECONOMICS
DIVISION OF ENVIRONMENTAL SYSTEMS ANALYSIS

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2024
www.chalmers.se

Navigating the Post-Industrial Recyclate Landscape

Policy Implications, Market Dynamics, and Allocation Methodologies in Life Cycle Assessment

GRETA GASCON RUDIN
DANIEL BRANTEBÄCK

Department of Technology Management and Economics
Division of Environmental Systems Analysis
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2024

Navigating the Post-Industrial Recyclate Landscape
Policy Implications, Market Dynamics, and Allocation Methodologies in Life Cycle Assessment
GRETA GASCON RUDIN
DANIEL BRANTEBÄCK

Department of Technology Management and Economics
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone +46 31 772 1000

Cover: Post-industrial recyclate pellets from Borealis.

Gothenburg, Sweden 2024

Navigating the Post-Industrial Recyclate Landscape
Policy Implications, Market Dynamics, and Allocation Methodologies in Life Cycle Assessment

GRETA GASCON RUDIN
DANIEL BRANTEBÄCK

Department of Technology Management and Economics
Chalmers University of Technology

Abstract

This thesis explores the landscape of post-industrial recyclates (PIR), investigating policy, market trends, environmental impact, and life cycle assessment (LCA) allocation methods. The study takes the perspective of Borealis, a prominent player in the petrochemical industry, with a special focus on two of their recycling plants located in Germany and Austria.

The policy analysis evaluates existing policies regarding PIR alongside a foresight-based scenario analysis. Findings reveal an absence of EU policy supporting PIR, contrasting with the abundance of policy support for post-consumer recyclates. The absence of policy support for PIR is likely due to its economic viability without such support, suggesting that current policy norms will persist. This sentiment is echoed by the scenario analysis, where no scenario indicated that PIR would require policy intervention to remain competitive in the market.

The market analysis, which focused on the German market, identified younger demographics as key drivers of sustainable consumption, offering opportunities for PIR integration in sectors such as cosmetics, technology, and pet-related products. Additionally, consumers tend to consider the environmental impact of their purchases more when investing in expensive, long-lasting items, making furniture and household equipment promising markets. The analysis also explored the German automotive industry, where demand for recyclates is rising, although impending EU regulation may limit PIR's potential.

The LCA findings revealed a lower environmental impact for PIR compared to virgin polypropylene (PP) across 14 out of 16 impact categories. System expansion allocation yielded distinct outcomes as it accounts for the emissions avoided when substituting virgin PP with PIR. Conversely, other methods - mass allocation, economic allocation and the cut-off approach - yield similar results. While both mass and economic allocation were deemed appropriate, mass allocation emerges as the optimal choice, better reflecting real-world drivers behind plastic production and waste generation.
Keywords: post-industrial recyclate, plastic, recycling, life cycle assessment, allocation, policy, scenario analysis, market analysis, circular economy.

Acknowledgements

We extend our heartfelt gratitude to Borealis for providing us with the opportunity to work on a very interesting and multi-faceted topic. A special acknowledgement is owed to Fredrik Bergfors for his excellent supervision, insightful discussions, and mentorship, both on a professional and personal level. We would also like to thank everyone at Borealis who contributed to this thesis, particularly Andreas Rößler-Czermak and Shannon Boonzaier.

Our sincere thanks to our examiner, Matty Janssen, for giving us all the time you could spare during these past few months.

Lastly, we would like to thank our respective families, extended family members, and friends for always believing is us and supporting us through these years of learning and personal growth.

Greta Gascon Rudin and Daniel Brantebäck, Gothenburg, June 2024

Contents

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

CEAP	Circular Economy Action Plan
CFC	Chlorofluorocarbon
CFF	Circular Footprint Formula
CPA	Circular Plastics Alliance
EoL	End-of-Life
EU	European Union
EU27+3	EU27 plus Norway, Switzerland and the United Kingdom
HDPE	High-density Polyethylene
ISO	International Organisation for Standardisation
LCA	Life Cycle Assessment
LCI	Life cycle Inventory
LCIA	Life cycle Impact Assessment
LDPE	Low-density Polyethylene
PCR	Post-consumer Recyclate
PCW	Post-consumer Waste
PE	Polyethylene
PEF	Product Environmental Footprint
PIR	Post-industrial Recyclate
PIW	Post-industrial Waste
PO	Polyolefin
PP	Polypropylene
PPWD	Packaging and Packaging Waste Directive
STEEPED	Societal, Technological, Economic, Environmental, Political, Ethical and Demographic aspects used in foresight-based analysis

List of Figures

List of Tables

1

Introduction

1.1 Background

To combat the pressing environmental challenges that are facing society today, the European Union (EU) introduced the Green Deal in 2019, a multifaceted initiative encompassing a spectrum of policies aimed at addressing various environmental concerns. At its core, the Green Deal seeks to propel the EU towards a modern, resource-efficient, and economically competitive society, with the ambitious aim of achieving climate neutrality by 2050 (European Commission, nd). Central to this transformative endeavour is the Circular Economy Action Plan (CEAP), launched in March 2020. As its name implies, this plan is designed to pivot Europe's economic framework towards a circular model wherein waste is repurposed as raw material rather than being discarded (European Commission, 2020). The EU expects that the circulation of resources will result in a more resource-efficient society, thereby minimising societal impacts on the environment, reducing the reliance on virgin materials extraction and mitigating waste-related pollution.

In this context, Borealis AG, a prominent global producer and distributor of polyolefins (PO), stands at the forefront of sustainable practices within its industry, particularly in the European market. With operations spanning over 120 countries, Borealis has been significantly involved in European polyethylene (PE) and polypropylene (PP) recycling since 2016, owning three recycling plants situated in Austria and Germany. The company's recycling operations primarily focus on reprocessing polyolefins derived from post-consumer waste originating in Europe. However, the company has recently expressed a desire to gain a deeper understanding of its post-industrial recyclate (PIR) products, which led to them carrying out a comprehensive PIR life cycle assessment (LCA) study in 2021. Today, Borealis' main interest lies in the choice of allocation method in the context of its PIR products and how previous studies and policy can motivate these choices. Furthermore, Borealis is interested in acquiring insight into the economic and political landscape and the future possibilities of PIR.

Borealis' Circular Initiatives

The petrochemical giant has long been a pioneer in adopting more ethical and environmentally friendly industry practices, placing sustainability at the core of its strategic vision, particularly in relation to the Circular Economy. For instance, as part of its commitment to fostering collaborative circular practices throughout the value chain, Borealis initiated its own program, named EverMinds™. A key objective for Borealis is to achieve a total capacity for circular solutions of 1.8 million tons by 2030 (Borealis, 2024b), encompassing recycled products and polymers specifically designed with recycling in mind. To put this figure into perspective, in 2022, Borealis successfully increased its total capacity for circular solutions to 148 kilotons, representing a 45 percent rise compared to the previous year (Borealis, 2024a). However, this achievement remains a mere fraction of the vast ocean of plastics generated annually. In 2022 alone, global production exceeded 180 million metric tonnes of PP and PE, with Europe accounting for 22 million tonnes (Plastics Europe, 2023).

However, Borealis is not producing PIR to appear circular or expand its product range; rather, it is driven by plastic production, which generates significant waste. Losses are inevitable in the industrial production of thermoplastics. Examples include plastic scraps, pellets with heterogeneous shapes caused by extrusion malfunctions, and contaminated material causing discolouration. Such defective materials fail to meet the stringent quality requirements for consumer sales. In response, Borealis adopts a sustainable approach by reprocessing these materials, either into blends of post-consumer recyclate (PCR) and PIR or into products comprising 100 percent PIR. These grades often exhibit more variation in mechanical properties and are consequently offered at a reduced price point.

There is intrinsic value in products derived from waste, given their generally lower environmental impact compared to virgin materials. This reduction partly stems from the absence of environmental burdens assigned to generated waste, a methodological choice known within LCA as allocation. Consequently, this reduced impact is reflected in the environmental footprint of manufactured products using recyclate as feedstock, making them much more attractive to customers. Furthermore, recycled products have the potential to replace the use of virgin materials in the technosphere, leading to a decrease in demand for virgin materials in society. This shift, hopefully, results in a lower share of virgin materials being produced.

Nevertheless, the question of allocating environmental impacts remains pertinent, as the waste stream used as PIR feedstock holds economic value and can be treated as a by-product within LCA. In the context of an LCA, the decision not to allocate any environmental impact to the waste stream used as PIR feedstock is not a certainty and may not be appropriate (European Commission, 2021c). This study aims to resolve this ambiguity and find a suitable solution that satisfies the laws, policies, LCA guidelines, existing research, and moral responsibility.

1.2 Purpose

This thesis aims to investigate how to appropriately allocate the environmental impacts from virgin plastic production and post-industrial waste (PIW) generation between the virgin plastic and PIW from Borealis. Given the inherent ambiguity in the value of recycled waste, and consequently, its regard as a product of equal worth compared to virgin plastic, the authors recognise the complexities arising in industrial systems with multiple outputs — specifically, the simultaneous generation of virgin plastic and waste products to be recycled. Addressing this is therefore an important challenge that will require an extensive analysis of existing research, policy and laws. Furthermore, the study aims to show how different allocation motivations will affect the environmental footprint of a PIR product from Borealis and compare it to its virgin plastic counterpart.

Additionally, this research aims to delve into the policy landscape surrounding PIR, seeking a nuanced understanding of the regulatory environment which may influence the scope choices of the subsequent LCA. Lastly, the study sets out to map the economic environment of PIR, shedding light on markets of interest and contributing to a holistic comprehension of the broader industry dynamics. Through these multifaceted aims, this thesis aims to contribute to the understanding of the environmental, policy, and economic dimensions of PIR, fostering informed decision-making and sustainable practices in the plastic industry.

1.3 Goals

Following the aim of the thesis, the study will attempt to answer the following research questions:

1. What is the current regulatory environment governing the production and use of PIR?
2. What are the markets of interest of PIR and what are the market trends?
3. How do different allocation scenarios affect the environmental footprint of Borealis' PIR?
4. What allocation method do we recommend Borealis to use in future PIR LCAs?

1.4 Limitations

Although this thesis analyses various aspects of PIR as a whole, the focal point consistently revolves around Borealis, their values and priorities. Moreover, this study adopts a European perspective for the policy analysis and focuses on Germany for both the market analysis and LCA.

In conducting the market analysis, it is important to note that the data is solely derived from secondary analyses, including published studies from statistical organisations and consultancies, which may entail limitations in terms of comprehensiveness and accuracy of results.

For the LCA, site-specific data from Borealis' recycling plant located in Germany was used to determine yields and energy requirements. Additionally, data from ecoinvent version 3.10 was employed to assess resources and emissions from the German electricity grid, as well as for lorry transport, the market for additives and waste incineration. It is important to note that all LCA results are pseudonymised to keep sensitive data confidential.

When allocating environmental loads to the post-industrial waste input material, the authors were constrained by the availability of data. The only accessible data for allocation purposes was the characterised results of an LCA of virgin plastic from Borealis in Germany. This limitation may introduce uncertainties in the accuracy of the environmental impact assessment for PIR.

2

Theory

This chapter will give more detailed explanations and information on important topics in the paper. This chapter will also present an overview of Borealis plastic production outside the LCAs system boundaries.

2.1 Circular Economy

Currently, most of our economic activities follow a linear cradle-to-waste structure (Benton et al., 2017). This linear model entails the extraction, utilisation and disposal of raw materials as waste. Its viability has been made possible due to the abundance of natural resources, cheap labour, and cheap means of waste disposal. However, since many natural resources are finite, this economic system cannot be sustained indefinitely and is bound to reach a breaking point. The pace at which we are approaching this tipping point is accelerated in large part by the increasing global population and rise of the middle class (Ellen MacArthur Foundation, 2013).

In response to the inherent limitations of the linear economy, the concept of a circular economy has emerged as a compelling alternative economic framework. The circular economy concept gained momentum in the late 1970s through a small number of academics, thought leaders, and businesses. Influential works such as Rachel Carson's *Silent Spring* (2000), served as a cautionary tale of the absence of birds in spring due to our environmental neglect. Similarly, publications like *Limits to Growth* by the Club of Rome, used simulations to demonstrate the finite nature of economic growth, while the concept of *spaceship earth* proposed by Barbra Ward and Kenneth Boulding underscored the imperative of stewardship over the planet's finite resources (Naustdalslid, 2014). Some of the earliest countries to adopt circular policies were Germany, Japan and China in the late 1990s and 2000s (Ellen MacArthur Foundation, 2013). This marked the beginning of a transformative journey towards a more sustainable and resilient economic system.

In summary, the circular economy aims to change today's linear cradle-to-waste system into a circular cradle-to-cradle where resources are reused or recycled. Drawing inspiration from the adaptability and resilience of natural ecosystems, the notion operates on the principle of a "waste is food" system, as observed in nature's cyclical processes (Ellen MacArthur Foundation, 2013). For the cradle-to-cradle model to be possible, a major shift in production methods is essential. Products and industrial systems need to be designed with a focus on reuse and recycling, as many existing products are hard or impossible to recover due to their intricate design. For instance, electronic waste suffers from this issue, with numerous components containing small amounts of diverse materials, rendering recycling financially unviable due to the requirement for environmentally hazardous substances and high thermodynamic conditions (Chen et al., 2019). Therefore, redesigning electrical parts to enhance dismantling and recycling capabilities is essential.

The hope is that a circular economy will be a major factor in solving many of the environmental issues we are faced with today such as the limits to natural resources by recycling materials, stopping land degradation by circulating nutrients in society, and lowering carbon emission by less carbon-intensive production. However, the circular economy concept has also faced criticism, particularly regarding its implementation and efficiency, with some highlighting a lack of scientific evidence for its effectiveness (Corvellec et al., 2021). Additionally, concerns have been raised about the finite nature of some materials, challenging the notion of indefinite circulation. Even if the benefits and feasibility of a circular economy are still argued today, it is still a vital part of the EU's strategy for achieving climate neutrality, making it a priority for industries operating within the EU today.

2.2 The Origins of PIR

In this section, the EU's legal definition of waste and by-products is explored. Additionally, a brief explanation of Borealis' plastic production process will be covered, as well as a clarification of where and how waste arises in the production of virgin plastic.

2.2.1 Legal Definitions

The term PIR lacks a specific legal definition in the European Union's Waste Framework directive (European Commission, 2021c). However, the International Organisation for Standardisation (ISO) provides a definition of a similar term, namely "pre-consumer material", and lists "post-industrial" as a synonym. Interestingly, the ISO chose to use the term *material* instead of *waste*. This is because the ISO's definition of waste diverges from that of the EU, emphasising that waste is any material that can't be reused or recycled. To avoid any misunderstanding, the ISO opts for the more inclusive term, material. Specifically, *"pre-consumer material"* is described by the ISO as a *descriptive term covering material diverted during a manufacturing process* (European Commission, 2021c). This definition includes an exclusion clause for re-utilised material capable of being reclaimed into the same process. This distinction results in the possibility of dividing the secondary material streams coming out of an industrial process into two flows: by-product and post-industrial material, i.e., waste. To determine whether the material falls under the legal definitions of "waste" or "by-product" within the EU, it is important to understand these terms.

The European Union Waste Framework Directive (European Parliament, 2008), in Article 3, defines waste as "*any substance or object which the holder discards or intends or is required to discard.*" Concurrently, Article 5 criteria (1) of the directive elaborates on the definition of a by-product, a section that underwent amendments in 2018 (European Parliament, 2008, 2018a). According to the current definition, "*Member States shall take appropriate measures to ensure that a substance or object resulting from a production process, where the primary aim is not the production of that substance or object, is considered not to be waste but to be a by-product, provided the following conditions are met*". These conditions include:

(i) Certainty about the future use of the substance or object.
(ii) Direct usability of the substance or object without further processing, except for normal industrial practices.
(iii) Production of the substance or object as an integral part of a production process.
(iv) Legality of further use, meaning the substance or object meets all relevant product, environmental, and health protection requirements for the specific use.

Article 5 criterion (2) introduces the possibility of exceptions to these conditions for specific substances or objects. Consequently, the article introduces a degree of interpretation when discerning whether a substance should be categorised as waste or a by-product, particularly in regard to criteria (ii) "normal industrial practices" and (iii) "produced as an integral part of production processes". To gain some more clarity into how these regulations could be interpreted, the Circular Plastics Alliance (CPA), a collaborative initiative under the European Commission, released a guide where they made the following distinctions (European Commission, 2021c). For criterion (ii), they categorised "normal industries practices" as the steps a producer takes in the creation of a product, for instance, filtration, washing, drying or adding materials necessary for future use. Processes that modified the size or shape such as balling, crushing or flaking were also included. What was not regarded as a "normal industry practice" were operations that addressed typical waste-related characteristics, such as contamination with hazardous or non-useful components. Processes that do not fall under the "without further processing" criterion of (ii) are sorting, melting and pelletisation.

In the case of criterion (iii), there are no clear rules for what is an integral part of the process (European Commission, 2021c). For instance, if the material leaves the factory site for further processing, it could be considered to not be an integral part of the process and, therefore, the material should be classified as waste. However, it is also stated that this does not necessarily mean that the classification from by-product to waste will or should apply in every case. The CPA goes on to say that a case-by-case basis is needed to set up guidelines to differentiate by-products from waste (European Commission, 2021c).

2.2.2 Borealis' Definitions

At Borealis, industrial waste from every stage of the production process is managed. In a nutshell, Borealis manufacture and sell a wide range of polyolefin pellets, each offering unique mechanical properties. While the company aims to optimise virgin pellet production, occasional malfunctions during manufacturing result in the generation of two additional material types: by-products and waste.

Borealis strictly differentiates between these classifications. A material qualifies as a by-product only if it is granulated and free from moisture or contamination. If these conditions are not met, the material will be labelled as waste, which is then recycled into PIR products at another location. This demonstrates that Borealis' internal process for separating waste from by-products follows EU regulations. Table 1 outlines the delineation between these categories.

Table 1: Classification of off-spec material at Borealis.

Classification	**Granule Shape**	**Wet and/or Contaminated**
By-Product	Yes	No
Waste	Yes	Yes
	No	-

The PIR comes from Borealis' factories. In their case, the plastic production process starts with ethylene or propylene as feedstock, which is bought from refineries. Let's take the example of PP production. The first processing stage is the polymerisation of propylene into PP, a process in which the propylene hydrocarbons are chemically bonded together to form long chains of polymer molecules. A Ziegler-Natta catalyst is used in the reactor to facilitate the reaction and to control parameters such as the reaction rate and the polymerisation yield. The PP chains coming out of the polymerisation stage are rather unstable and will fragment without further processing. Therefore, the material is brought to a compounding stage where additives are added to stabilise the hydrocarbons, but also to give the plastic the desired properties, e.g., colour and mechanical properties. The plastic is then taken to an extruder, which cuts the material into pellets.

Waste is generated in all stages of plastic production. During polymerisation, the material can sometimes agglomerate and produce lumps or blocks that cannot be used in the further processing of virgin plastic and are thus thrown out as waste, as illustrated in Figure 1. Moreover, when a polymerisation reaction needs to be stopped, the reactor must be flooded and emptied. The material coming out, being contaminated and wet, is here again sorted as waste.

Figure 1: Recyclable PP blocks sourced from Borealis.

The last big contributor to waste is when a change in production occurs. For instance, if a compounder producing black material switches to producing a transparent one, there will be a transition stage where a mix of both colours is produced until only material of the right colour is compounded. The mixed-colour material cannot be used and is therefore thrown out as waste.

Other forms of plastic waste from Borealis factories are floor sweep, streamers that aggregate in the pipe transport system, and waste from the quality lab where virgin plastics are tested. Finished pellets will be considered to be waste if they are wet, contaminated, or both. If pellets are neither wet nor contaminated, but do not meet customer quality requirements, they are instead referred to as a by-product.

2.3 Life Cycle Assessment

Within its field, life cycle assessment has emerged as a vital tool for quantifying the environmental impact of a good, taking the whole life cycle into consideration. To gauge the relevance of PIR within the LCA field of study, a literature search was conducted on our major databases: Scopus, Web of Science, ScienceDirect, and Google Scholar. The results, summarised in Table 2 show the total amount of search results across all four databases for each search. Google Scholar yielded the highest search results for all the search words used, and Web of Science had the least. The results clearly show that LCAs focusing on post-consumer recycling are more prevalent than those on pre-consumer recycling, as pre-consumer LCAs represent only 15 percent of the post-consumer search results and constitute a minuscule portion of the overall LCA research output. It is important to recognise that PCR has a significantly larger societal impact compared to PIR due to the disparity in waste volume.

Consequently, it is understandable that more research efforts have been dedicated to PCR. Despite this, the search results show a severe lack of LCA studies focused on plastic PIR, making it difficult to identify clear trends regarding the appropriate method of allocation. Therefore, it is crucial to conduct a thorough investigation of different allocation methods suited for this material.

Table 2: Amount of LCA-related search results for terms related to PIR compared with a PCR counterpart. Additionally, the term "LCA" was searched across all four databases, yielding a total of 1 118 249 hits.

Search word	Search hits	PCR comparative	Search hits
post-industrial recyclate	8	post-consumer recyclate	49
pre-consumer recyclate	2	post-consumer recyclate	49
pre-consumer recycling	60	post-consumer recycling	743
pre-consumer recycled	130	post-consumer recycled	1207
pre-consumer waste	550	post-consumer waste	2890
Total	**750**	**Total**	**4938**

2.3.1 Theoretical Framework

The LCA methodology is based on systems thinking to avoid unintentionally omitting important information when studying the emissions and resources used in the extraction of raw materials, production, use and waste management of a product. The procedure and results of an LCA can be used for multiple purposes such as decision-making, communication and learning. This section serves as a theoretical delineation of the practices involved in conducting LCAs and the required information therein. The LCA methodology presented closely follows the procedures described in Baumann and Tillman (2004) and ISO 14044 (2006).

2.3.1.1 The Goal and Scope

The first step of an LCA consists of the goal and scope definition, see Figure 2. This stage is perhaps the most important part of the LCA procedure, as it defines the aim and contextual aspects, the modelling aspects and the procedural aspects of the assessment. The goal of the study should answer questions such as what the intended application of the LCA is, who the intended audience is and what product and system the LCA is studying. Furthermore, the goal should formulate a set of specified questions that the LCA plans to answer.

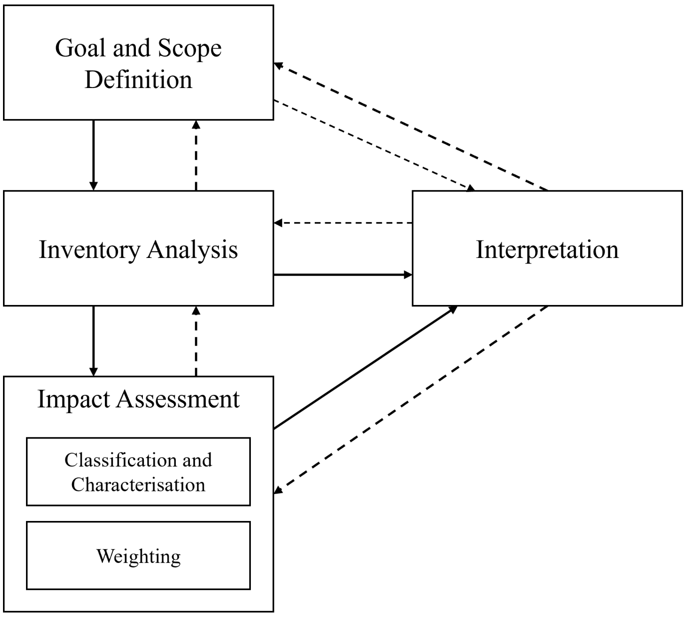


Figure 2: The LCA procedure according to Baumann and Tillman (2004). The boxes illustrate procedural steps, while the arrows indicate the order in which the steps are performed. Broken arrows signify possible iterations.

The scope encompasses various technical elements, including the type of LCA, the functional unit, system boundaries, impact categories, allocation choices and data quality requirements. As the term suggests, the **functional unit** outlines the system's function. For example, if the system were a car factory, the functional unit might be as broad as "one car produced." However, depending on the objectives of the LCA, the functional unit can be more specific, such as "one car produced meeting X and Y requirements." The selection of a representative functional unit is crucial, as it influences the definition of the reference flow to which all other resource and emission flows are linked.

The choice of **type of LCA** is largely based on its goal. If the LCA aims to account for the environmental impacts linked to a product or system, the LCA is attributional. If the LCA explores the environmental effects of a change in the system, the LCA is consequential.

In the scope definition, an initial simplified **flow chart** of the technical system is also included. Following that, the **system boundaries** are described in four dimensions (Tillman et al., 1994). Firstly, the boundaries in relation to natural systems delineate where the technical system begins and concludes, see Figure 3. Secondly, the geographical boundaries specify where the life cycle of the product takes place. Thirdly, the time horizon of the study is determined based on the lifetime of the product or the system. Lastly, boundaries within the technical system may be set to simplify calculations, e.g., cut-off criteria and allocation procedures. For instance, given that the production capital of a car factory has a minimal impact on each car unit produced, the emissions associated with its construction may be assumed to be negligible, i.e., cut off.

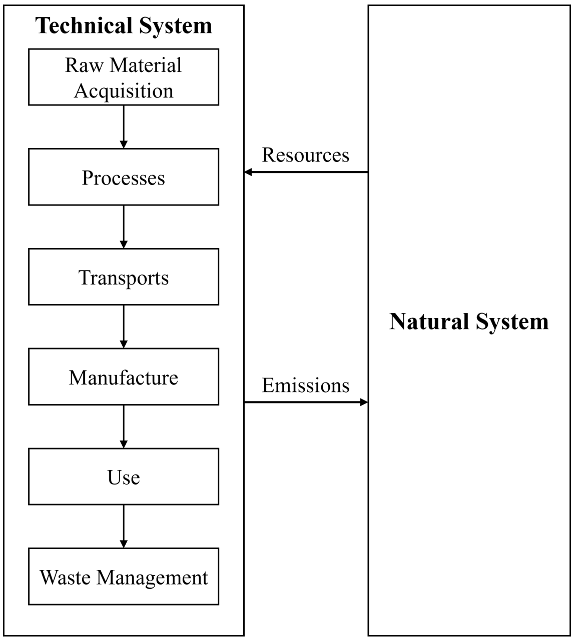


Figure 3: The LCA model according to Baumann and Tillman (2004). The boxes illustrate physical processes, while the arrows indicate flows of energy and substances.

Next, the **impact categories** selected for the study should be presented and motivated. Depending on the target audience, the impact categories can be presented in terms of more or less aggregated indicators, ranging from life cycle inventory results to a weighted index score. An comprehensive set of impact categories offers a holistic representation of a system's emissions and resource use, highlighting their effects across multiple dimensions.

If the technical system shares processes between multiple product systems, **allocation** of environmental loads is required. The choice of allocation method is thus also described in the scope. More about allocation is detailed in Section 2.4.

Describing a study's **data quality requirements** is important to ensure the relevance and accessibility of the information. According to the ISO standard (International Organization for Standardization, 2006), the data quality requirements should address the following:

- time-related coverage,
- geographical coverage,
- technology coverage,
- precision, completeness and representativeness of the data,
- consistency and reproducibility of the methods used throughout the LCA,
- sources of the data,

- uncertainty of the information.

Addressing time-related, geographical and technology coverage implies that the data should be relevant to the time, place and technology used in the technical system. For instance, if a study is performed in the present time, then data should be as recent as possible; if a manufacturing process is done in Sweden, then data regarding the electricity mix should be Swedish; and if technology has evolved, operating data should be representative of the technology used in the study. Naturally, an LCA should use as precise and complete data as possible to paint a truthful picture of the technical system, but it should also be reproducible. Therefore, it is important to be transparent in the data sources used, and explicitly communicate uncertainties and assumptions about the data.

A final part of the goal and scope is the description of the **procedural aspects** of the LCA, i.e., whether the report is to be publicly available, whether the LCA is to be critically reviewed and by whom. The procedural aspects introduce who the stakeholders are, e.g., the commissioner, the analysts or the data providers, and explain the cooperation relationship with them.

