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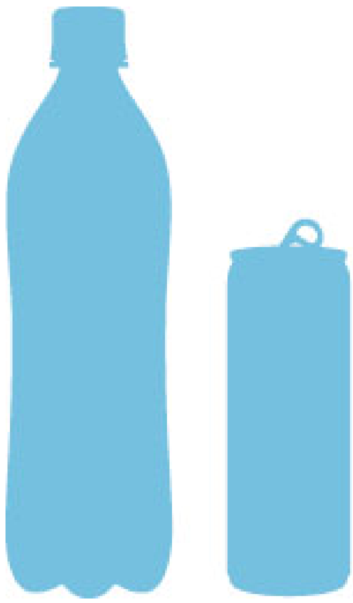

End-of-Life Pathways for Beverage Packaging

An LCA study on the Swedish deposit system, conventional recycling and incineration with energy recovery

Master's thesis in Industrial Ecology

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Abstract

In line with the EU Directive on Packaging and Packaging Waste (PPWD), a fundamental shift in how packaging is designed and managed is required to reduce environmental impacts and support the transition to a circular economy. This master's thesis conducts a life cycle assessment (LCA) of waste management systems for PET bottles and aluminium cans in Sweden. The systems studied are Returpack's deposit system, conventional recycling, and incineration with energy recovery. The study aims to investigate the environmental impact of each system based on four categories, in accordance with the LCA methodology. The study seeks to highlight the most significant processes by identifying key environmental hotspots across the systems and provide practical recommendations for promoting more sustainable packaging waste management in Sweden.

The study shows that the deposit system generally results in the lowest environmental impact, as it enables closed loop recycling and maintains high material quality. Incineration with energy recovery generally has the highest environmental impact. In all investigated impact categories, the recycling process is the largest contributor to the deposit and conventional recycling systems' environmental impact. A common factor contributing to the environmental impact across the three PET systems is the incineration of PET that cannot be recycled, along with other residual waste generated in the processes. Regarding aluminium cans, the high electricity consumption within the recycling process in the deposit system and the addition of metals in the conventional recycling process are the main contributors to the systems' environmental impact.

Differences in collection rates and consumer behavior between the systems were not fully accounted for, despite their potential to influence environmental impacts. Future studies should investigate these aspects to provide a more comprehensive assessment. The results highlight the importance of preserving material quality, efficient sorting, and technological advancements. Recycling is shown to be an effective strategy for a circular economy, particularly when implemented as closed loop recycling, as in the deposit system. This approach keeps materials in use longer and reduces the demand for new virgin resources.

Keywords: Life Cycle Assessment, LCA, Circular Economy, Deposit System, Recycling, Incineration with Energy Recovery, Beverage Packaging

Acknowledgements

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A big thank you also goes to our collaborators at RISE, who have provided us with valuable input, constructive feedback, and assistance throughout the project. Last but not least, we would like to thank all the companies, municipalities, county administrative boards and other experts who have shared invaluable insights and data that have been crucial for our thesis.

Moa Frisk & Linn Wilson, Gothenburg, June 2025

List of Acronyms

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

CBG	Compressed biogas
EPR	Extended producer responsibility
EoL	End-of-life
HDPE	High density polyethylene
HVO	Hydrotreated vegetable oil
LBG	Liquefied biogas
LCA	Life cycle analysis
LCI	Life cycle inventory assessment
LCIA	Life cycle impact assessment
PEF	Product environmental footprint
PET	Polyethylene terephthalate
PPWD	Packaging and Packaging Waste Directive
RVM	Reverse vending machine
URRC process	United Resource Recovery Corporation process
WF	Washed flakes

Glossary

Below are translations of words from English to Swedish that have been used throughout this thesis, listed in alphabetical order:

Bulk flow	Lösviktsflöde
Closed loop recycling	Sluten återvinning där materialet återvinns till samma typ av produkt, med liten eller ingen försämring i kvalitet.
Eddy current separator	Virvelströmsseparator
Food grade	Livsmedelsklassat
Intermediate storage	Mellanlager
Open loop recycling	Öppen återvinning där materialet återvinns till en annan typ av produkt, ofta med försämrad kvalitet
Reverse vending machine (RVM)	Pantautomat
Sieve	Sikt
Sorting analysis	Plockanalys
Two chamber rear trucks	Baklastad sopbil med två fack

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1 Introduction

Global resource consumption has continued to increase in the recent years (IRP, 2024). Global supply chains are characterized by high vulnerability due to global factors such as pandemics and inflation. The situation is further complicated by an expected increase in material demand over the coming decades, resulting from population growth and increasing consumption levels. In Sweden, material consumption has risen by 25% since 2010 (Naturvårdsverket, 2024b). Much of this consumption still follows the logic of a linear economy, typically described as "extract, make, dispose" (IRP, 2024).