2.3.1.2 Life Cycle Inventory Analysis

The second step of the LCA procedure is the life cycle inventory (LCI) analysis. This step encompasses constructing a flow model according to the system boundaries, collecting data for all the activities in the system, and calculating the environmental loads over the life cycle in relation to the functional unit.

A detailed flow model is constructed by linking different processes and quantifying material inflows and outflows. This can be done using software like SimaPro, openLCA or GaBi, which facilitate data gathering - one of the primary challenges encountered during the LCI phase. The goal and scope of the study dictate the type and quality of data. Data can be gathered from various sources, including measurements, models, reports, databases or experts. However, emission and resource use datasets are commonly sourced from licensed databases like ecoinvent, which can be exported into the LCA software.

In addition to collecting information on emissions, resources, products and by-products associated with each activity, it is necessary to know the physical relationship between flows. Although LCA software aids in data gathering, it does not assist in the calculation and normalisation of flows to the functional unit. Consequently, this task is performed in a spreadsheet using the collected information on yields and material losses.

2.3.1.3 Life Cycle Impact Assessment

In the life cycle impact assessment (LCIA), the environmental loads from the LCI are converted into environmental impacts. Impact categories serve as valuable tools for understanding the LCI results, as they aggregate the extensive list of environmental loads and contextualise them. Not every impact category considers all emissions and resource usage. For example, the global warming potential quantifies a broad spectrum of emissions like methane and chlorofluorocarbons (CFC) in relation to carbon dioxide, yet it omits considerations for substances such as phosphate or nitrogen, which are relevant to eutrophication.

In LCA software, LCI results are classified into their designated impact categories and characterised, meaning each load is recalculated by multiplying it with its characterisation factor specific to the impact category. These characterised impacts are then aggregated to yield the final environmental impact for each category, often presented through bar charts. Following this, a contribution analysis is performed to understand the impact of each activity on the total environmental impact within each impact category. This information is readily available in the software and can be made into charts in a spreadsheet.

Lastly, a sensitivity analysis is conducted to scrutinise the results. Here, one or more parameters deemed uncertain are tweaked, leading to a recalculation of the model and the presentation of new results alongside the original (base case) outcomes, highlighting the relative impact of uncertainty. Additional optional steps within LCIA, such as normalisation and weighting, are not carried out in this study. Normalisation seeks to provide context to the LCIA results by comparing them to a reference value, such as the actual or predicted magnitude of each impact. Weighting involves assigning factors that signify the relative importance attributed to different impact categories.

2.3.1.4 Interpretation

In the LCA methodology, the final stage involves interpreting results, wherein the LCIA results are integrated with the established goals and scope. This integration allows for drawing conclusions and formulating recommendations for the commissioner. While no explicit methodology is outlined, the ISO standard 14044:2006 suggests that life cycle interpretation should encompass identifying significant issues based on LCI and LCIA outcomes, conducting evaluations for completeness, sensitivity, and consistency, and ultimately drawing conclusions, outlining limitations, and offering recommendations.

2.4 Allocation

In LCA, allocation is needed when processes are shared with other product systems than that of the product under study (Baumann & Tillman, 2004). This scenario arises prominently in multi-input and multi-output processes, such as refining, where various inputs like crude oil, liquids, and gases converge to yield diverse outputs like gasoline, coke, and fuel oils. Given that not all inputs contribute uniformly to all outputs and some inputs generate multiple products, allocating environmental loads becomes necessary across these diverse products. The ISO 14044 standard defines allocation as *partitioning the input or output flows of a process or a product sys-*

tem between the product system under study and one or more other product systems (International Organization for Standardization, 2006). Allocation challenges are particularly pronounced in the context of multi-output processes, multi-input processes, and open-loop recycling.

The term open-loop recycling refers to when a product is reprocessed into recyclate which is used in a different application (Fedkin, 2024). This process typically results in material quality losses and the exclusion of certain secondary materials, such as glues and labels, from the recycling stream. In contrast, closed-loop recycling draws inspiration from closed loops found in nature, aligning with the biomimetic principle of Industrial Ecology (Ayres, 2004). The objective is to establish an infinite material cycle, wherein the material continually contributes to the production of the same product. While open-loop systems aim to extend the lifespan of a material before its eventual disposal, closed-loop systems strive to perpetuate the material within the loop indefinitely.

2.4.1 The ISO Recommendation

Ideally, allocation is to be avoided, which the ISO recommends doing through **increasing the level of detail of the life cycle modelling** or through **system expansion** (International Organization for Standardization, 2006). Increasing the level of detail could be done with multi-output and multi-input processes, however, it requires extensive work and can be difficult to achieve if the system is complex and specific data is not readily available. Unfortunately, this strategy is not applicable when dealing with open-loop systems. With system expansion, also known as displacement, a co-product is presumed to substitute for a product that is structurally or functionally identical, thereby avoiding its production and the emissions and use of resources involved. The main product receives a credit for this displacement in the form of negative emissions and resources used.

However, if allocation cannot be avoided, the standard suggests **allocation through partitioning** reflecting underlying physical relationships between products. These physical relationships may be mass, energy or exergy content, volume or molar mass, depending on technical-causal relationships and/or limiting factors. In instances where physical allocation is not viable, the standard's last recourse is allocation through partitioning based on other relationships between products, such as economic value.

When dealing specifically with technical recycling systems, the ISO distinguishes between closed-loop allocation procedures and open-loop allocation procedures. Irrespective of whether a system is considered open or closed-loop in terms of its technical description, the allocation procedure applied will depend on the changes to the inherent properties of the material. Therefore, if a product is recycled into another product which is used in a different application (i.e., open-loop recycling) without changes to its inherent properties, a closed-loop allocation procedure should be followed. This allocation method is called *closed-loop approximation* and is explained later on. If recycling results in changes in a product's inherent properties, an open-loop allocation procedure should be followed.

The problem with the open and closed-loop "allocation procedures" mentioned by the ISO 14044:2006 is that they are not defined in the standard. Baumann and Tillman (2004) present six allocation methods for open-loop recycling.

1. **The cut-off approach**: Only loads directly caused by a product are assigned to that product. The cut-off approach is often used when dealing with recycling processes where the material suffers from degradation (Schrijvers et al., 2016). Essentially, it can be seen as a form of economic allocation where waste holds negligible market value, thus rendering the system non-multifunctional (Olofsson & Börjesson, 2018). Under this method, only emissions and resource usage associated with the recycling of PIW into PIR are accounted for, eliminating the need for upstream production data of virgin plastic Furthermore, part of the emissions from the first recycling activity may be allocated to subsequently recycled products.
2. **Allocation in relation to the relative loss of quality**: A coefficient based on the relative quality of the recyclate compared to the virgin product is created and used to allocate the environmental loads across all products. The difficulty of this method lies in the quantification of product quality, especially when the recycled products are entirely different from the original virgin product. Moreover, this method requires data on the entire life cycle, from cradle to grave.
3. **The "all raw material acquisition generates waste" method**: All treatment of waste generated by the material life cycle is allocated to the virgin product since it would not have emerged without its creation.
4. **The "material lost as waste must be replaced" method**: The environmental loads of virgin material production and final waste are allocated to the last product of the life cycle since all value-creating man-made materials must be replaced. Thus, the loads from the first material recycling are allocated to the virgin product. This method requires data on the entire life cycle, from cradle to grave.
5. **The 50/50 method** is an approximation of system expansion that may be used if a material loses some of its inherent properties during recycling. The underlying assumption is that 50 percent of the recycled material replaces virgin material and that the other 50 percent replaces other recycled material. Thus, half of the environmental loads of a recycling process are allocated to the upstream product and the rest to the recycled product. Virgin material production and end-of-life treatment are equally allocated between the first and last products of the material life cycle.
6. **The closed-loop approximation** (also known as end-of-life recycling approach) is another approximation of system expansion. This method may be used if a material does not lose too much of its inherent qualities while assuming that the recycled material replaces virgin material without replacing other

recycled material. Here, the impacts stemming from end-of-life management are assigned to the virgin product, however, it is also credited for avoiding additional virgin product production to compensate for the material loss.

2.4.2 The European Commission's Recommendation

In an effort to standardise the framework for quantifying the environmental impacts across different product categories, the European Commission put forward the Product Environmental Footprint (PEF) Guide in 2013 (European Commission, 2013). Beyond its role as an accurate environmental assessment tool, the PEF method aims to make these types of studies more accessible, faster and cost-effective, while also enabling fair product comparisons. Since 2013, the guide has undergone updates and revisions to incorporate feedback from stakeholders and to ensure its alignment with the latest scientific knowledge.

The latest iteration of the PEF Guide introduces a new methodology, the circular footprint formula (CFF), designed to allocate the environmental loads in systems involving recycling, reuse or energy recovery (European Commission, 2021a). The CFF replaces the End-of-Life (EoL) formula required by the Commission Recommendation 2013/179/EU (European Commission, 2013), and must be used in PEF studies as dictated by the European Commission.

The CFF distributes environmental burdens among material, energy, and disposal stages. For intermediate products — those undergoing further transformation before being used — and cradle-to-gate studies, it is simplified by excluding the distribution, usage, and end-of-life stages, focusing on the recycled content and recyclability at the EoL. Currently, there are default parameter values for plastics to ensure consistency in CFF calculations (European Comission, 2022).

Although the CFF is still in its early stages, the methodology offers an interesting middle ground between the cut-off approach and closed-loop approximation that could provide a nuanced perspective in plastic recycling LCAs. Detailed explanations and equations related to the CFF are provided in Appendix A.

2.4.3 Allocation Choices in Practice

Ultimately, the choice of allocation method rests with the LCA practitioner, who may base their decision on recommendations outlined in standards such as the ISO 14044 (2006), or opt for an alternative allocation method deemed more appropriate for the particular scenario. In instances where such flexibility exists, practitioners may consider their own expertise or incorporate input from stakeholders to inform their decision-making process.

For example, the extraction of gold generates a significant amount of waste and by-products, like gravel, which hold a much lower market value. Given that the demand for gold drives the extraction process, choosing economic allocation in LCA instead of mass allocation makes more sense. If mass allocation were used, most of the environmental burden would fall on the by-product.

Another instance where physical allocation may not be chosen over economic allocation is when market demand cannot dictate the amount of product produced due to a linear relationship between the by-products, as argued by Azapagic and Clift (1999). This would be the case for PIR, where increasing demand would not lead to increased production capacity without engaging in fraudulent production practices.

Reviewing the limited LCAs of PIR reveals inconsistencies in allocation approaches for this material. While Tinz et al. (2023) opt for the cut-off approach, Horodytska et al. (2020) use system expansion. On the other hand, Schulte et al. (2023) claim that impacts from the virgin pre-chain are often allocated using economic allocation in plastic PIR LCAs, yet they do not provide sources for this claim. Taking a more systematic approach to allocation, as proposed by Schrijvers et al. (2020), which offers a methodology for determining the appropriate allocation method based on the goal and scope definition, suggests that PIR should be managed with allocation by partitioning. However, since partitioning is seldom employed for recycling according to their analysis, they propose resorting to the cut-off approach.

In summary, dealing with multi-output systems can prove difficult. An overview of the various allocation methodologies covered in this section is provided in Table 3.

Table 3: Description of allocation methods inspired by Das et al. (2021).

Method	**Description**
System expansion	Co-products are presumed to substitute for a product that is structurally or functionally identical, thereby avoiding its production and the emissions and use of resources involved. The main product receives a credit for this displacement.
Physical allocation	Process emissions and resource use are allocated among co-products based on their physical importance.
Economic allocation	Process emissions and resource use are allocated among co-products based on their market value.
Cut-off approach	Only loads directly caused by a product are assigned to that product.
Relative loss of quality allocation	Impacts are assigned to the different products in relation to the relative loss of quality.
All raw material acquisition generates waste	All treatment of waste generated by the material life cycle is allocated to the virgin product since it would not have emerged without its creation.
Material lost as waste must be replaced	The environmental loads of virgin material production and final waste are allocated to the last product of the life cycle.
50/50 method	System expansion approximation assuming 50/50 distribution of loads from recycling between virgin product and recycled product.
Closed-loop approximation	System expansion approximation assuming recycled material replaces virgin material without replacing other recyclate.
CFF	Method used within the PEF Guide. Allocation based on equations reflecting the material, energy and disposal environmental burdens or credits.

3

Methodology

In this section, the methodology for the project work is presented, illustrated by Figure 4. The methodology is structured into three main parts, each addressing the methods used to answer the specified questions and objectives.

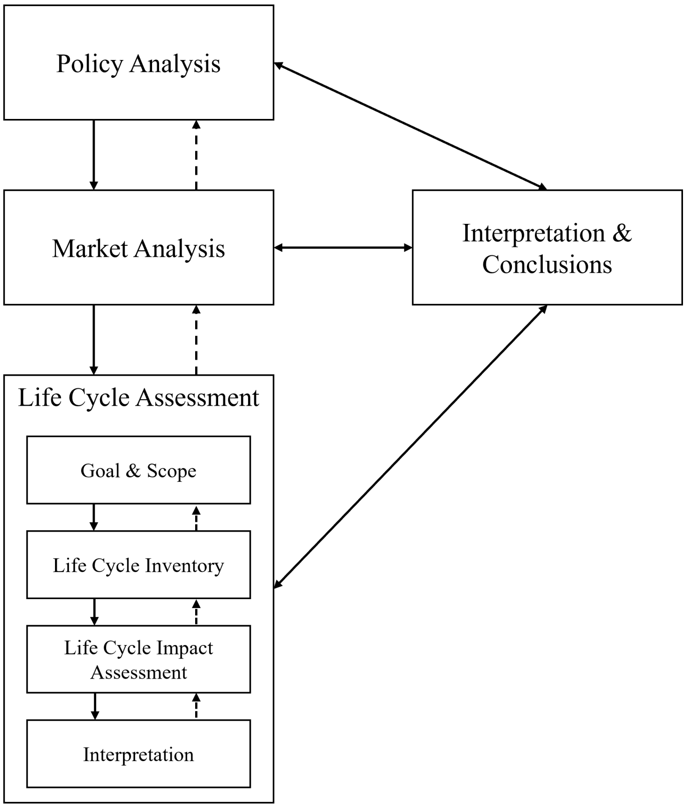


Figure 4: The workflow procedure of the study.

First, the regulatory environment surrounding PIR was mapped by doing a policy analysis. Subsequently, a market analysis was conducted to identify the markets of interest of PIR. Finally, a life cycle assessment was executed to answer research questions 3 and 4. By thoroughly explaining the methodology, the authors aim to provide transparency regarding the process employed to obtain the study's results, thereby facilitating reproducibility if necessary.

3.1 Policy Analysis

The policy analysis aims to comprehend the regulatory landscape concerning PIR, addressing critical questions such as the recognition of PIR in achieving recycling targets, potential legislative barriers to its use and trade within EU Member States, and the overall stance of EU policies on recycling and plastics within the industry.

The policy analysis methodology draws from the qualitative research framework outlined by Bell et al. (2019), which deals with qualitative data over quantitative metrics. This approach combines theory and data collection, where the theories are generated from the research. Although originally tailored for interview-based data collection, the methodology was adapted to suit a literature study by the authors. The method developed is found in Figure 5.

Common criticisms of qualitative research are the challenges in replicating the study, generalisations made from the information gathered, and lack of transparency, which are relevant considerations even with the adapted method. Although the absence of interviews may mitigate some of these concerns, they remain, particularly in the scenario analysis and scenario-building phases, where the authors' interpretations play a central role.

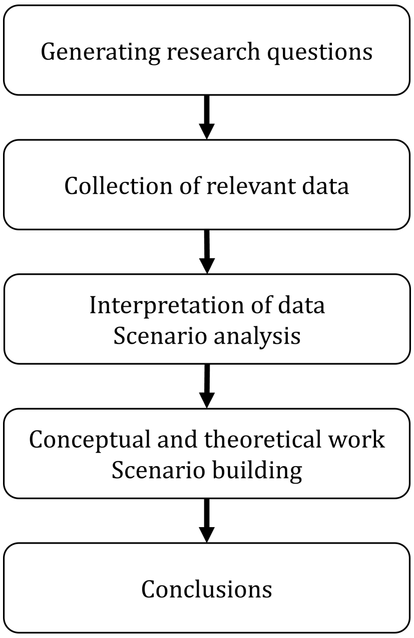


Figure 5: Methodology for the policy analysis conducted. The boxes illustrate procedural steps, while the arrows represent the order in which the steps are performed.

In qualitative research, formulating research questions begins with broad, more general questions (Bell et al., 2019). This approach allows for flexibility, as new insight gathered during data collection can reshape initial assumptions or uncover new avenues worth investigating. Starting with overly specific questions may restrict the ability to adapt or refine the research questions in response to new information. Therefore, the initial questions posed at the outset of the policy analysis were the following:

1. What EU policies already exist regarding plastic?
2. Are there any ongoing policies in development regarding plastic?
3. What are the EU's future goals regarding plastic?

These research questions enabled a thorough examination of EU policies, providing the opportunity to delve deeper into areas relevant to PIR.

The data collection process was conducted in two in two stages. Initially, an exploration of current EU policies was undertaken by reviewing legislative documents, official reports and press communications from the European Commission and Parliament. This phase aimed to grasp the EU's existing policy framework, discern its objectives, and ascertain what future policy plans may be.

The following step involved a literature review of organisational documents from stakeholders such as Plastics Europe, complemented by an unstructured interview with Borealis's head of public affairs. An unstructured interview is a technique wherein minimal questions are posed, enabling the interviewee to provide open-ended responses (Burgess, 1984). Follow-up questions can then be asked to explore the most relevant information further. Given the topic at hand, an unstructured interview approach was deemed the most suitable method.

The analysis and conceptual theory steps were conducted through scenario analysis and scenario building. Further elaboration on the methodology employed for these subsequent steps is provided in the following section.

Scenario Analysis

Future events can be studied with the help of scenario analysis, a method that entails developing a variety of feasible yet not necessarily probable future scenarios (Bunn & Salo, 1993). According to Ralph MacNulty (1977), a scenario is *a quantitative or qualitative picture of a given organisation or group, developed within the framework of a set of specified assumptions.* These scenarios offer snapshots of future plausible developments from the current situation, enabling organisations to make strategic decisions based on informed insights.

Various authors have defined scenario typologies in very different ways. This study adopts the typology proposed by Börjeson et al. (2006), who categorises scenarios into three main types: predictive, explorative, and normative. Predictive scenarios, as depicted in Figure 6, aim to answer the question "What will happen?". They seek to anticipate expected future events and present organisations with probable challenges and opportunities under certain conditions. Such scenarios typically rely on the assumption that the fundamental principles and patterns governing the development of a system will remain consistent over time, allowing analysts to extrapolate from existing trends and historical data.

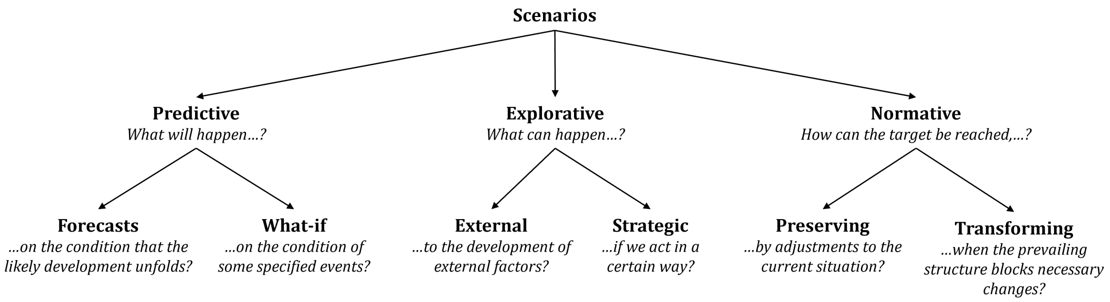


Figure 6: Scenario typologies according to Börjeson et al. (2006).

Predictive scenarios can be further divided into forecasts and *what-if* scenarios, which answer slightly different questions. Forecasts provide predictions based on the assumption that a most likely development will unfold. They are particularly useful when uncertainty is low, making them suitable for short-term planning. On the other hand, *what-if* scenarios explore the consequences of specific near-future events crucial for future development. As opposed to forecasts, none of the scenarios is inherently considered the most likely outcome; rather, they examine potential outcomes under different events, offering valuable insights into decision-making processes.

The second type of scenario analysis encompasses explorative scenarios, which seek to answer the question, "What can happen?". As the name implies, explorative scenarios are designed to delve into alternative futures by considering a wide spectrum of uncertainties and drivers of change. While they share similarities with *what-if* scenarios, the key distinction lies in their temporal perspective. Explorative scenarios often project from a future starting point, making them particularly suitable for long-term planning. Within explorative scenario analysis, sub-categories distinguish between external and internal drivers for development.

Lastly, normative scenarios address the question "How can the target be reached?". These scenarios are guided by specific objectives or defined futures to be realised, aiming to explore various pathways toward achieving them. Depending on whether substantial structural changes are anticipated to be necessary to reach the target, a preserving or transforming scenario analysis approach may be preferred.

Considering the study's focus on investigating the short-term effects of existing and anticipated policy shifts concerning industrial plastic waste recycling, an explorative external scenario analysis stands as the most appropriate methodology. This choice avoids a predictive forecasting approach, given the uncertainty surrounding the authors' capacity to determine the likelihood of specific external drivers. Börjeson et al. (2006) propose a general methodology for conducting scenario analyses, consisting of three general steps: idea generation, integration and a consistency check. For *what-if* scenarios, they specifically recommend generating ideas through surveys, workshops or the Delphi method, i.e., a method used to obtain expert opinions through iterative surveys. Then, the integration of the different parts of the system into a whole is generally done through mathematical modelling such as explanatory or optimising modelling. In the case of explorative scenario construction, the authors suggest checking consistency with cross-impact analysis and morphological field analysis.

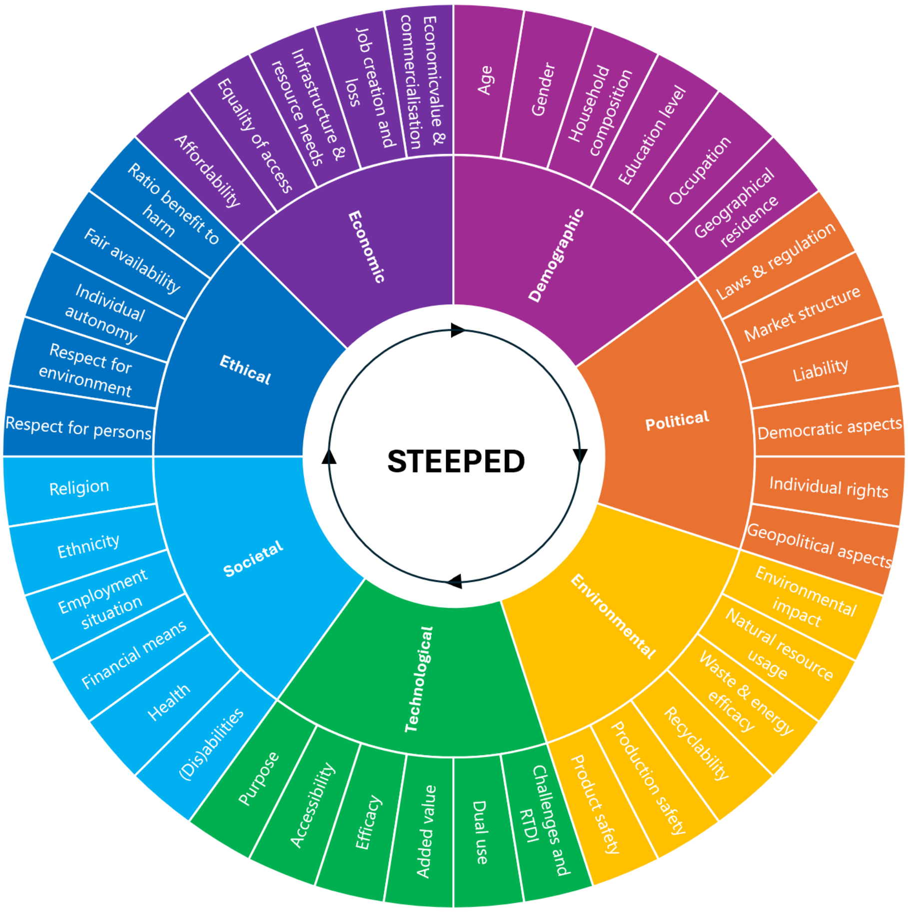


Figure 7: STEEPED wheel used in the conceptualisation of drivers from Woensel (2021).

Given the time constraint of the study, a simplified scenario analysis was conducted using the 2 × 2 matrix approach according to Rhydderch (2017). This method is cost-effective and straightforward for scenario building. The first step involves brainstorming and describing key drivers of change with the help of the STEEPED[1] wheel shown in Figure 7. The STEEPED scheme is a checklist with seven lenses through which the impacts of techno-scientific developments can be analysed: Societal, Technological, Economic, Environmental, Political, Ethical and Demographic.

---

[1] Rhydderch (2017) proposes using a STEEP (Social, Technological, Economic, Environmental, and Political) analysis, which originates from the method coined by Aguilar (1967). This thesis proposes adding the Ethical and Demographic aspects as seen in Woensel (2019) to the analysis to make it more multi-faceted.

Originally proposed by Woensel (2019), the STEEPED wheel is used by the Scientific Foresight Unit (STOA) at the European Parliament for conducting foresight-based policy analyses (Woensel, 2021).

From the generated list of drivers, the two drivers with the highest uncertainty and impact were selected. To ensure high-quality scenario analysis, it is crucial that these selected drivers are independent of each other and belong to different categories on the STEEPED wheel.

Based on these two dimensions, four scenario concepts were generated. Subsequently, the scenarios were further developed and refined during workshops conducted by the authors, with input from experts at Borealis. Thereafter, each scenario was analysed and evaluated qualitatively to assess its potential impact, risks, and implications for Borealis. Due to time constraints, no quantitative modelling was included.

3.2 Market Analysis

The primary aim of the market research is to find sectors or regions where recycled products could potentially have increased value. However, it is not intended to be an in-depth market analysis; rather, it focuses on identifying industries or geographic areas worthy of further exploration by Borealis. Furthermore, identifying markets with significant economic potential for PIR could influence the choice of allocation of environmental burdens from an LCA perspective.

When conducting a marketing analysis, the preferred method is primary data collection, which refers to data directly gathered by the authors (Bell et al., 2019). This can be achieved through various means, including surveys, questionnaires, or interviews. However, these methods are typically expensive and time-consuming. Given limitations in both time and resources, this study did not conduct any primary data collection. Instead, a secondary data analysis approach was adopted, which means using data not directly generated by the authors. This secondary analysis relied on publicly available information from articles, scientific literature, companies, and statistical organisations.

The secondary data approach to market analysis offers some benefits, notably the cost and time investment required, access to data compiled by experienced individuals, and the ability to examine a broader geographical area (Dale et al., 1988). However, reliance on secondary data also has its drawbacks, including lack of control over data collection methods, specific questions asked, available options on questionnaires, and the quality of the data (Bell et al., 2019). The practice of using publicly accessible data is commonly termed the "public domain data" method in marketing analysis guides (Day, 1981; Wojciech, 2023). However, despite providing instructions for data collection, these guides lack clear instructions on how to structure the analysis.

Given the absence of a definitive methodology for conducting a market analysis, the initial step involved a brainstorming session to explore potential approaches. During this session, it was decided to first investigate the German market, due to its size and the proximity to both recycling plants, reducing the need for transport. Subsequently, general web searches were conducted to gather articles and news on environmental purchasing behaviours, providing insight for further investigation. Each potential factor or market identified underwent additional research to validate the information and gather more specific data by looking at market research and statistical analyses. After finding several influential factors affecting purchasing behaviour, another brainstorming session was held to identify industries and products that could leverage one or more advantageous factors. This process produced a list of potential industries and product examples where PIR could offer added value due to its environmental benefits.

Moreover, a comprehensive analysis was conducted specifically for the automotive industry. This market was chosen due to the ongoing transition of the automotive industry towards sustainable manufacturing practices, coupled with the substantial presence of plastics in modern cars. Studies indicate that approximately 10 percent of a car’s weight and 50 percent of its volume consists of plastics (American Chemistry Council, 2023), with PP being the most common material used (Emilsson et al., 2019). The number of German car manufacturers and their need for high-quality plastic components made this industry an interesting market to investigate further. In contrast to the previous market analysis, this study placed less emphasis on market factors and instead focused on the utilisation of recycled plastics by different car manufacturers and assessed the potential of PIR within this sector.

The market analysis for automotive manufacturers involved examining their sustainable commitments and current initiatives, the volumes of recycled plastic needed compared to PIR supply, and reviewing EU policies. The investigation into their sustainable commitments aimed to better understand how German car manufacturers address their environmental impacts and whether recycled plastics are part of their strategy. Additionally, a comparison of the volume of recycled plastics used by manufacturers with the expected yearly supply of PIR was conducted to evaluate the potential impact of PIR in the automotive sector. Finally, relevant policies were explored to provide further context and determine if PIR could be a valuable resource for the automotive industry.

3.3 Life Cycle Assessment: the Goal and Scope

Since the methodological choices of the LCA study are motivated within the LCA study itself, this section begins directly with the goal and scope definition of the LCA conducted in this thesis. The LCI, LCIA and result interpretation can be found in the LCA results and discussion chapter (see Chapter 6).

3.3.1 The Goal

As one of the leading global companies in plastics, chemicals and refining, Borealis bears a significant responsibility for fostering a more sustainable future. To advance towards closing the material loop, Borealis took a pivotal step in 2020 by acquiring two mechanical recycling companies: mtm plastics in Niedergebra, Germany and Ecoplast in Wildon, Austria. Subsequently, in 2021, with revisions in 2022, Borealis conducted an LCA assessing the environmental impacts of the products produced at these facilities. In that study, PIR was regarded as an industrial by-product. However, it should now be recognised and treated as waste. This redefinition necessitates a reassessment of the LCA's allocation methods and results, prompting Borealis to revisit the study.

The primary objective of this LCA study is to assist Borealis in determining the environmental footprint of PIR plastic, depending on the chosen allocation method. Thus, the research objective is framed onto the following research question: *What is the environmental footprint of a post-industrial PP product from Borealis, and how does the allocation method chosen affect the results?*

Given that the definition change from by-product to waste only affects the PIR material, this study will focus on plastic products made solely out of PIR. Borealis produces two such products: NAV-128, made from PP, and NAV-122, made from a blend of LDPE and HDPE. To simplify the LCA and make the allocation comparisons clearer, the LCA will only analyse one of these products, NAV-128. Since NAV-128 is produced both at the mtm and Ecoplast plants, the choice to study PIR from only one of these facilities was made to simplify the study. Thus, this study assesses the NAV-128 coming from mtm plastics.

The study serves as an informational source on the environmental footprint of post-industrial PP products for Borealis as well as a basis for them to make an informed allocation decision concerning PIR products both for the present and the future.

The target audience comprises product managers, LCA experts and anyone else at Borealis involved or interested in the PIR business. Due to the sensitive nature of the data used in this study, both the LCI and the study results have been pseudonymised to ensure confidentiality.

3.3.2 The Scope

3.3.2.1 Type of LCA and Functional Unit

Due to the comparative nature of the study, this LCA is attributional. The purpose of the system is to produce propylene PIR pellets out of industrial waste. Therefore, the functional unit chosen is *1 kg of PIR PP pellets* at the gate of the mtm plant.

3.3.2.2 Impact Categories

To ensure the significance of the LCA's findings, particularly given the scientific proficiency of the target audience, the use of midpoint indicators is considered most relevant. In line with this approach, this LCA looks at the impact categories considered in the PEF method recommended by the European Commission (2021a), and uses the characterisation factors from the PEF version 3.1 (European Comission, 2022) to assess:

- Climate change, fossil [2]; expressed in [kg CO_2-eq]
- Acidification potential [mol H^+-eq]
- Freshwater eutrophication potential [kg P-eq]
- Marine eutrophication potential [kg N-eq]
- Terrestrial eutrophication potential [mol N-eq]
- Ozone depletion potential [kg CFC-11-eq]
- Photochemical oxidant formation [NMVOC-eq]
- Particulate matter formation [disease incidents]
- Human toxicity, carcinogenic [CTUh]
- Human toxicity, non-carcinogenic [CTUh]
- Freshwater ecotoxicity [CTUe]
- Ionising radiation, human health [kBq ^{235}U-eq]
- Resource use, minerals and metals [kg Sb-eq]
- Resource use, fossil [MJ]
- Land use [dimensionless]
- Water use [m^3 world-eq]

This list of impact categories aligns with those commonly used in LCA studies on plastic waste management (Alhazmi et al., 2021), while also incorporating land use, water use, and ionising radiation. A more detailed description and definition of each impact category can be found in Appendix C.

The complete set of impact categories chosen for this LCA provides a holistic perspective on environmental impacts. They encompass both global concerns (such as ozone depletion) and local issues (like particulate matter pollution), and span various time scales, from long-term considerations like climate change to more immediate concerns like human toxicity. Furthermore, given the fossil nature of PIR's source materials and the polluting activities within its supply chain, it is relevant and necessary to consider impacts on abiotic depletion, acidification, and eutrophication potentials.

---

[2] Impact associated with emissions of greenhouse gases resulting from the combustion or use of fossil fuels.

3.3.2.3 System Boundaries and Initial Flowchart

This cradle-to-gate LCA looks at the production of post-industrial PP from raw material extraction to the mtm factory gate where the PIR is pelletised and ready for sale. Beyond the primary plastics recycling processes, this also includes the end-of-life management of wastes generated during PIR production.

In the context of PIR, the question of the material's origin arises. Should industrial waste be considered as its raw material, or should we trace it back to the initial step of oil extraction and refining? Based on the perspective that PIR is essentially a remedy for surplus industrial waste rather than a deliberate production process, it is argued that the true raw material of PIR is PIW. Therefore, in this study, the cradle is considered to be the point of disposal of post-industrial waste, which occurs in the German Burghausen plant. A flowchart of the technical system is shown in Figure 8.

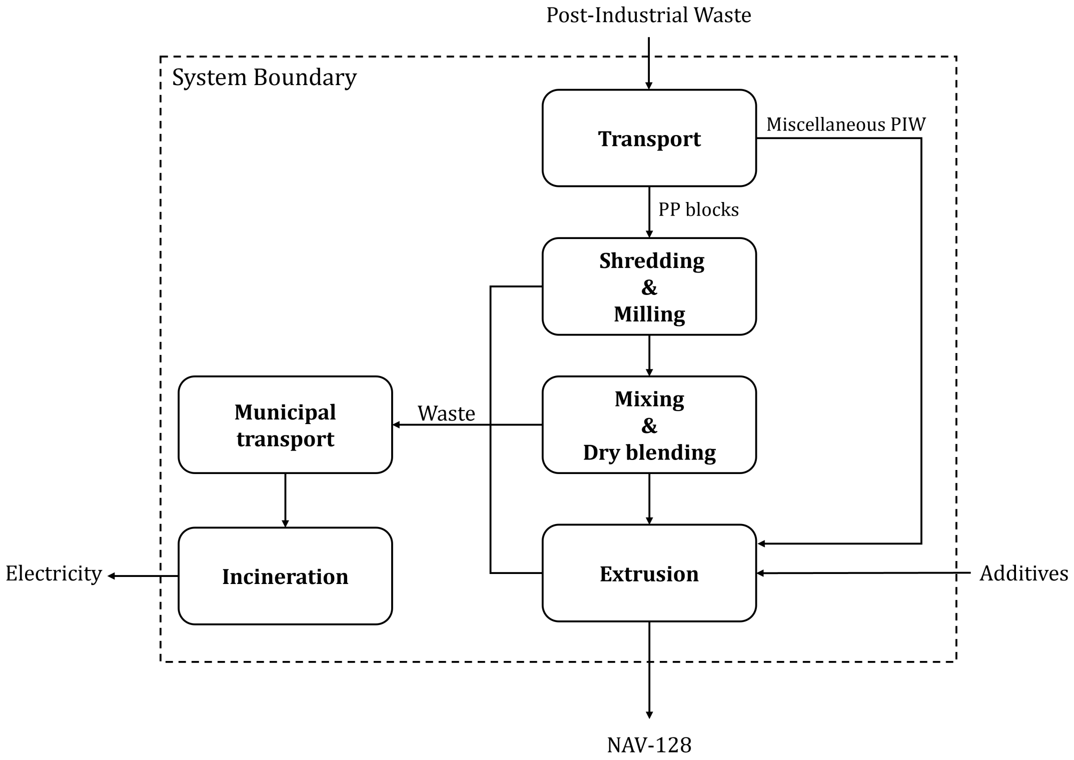


Figure 8: Initial flowchart of the recycling process of PIW at mtm.

The mtm plant processes approximately 1 300 to 1 500 tons of PIW annually, comprising roughly 80 percent blocks and 20 percent miscellaneous materials like contaminated pellets, floor sweep and laboratory waste (A. Rößler-Czermak, product owner at Borealis, personal communication, April 2, 2024). Originating from the Burghausen plant in Germany, this waste travels a distance of 570 kilometres via truck to reach mtm's facility. Upon arrival, the blocks undergo initial handling on conveyor belts transporting the material to its first processing stage: shredding and milling. During this phase, the plastic blocks are broken down into smaller particles. This fragmentation increases the material's surface area, which facilitates subsequent processing stages by rendering the plastic easier to handle and manipulate.

Following shredding and milling, the plastic material is mixed and dry-blended to ensure batch homogeneity in quality and appearance. Finally, the plastic is reshaped in the extruder, where it is subjected to a controlled melting, filtering and degassing process, resulting in the formation of pellets. During the extrusion, additives and colourants can be incorporated into the melt. While PP blocks must undergo shredding, milling, mixing, and dry blending before entering extrusion, miscellaneous PIW is already appropriately sized and can thus be directly sent to the extrusion stage.

Additionally, some material is lost during each processing stage, and this waste is sent to municipal incineration to be transformed into electricity.

Since the PIW is both sourced and processed in Germany, the geographical scope of this study is limited to this country. Nonetheless, many impacts throughout the PIR life cycle, including those stemming from the virgin PP production that yields PIW, have a global reach, which has been considered in the choice of environmental impacts. Furthermore, the result of the study will be relevant for as long as the analysed recycling plant produces PIR stemming from waste from the Burghausen facility operated by Borealis.

3.3.2.4 Allocation

A key part of this study is to deep-dive into the allocation of emissions and resources to PIW. Therefore, instead of choosing one allocation method, multiple allocation approaches are selected and analysed. The selection of a few relevant allocation methods for comparison is guided by several factors, including recommendations outlined in ISO standards, proposed open-loop allocation methods, and considerations regarding ethics and representativeness of real-world drivers behind PIR production. However, this selection is also constrained by the availability of necessary data for implementing a specific allocation method, the type of LCA performed and the applicability of the method for Borealis in the future.

Therefore, this LCA examines the following allocation methods:

1. System expansion
2. Mass allocation
3. Economic allocation
4. The cut-off approach

As outlined in Section 2.4 on allocation, system expansion is the ISO standard's preferred course of action when dealing with multi-output systems. This methodology assumes PIR to replace virgin plastic, thereby attributing negative environmental burdens to PIR due to the elimination of the need for virgin plastic production. However, criticism arises regarding this assumption (Das et al., 2021; Azapagic & Clift, 1999), as recycled products may not always serve as direct substitutes, leading instead to increased plastic availability in the market. Nevertheless, given the potential for PIR to substitute virgin plastic in various applications like automotive and packaging, investigating system expansion remains worthwhile.

Figure 9 presents a flowchart illustrating the system expansion used in this study. The LCA results of a virgin PP from Borealis are required to perform a system expansion, data which is presented in Table 13 in Appendix D. When the technical system according to Figure 8 has been modelled, the system can be expanded and results can be calculated by subtracting the virgin PP results from the modelled results.

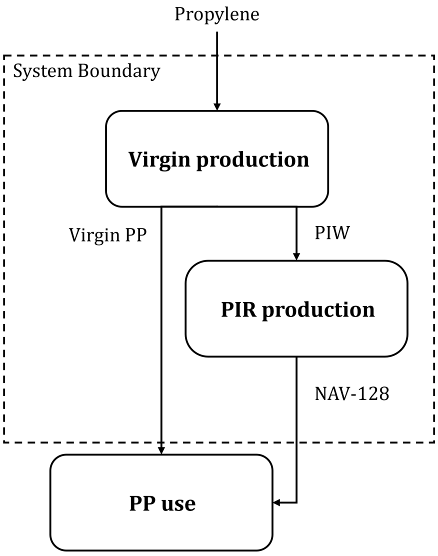


Figure 9: Flowchart of the system with system expansion.

Additionally, mass and economic allocation methods are examined due to the disparity in the quantities of virgin PP and PIW produced at Borealis, alongside the significant market value of plastics. Given that PIW constitutes a relatively small fraction compared to the volume of virgin plastic produced, and often arises unintentionally, it appears reasonable to allocate environmental burdens accordingly. Conversely, if PIR holds considerable value to consumers, arguments could support allocating the environmental impact according to this rationale.

Allocation by partitioning involves calculating an allocation factor for PIR, which is then applied to the LCIA results of virgin PP. Equations 1 and 2 demonstrate how these factors are calculated for mass and economic allocation, respectively, where m represents the mass of either PIW or virgin PP produced by Borealis, and p indicates the net price of either PIW or virgin PP sold by Borealis.

$$F_{mass} = \frac{m_{PIW}}{m_{PIW} + m_{virgin}} \tag{1}$$

$$F_{eco} = \frac{p_{PIW} \cdot m_{PIW}}{p_{PIW} \cdot m_{PIW} + p_{virgin} \cdot m_{virgin}} \tag{2}$$

Lastly, the cut-off approach is included as a contender since it can be argued that NAV-128 should only be assigned environmental impacts directly caused by its production and were the virgin PP production to cease, then there would be no PIR produced. Accordingly, under this approach, virgin plastic would bear the entirety of the environmental burdens, while recyclates would be exempt from such burdens. Only the environmental impacts of subsequent processing steps are taken into account.

3.3.2.5 Limitations

The LCA excludes environmental loads associated with production capital and personnel as these effects are considered negligible compared to the impacts of the system per functional unit. Furthermore, material flows contributing to less than one percent of the mass input of the product system are cut off since they are deemed to be of little environmental significance. Consequently, the handling of any impurities such as metals, which constitute 0.4 percent of the PIW mass input, is not included in the study.

Lastly, a cut-off approach is implemented for the energy generated from PIW incineration, which exits the plant without any environmental credits or burdens attributed to it.

This LCA does not account for the specific stage within the virgin production process where waste is generated. For instance, floor sweep originating from the extrusion step has undergone more production steps than PP blocks derived from polymerisation. Consequently, floor sweep has incurred a higher environmental impact. However, when allocating the environmental burden attributed to PIR from the virgin process, it is assumed that the PIW has undergone the complete production process.

The energy mix utilised is derived from Germany's gross national generation over a year. However, it is important to note that the energy mix varies both seasonally and depending on the time of the day. Due to a lack of available data on both the fluctuations of Germany's energy mix and the specific production times of PIR at mtm, it is assumed that mtm produces a consistent amount of PIR throughout the entire year, matching the energy mix over that same period.

The emissions from transport do not take into account any possible scenarios that may increase the emission, such as traffic or possible stops along the way.

3.3.2.6 Data Quality Requirements

Borealis provided all the primary data utilised in this study, sourced from the mtm recycling and the Burghausen plants in Germany. Primary data from Borealis encompasses all the foreground data used for this system and some of the required background data.

The quality of data Borealis provided varied, with most of it derived from already made studies conducted by external consultants and critically reviewed. Unfortunately, Borealis could not provide the methodology for these studies, making it impossible to assess if these results align with the proposed methodology of this LCA. Therefore, the procedural choices made in the environmental assessment of the upstream supply chain are unknown and could affect the results of this study.

Additionally, some data acquired from Borealis relies on expert estimates, such as yields or the origins of material inputs to the system. In instances where Borealis data was either unavailable or insufficient, aggregated data from ecoinvent version 3.10 was utilised. The selection of this data was determined by factors including reliability, completeness, accessibility, geographical correlation, and temporal correlation. Therefore, whenever possible, datasets specific to Germany were preferred.

The mathematical modelling of the LCA system was performed using the software tool openLCA.

3.3.3 Procedural Aspects

This LCA study will not be critically reviewed by a third-party organisation but will be presented both at Borealis and at Chalmers as part of a master’s thesis.

4

Policy Research

Plastic plays a multifaceted and extensive role across Europe, drawing significant attention from policymakers due to environmental concerns. Presently, policy efforts predominantly target plastic packaging, despite a substantial portion of plastics being utilised in non-packaging sectors. According to a report by Plastics Europe (2023), the demand for plastic in the EU27+3 countries amounted to 54 million tonnes in 2022. Among this, 39 percent is allocated to packaging, leaving the remaining 61 percent distributed across various sectors. Notably, building and construction, followed by the automotive industry, electrical and electronic equipment, household goods, agriculture, and other miscellaneous sectors, see Figure 10.

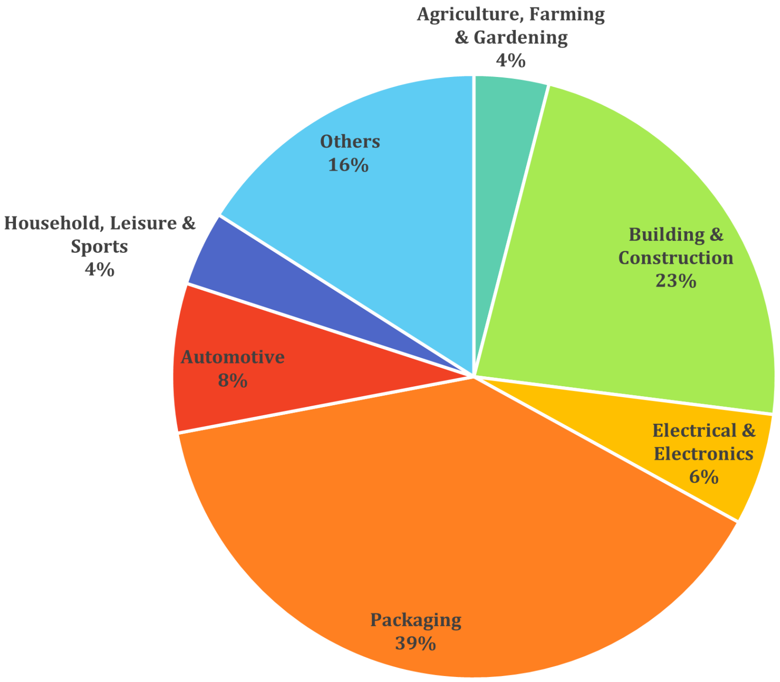


Figure 10: EU27+3 demand for plastics across sectors (Plastics Europe, 2023).

The search for specific policies, strategic plans, or legislation addressing the intersection of the plastic, waste, and industrial production sectors yields little to no results. This omission underscores a notable gap in addressing recycling practices within industrial contexts. While the 2015 CEAP outlines the commitments made by the EU to advance towards a more circular society (European Commission, 2015), its direct implications for PIR plastics remain unclear. The absence of specific mentions of PIR within the action plan shows the need for further investigation into how industrial recycling fits into the EU's circular economy goals.

According to the European Head of Sustainability Public Affairs at Borealis, the decision to exclude PIR from the EU's incentivisation scheme is primarily driven by two factors (V. Spencer, personal communication, March 5, 2024). Firstly, PIR has not suffered any market failures, unlike PCR. A market failure occurs when supply and demand are imbalanced, leading to an inefficient market. Spencer notes that PCR has faced such imbalances due to the unattractiveness of the material because of lower quality, resulting in supply far outweighing demand. In response, policies have been introduced to stimulate demand, such as minimum recycled content requirements in plastic packaging European Parliament (2018b). Since PIR has maintained steady market demand, such policies have not been necessary. Secondly, there is a concern that incentivising PIR could encourage fraudulent activities, with plastic manufacturers potentially diverting resources to produce more PIW instead of virgin plastic. However, this argument seems questionable and counterintuitive, as it implies that manufacturers would willingly sacrifice efficiency and profitability in their production processes.

Nevertheless, by analysing the CEAP together with subsequent policy actions and the yet-to-be-adopted 2020 New Circular Economy action plan, we can gain insights into the trajectory of PIR plastic within EU policy-making. In EU policy, and particularly within the CEAP, four key areas influencing PIR were identified: plastic and plastic packaging, waste management, industry development, and cross-border shipping of waste. These specific areas were selected due to their significant influence on the feasibility and economic incentives for expanding the recycling of post-industrial plastic waste. Examining the policy strategies within these realms will unveil the extent to which PIR is taken into account in EU-level decision-making processes.

4.1 Plastic and the Packaging and Packaging Waste Directive

Existing waste and recycling policies predominantly address plastic waste management within realms such as construction and demolition, plastic packaging, and waste from electrical and electronic equipment. According to the 2015 CEAP, only 25 precent of collected plastic is recycled with, 50 percent ending up in landfills, highlighting the significant environmental impact, particularly on marine pollution. Therefore, the EU has designated plastic as a high-priority material, emphasising that achieving higher recycling rates is a crucial step in pursuing circularity. The action plan outlines strategies for boosting recycling rates across the entire life cycle, including implementing ecodesign and improving collection and certification schemes for collectors. Special emphasis has been placed on packaging with EU-wide recycling targets (European Commission, 2015).

To boost recycling rates, ambitious targets have been set for Member States to achieve by 2025, particularly aiming for a 65 percent recycling rate for packaging waste and a 55 percent rate for municipal waste (European Parliament, 2018b, 2008). These targets aim to mitigate emissions generated during the extraction and processing of virgin resources while reducing dependencies and strengthening the EU's strategic autonomy for critical materials. However, with such ambitious goals, it is surprising that there is no mention of the raw material manufacturer's role in meeting overall recycling objectives.

In a position paper regarding the revision of the Packaging and Packaging Waste Directive (PPWD) announced by the European Commission in October 2020, Plastics Europe emphasises the importance of including pre-consumer waste as an equal contributor in recycled content targets (Plastics Europe, 2021). The prompt to include pre-consumer plastic in the PPWD revision stems from the directive's introduction of minimum recycled content targets for the plastic component in packaging, see Table 4. However, the directive specifically states that the recycled plastic utilised must originate from post-consumer sources (Ragonnaud, 2023). Plastics Europe underscores the necessity of incentivising waste collection, sorting, and recycling of pre-consumer waste at the policy level, signalling to EU legislators the need for further action in this regard.

Table 4: Proposed targets regarding the minimum percentage of recycled content sourced from post-consumer plastic waste per unit of packaging (Ragonnaud, 2023).

Type of packaging	From 2030	From 2040
Contact-sensitive packaging made from plastic materials other than PET (except single-use plastic beverage bottles)	10%	50%
Single-use plastic beverage bottles	30%	65%
Other packaging	35%	65%

Furthermore, Plastics Europe points out the importance of granting companies access to all types of plastic waste — both pre-consumer and post-consumer — to scale up chemical and mechanical recycling processes. This access is necessary for meeting recycled content targets in plastic products and improving the quality of recycled plastic streams. Since 2020, the European Parliament has adopted a report on the proposal, which serves as Parliament's position for negotiations with the Council (European Parliament, 2024). Despite the incorporation of 207 amendments into the report, none have addressed the inclusion of pre-consumer plastics yet. Additionally, the 2020 CEAP expanded its commitments to include minimum recycled content requirements in the automotive and construction sectors as well (European Commission, 2020). Although these measures have not yet been implemented, the policy under development for the automotive industry specifies that only PCR plastic will be counted towards the targets, excluding PIR. (European

Commission, 2023b). The specifics regarding the minimum requirements for construction are currently unknown. However, considering the EU's past actions, the prospect of PIR being included seems doubtful. Although the PPWD revision and the CEAP clearly show the EU's commitment to increasing recycling rates within the EU, the role of post-industrial waste remains uncertain and will depend on the further revision of these strategies.

4.2 Waste Management

In the 2015 CEAP, the EU expressed its commitment to adopting the waste hierarchy, prioritising prevention as the most favourable outcome, followed by reuse, recycling, energy recovery, and disposal as the last resort (European Commission, 2015). This was done with an amendment to the waste directive, where the EU encouraged each member state to add incentives for promoting waste hierarchy (European Parliament, 2018a). While the EU offered suggestions for incentives, the implementation was left to the discretion of each Member State, potentially impacting companies that recycle their post-industrial waste, contingent upon each Member State's implementation. However, the EU also acknowledged that waste generation is inevitable regardless of the system's efficiency. Therefore, the EU is committed to promoting policies that facilitate the injection of waste back into the economy, minimising resource losses to the greatest extent possible.

Regarding waste, the CEAP's primary focus lies in the post-consumer stage, with the main aim of improving household recycling across all EU Member States. Less explicit attention is given to industrial waste management. Whenever mentioned, it remains unclear whether it refers to post-industrial or post-consumer waste, since one often-mentioned waste sector is construction (European Commission, 2015). The EU also seeks to revise waste laws to provide clearer definitions of the terms waste and by-products, while also harmonising these laws across all EU Member States. Additionally, the EU seeks to enhance the utilisation of secondary raw materials, emphasising the need for clear end-of-waste legislation and quality control regulations (European Commission, 2015). While the CEAP does not explicitly differentiate between post-consumer and pre-consumer sources when mentioning secondary raw materials, the predominant focus on post-consumer waste in EU policies suggests a bias toward this specific waste type.

Amendments to the waste directive included recycling targets, however, these were exclusively regarding municipality waste (European Parliament, 2018a). This exclusion underscores the EU's limited focus on post-industrial waste, potentially rendering it less desirable. The waste directive amendments also included updates to the definitions of waste and by-products. However, these revisions still leave uncertainties open to interpretation (European Commission, 2021c). Additionally, the amendments outlined a strategy for developing a legal framework for end-of-waste (European Parliament, 2018a). The strategy involves enabling each Member State to develop its end-of-waste legislation and monitoring its effects. Subsequently, the

EU will assess if Union-wide legislation for end-of-waste is necessary. This indicates that the establishment of a Union-wide legal framework for end-of-waste criteria is a distant prospect, potentially impeding the development of PIR products. In the EU's CEAP 2020, post-consumer waste and improving household recycling rates are still the major focus, with a clear absence of post-industrial waste.

4.3 Industry

In the industrial sector, the 2015 CEAP recognises the unique resource requirements and waste generation across industries, thus affirming its commitment to promoting the 'best available technique reference document' (BREF) (European Commission, 2015). It underscores waste reduction and industrial symbiosis as key strategies to enhance circularity. Additionally, the EU aims to foster collaboration with industries to develop a market for secondary raw materials, emphasising the establishment of supply chains and creating demand for these materials. Furthermore, as of January 2023, the Corporate Sustainability Reporting Directive mandates a wide range of large companies and listed small and medium-sized enterprises to report their sustainability (European Parliament, 2022).

However, the CEAP's industrial strategy falls short in addressing the recycling of industrial waste. While initiatives to develop markets and supply chains for secondary raw materials could benefit the PIR market, concerns remain regarding potential overemphasis on post-consumer waste, possibly neglecting post-industrial waste. This follows in line with the EU's industrial policies since 2015, where no benefits to post-industrial waste could be found.

4.4 Safe Shipping within the EU

The EU has recognised that the challenge of transporting secondary raw materials cross-border is a significant barrier to its success (European Commission, 2015). The lack of clear EU-wide legal definitions for secondary raw materials makes cross-border shipping challenging due to restrictions on exporting and importing waste (European Commission, 2015). Additionally, the lack of common EU laws governing the import and export of waste results in varying rules among nations. The EU believes that enhancing existing end-of-waste regulation, clearly defining secondary raw materials, introducing quality standards and striving to standardise waste transport rules across EU Member States will help facilitate cross-border shipping (European Commission, 2015).

The action report indicates that the EU intends to increase the mobility of waste materials destined for recycling. Enabling more mobility of movement of post-industrial waste would positively impact the production of PIR products. However, if post-industrial waste is not included in the EU's initiatives to increase the cross-border shipping of waste, these policies will not impact PIR.

As a general rule, transfrontier shipments of waste typically require a permit. However, there are exceptions for non-hazardous waste designated for recovery, such as PE and PP, which are considered non-hazardous as of January 2021, under the Basel Convention and EU law No. 1013/2006 on shipments of waste (European Parliament, 2021). These polyolefins are classified as green-listed waste under Annex III, subject to specific procedural requirements outlined in Article 18. This article details the necessary documentation and contractual obligations between shippers and recipients of waste exceeding 20 kg destined for recovery and waste explicitly destined for laboratory analysis, ensuring accountability for waste management. Additionally, Member States may request shipment information for regulatory purposes, maintaining confidentiality as per legal mandates.

Under EU law, green-listed plastic waste includes non-halogenated polymers like PE, PP, polystyrene (PS), acrylonitrile butadiene styrene (ABS), polyethylene terephthalate (PET), polycarbonates (PC), and polyethers, with international and national specifications offering further guidance.

In conclusion, the cross-border shipment of polyolefin waste for recycling is allowed within EU Member States by EU law. Nevertheless, national legislation plays a crucial role in shaping these regulations. Fortunately, both Austrian and German waste laws follow the EU directive, enabling polyolefin waste shipment from Borealis plants located outside the countries (Austrian Parliament, 2002; German Parliament, 2007).

4.5 Scenario Analysis

Following the mapping of the current policy landscape, the scenario analysis delves into projecting future market and policy dynamics concerning PIR and recyclates in general. Table 5 illustrates the primary drivers of change identified through brainstorming sessions utilising the STEEPED wheel, detailing the levels of uncertainty and impact assigned to each.

The scenario analysis will focus on the two drivers with the highest levels of uncertainty and impact as seen in Table 5, i.e., "ethylene and propylene prices" and "technological improvement in recycling". Background information on each driver is given below to provide a better understanding of the implications and political, environmental and economic dynamics behind each driver. The remaining drivers which are not used in the scenario analysis are similarly described in Appendix B.

Ethylene and Propylene Prices

The price of ethylene and propylene is an important driver in understanding market changes in virgin and recycled plastics since these chemicals are central in the production of virgin plastics. Therefore, studying the general development of ethylene and propylene prices can give insights into whether virgin plastic or recyclate is the

Table 5: Drivers identified through brainstorming sessions using the STEEPED wheel.

Driver	STEEPED Category	Level
Ethylene and propylene prices	Economy	High uncertainty Medium impact
Technological improvement in recycling	Technology & Environmental	Medium uncertainty High impact
The public opinion on recycling	Ethical	Low uncertainty Low impact
The inclusion of PIW in EU policy	Political	Medium uncertainty Low impact
Recycled contents in high-performance sectors	Political	Low uncertainty High impact
Geopolitical stability	Political	High uncertainty Low impact

more attractive alternative for manufacturers to use in their production.

In a nutshell, low ethylene and propylene prices lead to cheaper production of virgin plastic. Naturally, manufacturers tend to choose low-cost, virgin plastic over more sustainable alternatives, since the production costs for the latter have not decreased. Conversely, recycled plastic becomes a more cost-efficient option if these prices increase, which also increases the incentive to recycle.

The main drivers behind surges and crashes of ethylene and propylene prices are external crises affecting the supply and demand of oil globally. For instance, the Gulf War of the 1990s, the 2008 financial crisis and the COVID-19 pandemic. Most recently, the COVID-19 pandemic led to many non-essential industries shutting down and people being confined at home, resulting in a huge decrease in mobility and consumption, decreasing the demand for oil which leads to a decrease in oil prices. While ethylene and propylene prices generally correlate with oil prices, see Figure 11, there may be variances influenced by operational factors during the cracking process.

But what does this mean in terms of forecasting PIR market trends? Needless to say, there is a very high degree of uncertainty in predicting the direction of ethylene and propylene prices. The COP28 decision in December 2023, which outlined plans to phase out fossil fuels, particularly affects oil consumption given its primary use as a fuel source (European Parliament, 2023). Consequently, this agreement implies a potentially steep decline in global oil demand and subsequent oil, ethylene and propylene prices.

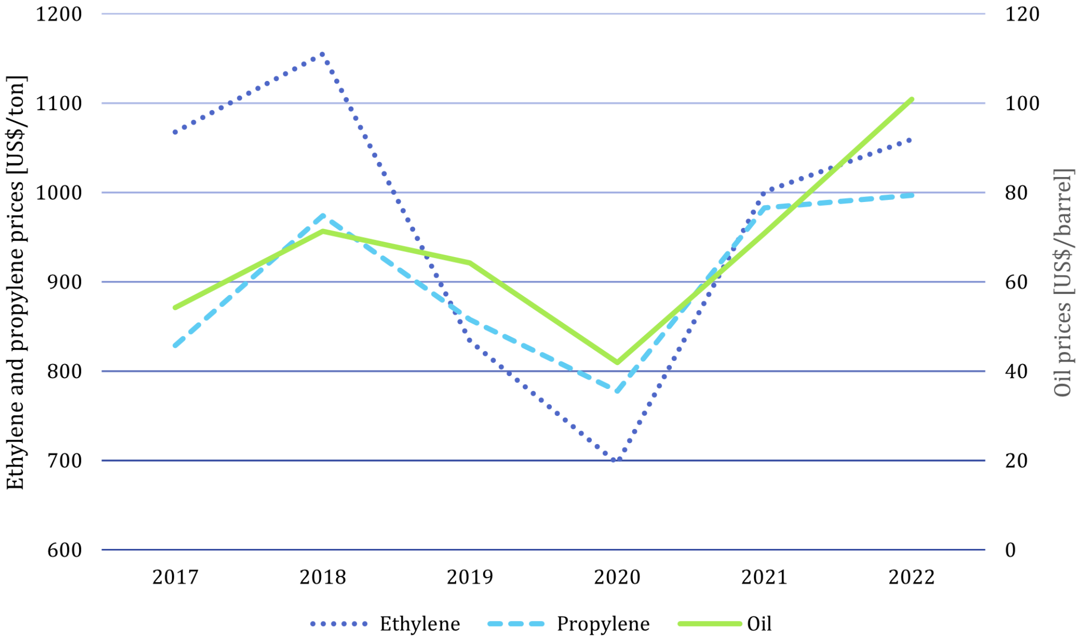


Figure 11: Historical prices of ethylene, propylene and oil, showing dependency. Source: Krungsri Research (2023), Krungsri Research (2022) and en2x (2024).

However, the impact price fluctuations would have on PIR remains unclear. In periods of cheap ethylene and propylene, there would be no financial incentive to buy PIR over virgin. Only environmentally-conscious manufacturers would remain loyal to PIR. Conversely, in periods of expensive ethylene and propylene, the production of virgin and PIR would slow down, and the production of PCR would increase. In summary, the impact of oil prices on the PIR market might be medium to low.

Technological Improvement

This driver explores the potential impacts technology improvements could have on the recycling market and its consequences for PIR. Currently, 99 percent of plastics recycled in the EU is done by mechanical recycling (Nikiema & Asiedu, 2022). However, this method yields a lower-quality product compared to its virgin counterpart, mainly due to polymer degradation, contamination, and an unclear mix of plastics in the recycling stream. Even in PIR, where some of these issues are mitigated due to more comprehensive knowledge of the feedstock, absence of contamination from the public sector and the shorter lifetime of the polymers, the outcome still results in a product of diminished quality. It is crucial to understand that although plastics generally have a long lifespan, they degrade over time due to factors like oxygen, ultraviolet light, and temperature, exacerbated by repeated reprocessing at high temperatures. Consequently, plastic cannot be mechanically recycled indefinitely. Present-day investments in recycling technologies primarily aim to boost recycling rates and the quality of PCR. Nevertheless, it is important to note that improvements in the realm of PCR will have a significant impact on PIR as well.

One of the technological advancements with the potential to significantly enhance the collection and recycling rates of plastic is improved mechanical sorting methods. Improvements in this area could lead to both a higher quality and better quality of PCR plastics. The increased quantity arises from the ability to separate a greater volume of plastic from the waste stream. The enhanced quality of PCR plastic would be a result of improved sorting methods, enabling better separation of various types of plastic waste.

Moreover, an up-and-coming technology is dissolution recycling, where plastic recyclables undergo a washing process with a solvent to eliminate contaminations, resulting in a substantial quality improvement (Gravgaard et al., 2024). Another emerging technology is chemical recycling methods like glycolysis, methanolysis and gasification. In these processes, plastic polymers are broken down into monomers that can serve as feedstock for the polymerisation of new plastic, with virgin-like qualities (Nikiema & Asiedu, 2022). While concerns have been raised about chemical recycling, including its high energy demand requirements and lower yield compared to mechanical recycling, it holds a unique capability to recover plastics that mechanical recycling cannot (Plastic Europe, 2024). This prevents incineration or landfill disposal, both of which are environmentally worse outcomes compared to chemical recycling (European Commission, 2023a).

Improved mechanical recycling and sorting methods would most likely lead to an increase in recyclates on the market, potentially reducing the demand for virgin plastics and subsequently affecting the volume of PIR produced. However, mechanical recycling cannot address all contamination and polymer degradation issues, there would still be a demand for virgin plastics in various sectors. The growing acceptance and trust in recycled plastics due to the increased share of the market might benefit PIR.

Dissolution would help address any contamination concerns about plastic waste. Even though the benefits would be for PCR, increased trust in recycled products still offers potential benefits for PIR, especially in scenarios where consumers may not fully know the difference between PIR and PCR.

Chemical recycling holds the most significant potential in transforming the plastic recycling market. With its ability to produce virgin-like quality, PCR could become a viable material for all industries, potentially minimising the need for virgin plastics. In a market with a majority of recyclates, PIR's environmental benefits may be up for debate, how will a product directly from virgin plastic production waste be compared to a product produced with PCW as a feedstock. Additionally, there could be debate surrounding the definition of what should be considered PIR, particularly about whether the material obtained from chemical recycling should be regarded as secondary raw material. Depending on the consensus this will greatly affect the amount of PIR available. In a scenario of high circularity in society, PIR's current advantage as an environmentally friendly product would diminish due to the abundance of recycled material on the market. Finding markets where PIR would have an increased value would therefore be impossible. PIR's profitability would then instead depend on whether it is cheaper to produce than PCR of similar quality.

If substantial technological improvements do not occur, and mechanical recycling continues as the predominant method in the EU, PIR would retain its advantage as a higher quality recyclate. Consequently, without notable enhancements to the recycling process, virgin plastic production would grow with increasing demand for plastic products. Although the increased production would yield more PIW for PIR production, the volume of PIR generated would remain negligible when compared to the overall plastic production. Therefore, PIR could never serve as a significant plastic source for any industry, necessitating the need to identify niche markets where its value can be fully realised.

The uncertainty regarding technological improvements lies not in whether they will occur but rather in the extent of their development and their economic viability. The increasing investment in new recycling technologies indicates a growing interest in improving recycling methods (Plastics Europe, 2024). Considering the many different technologies that could be adopted at different levels in the future and the difference in their capabilities, this driver holds a moderate level of uncertainty. Evaluating the potential impact of technological improvements on PIR, it is deemed to be very high, resulting in a high impact for this driver.

4.5.1 Scenario Building

The two drivers chosen for the scenario building were the price of ethylene and propylene and technological improvement. These were selected due to them both having a high impact and high uncertainty. The matrix produced from these two gave four distinct possible future scenarios.

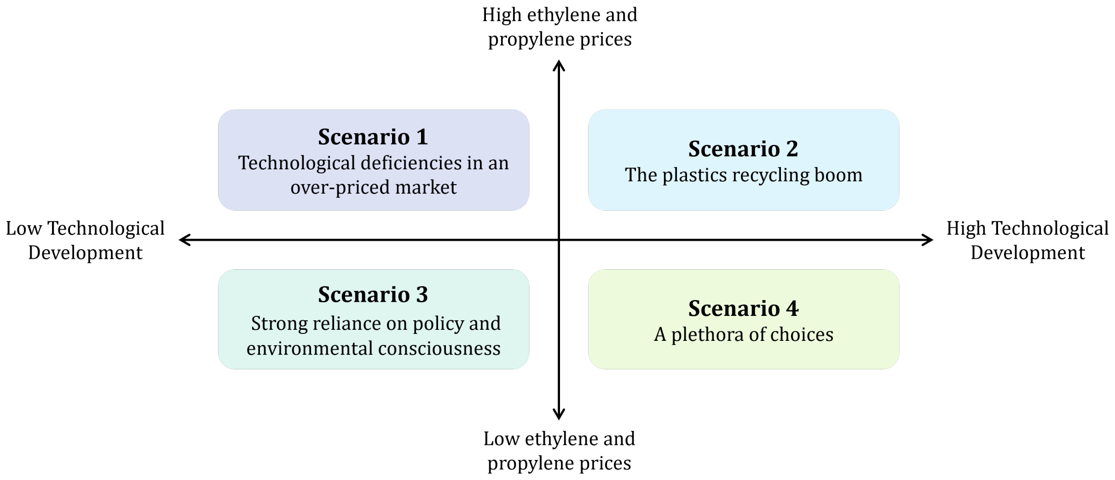


Figure 12: Four distinct scenarios constructed based on the chosen drivers, ethylene and propylene prices and technological development.

4.5.1.1 Technological Deficiencies in an Over-priced Market

More expensive feedstock for the virgin production of plastic would drive many industries to look towards recycling alternatives, leading to a reduction in the production of virgin plastics, and consequently, a decrease in the availability of PIR in the market. Assuming continued technological advancements in mechanical recycling and sorting, coupled with the increased cost of virgin feedstock, more plastic will be extracted from the waste stream. However, technologies such as dissolution and chemical recycling have yet to penetrate the market, making virgin plastic the only option in areas where high-quality plastics are required. Despite recycling becoming the optimal economical choice, the demand for high-quality plastic remains substantial, requiring continued reliance on fossil-based inputs.

The high prices of virgin plastic will cause the demand for recyclates to increase massively, aligning economic and environmental interests and diminishing the necessity for policy interventions to promote circularity in the plastic market. Schemes aimed at enhancing the recycling of high-quality plastics could become more popular, as companies look for cheaper ways to produce products with high-quality requirements. Nevertheless, the significant demand for lower-cost, high-quality recyclates would mean increased volumes would not affect the demand for PIR.

With the increased costs of virgin plastics, and therefore PIR, price would become a more important factor when buying products. Although the environmental aspect would remain relevant, most customers are likely to opt for lower-quality PCR whenever feasible, given the substantial price disparity. Consequently, the primary value of PIR would be its cost-effectiveness relative to virgin plastics, coupled with the added environmental benefits. Furthermore, the vast price differences and demand for recyclates would stimulate more investments in recycling technologies.

4.5.1.2 Strong Reliance on Policy and Environmental Consciousness

A cheap cost of virgin feedstock and minimal technological advancements in recycling technologies would create a landscape where virgin plastic is the most economically desirable option. While lower costs for producing virgin plastics may not directly impact the cost of producing PCR, exceptionally low raw material prices could render recyclates more expensive to produce than virgin plastics. In a scenario where the economically optimal choice is to purchase virgin plastics, their production would also be expected to increase, leading to a higher volume of PIR and continued reliance on fossil-based plastics.

The EU would still be committed to achieving its goal of moving towards a more circular market and its target to be carbon neutral by 2050. With the absence of strong economic incentives from the market, the survival of plastic recyclers would depend mainly on policies. The stringency of these requirements and the associated costs of non-compliance would play a crucial role in determining the size of the plastic recycling business. Additionally, the high cost of recycling would lead to minimal investments in new technologies, resulting in a low rate of innovation.

There would be an economic cost associated with the environmental benefits of choosing PCR recyclates, resulting in public environmental perception becoming another crucial factor for the success of the recycling market. However, since the cost of PIR is directly influenced by the price of virgin feedstock, PIR would be an economically competitive product, with its environmental benefits compared to virgin plastic serving as an additional value. The additional value of PIR would depend on how its environmental impacts are attributed, and the environmental consciousness of customers.

4.5.1.3 The Plastics Recycling Boom

In a scenario characterised by high ethylene and propylene prices and a technological landscape where chemical and/or dissolution recycling are economically viable options, all types of recyclates would emerge as preferable alternatives to virgin plastics. With high feedstock costs, the production of virgin plastics would become very expensive, subsequently driving up prices in the PO market. Consequently, manufacturers would naturally shift their focus towards recycled alternatives, which offer better pricing and environmental benefits without compromising on quality. This shift in demand would lead to a sharp decline in the utilisation of virgin plastics, prompting plastic manufacturers to scale back their production of virgin materials. As a result, the volume of PIR introduced into the market would decrease.

Within this landscape, the most sought-after recyclates in the PO plastic market would primarily consist of premium PCR, with standard PCR serving as a secondary option for applications requiring less stringent plastic properties. For cost-efficiency reasons, chemical recycling would be used to recycle highly contaminated plastics, while higher-quality post-consumer waste (PCW) streams and PIR would continue to be mechanically recycled. Premium PCR, derived from chemical recycling technologies, would stand out as a readily available and competitive option. Meanwhile, standard PCR, sourced from mechanical recycling processes, would still offer a cost-effective alternative to chemical recycling, with advancements in sorting technologies further enhancing the quality of these materials compared to contemporary PCR offerings.

In this scenario, Europe could witness a market-driven phase-out of fossil resources. Nevertheless, with the ongoing rise in demand for plastics, the necessity to introduce new plastic into society remains. This introduction could occur through either fossil-based plastic or alternative sources like bioplastics. Moreover, it is anticipated that such a societal shift would require minimal intervention from policymakers to adhere to and achieve circularity targets. Concurrently, the EU would persist in setting progressively ambitious targets.

Subsequently, the transition towards recyclates would not necessarily depend on environmentally conscious producers to fuel its momentum. However, amongst producers specifically seeking recycled materials, the environmental benefits of one recycled plastic over the other would be a significant factor. In this area, PIR could be at a disadvantage compared to the PCR alternatives depending on the allocation method used in LCA and on the energy requirements of chemical recycling.

4.5.1.4 A Plethora of Choices

This scenario bears resemblances to the *Plastics Recycling Boom* scenario. The low prices on raw materials for PO plastic production would drive down costs for virgin PO, potentially making it cheaper than recycling causing a market failure for recyclates. However, the availability of economically viable chemical recycling for PCR could significantly influence the market dynamics. Similar to the *Plastics Recycling Boom* scenario, PCR solutions derived from chemical recycling would offer higher-quality alternatives to mechanically recycled materials, potentially gaining traction in applications requiring stringent plastic properties.

Addressing the potential market imbalance caused by low feedstock prices would necessitate robust regulatory measures, such as stringent sanctions, taxes, or subsidies. Moreover, the environmental consciousness among producers would remain important, albeit to varying degrees depending on market conditions and regulatory pressures. Once again, the attractiveness of PIR on the plastics market would largely be defined by the environmental impact attributed to it and the acceptance of this assessment by government authorities.

4.6 Conclusions

The EU has identified plastic as a high-priority material, requiring higher recycling rates to achieve the targets set in the Green Deal. This is reflected in the EU's ambitious recycling targets: 65 percent of packaging waste and 55 percent of municipal waste by 2025. Additionally, the EU is promoting ecodesign and improving waste collection. Special attention has been given to packaging, with the PPWD introducing minimum recycled content requirements. Furthermore, EU waste shipping policies have greenlisted many non-halogenated polymers, such as PP and PE, facilitating cross-border shipment of these waste streams within the EU. Minimum recycling content requirements for the automotive industry are currently under development, with plans to establish similar policies for the construction sector.

Based on policy research and inputs from Borealis' Head of Sustainability Public Affairs, it was deemed that there is currently no EU-level regulation specifically addressing PIR. Despite calls by Plastics Europe to incorporate post-industrial materials into regulations like the PPWD, there is no indication of EU compliance. The fact that PIR has not suffered any market failures and has remained economically competitive without policy support is likely the primary reason it is not included in EU policies.

While there is hope that chemical and/or dissolution recycling technologies will significantly advance in the coming 10 to 20 years, their higher costs compared to mechanical recycling mean that mechanical methods will remain prevalent for both PIR and PCR. PIR is therefore expected to maintain a favourable market position in sectors that do not mandate virgin or specified PCR contents and where the lower costs and reduced environmental impact of PIR are valued. Consequently, there is no foreseeable scenario in which a market failure for PIR material occurs, eliminating the necessity for policymakers to regulate this market.

The environmental benefits of PIR are an important factor when determining its future value. The possibility of selling PIR in the future as a cheap product may not be dependent on any environmental aspects, however, if Borealis wants to be able to sell it at a premium the environmental aspect is crucial. Since PIR is of lower quality than virgin plastics the potential economic value of PIR relies heavily on its environmental benefits. With the absence of policy support, the allocation of environmental impacts on PIR will have a great effect on its value to the market.

5

Market Analysis

Identifying markets where the environmental benefits of PIR are highly valued is imperative for maximising its value proposition, benefiting both Borealis and the environment while appealing to conscientious businesses and consumers. Therefore, it is essential to target markets where the environmental performance is appreciated by the manufacturer and end consumer. This leaves out industries like building and construction, as they are not directly connected to the end consumer.

Given the limited supply of PIR, finding markets and producers close to the recycling plant is vital to maximise economic and environmental benefits. Borealis' recycling plants in Germany and Austria spotlight Germany as an interesting market due to its importance in Europe, and thus, its potential as a marketplace for PIR. This market analysis takes two approaches to identify markets where PIR would succeed in the long run: by examining the generational shopping trends and assessing the emerging market for recyclates in automotive applications.

5.1 A Generational Analysis

Exploring the generational differences in sustainable product preferences poses an interesting avenue for Borealis' strategic considerations. Should the company prioritise securing customers targeting the younger demographic, or is the variance in sustainability consciousness inconsequential?

Market research has shown that younger demographics, namely millennials born between 1980 and 1996 and Gen Z born between 1997 and 2012, have a higher consideration for a product's ecological footprint (Lühmann, M., 2023; Packaging Europe, 2022; NielsenIQ, 2018, 2022). This makes the two young generations a clear target for marketing products with added environmental value. Although Gen Z presently constitutes a relatively small segment, accounting for approximately 5 percent of total spending in the U.S. in 2023, projections indicate a substantial surge to 17 percent by 2030 as more individuals from this generation enter the workforce (EcoCart, 2023). Notably, Gen Z's spending habits reveal that they spend most of their money on fashion, makeup and beauty products, technology and pets.

Moreover, a market analysis from 2020 in the U.S., as depicted in Figure 13, highlights clear differences in shopping preferences between millennials and Gen Z compared to older generations. Despite this variance, all generations have a relatively high consideration for sustainable brands. Corroborating this, a study by GfK (2023b) found that 60 percent of global consumers expressed a willingness to pay a 10 percent premium for items such as clothing, refrigerators, vehicles, and smartphones if they were proven to be more environmentally friendly. This underscores that while younger demographics may prioritise environmental considerations in their purchasing decisions, sustainability resonates across age groups, demonstrating the value of eco-friendly products in modern society.

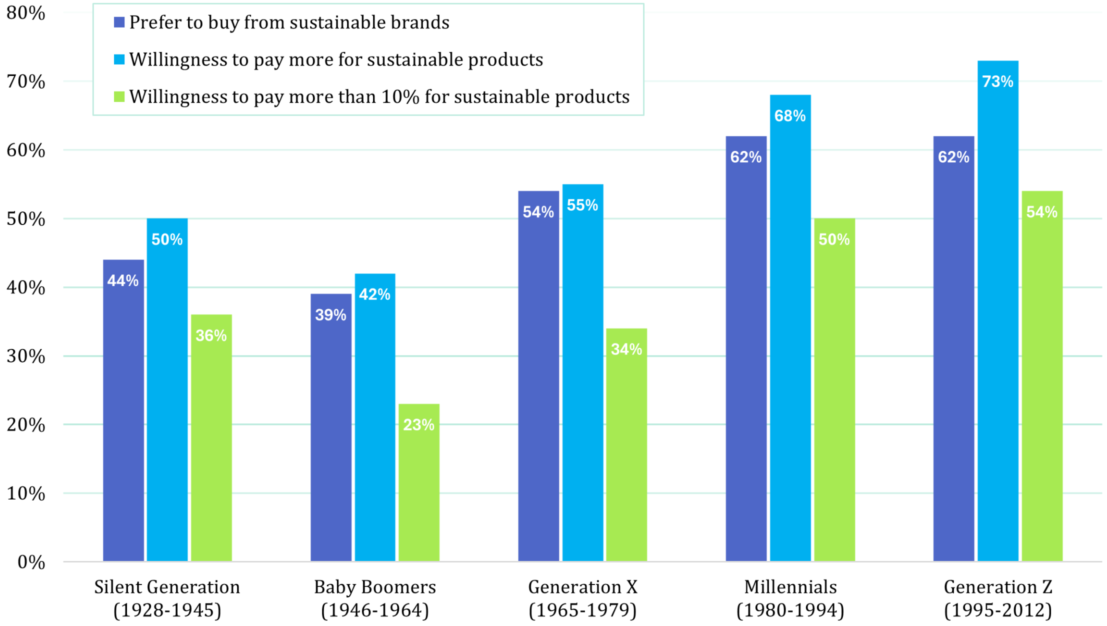


Figure 13: Survey results of a U.S. consumer study on sustainable shopping practices with over 1000 participants. Source: First Insight (2020).

Although Figure 13 suggest that consumers are prepared to pay more for a more sustainable product, it is generally unnecessary to raise the price of a product when substituting virgin plastic with recyclate. As noted by Nordin et al. (2019), the price of recycled plastic can fluctuate widely, ranging from up to 90 percent of the price of virgin material to potentially dipping into negative territory. This observation is supported by recent data, as depicted in Figure 14, which illustrates that the average prices of most PO recyclates remain lower than that of virgin plastic. The exception to the trend is the natural PCR, which refers to recycled plastic of transparent or translucent colour. In the case of natural PP PCR, its prices have exceeded those of virgin PP copolymer by 20 percent, whereas natural low-density polyethylene (LDPE) PCR and virgin LDPE exhibit nearly identical prices. This underscores the high value placed on premium recyclate due to its environmental benefits, quality and limited supply. However, it also demonstrates that the use of other types of recyclates typically results in cost savings. Therefore, incorporating recyclates into a product should, in many cases, not result in an increase in the final product price.

Analysing the German market landscape shows a similar pattern to the U.S., with

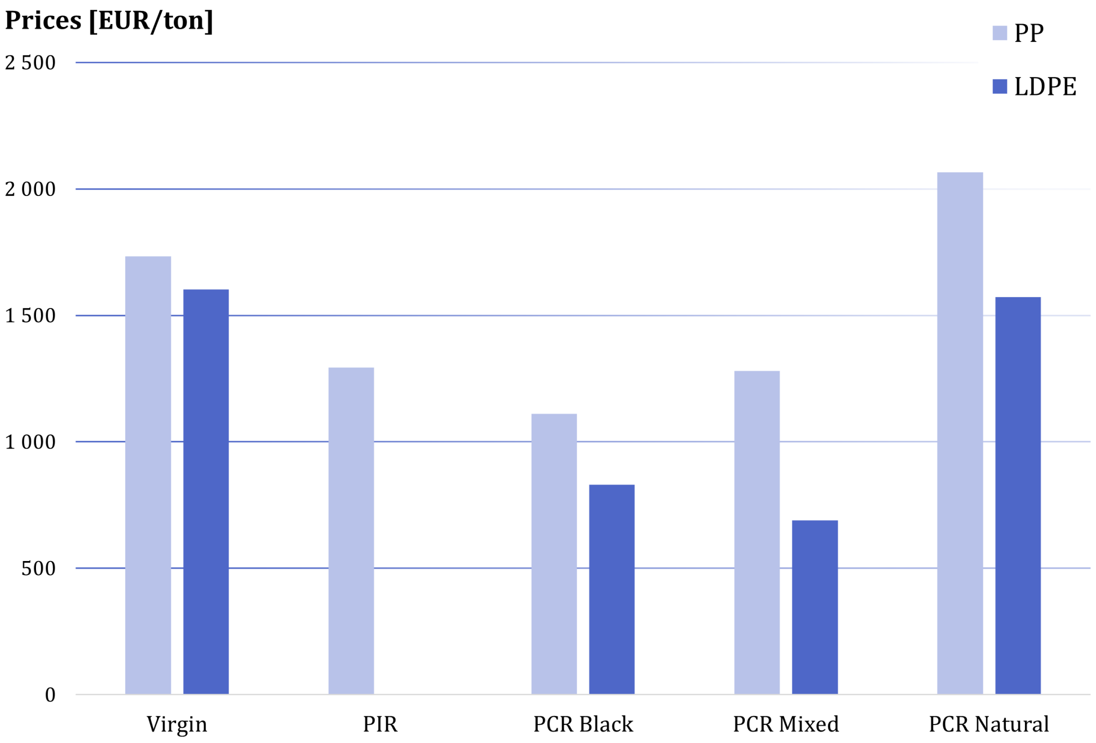
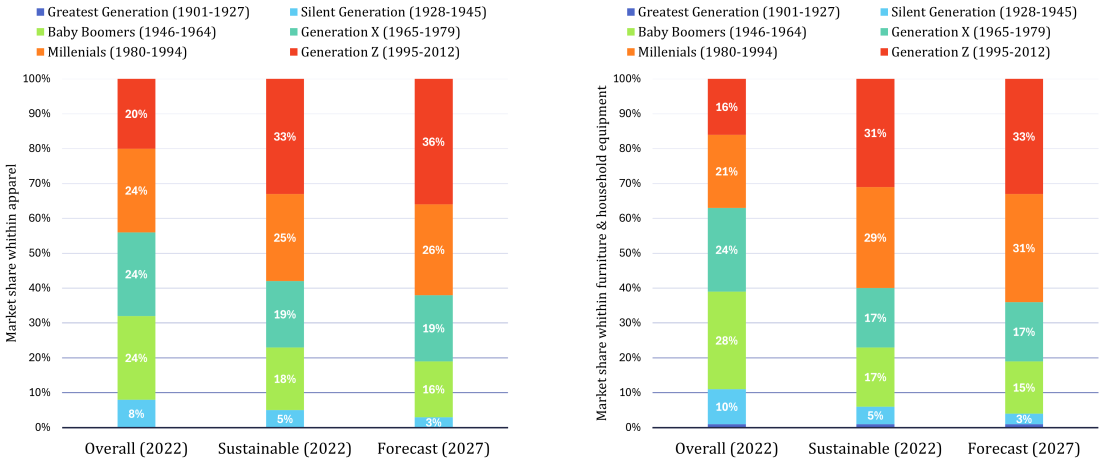


Figure 14: Average prices of virgin and recycled PP and LDPE during the period May 2021 to December 2023. Data for virgin PP is for PP copolymer, which is consistently higher priced than PP homopolymer. Data for post-industrial LDPE was not available. Source: Independent Commodities Intelligence Services (ICIS) (2024).

millennials and Gen Z commanding a larger share of sustainable product consumption compared to the overall market (Lühmann, M., 2023). As illustrated in Figure 15, projections for 2027 indicate a further amplification of this trend, signalling an increased consumer demand for sustainable products in both markets. However, it is important to note that survey studies may yield contrasting views regarding Gen Z's attitude toward sustainable behaviour. For instance, a study by Kirsch (2023) suggests that only 11 percent of Gen Z intend to actively reduce their carbon footprint, indicating that sustainable consumption might not be a top priority for this demographic. Despite this discrepancy, the majority of studies align with the global trend that millennials and Gen Z value sustainable products (Lühmann, M., 2023; Packaging Europe, 2022; NielsenIQ, 2018, 2022).

Furthermore, market research conducted by GfK (2023a) underscores that a significant majority of Germans express willingness to pay a premium for sustainable options across major (70%) and everyday (64%) purchases, showing a pervasive inclination toward environmentally conscious consumption. Thus, despite uncertainties surrounding Gen Z's stance on sustainability, the overall German market exhibits a prevailing preference for products with a low environmental impact. Therefore, it may be prudent to explore applications for PIR in products classified as "major purchases", beyond focusing solely on markets targeted at younger demographics.



(a) Generational market share within the apparel sector in Germany.

(b) Generational market share within the furniture and household equipment sector in Germany.

Figure 15: Market share of different generations over two markets in Germany. The chosen markets are deemed to be relevant to understanding the shift towards sustainable material choices like plastics. Source: Lühmann, M. (2023).

Even though Germans are generally inclined to pay more for sustainable products, it is important to keep in mind that this willingness to pay may not extend to plastic recyclates. This is primarily due to the perception that items made from recycled plastics may be of inferior quality, thereby not justifying a higher price point. Research on sustainable goods indicates that consumer willingness to pay more is often influenced by labels such as "natural," "biological," or "organic," which suggest higher quality and health benefits (Schuitema & De Groot, 2015; Janssen & Hamm, 2012; Ghazali et al., 2017; Aschemann-Witzel & Zielke, 2017). For instance, a study of hoodies made from recycled material revealed similar results, where consumers were unwilling to pay more, and most wanted a discounted price (Pretner et al., 2021). Although hoodies and plastic are very different products, they both suffer from the perception of inferior quality compared to their virgin counterparts. Therefore, it is not unreasonable to assume a similar attitude towards products made from PIR.

Additionally, it is important to consider that hoodies represent minor purchases, whereas plastic is a component of major and minor purchases, giving the latter a distinct advantage. Although the hoodie study was conducted in the U.S. and Italy, suggesting potential variances in results for Germany, findings from GfK indicate that Germany and Italy share a similar willingness to pay more for environmentally beneficial major purchases, which would indicate minor discrepancies (Süptitz, 2023). This underscores the complexity surrounding willingness-to-pay data, particularly when the sole sustainable benefit of a product is its environmental impact.

In summary, market research indicates that age, perceived quality, and the significance of the purchase — whether major or minor — affect the willingness to pay for environmental benefits. Targeting producers in sectors where Gen Z and millennials predominantly spend their money is strategic; this approach will be effective both presently and in the future, as their disposable income grows and more individuals from these demographics enter the workforce. Additionally, integrating PIR into products where the perceived quality does not primarily come from the plastic used can be advantageous, e.g., in headphones which are mainly judged by the sound quality rather than the casing. However, it is vital to acknowledge that a product's outer appearance is very important, making PIR more suitable for non-visible parts in products with a longer lifetime. Lastly, there is a discrepancy in the willingness to prioritise sustainability depending on the type of purchase. The data clearly shows that sustainability considerations are lower for minor and more frequent purchases. Therefore, identifying products that encompass multiple factors will maximise the chance of finding successful markets.

The first markets considered were fashion, make-up and beauty, technology, and pets, i.e., where Gen Z spends most of their disposable income. Among these, fashion was deemed an inappropriate market due to the lack of need for PIR plastic material. The other three, however, were found to have the potential to include products that could benefit from PIR. Additionally, furniture and household equipment emerged as an interesting market, with younger generations making the majority of sustainable purchases, according to the study displayed in Table 15. Since most furniture and household equipment purchases are major, it presents potential for PIR. While material durability and resistance to daily wear and tear are less crucial in technology-related products, which typically have shorter lifespans (except for televisions, but which are typically immobile and suffer from little wear and tear) (Magnier & Mugge, 2022), end-users still prioritise aesthetics for their durable household appliances. Therefore, it is advisable to use PIR in non-visible components to maintain product appeal while benefiting from its environmental advantages.

The potential markets identified and examples of products are included in Table 6.

Table 6: Markets of interest according to the conducted generational and demographic market research trends.

Potential markets	PIR interest	Example products
Make-up & Beauty	Yes. However, consumer sustainability focuses on non-plastic products.	Casings, make-up packaging, brushes, containers.
Technology	Yes, quality perception lies in technical components.	Phone cases, buttons, components, earbuds, earphones, protection casings.
Pets	Yes	Toys, feeding bowls, necklaces, baskets.
Furniture	Yes, better suited for stationery products.	Lamps, hangers, shelves.
Household equipment	Yes, especially in non-visible parts.	Kitchenware, white goods, air conditioners.

5.2 Emerging markets: Recycled Plastics in Automotive

Historically, recycled plastic has mostly found its application in low-value end-products. Post-consumer LDPE recyclate typically serves in plastic film, bags, and packaging, while the more rigid high-density polyethylene (HDPE) and PP recyclates are used for items such as bins, gardening articles, pallets, containers, and packaging. In essence, recyclate has largely been favoured in products where aesthetics take a backseat.

However, today companies are introducing recycled plastic into products with higher requirements. Notably, several German car manufacturers have already incorporated recycled plastic into various vehicle components. BMW, for instance, currently uses up to 20 percent recycled plastic parts in its vehicles, with plans to exceed 40 percent by 2030 (BMW, 2024). Similarly, Mercedes-Benz features components crafted from 60 percent recycled plastic in models like the EQS, while Audi's Q4 e-tron boasts 27 components fashioned from recyclates (Mercedes-Benz Group, 2024b; Audi, 2022). Even luxury brands like Porsche are looking at the utilisation of recycled plastics in upcoming all-electric vehicle projects starting production after 2026 (Porsche, 2023).

Nevertheless, the biggest challenge is finding sufficient volumes of recycled plastic of the right quality according to companies wishing to use recycled plastic (Nordin et al., 2019). In the automotive sector, stringent material criteria are imperative to meet safety standards, encompassing crash resilience, heat resistance, and consistent qualitative attributes such as texture, appearance, and odour throughout the vehicle's lifespan (Audi, 2022). Assuming that the entirety of Borealis' annual PIR production, approximately 5 000 tons, meets these rigorous quality conditions, a significant opportunity emerges. For instance, considering that approximately 78.3 kilograms of a Mercedes-Benz EQS can be derived from recycled plastic (Mercedes-Benz Group, 2024b), Borealis hypothetically possesses the capacity to supply Mercedes-Benz Sindelfingen with enough plastic to manufacture well over 63 000 EQS cars. To put this into perspective, the Sindelfingen plant's current annual production spans 222 000 cars across six models as of 2023 data (Mercedes-Benz Group, 2024a). This calculation underscores the potential scale of impact that Borealis could have in supplying recycled plastic for high-quality automotive applications, given the appropriate quality assurances.

However, it is crucial to note that the EU is in the process of developing legislative minimum recycled content requirements in the automotive sector (European Commission, 2023b). The current integration of recyclates in the German automotive industry may be a preliminary measure to ensure compliance with these targets once the policy is enacted. Moreover, similar to packaging regulation these requirements will exclusively apply to recyclates derived from post-consumer waste (European Commission, 2023b). Given that PIR will not contribute to meeting the minimum requirements, there is a concern that automotive manufacturers might opt to utilise only PCR and virgin material to maximise component quality or streamline production processes.

5.3 Conclusions

Navigating towards a market that fully appreciates the benefits of PIR remains a great challenge, with no definitive answer regarding where Borealis should distribute its PIR products. However, prioritising local producers is crucial for maximising the value of PIR. Not only does it reduce transportation costs but it also minimises the environmental footprint of PIR, a significant selling point given its inherent lower environmental impact. Moreover, emerging trends suggest that the younger demographic will constitute a pivotal consumer base for sustainable products.

With Gen Z allocating a substantial portion of their expenditures to cosmetics, technology, and pet-related markets (EcoCart, 2023), the recommendation from this analysis is to investigate whether companies in these sectors are inclined towards sustainability initiatives. Furthermore, market research underscores Germany's overarching environmental consciousness, suggesting that focusing solely on specific age groups may be unnecessary. Notably, Germans are inclined to consider environmental impacts and are willing to pay more for sustainable products when making major purchases. This suggests that PIR would yield significant value when integrated into products intended for long-term use, such as furniture and household equipment.

Furthermore, integrating PIR into higher-value products such as automotive components could be a potential way to fully capitalise on PIR's higher quality compared to most other recyclates. However, challenges persist in ensuring the availability of PIR of the required quality and quality. Borealis, with an annual production of approximately 5 kilotons of PIR, faces fluctuations in output, with around 3 to 4 kilotons produced in 2022 (S. Kahlen, personal communication, January 31, 2024). This variability can pose problems for automotive manufacturers reliant on consistent plastic supply. Moreover, despite Borealis' potential to supply significant volumes for automotive applications, impending EU regulations mandating minimum recycled content pose concerns for PIR's future viability in this market.

6

Life Cycle Assessment

In this chapter, the results of the LCA are presented and discussed. This includes LCI and LCIA results, followed by an interpretation of the findings and recommendations for Borealis. The goal and scope of the study are defined in the methodology chapter, Section 3.3.

6.1 Life Cycle Inventory

In this section, the data utilised in the LCA is presented, along with details regarding its source and relevance to the study. The data has been categorised into five sections: allocation of PIW, composition of PIW, transportation, the recycling process and incineration of process waste, which are presented in this order. Additionally, a detailed flowchart of the technical system, including the virgin PP production processes where PIW is generated, is illustrated in Figure 16.

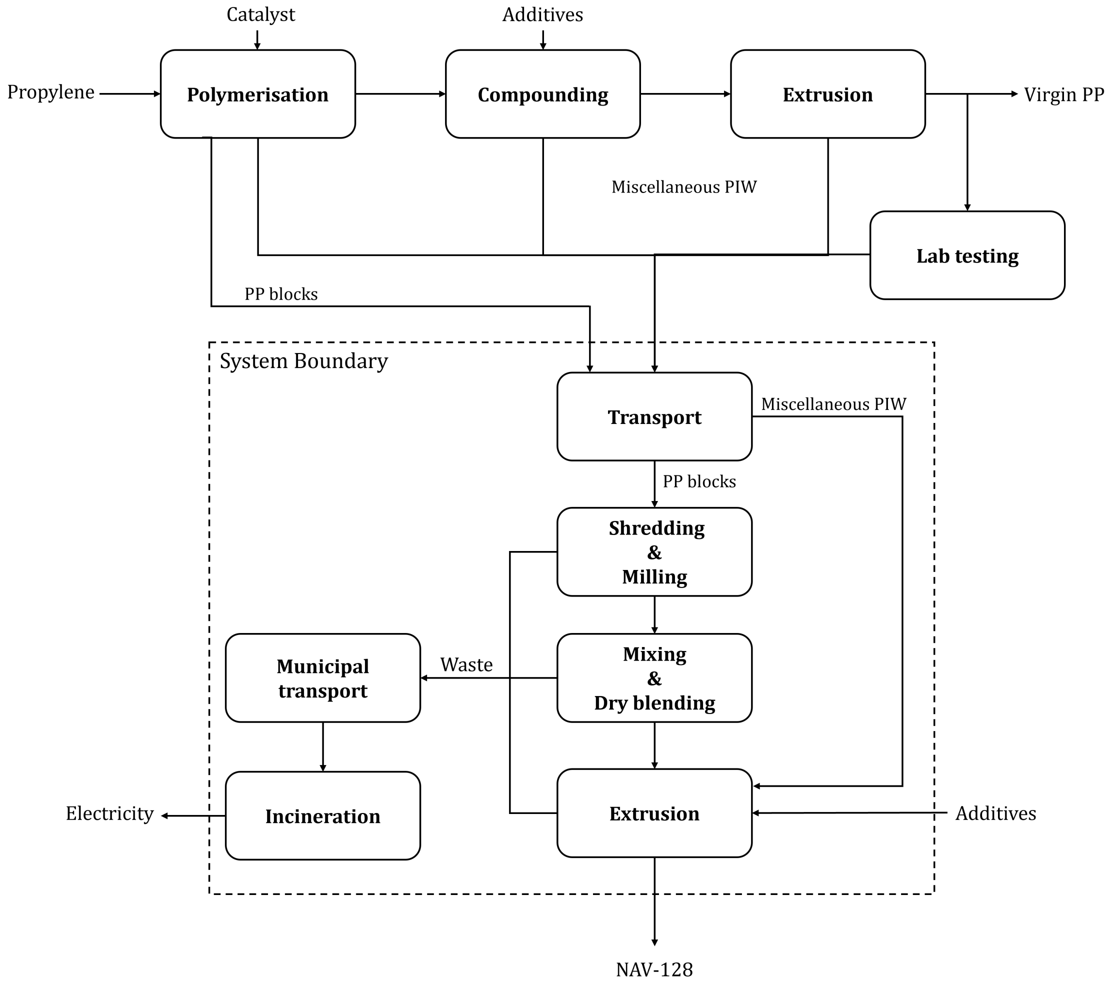


Figure 16: Flowchart of the technical system in which NAV-128 is produced, including background information on the virgin PP production process.

6.1.1 Allocation of PIW

The allocation data is sourced from Borealis. The mass of PIW is based on the annual amount of PIW processed at mtm plastics. Furthermore, the price used for the PIW allocation is derived from the average cost of PIW feedstock utilised at mtm for NAV-128 production in 2023.

As for virgin PP, its production mass is based on the quantity of PP homopolymer sold from the Burghausen plant during 2023. Subsequently, the price used for virgin PP is derived from the product HJ335MO, as recommended by Borealis, due to its structural and application similarities to NAV-128. While the exact values of the parameters used in the calculation of the mass and economic allocation factors cannot be disclosed, it is noted that the quantity of virgin PP produced is 184 times higher than the quantity of PIW, and the market value of virgin PP is about 5 times higher than that of PIW. Thus, the allocation factors below were calculated.

$$F_{mass} = 0.54\% \tag{3}$$

$$F_{eco} = 0.11\% \tag{4}$$

Additionally, characterised LCIA results for virgin PP were provided by Borealis. This data shows the average impact of all PP virgin products produced at Burghausen, sourced from a study conducted in 2022. These values served as a basis for allocating environmental burdens to the PIW. More information about this study is available in Appendix D, along with the impact data for virgin PP in Table 13.

6.1.2 Composition of PIW

The data regarding the PIW composition is an estimate provided by product managers at Borealis during interviews. This information pertains specifically to the waste generated at the Burghuasen plant in Germany, from where it is subsequently sent to mtm for recycling. The data acquired from these interviews can be found in Table 7.

Table 7: The composition and content of PIW form Burghausen.

Input	Quantity	Description
PP block	80%	Goes through shredding, milling, mixing and dry blending before extrusion.
Miscellaneous PIW	20%	Contaminated pellets, floor sweep, lab waste. Goes directly to extrusion.

6.1.3 Transport

The data regarding the transport of PIW from Burghausen to mtm was provided by Borealis product managers. For transporting miscellaneous PIW, tarpaulin trucks with a loading area of 12.60 x 2.40 m and a lateral loading height of 2.60 m are used. The PP blocks are transported separately in dump trucks. The travel distance between Burghausen and mtm was determined by looking at possible routes on Google Maps. The provided information is found in Table 8.

Table 8: Transport data for the PIW.

Parameter	**Data**
Distance Burghausen - mtm	570 km
Tarpaulin truck maximum capacity	24 tons
Dump truck maximum capacity	15 – 20 tons

The emission data for the transport was taken from ecoinvent, with the flow chosen for the transport of both PP blocks and miscellaneous materials being *"transport, freight, lorry >32 metric ton, EURO6"*. The provider chosen was *"transport, freight, lorry >32 metric ton, EURO6 | transport, freight, lorry >32 metric ton, EURO6 | Cutoff, U - RER"*, indicating that the data is representative of Europe (RER). The reason for choosing such >32-ton trucks is that smaller trucks than that have the capacity to freight an average of 5.79 tons, whereas >32 ton can transport an average of 15.96 tons (ecoinvent, nd), which is more accurate to the amount transported in this system.

6.1.4 The Recycling Process

The production process of PIW at mtm was provided through interviews with Borealis product managers. The recycling process of PP blocks includes shredding and milling, mixing and dry blending, and extrusion, while pellets and powder go directly to the extrusion step. Additionally, the interview provided an estimate of the proportion of PIW that is transformed into PIR and the amount of material lost during the process. It was assumed that an equal share of the material lost to waste incineration occurred in each of the three production steps. The data used in the LCA is found in Table 9.

Table 9: Outputs from the mtm recycling plant.

Output	**Quantity**	**Description**
NAV-128	95%	Desired product.
Lost material	2%	Material that is stuck or lost in machines and starting material which is reused.
Waste to incineration	3%	Incinerated outside of mtm plant.

The energy requirements for each step in the process were provided by Borealis. This data is specific for handling post-industrial materials at the mtm plant. Table 10 provides the energy requirements for each process, derived from the average energy consumption from 2019 to 2021 in each production step.

Table 10: [Pseudonymised data] Energy consumption in the PIR production process. The site-specific data is expressed in kilowatt hour per ton extrudate.

Process	**Energy requirement**	**Unit**
Shredding & Milling	64.3	kWh/t extrudate
Mixing & Dry blending	106.5	kWh/t extrudate
Extrusion	745.9	kWh/t extrudate

The mtm plant sources all its energy from the German national electricity grid. Data from ecoinvent version 3.10 on Germany's electricity mix is used to calculate the emissions from mtm's electricity consumption. The specific flow chosen in ecoinvent is *"electricity, medium voltage"*, with the provider *"market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - DE"*. This dataset reflects Germany's electricity mix data from 2020, which featured a larger share of nuclear energy compared to 2023, as illustrated in Figure 17. The reduction in nuclear energy has been offset by increased contributions from solar photovoltaic, wind, and coal power sources.

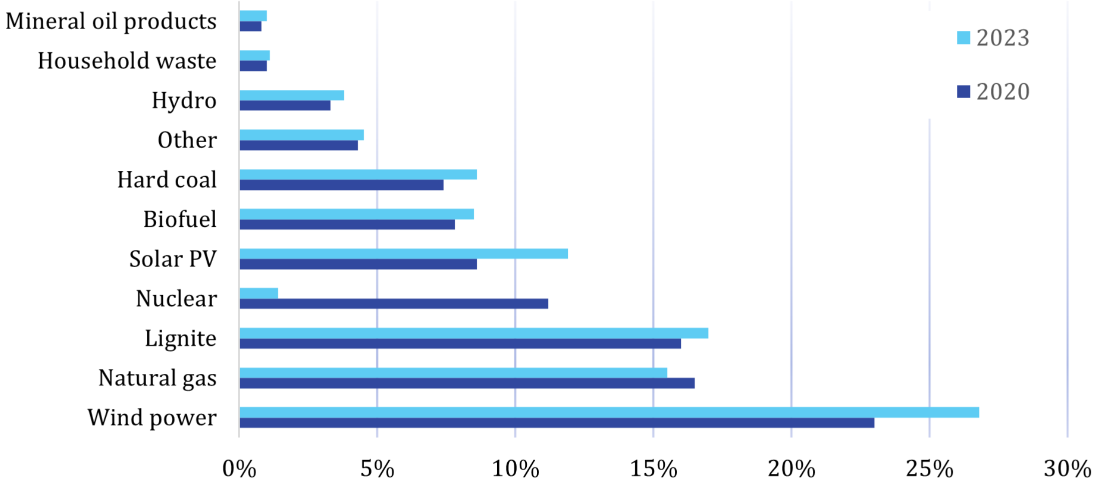


Figure 17: German electricity mix composition in 2020 versus 2023 (Arbeitsgemeinschaft Energiebilanzen (AGEB), 2023).

The additive mixture incorporated into the PIW during extrusion consists of four additives constituting 28 percent of the mixture, with the remaining 72 percent being carrier material, which is PIW itself. This mixture is introduced to the plastic at a ratio of 1 percent of the total mass input. However, the specifics regarding what additives are used and the exact formulation of the mixture are confidential. Emission data for the additives was taken from ecoinvent 3.10.

6.1.5 Incineration of Process Waste

The waste generated at mtm is incinerated at a municipal waste treatment plant. This process involves transporting the waste from mtm to the municipal facility and subsequently incinerating the PP plastic waste. To determine the distance between mtm and the waste incineration plant, Google Maps was used, and three waste facilities were identified, located 70, 80 and 82 km away from mtm. A conservative estimate of 90 km was chosen as the distance between mtm and the incineration plant.

The emission data related to waste transportation was sourced from ecoinvent. The flow *"municipal waste collection service by 21 metric ton lorry"* and the provider *"municipal waste collection service by 21 metric ton lorry | municipal waste collection service by 21 metric ton lorry | Cutoff, U - CH"* were selected from the database. Consequently, the data is representative of Switzerland (CH), which is assumed to be a better estimation for its neighbouring country, Germany, than opting for the global (GLO) or rest-of-the-world (RoW) datasets.

The incineration of PP plastic waste at the municipal waste treatment centre was also taken from the ecoinvent database. The flow chosen was *"waste polypropylene"* from the provider *"treatment of waste polypropylene, municipal incineration FAE | waste polypropylene | Cutoff, U - CH"*.

6.2 Life Cycle Impact Assessment

The results from the life cycle modelling are presented throughout Figures 18 to 25, where the environmental impact of NAV-128 for the different allocation cases is shown next to that of virgin PP from Burghausen. A detailed breakdown of the underlying data used to construct the figures can be found in Tables 14 and 15 available in Appendix E.

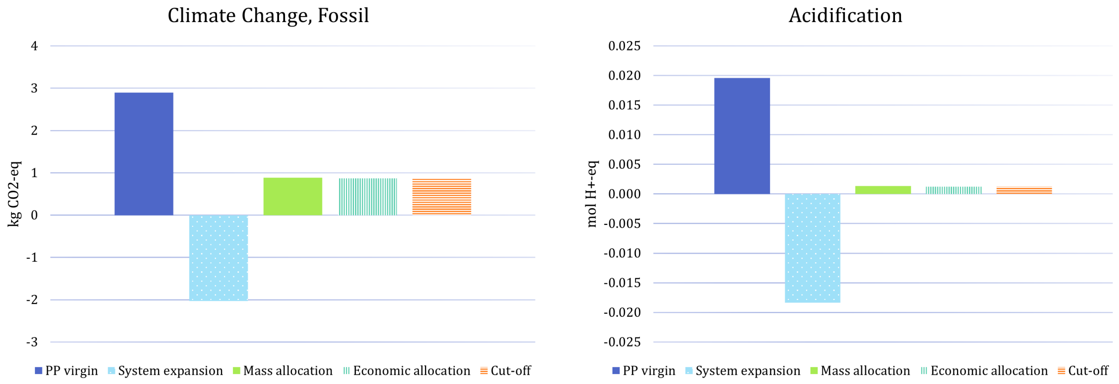


Figure 18: [Pseudonymised data] Impact of NAV-128 on climate change from fossil fuel use and acidification across four allocation cases, compared to impacts from virgin PP.

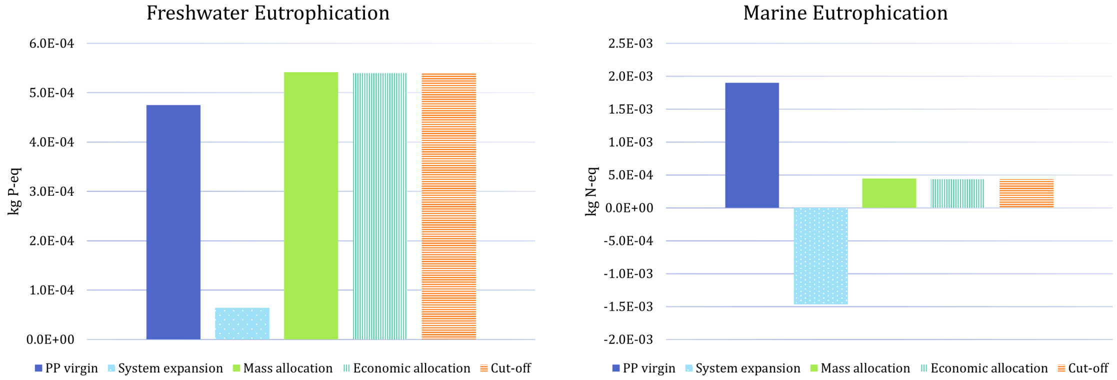


Figure 19: [Pseudonymised data] Impact of NAV-128 on freshwater and marine eutrophication across four allocation cases, compared to impacts from virgin PP.

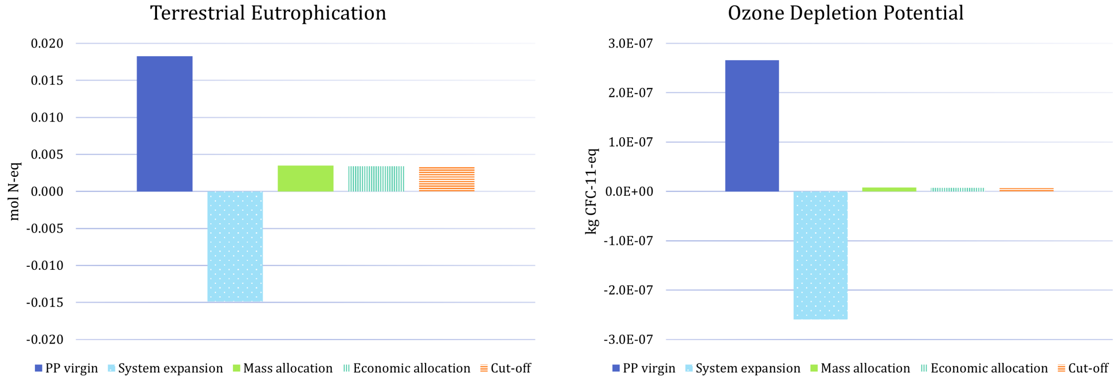


Figure 20: [Pseudonymised data] Impact of NAV-128 on terrestrial eutrophication and ozone depletion across four allocation cases, compared to impacts from virgin PP.

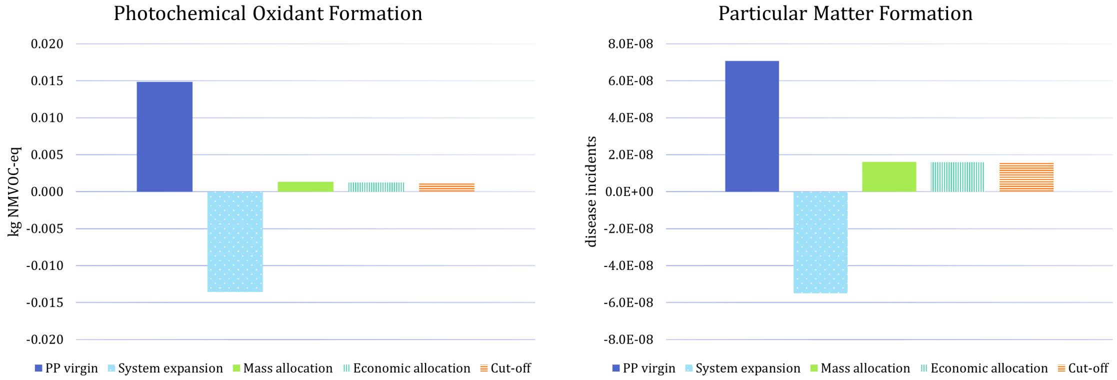


Figure 21: [Pseudonymised data] Impact of NAV-128 on photochemical oxidant and particulate matter formation across four allocation cases, compared to impacts from virgin PP.

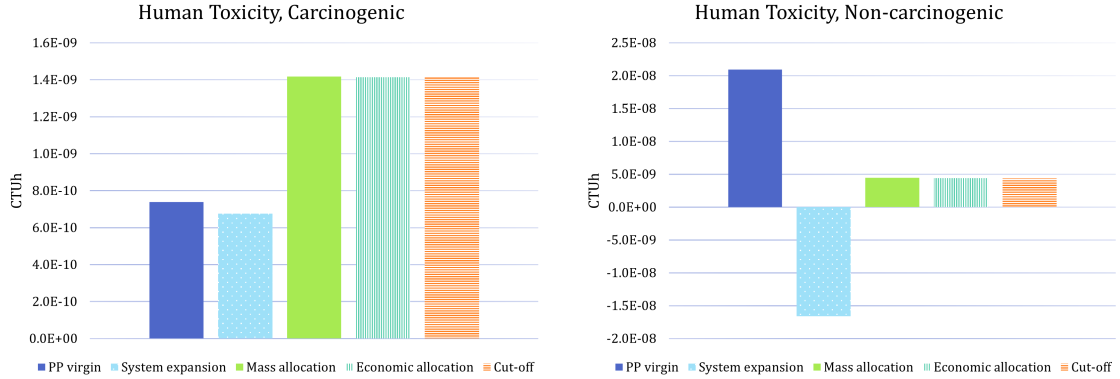


Figure 22: [Pseudonymised data] Impact of NAV-128 on human toxicity across four allocation cases, compared to impacts from virgin PP.

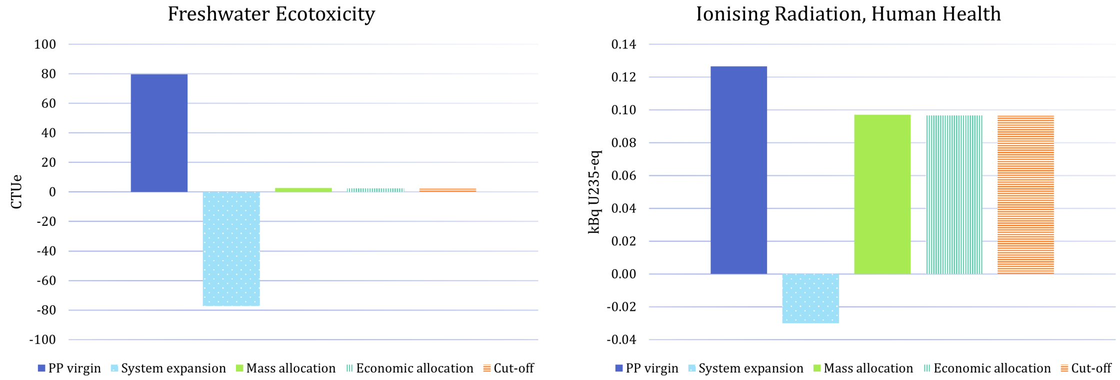


Figure 23: [Pseudonymised data] Impact of NAV-128 on freshwater ecotoxicity and ionising radiation across four allocation cases, compared to impacts from virgin PP.

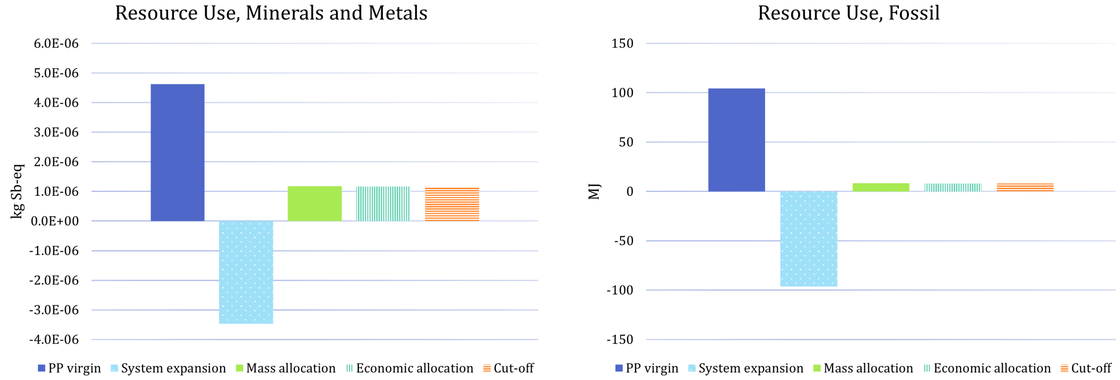


Figure 24: [Pseudonymised data] Impact of NAV-128 on abiotic depletion across four allocation cases, compared to impacts from virgin PP.

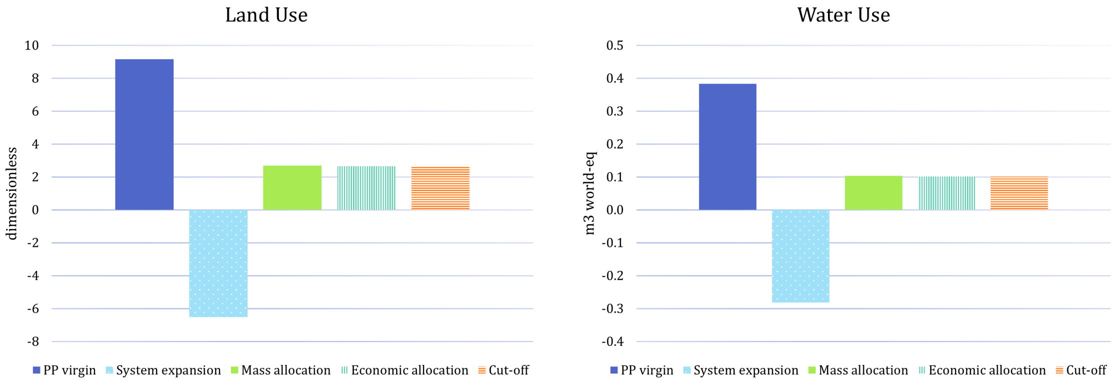


Figure 25: [Pseudonymised data] Impact of NAV-128 on land use and water use across four allocation cases, compared to impacts from virgin PP.

The impact assessment results reveal that the impacts using mass allocation, economic allocation, and the cut-off approach are nearly identical across all analysed categories. On average, the impacts obtained using mass allocation are 5 percent higher than those obtained using the cut-off approach, while economic allocation yields impacts only 1 percent higher compared to the cut-off approach. PIR exhibits a higher impact than virgin PP in only two out of the sixteen analysed impact categories, namely freshwater eutrophication and carcinogenic human toxicity. Aside from that, PIR consistently demonstrates noticeably lower environmental impact across the board, ranging from a 24 percent reduction in impact for ionising radiation to as low as a 97 percent reduction in impact for freshwater ecotoxicity or ozone depletion while using the cut-off approach, mass or economic allocation.

When employing system expansion, PIR exhibits lower environmental impacts than virgin PP without exception. These reductions span from a 9 percent decrease in impact for carcinogenic human toxicity to as much as a 197 percent decrease for freshwater ecotoxicity or ozone depletion. In cases where the environmental impact of virgin PP exceeds that of PIR, system expansion results in negative environmental burdens, or credits.

6.2.1 Contribution Analysis

In this section, the LCIA results delineate the impacts of various processing steps on each impact category, spanning extrusion, additives, mixing & dry blending, shredding & milling, transport, and incineration. The data presented is from the PIR production process and excludes any impact attributed to the PIW from the virgin PP production, although it would not be visible on the bar charts. Essentially, the charts reflect the impact contribution in a scenario where the cut-off approach is employed. The data is depicted as a percentage of the total impact within each impact category and can be found in Figure 26 and 27. Additionally, Figure 28 provides a detailed breakdown of the contribution each electricity generation process has for each impact category. Tables with detailed contribution results can be found in Appendix F.

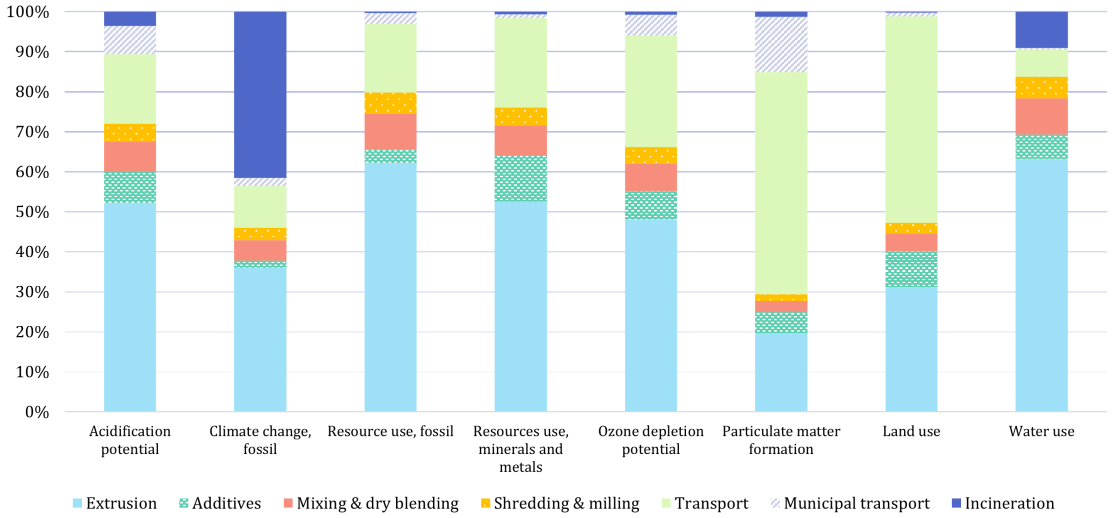


Figure 26: Contribution of each process to the different impact categories in the cut-off case.

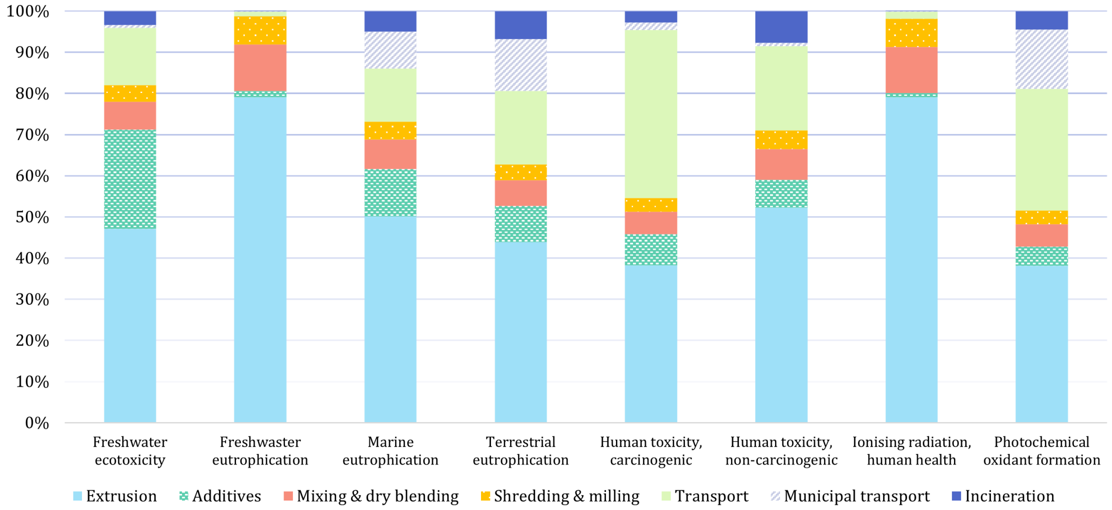


Figure 27: Contribution of each process to the different impact categories in the cut-off case.

Extrusion emerges as the biggest contributor in most impact categories, owing to its high energy demand compared to mixing & dry blending and shredding & milling. This disparity in energy requirements consistently leads to extrusion exerting a greater environmental impact than the other two processes. Similarly, given that mixing & drying necessitates more energy than shredding & milling, it consistently holds the larger impact between the two, as depicted in both Figure 26 and 27. Consequently, in instances where the impact of extrusion diminishes, either transport or incineration assumes a significant share of the impacts, as observed in the case of climate change, as depicted in Figure 26.

All three production steps rely on electricity from the German grid, resulting in a similar environmental impact. Extrusion dominates in freshwater eutrophication and ionising radiation, accounting for 80 percent in both. Similarly, mixing & dry blending and shredding & milling had their largest contribution share to freshwater eutrophication and ionising radiation, with each process contributing 11 and 7 percent respectively to both impacts. Additionally, all three production processes share a common impact where they contribute the least, which is particulate matter formation, with extrusion contributing 20 percent, mixing & dry blending 3 percent, and shredding & milling 2 percent.

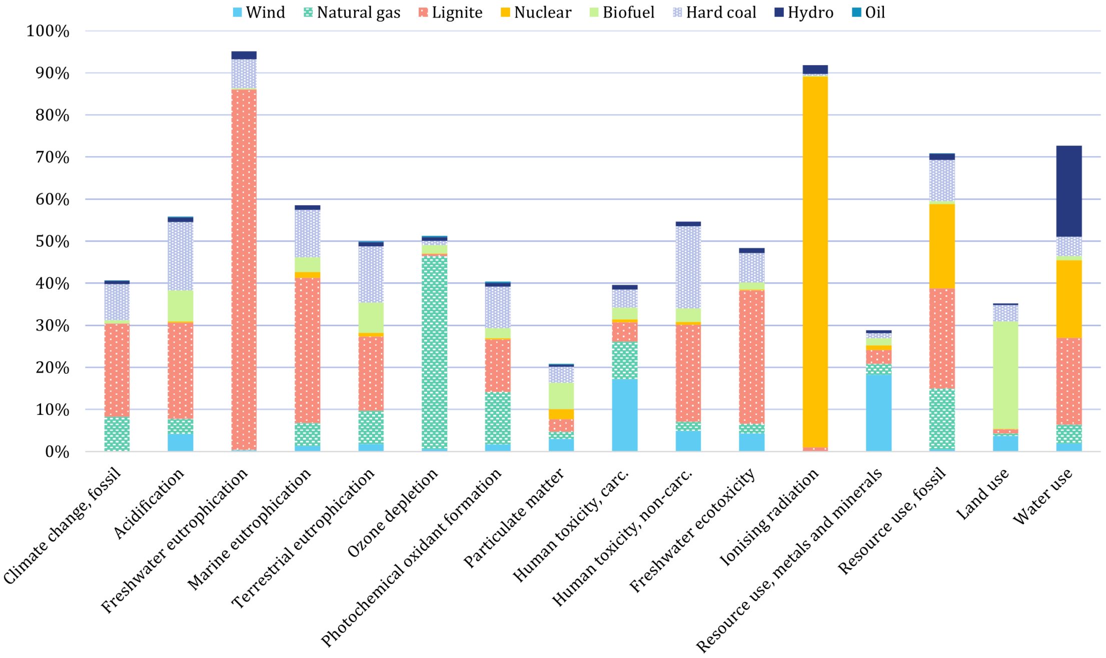


Figure 28: Contribution of electricity from the German grid to the different impact categories in the cut-off case.

Given the significant impact of electricity on the environmental footprint of PIR, it is interesting to take a closer look at the grid's composition. The contribution of the German grid illustrated in Figure 28 reveals that lignite and hard coal, the two coal-based processes, collectively constitute the largest contribution for most impact categories. Additionally, electricity has the largest total impact on freshwater eutrophication primarily due to lignite, and on ionising radiation mainly due to nuclear power.

Returning to Figure 26 and 27, and looking at the environmental impacts of the additives introduced during the extrusion process reveals its most significant impact is to freshwater ecotoxicity, comprising 24 percent of the total impact. Conversely, additives had the least impact on climate change and freshwater eutrophication with

2 and 1 percent respectively.

The subsequent process depicted in the figures is the transport of PIW from Burghausen to mtm plastic. This transportation phase exhibits its highest impacts in particulate matter formation, land use, and carcinogenic toxicity, constituting 55, 52, and 41 percent respectively. Major contributors to particulate matter formation include road construction and tyre and brake wear. Land use emissions primarily stem from roads, while direct fuel emissions and vehicle construction significantly influence human carcinogenic health. In contrast, transport has the lowest impact on ionising radiation, accounting for only 0.2 percent of the total impact.

Following transportation, the next process is municipal transport, involving the transport of waste from mtm plastic to municipal incineration facilities. This process has the most significant impact on photochemical oxidant formation, particulate matter formation, and terrestrial eutrophication, contributing 14, 14, and 13 percent respectively. Conversely, municipal transport has the least impact on freshwater eutrophication and ionising radiation, contributing less than 0.1 percent of the total impact.

Finally, the last process is incineration, where waste from mtm plastic is incinerated at municipal waste treatment facilities. The incineration demonstrates its greatest impact on climate change comprising 41 percent of the total impact. However, the absence of energy recovery data in the ecoinvent dataset for municipal incineration may have influenced the results. Conversely, incineration has the least impact on freshwater eutrophication and ionising radiation, accounting for less than 0.1 in both cases.

6.2.2 Sensitivity Analysis

A sensitivity analysis is conducted on the most uncertain modelling factor, which is the amount of waste generated in the process and subsequently incinerated. The life cycle modelling used a yield of 95 percent NAV-128 with 3 percent waste directed to incineration (see Table 9), based on an expert estimate from Borealis. To test the robustness of the LCA results, the sensitivity analysis contrasts these results with those of a scenario wherein the amount of waste generated is doubled to 6 percent. Both cases reflect results using a cut-off approach for allocating environmental loads to PIW.

The sensitivity analysis presented in Figure 29 shows that the scenario with 6 percent waste results in elevated environmental impacts across all impact categories, except for freshwater eutrophication and ionising radiation, which exhibit no variation compared to the base case. The most significant increase occurs in fossil climate change, with a 47 percent surge in impact compared to the base case, followed by terrestrial eutrophication and photochemical oxidant formation, both increasing by 21 percent. This is expected, given that incineration contributes significantly to these three impacts, as discussed in the contribution analysis.

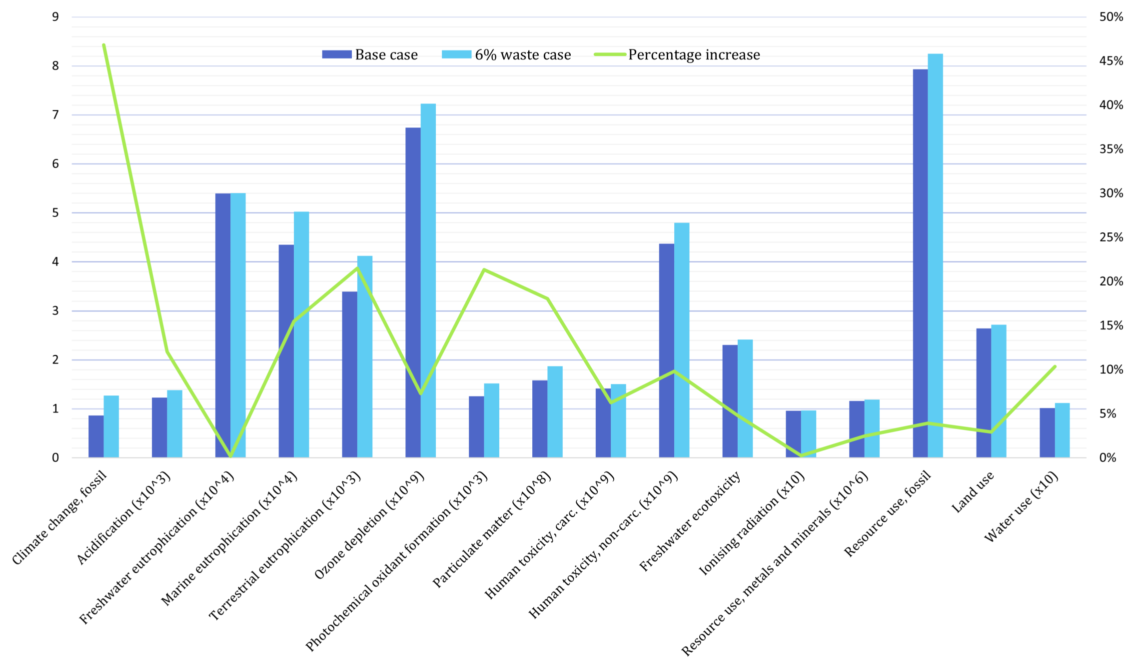


Figure 29: [Pseudonymised data] Sensitivity analysis performed across all impact categories. The base case (3% waste to incineration, cut-off) is compared to a case with 6% waste.

Nevertheless, the impacts remain small compared to those of virgin PP across all impact categories, except for freshwater eutrophication and carcinogenic human toxicity, which already surpass those of virgin PP in the base case.

6.3 Interpretation

Except for system expansion, allocation differences are minimal. This is attributed to the significantly smaller output of PIW compared to virgin PP homopolymer, influencing both the economic and mass allocation factors, as seen in Equations 1 and 2. Since these factors are close to zero, the impacts from virgin PP production allocated to the PIW used at mtm are negligible. Consequently, the results closely resemble those obtained using the cut-off approach, which accounts solely for impacts arising after the PIW exits the virgin production plant.

It is worth noting that the annual quantity of virgin PP considered in the calculation of the allocation factors only includes PP homopolymer. If the total output of PP produced at Burghausen had been used, encompassing PP copolymer, PP compound, and random PP copolymer, the allocation factor would have decreased by 50 percent, thus reducing the allocated environmental impacts accordingly. Since it is plausible that some of the PIW originates from these other polymer production processes, the resulting environmental impacts using the mass and economic allocation methods could align even more closely with those using the cut-off approach.

Overall, the LCA shows that PIR has significantly lower environmental impacts compared to virgin plastic. Key impact categories, particularly those falling within the high-risk area of the EU Consumption Footprint assessment against Planetary Boundaries in Germany (European Commission, 2021b), reveal the following results:

- Fossil climate change: PIR exhibits a 170 percent lower impact with system expansion and a 70 percent lower impact with either mass or economic allocation, or the cut-off approach.
- Freshwater ecotoxicity: PIR demonstrates a 197 percent lower impact with system expansion and a 97 percent lower impact with either mass or economic allocation, or the cut-off approach.
- Particulate matter formation: PIR shows a 178 percent lower impact with system expansion, a 78 percent lower impact with economic allocation or the cut-off approach, and a 77 percent lower impact with mass allocation.
- Resource use, fossil: PIR displays a 192 percent lower impact with system expansion and a 92 percent lower impact with either mass or economic allocation, or the cut-off approach.
- Resource use, metals and minerals: PIR displays a 175 percent lower impact with system expansion, a 75 percent lower impact with economic allocation or the cut-off approach, and a 74 percent lower impact with mass allocation.

Surprisingly, there are two impact categories where PIR showcases larger impacts than virgin PP: freshwater eutrophication and carcinogenic human toxicity. The largest contributors to freshwater eutrophication are the electricity demands of extrusion and mixing & dry blending, sourced from the German electricity grid. More specifically, the largest impacts stem from lignite mining and waste management, which is the third largest energy source in the German electricity mix, as illustrated in Figure 17. As for carcinogenic human toxicity, electricity (47 percent) and transport of PIW to mtm (41 percent) stand out as the largest contributors.

Several factors could account for why the impact of PIR appears larger than that of virgin PP. Firstly, the production process of 1 kg of virgin PP may be significantly more energy-efficient than that of an equivalent quantity of PIR, possibly due to the economies of scale inherent in virgin PP production at a large petrochemical production plant such as Borealis Burghausen. Indeed, Burghausen produces 400 times more virgin PP and 180 times more PP homopolymer than the amount of NAV-128 produced by mtm. Secondly, the disparity in LCIA results could stem from differences in scope and modelling choices between this LCA and the LCA of virgin PP. While it is likely that the LCA practitioners of the virgin PP used recent and geographically relevant energy data, there is a possibility that they relied on European averages, which could impact the results. Lastly, the environmental impact of transportation by truck over significant distances may not be as substantial per kg of virgin PP produced as it is for PIR. For instance, the impact of transporting the propylene used in PP production depends on various factors, such as tank capacity, transport distance, means of transportation, and the life cycle modelling data employed. Therefore, it is difficult to pinpoint the exact cause behind these outliers without having access to the complete LCA study of the virgin PP from Burghausen.

The impact of electricity use is by far the biggest source of emissions across all the impact categories, reaching close to or over 50 percent of the contribution share in almost all categories. Therefore, finding ways to reduce the electricity required for the process, or transitioning exclusively to purchasing renewable energy from the market, would be the best course of action for mitigating the environmental impact of NAV-128 across all impact categories.

Considering electricity use and its environmental repercussions, it is important to take into consideration the changes to the German electricity mix since 2020, the baseline year for the ecoinvent data used. The contribution results in Figure 28 show that lignite and hard coal have by far the largest impact across almost all impact categories. As depicted in Figure 17, the share of lignite and hard coal has increased in 2023, implying that the current production of NAV-128 could yield somewhat higher environmental impacts than currently indicated. This is especially true for some key impact categories where fossil power sources weigh the most: acidification, fossil climate change freshwater eutrophication and freshwater ecotoxicity. Furthermore, the increase in wind power from 23 to almost 27 percent could increase the impact of PIR on carcinogenic human toxicity and metal and mineral resource usage due to the considerable material intensity required for wind turbines.

However, the decline in the share of nuclear power suggests a significantly reduced impact on ionising radiation in 2023 since nuclear energy is by far its biggest contributor (88%). Overall, the decreased use of nuclear and compensation with lignite, hard coal and wind power is expected to affect the results negatively.

6.4 Allocation: Discussion and Recommendations

Based on the results from the life cycle assessment, it is clear that the choice of an allocation method has a significant impact on the environmental performance of NAV-128. Opting for system expansion versus any other of the three allocation methods proposed yields significantly different outcomes. However, the difference in environmental impact is so small between the uses of the cut-off approach, mass and economic allocation, that it may be argued that using any of those can be motivated. Therefore, the first question that arises is whether system expansion is recommended.

System Expansion

System expansion relies on the premise that an alternative way exists for producing a product which fulfils a specific function. Therefore, if a company like Borealis consistently sells its PIR to businesses which interchangeably use virgin plastic and PIR, it can be inferred that the PIR has effectively reduced the demand for an equivalent quantity of virgin plastic, thereby avoiding its production. However, if a manufacturer shifts its business strategy towards acquiring more sustainable raw materials and opts to exclusively buy recycled plastic (as observed in the automotive industry), then the PIR no longer replaces virgin plastic and cannot be credited with avoiding its production.

With a growing number of businesses embracing sustainable practices, it is plausible that a large number of manufacturers will exclusively demand recycled plastics. This would require assessing the environmental impact of PIR on a customer-by-customer basis, as the appropriateness of using system expansion varies depending on individual circumstances, which could prove complex and time-consuming. Moreover, since Borealis aims to attract environmentally conscious customers who prefer recycled plastic, promoting PIR as a substitute for virgin plastic, i.e., a product with negative environmental burdens, would not be relevant or accurate from an ethical and scientific point of view.

Therefore, using system expansion to reflect the environmental burdens of PIW and thus, of PIR, is not recommended. As a result, the focus now shifts towards examining the other three allocation methods analysed in this study: the cut-off approach, economic allocation, and mass allocation.

The Cut-off Approach

Although allocating using the cut-off approach, or economic or mass allocation does not yield significant differences in environmental impacts for NAV-128, it is crucial to acknowledge that the choice between these methods holds ethical implications. Furthermore, the recommended method could impact future LCAs conducted at Borealis. Hence, determining which method is most appropriate is still an important decision.

At first glance, the negligible impact of PP virgin production on NAV-128 when allocating based on mass or economic value supports the argument for the appropriateness of the cut-off approach. The methodology outlined in the *Plastics LCA* report by Nessi et al. (2021) from the Joint Research Centre of the European Commission suggests avoiding the use of any cut-off approach whenever possible, yet acknowledges its potential application in scenarios where a mass or energy flow, as well as the total environmental impact, is less than 3 percent. The environmental impacts assigned to NAV-128 using economic allocation represent approximately 1 percent of the total, which aligns with the principles of this method. However, it falls short in the case of mass allocation, where the average impact allocated is about 5 percent. Moreover, Nessi et al. (2021) emphasises that waste with an economic value should be treated as any other by-product in the LCA system, rendering the cut-off approach inadequate.

Furthermore, excluding the upstream processes to potentially reduce the perceived impacts of a recycled product can be viewed as unethical behaviour. As society gravitates toward more circular practices, where waste becomes an ever-increasing source of feedstock for production, discerning the difference in environmental burdens between waste streams will become more important. Therefore, allocating upstream processes is the best choice at the present and for the future. Consequently, the cut-off approach emerges as an unsuitable choice for allocation.

Mass and Economic Allocation

As previously described, the ISO 14044 (2006) only recommends using allocation by partitioning if increasing the level of detail or system expansion is not feasible. Within this framework, the standard then prioritises physical allocation, for instance, based on mass, energy or volume, over economic allocation. However, relying on physical relationship factors may fail to accurately reflect the drivers behind a process, as illustrated by the gold and gravel example discussed in Section 2.4 on allocation.

In cases where mass allocation alone does not capture the underlying reason for a process, incorporating the total economic value of both products provides a more representative allocation method. Furthermore, there are other instances where mass allocation may be inappropriate, particularly when there is a proportional relationship in a process and the market demand cannot dictate the amounts produced of each product (Azapagic & Clift, 1999). In such cases, where physical relationships are unsuitable for allocation, the ISO suggests employing alternative methods such as economic allocation. While the relationship between PP virgin and PIW is not strictly proportional, PIW remains a waste product whose production cannot be dictated by market demand, similar to a proportional relationship.

When determining whether mass or economic allocation is more suitable in the PIR case, there is no definitive answer. The key consideration is ensuring that the chosen allocation method accurately reflects the real-world drivers behind the production of NAV-128. In virgin production, the objective is to minimise waste while maximising the production of PP. Consequently, unless more efficient methods of producing virgin PP are developed, the waste-to-product ratio is likely to remain consistent. If one were to use economic allocation the environmental burden of PIR would change based on the price of PIW, while in a scenario where mass is used, it would not. Therefore, the question that needs to be answered when deciding between these two allocation methods is whether or not the price of PIW is relevant to the virgin process.

When contemplating this question, it becomes evident that the production of virgin PP and the ensuing waste generation remain unaffected by the price of PIW. As previously mentioned, the primary objective of virgin production is to maximise the efficiency of PP manufacturing. This objective is also reflected in the physical relationship, where PIW constitutes only a fraction of the total PP output. At present, with the price of virgin PP surpassing that of PIW, mass allocation is the most conservative estimate, thereby arguably representing the most ethical approach.

Nonetheless, there are potential advantages to using economic allocation. The price of plastic waste holds significant importance in EU policy-making and incorporating it into environmental impacts could prove beneficial. Furthermore, integrating economic value into allocation could serve as a balancing measure, since the economic value of PIW comes primarily from its environmental benefits. This could be relevant in a scenario where the price of PIW massively increases, however, the price increase needed for this to affect NAV-128 is highly unrealistic.

Since the price of PIW has no discernible impact on virgin production, there is also no compelling reason to use economic allocation. Hence, adhering to the ISO recommendation and leveraging the physical relationship to allocate impacts appears to be the most logical course of action. This leads to mass allocation being the recommended method to use when allocating environmental burdens between virgin PP and the PIW feedstock for NAV-128 production.

7

Conclusion

This thesis has investigated the post-industrial recyclate landscape from a policy, market and environmental perspective for Borealis, a prominent player in the petrochemical industry. The research unfolded in three phases, each aiming to answer specific research questions. Firstly, the authors performed an in-depth analysis of the European Union's policies and strategies, culminating in a foresight-based scenario analysis.

Secondly, a market analysis was conducted to identify key markets of interest for Borealis' PIR products. While Borealis produces PIR in Germany and Austria, the German market was emphasised in the analysis due to its size, with similar behavioural patterns assumed in neighbouring markets. Therefore, the analysis focused on generational dynamics within the German market to understand consumer behaviour and environmental consciousness across different age groups.

Finally, the environmental impacts of a Borealis post-industrial PP product were calculated with a life cycle assessment, comparing various allocation approaches. The overall research yielded the following conclusions.

What is the current regulatory environment governing the production and use of PIR?

Currently, there are no EU policies specifically targeting PIR, nor any indication that this will change. Despite some stakeholder suggestions, such as integrating PIR into the PPWD policy, the EU has not shown any signs of compliance. This reluctance likely arises because PIR has not experienced any market failures, and has been a profitable product without policy intervention, unlike PCR. Similarly, the scenario analysis predicted no scenario where policy intervention was necessary for PIR to remain profitable, which was not true for PCR. Additionally, the EU may be wary of potential fraudulent activity if PIR were to receive a similar policy treatment as PCR.

What are the markets of interest of PIR and the market trends?

It is essential for Borealis to prioritise local markets that recognise the environmental benefits of PIR materials over virgin plastic. This not only helps in reducing transportation costs but also in minimising the environmental footprint associated with product distribution.

The research highlights the significant role of the younger demographic, particularly Gen Z, in driving sustainable product consumption. Given that this demographic allocates a substantial portion of their spending to sectors such as cosmetics, technology and pet-related products, Borealis should explore opportunities for integrating PIR into these industries and find customers catering to these sectors. Furthermore, the study found that German consumers are willing to invest in environmentally beneficial products, particularly those intended for long-term use, such as furniture and household equipment.

Furthermore, market analysis on one of Germany's largest industrial sectors indicates that integrating PIR into higher-value products like automotive components could leverage its superior quality compared to other recyclates. However, challenges persist in ensuring consistent PIR quality and availability, with Borealis facing production fluctuations. Despite its potential, impending EU regulations mandating minimum recycled content of PCR may impact PIR's viability in automotive applications.

How do different allocation scenarios affect the environmental footprint of Borealis' PIR?

All four allocation methods resulted in a reduced environmental footprint for PIR compared to PP virgin across all impact categories except freshwater eutrophication and carcinogenic human toxicity. It is uncertain whether these discrepancies stem from production differences between PIR and PP virgin or modelling choices made in the LCAs.

Among the allocation methods examined in the LCA, only system expansion showed a noticeable difference in environmental impact. In contrast, the cut-off approach, mass allocation, and economic allocation produced nearly identical results, differing on average by only 5 and 1 percent compared to when using the cut-off approach, for mass and economic allocation respectively. The difference in system expansion lies in its allocation approach. While the other methods gauge the environmental impacts of the PIR product itself, system expansion focuses on the emissions avoided by choosing PIR over a virgin alternative, resulting in negative emissions across most impact categories. Conversely, the similarity in results among the other three methods stems from the significant mass disparity between virgin PP and PIW. Using mass allocation, only 0.54 percent of virgin polypropylene's environmental impacts were allocated to the PIW, and 0.11 percent using economic allocation.

What allocation method do we recommend Borealis use in future PIR LCAs?

The choice of allocation method significantly influences the environmental performance of PIR, with system expansion yielding markedly lower impacts compared to other methods. While system expansion may reflect reduced demand for virgin plastic under certain conditions, its application becomes complex and impractical as businesses increasingly demand recycled plastics exclusively. Moreover, promoting PIR as a substitute for virgin plastic may not be ethically or scientifically accurate, given the evolving landscape of sustainable practices, where manufacturers no longer automatically use virgin plastic as their primary raw material.

Although seemingly straightforward, the cut-off approach presents ethical concerns as it excludes upstream processes and fails to accurately reflect the environmental burdens associated with recycled products. Furthermore, its application is not recommended by ISO standards and scientific literature, which advocate for methods that consider the full life cycle of products.

Moving forward, the debate remains between mass allocation and economic allocation. Mass allocation emerges as the superior method for distributing environmental burdens in the virgin production process due to its closer alignment with the real-world drivers of production and waste generation. Given that the economic value of PIW and virgin materials does not influence PIW generation, including it in the allocation of environmental burdens becomes unnecessary. Furthermore, mass allocation appears to be the most conservative and ethically sound approach, aligning with ISO recommendations. Hence, mass allocation is the recommended method for allocating environmental burdens between virgin plastic and PIW feedstock for PIR production.

Future Research

Given the limitations in data availability for the LCA conducted in this study, especially regarding missing LCI data for virgin PP from Burghausen, it is recommended that Borealis initiate a follow-up LCA study. This subsequent LCA analysis should employ mass allocation with LCI data instead of the LCIA data used in this study.

Additionally, the ongoing development of the CFF allocation method holds significance for Borealis, particularly if they intend to adhere to the European Commission's recommendation to use the PEF method for assessing the environmental footprint of PIR. Therefore, it is important to closely track the development of the CFF and PEF methods alongside the EU's recommendations and policy updates.

Bibliography

Aguilar, F. J. (1967). *Scanning the business environment.* Macmillan.

Alhazmi, H., Almansour, F. H., & Aldhafeeri, Z. (2021). Plastic waste management: A review of existing life cycle assessment studies. *Sustainability*, 13(10), 5340. https://doi.org/10.3390/su13105340.

American Chemistry Council (2023). Chemistry and Automobiles: Lighting the Way to the Future of Motor Vehicles. *America's Plastic Makers.* Availibale at: `https://plasticmakers.org/resource/chemistry-and-automobiles/`.

Arbeitsgemeinschaft Energiebilanzen (AGEB) (2023). Energy balance 2000 to 2030. Available at: `https://ag-energiebilanzen.de/en/data-and-facts/energy-balance-2000-to-2030/?wpv-jahresbereich-bilanz=2021-2030-en`.

Aschemann-Witzel, J. & Zielke, S. (2017). Can't buy me green? a review of consumer perceptions of and behavior toward the price of organic food. *Journal of Consumer Affairs*, 51(1), 211–251. https://doi.org/10.1111/joca.12092.

Audi (2022). Pilot Project: Physical Recycling Makes Mixed Plastic Waste Recyclable. *Audi Mediacenter.* Available at: `https://www.audi-mediacenter.com/en/press-releases/pilot-project-physical-recycling-makes-mixed-plastic-waste-recyclable-14931`.

Austrian Parliament (2002). Bundesgesetz über eine nachhaltige Abfallwirtschaft (Abfallwirtschaftsgesetz 2002 – AWG 2002). *Rechtsinformationssystem des Bundes.* As amended trough BGBl. I Nr. 66/2023.

Ayres, R. U. (2004). On the Life Cycle Metaphor: where Ecology and Economics Diverge. *Ecological economics*, 48(4), 425–438. https://doi.org/10.1016/j.ecolecon.2003.10.018.

Azapagic, A. & Clift, R. (1999). Allocation of environmental burdens in multiple-function systems. *Journal of Cleaner Production*, 7(2), 101–119. https://doi.org/10.1016/S0959-6526(98)00046-8.

Baumann, H. & Tillman, A. (2004). *The Hitch Hiker's Guide to LCA.* Studentlitteratur.

Bell, E., Bryman, A., & Harley, B. (2019). *Business research methods.* Oxford university press, fifth edition.

Benton, D., Hazell, J., & Hill, J. (2017). *The Guide to the Circular Economy: Capturing Value and Managing Material Risk.* Routledge. https://doi.org/10.4324/9781351274364.

BMW (2024). Recyclates: Efficient recycling with secondary materials. Available at: `https://www.bmw.com/en/magazine/sustainability/circular-lab/recycle/efficient-recycling-with-secondary-materials.html`.

Borealis (2024a). Circular Economy. *Borealis.* `https://www.borealisgroup.com/sustainability/circular-economy`.

Borealis (2024b). Sustainability. *Borealis.* `https://www.borealisgroup.com/sustainability`.

Bunn, D. W. & Salo, A. A. (1993). Forecasting with scenarios. *European Journal of Operational Research*, 68(3), 291–303. https://doi.org/10.1016/0377-2217(93)90186-Q.

Burgess, R. G. (1984). *In the Field: An Introduction to field Research.* Routledge. https://doi.org/10.4324/9780203418161.

Börjeson, L., Höjer, M., Dreborg, K.-H., Ekvall, T., & Finnveden, G. (2006). Scenario types and techniques: Towards a user's guide. *Futures*, 38(7), 723–739. https://doi.org/10.1016/j.futures.2005.12.002.

Carson, R. (2000). *Silent Spring.* Penguin Classics.

Chen, Z., Yang, N., Shi, Q., Kuang, X., Qi, J., & Wang, T. (2019). Recycling Waste Circuit Board Efficiently and Environmentally Friendly through Small-Molecule Assisted Dissolution. *Scientific Reports*, 9. Available at: `https://www.nature.com/articles/s41598-019-54045-w#citeas`.

Corvellec, H., Stowell, A., & Johansson, N. (2021). Cririques of the Circular Economy. *Journal of Industrial Ecology*, 26(2), 421–432. https://doi.org/10.1111/jiec.13187.

Dale, A., Arber, S., & Proctor, M. (1988). *Doing Secondary Analysis.* London: Unwin Hyman.

Das, S., Liang, C., & Dunn, J. B. (2021). Life Cycle Assessment of Polymers and Their Recycling. In *Circular Economy of Polymers: Topics in Recycling Technologies.* ACS Publications. https://doi.org/10.1021/bk-2021-1391.ch008.

Day, G. (1981). Strategic Market Analysis and the Definition: an Integrated Approach. *Strat.Mgmt*, 2(3), 281–299. https://doi.org/10.1002/smj.4250020306.

EcoCart (2023). 42 Statistics on Gen Z Shopping Habits. Available at `https://ecocart.io/gen-z-spending-habits/`.

ecoinvent (2023). ecoinvent Version 3.9. Available at: `https://support.ecoinvent.org/ecoinvent-version-3.9`.

ecoinvent (n.d.). transport, freight, lorry >32 metric ton, euro6. *ecoQuery.* Available at: https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/11457/documentation.

Ellen MacArthur Foundation (2013). Towards the Circular Economy: an Economic and Business Rationale for an Accelerated Transition. 1.

Emilsson, E., Dahllöf, M., & Söderman, M. (2019). Plastic in passenger cars a comparision over types and time. *IVL Svenska Miljöinstitutet.* Avalible at: https://www.ivl.se/download/18.694ca0617a1de98f4737b5/1628417001506/FULLTEXT01.pdf.

en2x (2024). Average annual Brent crude oil price from 1976 to 2024 (in U.S. dollars per barrel). *Statista.* Available at: https://www.statista.com/statistics/262860/uk-brent-crude-oil-price-changes-since-1976/.

European Comission (2022). Environmental Footprint reference packages. Available at: https://eplca.jrc.ec.europa.eu/LCDN/developerEF.html.

European Comission (2023). Critical Raw Materials: ensuring secure and sustainable supply chains for EU's green and digital future. Available at: https://ec.europa.eu/commission/presscorner/detail/en/ip_23_1661.

European Commission (2013). Commission Recommendation of 9 April 2013 on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations (2013/179/EU). *Official Journal of the European Union.* Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32013H0179.

European Commission (2015). Circular Economy Action Plan (COM(2015) 614). Avalible at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52015DC0614.

European Commission (2020). A new Circular Economy Action Plan (COM/2020/98). *Official Journal of the European Union.* https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN.

European Commission (2021a). Commission Recommendation on the use of the Environmental Footprint Methods to Measure and Communicate the Life Cycle Environmental Performance of Products and Organisations (C/2021/933). *Official Journal of the European Union.* Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=PI_COM:C(2021)9332.

European Commission (2021b). *Consumption Footprint Platform.* Technical report, European Commission. Available at: https://eplca.jrc.ec.europa.eu/ConsumptionFootprintPlatform.html.

European Commission (2021c). *Guidance on Waste Definitions.* Technical report, Circular Plastics Alliance. Avalible at: https://ec.europa.eu/docsroom/documents/46954/attachments/8/translations/en/renditions/pdf.

European Commission (2023a). Environmental and Economic Assessment of Plastic

Waste Recycling. *Publications Office of the European Union.* Avalible at : `https://publications.jrc.ec.europa.eu/repository/handle/JRC132067`.

European Commission (2023b). On circularity Requirements for Vehicle Design and on Management of End-of-life Vehicles, Amending Regulations (EU) 2018/858 and 2019/1020 and Repealing Directives 2000/53/EC and 2005/64/EC (COM/2023/451). *Official Journal of the European Union.* Available at: `https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52023PC0451`.

European Commission (n.d.). The European Green Deal. *European Commission.* Avalible at: `https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en`.

European Parliament (2008). On Waste and Repealing Certain Directives (2008/98/EC). *Official Journal of the European Union.* Avalible at: `https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32008L0098`.

European Parliament (2018a). Amending Directive 2008/98/EC on Waste (EU 2018/851). *Official Journal of the European Union.* Avalible at: `https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32018L0851`.

European Parliament (2018b). Amending Directive 94/62/EC on packaging and packaging waste (EU 2018/852). *Official Journal of the European Union.* Available at: `https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32018L0852`.

European Parliament (2021). Regulation on shipments of waste ((EC) No 1013/2006). *Official Journal of the European Union.* Available at: `https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02006R1013-20210111#tocId56`.

European Parliament (2022). Amending Regulation (EU) No 537/2014, Directive 2004/109/EC, Directive 2006/43/EC and Directive 2013/34/EU, as regards corporate sustainability reporting ((EU) 2022/2464). *Official Journal of the European Union.* Avalible at: `https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32022L2464`.

European Parliament (2023). COP28 climate talks agree on transitioning away from fossil fuels. Available at: `https://www.europarl.europa.eu/news/sv/press-room/20231205IPR15686/cop28-climate-talks-agree-on-transitioning-away-from-fossil-fuels`.

European Parliament (2024). Legislative Train Schedule. Avalible at `https://www.europarl.europa.eu/legislative-train/schedule`.

Fedkin, M. V. (2024). Recycling: Open-loop Versus Closed-loop Thinking. *The Pennsylvania State University.* `https://www.e-education.psu.edu/eme807/node/624`.

First Insight (2020). The State of Consumer Spending: Gen Z Shoppers Demand Sustainable Retail.

German Parliament (2007). Gesetz zur Ausführung der Verordnung (EG) Nr. 1013/2006 des Europäischen Parlaments und des Rates vom 14. Juni 2006 über die Verbringung von Abfällen 1) und des Basler Übereinkommens vom 22. März 1989 über die Kontrolle der grenzüberschreitenden Verbringung gefährlicher Abfälle und ihrer Entsorgung 2) (Abfallverbringungsgesetz - AbfVerbrG). *Bundesministerium der Justiz.* As amended trough July 19, 2007 (BGBl. I S. 1462).

GfK (2023a). Desire to Buy Sustainably Remains Robust in Germany and UK. Available at: `https://www.gfk.com/blog/propensity-to-buy-sustainably-holding-strong-in#:~:text=German%20shoppers'%20sustainability%20index%20rating,slightly%20higher%20than%20UK%20shoppers`.

GfK (2023b). Understanding Retail Consumers' Mindset. Available at `https://www.gfk.com/insights/understand-retail-consumers-mindset`.

Ghazali, E., Soon, P. C., Mutum, D. S., & Nguyen, B. (2017). Health and cosmetics: Investigating consumers' values for buying organic personal care products. *Journal of Retailing and Consumer Services*, 39, 154–163. https://doi.org/10.1016/j.jretconser.2017.08.002.

Gravgaard, D., Henriksen, M., & Hinge, M. (2024). Dissolution Recycling for Recovery of Polypropylene and Glass Fibers. *J Master Cycles Waste Management*, 26, 961-969. https://doi.org/10.1007/s10163-023-01873-8.

Horodytska, O., Kiritsis, D., & Fullana, A. (2020). Upcycling of printed plastic films: LCA analysis and effects on the circular economy. *Journal of Cleaner Production*, 268, 122138. https://doi.org/10.1016/j.jclepro.2020.122138.

Independent Commodities Intelligence Services (ICIS) (2024). Chemicals. Available at: `https://www.icis.com/explore/`.

International Organization for Standardization (2006). Environmental Management — Life Cycle Assessment — Requirements and Guidelines . (ISO 14044:2006).

Janssen, M. & Hamm, U. (2012). Product labelling in the market for organic food: Consumer preferences and willingness-to-pay for different organic certification logos. *Food quality and preference*, 25(1), 9–22. https://doi.org/10.1016/j.foodqual.2011.12.004.

Kirsch, K. (2023). Germany Lifestyles of Generation Z Market Report 2023. *Mintel.* Avalible at: `https://store.mintel.com/report/germany-lifestyles-of-generation-z-market-report`.

Krungsri Research (2022). Price of propylene worldwide from 2017 to 2022 (in U.S. dollars per metric ton). *Statista.* Available at: `https://www.statista.com/statistics/1170576/price-propylene-forecast-globally`.

Krungsri Research (2023). Price of ethylene worldwide from 2017 to 2022 (in U.S. dollars per metric ton). *Statista.* Available at: `https://www.statista.com/statistics/1170573/price-ethylene-forecast-globally/`.

Lühmann, M. (2023). Gen Z and millennials: The generational gap in sustainable consumption. *Statista.*

Magnier, L. & Mugge, R. (2022). Replaced too soon? An exploration of Western European consumers' replacement of electronic products. *Resources, Conservation and Recycling*, 185, 106448. https://doi.org/10.1016/j.resconrec.2022.106448.

Mercedes-Benz Group (2024a). Mercedes-Benz Plant Sindelfingen. Available at: `https://group.mercedes-benz.com/company/locations/production-network-sindelfingen.html`.

Mercedes-Benz Group (2024b). On the road to the circular economy. Available at: `https://group.mercedes-benz.com/responsibility/sustainability/resources/circular-economy.html`.

Naustdalslid, J. (2014). Circular Economy in China – the Environmental Dimension of the Harmonious Society. *International Journal of Sustainable Development & World Ecology*, 21(4),303-313. https://doi.org/10.1080/13504509.2014.914599.

Nessi, S., Sinkko, T., Bulgheroni, C., Garcia-Gutierrez, P., Giuntoli, J., Konti, A., Sanye Mengual, E., Tonini, D., Pant, R., Marelli, L., et al. (2021). Life Cycle Assessment (LCA) of alternative feedstocks for plastics production. *Publications Office of the European Union: Luxembourg.*

NielsenIQ (2018). *Was 2018 the year of the influential sustainable consumer?* Available at: `https://nielseniq.com/global/en/insights/analysis/2018/was-2018-the-year-of-the-influential-sustainable-consumer/`.

NielsenIQ (2022). *Socially Conscious Shoppers Expect New Levels of Transparency From Brands* . Available at: `https://nielseniq.com/global/en/insights/analysis/2018/was-2018-the-year-of-the-influential-sustainable-consumer/`.

Nikiema, J. & Asiedu, Z. (2022). A Review of the Cost and Effectiveness of Solutions to Adress Plastic Pollution. *Environmental science and pollution research international*, 17, 24547–24573. https://doi.org/10.1007/s11356-021-18038-5.

Nordin, H. L., Lindkvist, L., Boss, A., Baumann, H., & Boberg, N. (2019). Kartläggning av plastavfallsflöden, återvinningsmetoder och marknader: kunskapsunderlag för ett returraffinaderi. *IVL Svenska Miljöinstitutet.*

Olofsson, J. & Börjesson, P. (2018). Residual biomass as resource–life-cycle environmental impact of wastes in circular resource systems. *Journal of Cleaner Production*, 196, 997–1006. https://doi.org/10.1016/j.jclepro.2018.06.115.

Packaging Europe (2022). More Than Half of Gen Z Consumers Influenced by Packaging Sustainability, According to New Research. *Packaging Europe.* Available at: `https://packagingeurope.com/news/more-than-half-of-gen-z-consumers-influenced-by-packaging-sustainability-according-to-new-research/8176.article`.

Plastic Europe (2024). Chemical Recycling and Mass Balance Explained. Avalible at: `https://plasticseurope.org/knowledge-hub/chemical-recycling-mass-balance-explained/`.

Plastics Europe (2021). PlasticsEurope's position on Recycled Content for plastics packaging under the review of the Directive 94/62/EC on Packaging and Packaging Waste (PPWD). Available at: `https://plasticseurope.org/wp-content/uploads/2021/11/Plastics_Europe_position_on_PPWD_MRC_final-5.pdf`.

Plastics Europe (2022). *Eco-profiles program and methodology, version 3.1.* Technical report. Available at: `https://plasticseurope.org/wp-content/uploads/2024/03/PlasticsEurope-Ecoprofiles-program-and-methodology_V3.1.pdf`.

Plastics Europe (2023). Plastics – the fast Facts 2023. Available at: `https://plasticseurope.org/resources/market-data/`.

Plastics Europe (2024). European Plastics Manufactures Plan 8 Billion Euros of Investment in Chemical Recycling. Avalible at: `https://plasticseurope.org/media/european-plastics-manufacturers-plan-7-2-billion-euros-of-investment-in-chemical-recycling-2/`.

Porsche (2023). Consumption of resources and sustainable raw materials in vehicles. *Porsche Newsroom.* Available at: `https://newsroom.porsche.com/en/sustainability/circular-economy/porsche-consumption-of-resources-sustainable-raw-materials-in-vehicles.html`.

Pretner, G., Darnall, N., Testa, F., & Iraldo, F. (2021). Are Consumers Willing to Pay for Circular Products? The Role of Recycled and Second-hand Attributes, Messaging, and Third-party Certification. *Resources, Conservation and Recycling*, 175. https://doi.org/10.1016/j.resconrec.2021.105888.

Ragonnaud, G. (2023). Revision of the Packaging and Packaging Waste Directive. *European Parliamentary Research Service.* Available at: `https://www.europarl.europa.eu/RegData/etudes/BRIE/2023/745707/EPRS_BRI(2023)745707_EN.pdf`.

Ralph MacNulty, C. A. (1977). Scenario development for corporate planning. *Futures*, 9(2), 128–138. https://doi.org/10.1016/0016-3287(77)90005-2.

Rhydderch, A. (2017). Scenario building: The 2x2 matrix technique. *Futuribles International.* Available at: `https://www.researchgate.net/publication/331564544_Scenario_Building_The_2x2_Matrix_Technique`.

Schrijvers, D., Loubet, P., & Sonnemann, G. (2020). Archetypes of Goal and Scope Definitions for Consistent Allocation in LCA. *Sustainability*, 12(14). https://doi.org/10.3390/su12145587.

Schrijvers, D. L., Loubet, P., & Sonnemann, G. (2016). Critical review of guidelines against a systematic framework with regard to consistency on allocation procedures for recycling in lca. *The International Journal of Life Cycle Assessment*, 21, 994–1008. DOI:10.1007/s11367-016-1069-x.

Schuitema, G. & De Groot, J. I. (2015). Green consumerism: The influence of product attributes and values on purchasing intentions. *Journal of Consumer Behaviour*, 14(1), 57–69. https://doi.org/10.1002/cb.1501.

Schulte, A., Kampmann, B., & Galafton, C. (2023). Measuring the Circularity and Impact Reduction Potential of Post-Industrial and Post-Consumer Recycled Plastics. *Sustainability*, 15(16). 12242; https://doi.org/10.3390/su151612242.

Süptitz, P. (2023). Europe's big 4 willing to pay more for major purchases if sustainably produced. *GfK*. Available at: `https://www.gfk.com/blog/europes-big-4-willing-to-pay-more-for-major-purchases-if-sustainably-produced`.

The Recycling Partnership (2023). Consumer Research on Recycling Behavior and Attitudes Regarding On-Pack Labeling. *The Recycling Partnership*. Avalible at: `https://recyclingpartnership.org/consumer-research-on-recycling-behavior-and-attitudes-regarding-on-pack-labeling/`.

Tillman, A. M., Ekvall, T., Baumann, H., & Rydberg, T. (1994). Choice of system boundaries in life cycle assessment. *Journal of Cleaner Production*, 2(1), 21–29. https://doi.org/10.1016/0959-6526(94)90021-3.

Tinz, J., de Ancos, T., & Rohn, H. (2023). Carbon footprint of mechanical recycling of post-industrial plastic waste: Study of abs, pa66gf30, pc and pom regrinds. *Waste*, 1(1), 127–139. https://doi.org/10.3390/waste1010010.

Woensel, L. V. (2019). *A bias radar for responsible policy-making: foresight-based scientific advice*. Springer Nature.

Woensel, L. V. (2021). Guidelines for foresight-based policy analysis. *European Parliament*. Avalible at: `https://www.europarl.europa.eu/RegData/etudes/STUD/2021/690031/EPRS_STU(2021)690031_EN.pdf`.

Wojciech, Z. (2023). Top 10 market Research Methods: Conquer the Market with your Product. *miquido*. `https://www.miquido.com/blog/market-research-methods/`.

A

Appendix: The Circular Footprint Formula

For any given product system, the CFF can be divided into three parts, reflecting the material, energy and disposal environmental burdens or credits, as described by Equations 5 to 8. The parameters used in the equations are described in Table 12.

$$CFF_{tot} = CFF_{material} + CFF_{energy} + CFF_{disposal} \tag{5}$$

$$\begin{split} CFF_{material} = (1 - R_1)E_V + R_1 \times (A \times E_{rec} + (1 - A)E_V \times \frac{Q_{Sin}}{Q_P}) \\ + (1 - A)R_2 \times (E_{recEoL} - E_V^* \times \frac{Q_{Sout}}{Q_P}) \end{split} \tag{6}$$

$$\begin{split} CFF_{energy} = {} & (1 - B)R_3 \\ & \times (E_{ER} - LHV \times X_{ER,heat} \times E_{SE,heat} - LHV \times X_{ER,elec} \times E_{SE,elec}) \end{split} \tag{7}$$

$$CFF_{disposal} = (1 - R_2 - R_3)E_D \tag{8}$$

However, for intermediate products and cradle-to-gate studies, the distribution, usage, and end-of-life stages are excluded (European Commission, 2021a). Thus, the parameters R_2, R_3 and E_D are set to zero, simplifying the CFF formula to:

$$CFF_{tot} = (1 - R_1)E_V + R_1 \times (A \times E_{rec} + (1 - A)E_V \times \frac{Q_{Sin}}{Q_P}. \tag{9}$$

Here, R_1 represents the proportion of material input that has been recycled from a previous system, E_V is the specific emissions and resources consumed (per functional unit) arising from the acquisition and pre-processing of virgin material, A is the allocation factor of burdens and credits between supplier and user of recycled materials, E_{rec} is the specific emissions and resources consumed (per functional unit) arising from the recycling process of the recycled material, including collection, sorting and transportation process, Q_{Sin} is the quality of the in-going secondary material, and Q_P is the quality of the virgin material.

Setting the factor A to 1 would effectively be the same as allocating based on the cut-off approach, whereas setting it to 0 would mirror using a closed-loop approximation.

However, in PEF studies, the A factor values should be in the range $0.2 \leq A \leq 0.8$ to ensure that both aspects of recycling, recycled content and recyclability at the EoL, are consistently accounted for (European Commission, 2021a). For plastics, default values are available for the parameters A, R_1 and $\frac{Q_{Sin}}{Q_P}$ in Table 11.

Table 11: Default values for some of the parameters used in the CFF based on the document used in the PEF pilot phase (version 2.1 of May 2020) (European Comission, 2022).

Parameter	PP	PE
A	0.5	0.5
R_1	0	0
Q_{Sin}/Q_P	0.9	0.75 – 0.9

With these values, Equation 9 equates the CFF to the specific emissions and resources consumed from the acquisition and pre-processing of virgin material (E_V) in cradle-to-gate PEFs of PE and PP.

Table 12: Description of parameters included in the CFF.

Parameter	Description
A	Allocation factor of burdens and credits between supplier and user of recycled materials.
B	Allocation factor of energy recovery processes. It applies both to burdens and credits.
Q_{Sin}	Quality of the in-going secondary material, i.e., the quality of the recycled material at the point of substitution.
Q_{Sout}	Quality of the outgoing secondary material, i.e., the quality of the recyclable material at the point of substitution.
Q_P	Quality of the primary material, i.e., quality of the virgin material.
R_1	The proportion of material in the input to the production that has been recycled from a previous system.
R_2	The proportion of the material in the product that will be recycled (or reused) in a subsequent system. Therefore, R_2 shall take into account the inefficiencies in the collection and recycling (or reuse) processes. R_2 shall be measured at the output of the recycling plant.

Continued on next page

Table 12 – *Continued from previous page*

Parameter	**Description**
R_3	The proportion of the material in the product that is used for energy recovery at EoL.
E_{rec}	Specific emissions and resources consumed (per functional unit) arising from the recycling process of the recycled (reused) material, including collection, sorting and transportation process.
E_{recEoL}	Specific emissions and resources consumed (per functional unit) arising from the recycling process at EoL, including the collection, sorting and transportation processes.
E_V	Specific emissions and resources consumed (per functional unit) arising from the acquisition and pre-processing of virgin material.
E_V^*	Specific emissions and resources consumed (per functional unit) arising from the acquisition and pre-processing of virgin material assumed to be substituted by recyclable materials.
E_{ER}	Specific emissions and resources consumed (per functional unit) arising from the energy recovery process (e.g., incineration with energy recovery, landfill with energy recovery, etc.).
$E_{SE,heat}/E_{SE,elec}$	Specific emissions and resources consumed (per functional unit) that would have arisen from the specific substituted energy source, heat and electricity respectively.
E_D	Specific emissions and resources consumed (per functional unit) arising from the disposal of waste material at the analysed product's EoL, without energy recovery.
$X_{ER,heat}/X_{ER,elec}$	The efficiency of the energy recovery process for both heat and electricity.
LHV	Lower heating value of the material in the product used for energy recovery.

B

Appendix: Drivers of Change in Scenario Analysis

The Public Opinion on Recycling

The public's perception of recycling as a vital waste-management solution and the growing preference for products made from sustainable materials have gained significant traction in recent years. A study surveying 1310 U.S. consumers found that recycling is viewed as the key to the circular transition, with 82 percent expressing disappointment if products labelled as recyclable are not actually recycled (The Recycling Partnership, 2023). However, what if this sentiment were to change?

In a scenario where recycling loses popularity, possibly due to propaganda or new scientific findings indicating adverse environmental and health impacts, opposition to current EU regulations on recycling targets and mandatory content could arise among governments, industries, and consumers. Some may even boycott products containing recycled plastics and refuse to participate in waste sorting practices. Manufacturers might cease highlighting the recycled content of their products on labels.

Conversely, if recycling continues gaining popularity, more consumers and manufacturers will seek out products made with recyclate. This heightened demand would drive industry investment in research and development for more efficient recycling methods, such as chemical or dissolution recycling, resulting in increased production of recycled plastics to meet demand. Policymakers would likely enact stricter regulations to achieve higher recycling targets, while companies would capitalise on the trend by promoting products containing recycled materials, making PIR a sought-after material.

Given the current scientific consensus and robust regulatory framework surrounding recycling, the likelihood of a significant shift in public opinion on recycled materials is low. Consequently, the potential impact of such a shift would be relatively minimal, given the already high level of public support for recycling initiatives.

Recycling Contents in High-performance Sectors

This scenario would expand the EU's current policy of implementing mandatory requirements for products. Policies would not only be limited to products with lower quality demands, as seen in the existing policy on packaging. Instead, mandatory recycling content policies would be broadened to encompass products with high-quality requirements, such as the food or medical industry. Consequently, high-quality recycled plastic would then become a highly sought-after material.

The impact of EU imposing mandatory requirements for high-quality plastic products is challenging to predict. While the immediate effect of such a policy may be an upswing in the value and demand for PIR, the limited volumes of PIR would necessitate sourcing a significant quantity of material from other sources. If in this scenario PIR prices were to rise above their virgin counterparts, it could potentially prompt plastic producers to intentionally generate more waste in their production process. Furthermore, the higher value of PIR would incentivise plastic producers to import PIW from outside the EU, partly offsetting the environmental benefits of recycling with increased global shipping. However, depending exclusively on PIR for the high-quality plastic requirements is not feasible. Even with PIR sourced from global PIW, it would fall short of meeting demands, meaning that other alternatives for high-quality recycling would need to be developed. In this scenario, PIR could serve as a valuable resource to assist industries in meeting mandatory recycling content requirements. However, it could never be the primary feedstock due to its limited availability.

In the scenario that no recycling content requirements for high-quality plastic products occur, or even in the case that the ones currently in place are removed, its impact on PIR would most likely be minimal. Currently, no policies are pushing for the use of PIR, and its success relies on finding consumers seeking a cost-effective and environmental option. Without any requirements for high-quality plastics, PIR would be in the same situation that it finds itself in today.

Like most other EU policies, the mandatory requirements are formulated in collaboration with the industries they impact. Consequently, the prospect of the EU introducing policies that would to challenging or impossible for industries to fulfil is highly improbable. Therefore, requirements for high-quality plastic products would be highly improbable without better recycling methods.
The EU policies on mandatory requirements are developed in collaboration with the industries it concerns. This means that the likelihood that the EU would introduce policies that would be hard or impossible for industry to meet is highly unlikely, therefore, this scenario has low uncertainty.

The Inclusion of PIW in EU Policy

Currently, PIR is not included within the EU's recycling targets or the mandatory recycling content regulations for plastic packaging. This means there is no incentive for EU Member States or industries to promote PIR. However, what would the effect be if PIR where to be included in these policies and could be an alternative to PCR. how would the landscape shift under these circumstances and how big would its effect be.

The inclusion of PIR in the EU's policies might not exert a substantial impact. Although the market for PIR would likely expand, with its selling points now encompassing not only quality and ethical considerations but also contributing to recycling content requirements. However, the limited amount of PIR available would mean a low effect on the recycling market as a whole. These policies would make PIR easier to sell, but its market value might not see a substantial rise. This is because of its restricted volume, preventing it from replacing PCR. For PIR's higher quality to be a significant factor, it would have to be used in more niche markets with low material flows. Incorporating PIW recycling into the recycling target would likely have minimal effects on the plastic industry, as most waste is already being reused to some extent. Even if this policy results in an increase in PIW used as feedstock for PIR, the volume increase would be marginal and have a low impact.

In this scenario, the EU persists in excluding PIR from its recycling policies. PIR value would continue to derive from its superior quality in comparison to PCR recyclates, coupled with the ethical selling point of being a recycled material. The ongoing challenge in this scenario would remain unchanged, to identify customers who appreciate the recycled nature of PIR and are willing to pay a premium for it.

Given that the incorporation of PIR into EU policies would not substantially enhance the value or production volume, the overall impact is relatively low. While selling PIR might be easier with its inclusion in policies, the challenge of finding a market where its value can be fully realised remained the same for both scenarios, also implying a low impact. Presently, the EU has not shown any indication of considering the inclusion of PIR in its recycling policies, although its absence has been recognised by the CPA. However, since the EU shows no indication the uncertainty regarding this scenario is low.

Geopolitical Stability

Geopolitical stability has a big impact on politics and the economy. Increased geopolitical stability leads to more open global trade and a global economy, encouraging foreign investment and fostering cooperation among nations. Paradoxically, the current circular economy model within the EU tends to be local and protectionist, partly driven by the objective of safeguarding European autonomy and sovereignty over critical materials (European Comission, 2023). While this does not equate the circular economy with geopolitical instability, its implementation and oversight are more manageable on a smaller scale. Despite aiming to incentivise investment within the European market, circular initiatives like mandatory recycling standards may pose challenges for external producers seeking to penetrate the European market since they have to comply with stricter regulations.

The most important consequence of geopolitical stability regarding plastic and PIR is its effects on oil supply and oil prices. With increased stability, there is less need to worry about oil and its derivatives, propylene and ethylene. Conversely, in war times, the EU may be cut off from oil commerce, which would push the EU to increase its recycling efforts to preserve critical materials. EU sovereignty therefore becomes even more important. Therefore, this driver is very closely related to the driver "Ethylene and propylene prices".

C

Appendix: Impact Category Definitions

Description of the impact categories used in the EF method as defined by the European Commission (2021a) Recommendation C(2021)9332.

C.1 Climate Change, Fossil

This category covers greenhouse gas emissions to any media originating from the oxidation and/or reduction of fossil fuels by means of their transformation or degradation (e.g. combustion, digestion, landfilling, etc.). This impact category includes emissions from peat (used as a fuel) and calcination, and uptakes due to carbonation.

Fossil climate change is one of three sub-categories which constitute the impact category "climate change, total", the other two being biogenic climate change and climate change from land use and land use change. The consequences of these emissions include increased average global temperatures and sudden regional climatic changes.

Fossil climate change is expressed in carbon dioxide equivalents (kg CO_2-eq).

C.2 Acidification Potential

This category addresses impacts due to acidifying substances in the environment. Emissions of NO_x, NH_3 and SO_x lead to the release of hydrogen ions (H^+) when the gases are mineralised. The protons contribute to the acidification of soils and water when they are released in areas where the buffering capacity is low, resulting in forest decline and lake acidification.

Acidification potential is expressed in hydrogen ion equivalents (mol H^+-eq).

C.3 Eutrophication Potential

This impact category is related to nutrients (mainly nitrogen and phosphorus) from sewage outfalls and fertilised farmland that accelerate the growth of algae and other vegetation in water.

The degradation of organic material consumes oxygen, resulting in oxygen deficiency and, in some cases, fish death. Eutrophication translates the quantity of substances emitted into a common measure, expressed as the oxygen required for the degradation of dead biomass.

To assess the impacts due to eutrophication, three EF impact categories are used: eutrophication, terrestrial; eutrophication, freshwater; eutrophication, marine. These are expressed in nitrogen equivalents (mol N-eq), phosphorus equivalents (kg P-eq) and nitrogen equivalents (kg N-eq), respectively.

C.4 Ozone Depletion Potential

This impact category accounts for the degradation of stratospheric ozone due to emissions of ozone-depleting substances, for example, long-lived chlorine and bromine-containing gases (e.g. chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), halons).

Ozone depletion potential is expressed in trichlorofluoromethane equivalents (kg CFC-11-eq).

C.5 Photochemical Oxidant Formation

This impact category accounts for the formation of ozone at the ground level of the troposphere caused by photochemical oxidation of volatile organic compounds (VOCs) and carbon monoxide (CO) in the presence of nitrogen oxides (NO_x) and sunlight.

Photochemical oxidant formation is expressed in non-methane volatile organic compounds equivalents (kg NMVOC-eq).

C.6 Particulate Matter

This impact category accounts for the adverse effects on human health caused by emissions of particulate matter and its precursors (NO_x, SO_x, NH3).

Particulate matter formation is expressed in disease incidents.

C.7 Human Toxicity

Human toxicity accounts for adverse health effects on human beings caused by the intake of toxic substances through inhalation of air, food/water ingestion, and penetration through the skin. Within environmental impact assessment, two distinct impact categories are associated with human toxicity: carcinogenic and non-carcinogenic effects. These categories delineate the adverse health outcomes linked specifically to cancer or other non-cancer effects, excluding those caused by particulate matter/respiratory inorganics or ionising radiation.

Human toxicity is expressed in comparative toxic units (CTUh).

C.8 Freshwater Ecotoxicity

This impact category addresses the toxic impacts on an ecosystem, which damage individual species and change the structure and function of the ecosystem. Ecotoxicity is a result of a variety of different toxicological mechanisms caused by the release of substances with a direct effect on the health of the ecosystem.

Freshwater ecotoxicity potential is expressed in comparative toxic units (CTUe).

C.9 Ionising Radiation, Human Health

This impact category accounts for the adverse health effects on human health caused by radioactive releases.

Ionising radiation, human health, is expressed in uranium-235 equivalents (kBq ^{235}U-eq).

C.10 Resource Use

Resource use, fossil, addresses the use of non-renewable fossil natural resources like natural gas, coal and oil. On the other hand, resource use, minerals and metals, pertains to the use of non-renewable abiotic (non-living) natural resources such as iron ore and other minerals.

Fossil resource use and minerals and metals resource use are expressed in terms of net calorific value (MJ) and antimony equivalents (kg Sb-eq), respectively.

C.11 Land Use

This impact category is related to the use (occupation) and conversion (transformation) of land area by activities such as agriculture, forestry, roads, housing, mining, etc. Land occupation considers the effects of the land use, the amount of area involved and the duration of its occupation (changes in soil quality multiplied by area and duration). Land transformation considers the extent of changes in land properties and the area affected (changes in soil quality multiplied by the area).

Land use is dimensionless.

C.12 Water Use

This impact category represents the relative available water remaining per area in a watershed after demand from humans and aquatic ecosystems has been met. It assesses the potential for water deprivation, to either humans or ecosystems, based on the assumption that the less water remaining available per area, the more likely it is that another user will be deprived.

Water use is expressed in cubic meters of world water equivalents (m^3 world-eq).

D

Appendix: Characterised Results of Virgin Polypropylene

The data provided originates from a critically reviewed LCA study of all Borealis PP products across different production sites. From this study, an average of the LCIA results of two products from Burghausen was taken.

The study was performed in 2022 and follows the Plastics Europe eco-profiles methodology version 3.1 (Plastics Europe, 2022). Since then, it has been updated to include the latest ecoinvent data, transitioning from version 3.8 to 3.9. This update was particularly focused on incorporating the most recent information regarding oil and gas supply chains (ecoinvent, 2023).

It is important to note that an economic allocation methodology was already applied at the stage of polymerisation and pelletising to account for the by-products generated during these processes.

Table 13: [Pseudonymised data] LCIA results for virgin PP production at Burghausen.

Impact category	**Unit**	**Value**
Climate change, fossil	kg CO_2-eq	2.90
Acidification potential	mol H^+-eq	1.96E-02
Freshwater eutrophication	kg P-eq	4.75E-04
Marine eutrophication	kg N-eq	1.90E-03
Terrestrial eutrophication	mol N-eq	1.83E-02
Ozone depletion potential	kg CFC-11-eq	2.66E-07
Photochemical oxidant formation	NMVOC-eq	1.48E-02
Particulate matter formation	disease incidents	7.08E-08
Human toxicity, carcinogenic	CTUh	7.38E-10
Human toxicity, non-carcinogenic	CTUh	2.09E-08

Continued on next page

Table 13 – *Continued from previous page*

Impact category	**Unit**	**Value**
Freshwater ecotoxicity	CTUe	79.6
Ionising radiation, human health	kBq ^{235}U-eq	1.27E-01
Resource use, metals and minerals	kg Sb-eq	4.63E-06
Resource use, fossil	MJ	104.4
Land use	dimensionless	9.17
Water use	m^3 world-eq	3.83E-01

E

Appendix: Detailed LCIA Results

Table 14: [Pseudonymised data] LCIA results for NAV-128 at mtm using system expansion and mass allocation for the PIW.

Impact category	**Unit**	**System expansion**	**Mass allocation**
Climate change, fossil	kg CO_2-eq	-2.03	8.81E-01
Acidification	mol H^+-eq	-1.84E-02	1.34E-03
Freshwater eutrophication	kg P-eq	6.44E-05	5.42E-04
Marine eutrophication	kg N-eq	-1.47E-03	4.45E-04
Terrestrial eutrophication	mol N-eq	-1.49E-02	3.49E-03
Ozone depletion	kg CFC-11-eq	-2.59E-07	8.18E-09
Photochemical oxidant formation	NMVOC-eq	-1.36E-02	1.33E-03
Particulate matter	disease incidents	-5.49E-08	1.62E-08
Human toxicity, carcinogenic	CTUh	6.75E-10	1.42E-09
Human toxicity, non-carcinogenic	CTUh	-1.66E-08	4.48E-09
Freshwater ecotoxicity	CTUe	-77.32	2.73
Ionising radiation	kBq ^{235}U-eq	-3.01E-02	9.71E-02
Resource use, metals and minerals	kg Sb-eq	-3.47E-06	1.18E-06
Resource use, fossil	MJ	-96.44	8.50
Land use	dimensionless	-6.53	2.69
Water use	m^3 world-eq	-2.82E-01	1.04E-01

Table 15: [Pseudonymised data] LCIA results for NAV-128 at mtm using economic allocation and a cut-off approach for the PIW.

Impact category	**Unit**	**Economic allocation**	**Cut-off**
Climate change, fossil	kg CO_2-eq	8.68E-01	8.65E-01
Acidification	mol H^+-eq	1.25E-03	1.23E-03
Freshwater eutrophication	kg P-eq	5.40E-04	5.39E-04
Marine eutrophication	kg N-eq	4.37E-04	4.35E-04
Terrestrial eutrophication	mol N-eq	3.42E-03	3.39E-03
Ozone depletion	kg CFC-11-eq	7.03E-09	6.74E-09
Photochemical oxidant formation	NMVOC-eq	1.27E-03	1.25E-03
Particulate matter	disease incidents	1.59E-08	1.58E-08
Human toxicity, carcinogenic	CTUh	1.41E-09	1.41E-09
Human toxicity, non-carcinogenic	CTUh	4.39E-09	4.37E-09
Freshwater ecotoxicity	CTUe	2.39	2.30
Ionising radiation	kBq ^{235}U-eq	9.66E-02	9.65E-02
Resource use, metals and minerals	kg Sb-eq	1.16E-06	1.16E-06
Resource use, fossil	MJ	8.05	7.94
Land use	dimensionless	2.65	2.64
Water use	m^3 world-eq	1.02E-01	1.01E-01

F

Appendix: Detailed Contribution Analysis Results

In this section, the numeric values from the contribution analysis are presented for each activity and impact category in Tables 16–19.

Table 16: [Pseudonymised data] Contribution analysis results for NAV-128 at mtm using the cut-off approach for the PIW. (1/4)

Activity	**Climate change** (kg CO_2-eq)	**Acidification** (mol H^+-eq)	**Freshwater eutrophication** (kg P-eq)	**Marine eutrophication** (kg N-eq)
Transport	9.01E-2	2.13E.4	6.37E-6	5.59E-05
Shredding & Milling	2.69E-2	5.55E-05	3.68E-05	1.88E-05
Mixing & Dry Blending	4.45E-2	9.17E-05	6.1E-05	3.11E-05
Extrusion	3.12E-01	6.43E-04	4.27E-04	2.18E-04
Additives	1.52E-02	9.59E-05	7.880E-06	5.02E-05
Municipal Transport	1.76E-02	8.71E-05	3.24E-07	3.91E-05
Incineration	3.59E-01	4.39E-05	3.24E-07	2.18E-05
Total	8.65E-01	1.23E-03	5.39E-04	4.34E-04

Table 17: [Pseudonymised data] Continuation of the contribution analysis results for NAV-128 at mtm using the cut-off approach for the PIW. (2/4)

Activity	**Terrestrial eutrophication** (mol N-eq)	**Ozone depletion** (kg CFC-11-eq)	**Photochemical oxidant formation** (NMVOC-eq)	**Particulate matter** (disease incidents)
Transport	6.04E-04	1.88E-09	3.70E-04	8.78E-09
Shredding & Milling	1.28E-04	2.79E-10	4.12E-05	2.69E-10
Mixing & Dry Blending	2.12E-04	4.63E-10	6.81E-05	4.44E-10
Extrusion	1.49E-03	3.24E-09	4.77E-04	3.11E-09
Additives	2.99E-04	3.24E-9	5.87E-05	8.22E-10
Municipal Transport	4.29E-04	3.45E-10	1.80E-04	2.18E-09
Incineration	2.30E-04	5.25E-11	5.67E-05	1.99E-10
Total	3.39E-03	6.73E-09	1.25E-03	1.58E-08

Table 18: [Pseudonymised data] Continuation of the contribution analysis results for NAV-128 at mtm using the cut-off approach for the PIW. (3/4)

Activity	**Toxicity carcinogenic** (CTUh)	**Toxicity non-carcinogenic** (CTUh)	**Freshwater ecotoxicity** (CTUe)	**Ionising radiation** (kBq ^{235}U-eq)
Transport	5.77E-10	8.93E-10	3.20E-01	1.64E-03
Shredding & Milling	4.66E-11	1.97E-10	9.35E-02	6.58E-03
Mixing & Dry Blending	7.72E-11	3.26E-10	1.55E-01	1.09E-02
Extrusion	5.41E-10	2.28E-09	1.09	7.62E-02
Additives	1.07E-10	2.96E-10	5.55E-01	9.45E-04
Municipal Transport	2.54E-11	3.67E-11	1.59E-02	8.68E-05
Incineration	2.99E-11	3.37E-10	7.74E-02	5.79E-05
Total	1.41E-09	4.37E-09	2.30	9.65E-02

Table 19: [Pseudonymised data] Continuation of the contribution analysis results for NAV-128 at mtm using the cut-off approach for the PIW. (4/4)

Activity	**Resource use metals & minerals (kg Sb-eq)**	**Resource use (MJ)**	**Land use (dimensionless)**	**Water use (m^3 world-eq)**
Transport	2.58E-07	1.35	1.36	6.80E-03
Shredding & Milling	5.24E-08	4.26E-01	7.07E-02	5.53E-03
Mixing & Dry Blending	8.68E-08	7.05E-01	1.17E-01	9.16E-03
Extrusion	6.08E-07	4.94	8.21E-01	6.41E-02
Additives	1.33E-07	2.63E-01	2.38E-01	6.19E-03
Municipal Transport	1.11E-08	2.19E-01	2.45E-02	3.96E-04
Incineration	7.64E-09	2.62E-02	6.33E-03	9.25E-03
Total	1.16E-06	7.93	2.64	1.01E-01

DEPARTMENT OF TECHNOLOGY MANAGEMENT AND ECONOMICS
DIVISION OF ENVIRONMENTAL SYSTEMS ANALYSIS
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden
www.chalmers.se

CHALMERS
UNIVERSITY OF TECHNOLOGY