Extended Producer Responsibility (EPR) schemes, starting with the 1994 Directive on packaging and packaging waste, were an early step in EU waste policy to manage end-of-life products and pursue goals like recovery and recycling (Pouikli, 2020). However, current EPR schemes have had limited influence on promoting eco-design and have not succeeded in motivating packaging producers to adopt circular approaches. As a result, linear features such as single-use packaging and high levels of unrecycled waste remain widespread. EPR schemes represent an important step in managing packaging waste, yet further progress is needed to fully realize circular design principles. The circular economy aims to keep products, materials, and resources in use for as long as possible, thereby reducing waste generation and minimizing environmental impacts (IRP, 2024).

However, in Sweden alone, approximately 1.7 million tonnes of plastic waste is generated annually, of which nearly 80% is incinerated (Naturvårdsverket, 2024a). Only a small share of the produced plastic is recycled. The heavy reliance on incineration results in significant greenhouse gas emissions. More than half of the CO_2-equivalents from the electricity and district heating sector comes from the combustion of fossil based materials. Furthermore, more than half of the greenhouse gas emissions associated with the life cycle of plastic result from its incineration.

In contrast to plastic, the most common pathway for aluminium is recycling. According to Geological Survey of Sweden (2022) the average recycling rate of aluminium is 73%. Only about 5% of the energy needed for primary production of aluminium is needed to recycle the metal. Combined with aluminium's high metal value, this makes recycling both energy-efficient and economically attractive. Currently, more than one third of Europe's aluminium production comes from recycled aluminium. Open loop recycling is the most common type of recycling for aluminium (Paraskevas et al., 2015). The drawback of open loop recycling is that it often includes down cycling to alloys with lower purity requirements. In contrast, closed loop recycling aims to maintain the quality and alloy composition of the aluminium, recycling it back to the same or another high quality application.

To support the transition to a circular economy, various incentives have been introduced at both European and national levels (European Union, 2025). One such initiative is the EU regulation on packaging and packaging waste, where EU countries aim to take measures to minimize the environmental impact of packaging. By 2030, 70% of all packaging waste must be recycled, including 55% of plastic and 60% of aluminium. Sweden has therefore adopted an updated regulation on extended producer responsibility in response to this directive (SFS 2022:1274). In this regulation, it is stated, among other things, that plastic beverage bottles and aluminium beverage cans must be included in a return system.

In Sweden, Returpack has been the producer responsibility organization responsible for almost all PET and aluminium beverage packaging since 1984 (Pantamera, 2025c). Returpack manages the only authorized recycling system for beverage packaging. This system is a closed loop system where cans become cans and bottles become bottles again. Returpack is responsible for the collection, sorting, and baling of the packaging, which is then sold to recyclers and later producers of new beverage packaging. Consumers pay a deposit fee for each beverage container, which is refunded when the container is returned through the deposit system. In addition to this, producers are charged a packaging fee by Returpack to cover the costs associated with the collection and handling of the returned packaging. The national collection goal for both aluminium cans and plastic bottles is established at 90%. In year 2024, the measured collection rate was 87.6%. To meet the national goal, Returpack works to increase accessibility, simplicity and outreach to the public.

This study will investigate Returpack's deposit system and its environmental impact. Additionally, it will investigate two different end of life alternatives, conventional material recycling and material incineration with energy recovery, focusing on their individual environmental impacts. This study aims to provide a broader understanding of different waste management alternatives and their environmental impact.

1.1 Aim and research questions

According to the Swedish Waste Ordinance, Avfallsförordningen, (SFS 2022:614), consumers are legally obligated to return plastic bottles and metal cans to the designated deposit return system. However, in practice, some packaging may still end up in the recycling bin or be discarded as residual waste, which in Sweden is typically treated by incineration with energy recovery. Therefore, although the ordinance requires consumers to use the deposit system, three practical disposal routes exist: returning to the deposit system, placing packaging in recycling bins, or disposing of it via residual waste.

The aim of the study is to investigate the environmental impact of deposit systems, conventional recycling, and incineration with energy recovery. The study includes three waste management pathways for PET bottles, deposit system, conventional recycling, and incineration with energy recovery and two pathways for aluminium cans, deposit system and conventional recycling. Incineration with energy recovery is excluded for aluminium due to a minor portion being treated as residual waste. By collecting data on the separate systems and performing an LCA study, the aim is to analyze their individual environmental impacts and how they share similarities and differences.

Furthermore, the study aims to identify environmental hotspots. Hotspots are the activities that cause the greatest environmental impact of a product system (Baumann & Tillman, 2004). Identifying such hotspots can help target the most effective improvements within the systems and support decision making towards more sustainable waste management strategies. To facilitate understanding of the three different end-of-life systems, an initial flow chart illustrating their structure is presented in Figure 1.1. The system boundaries are explained later Section in 3.2.2.

To support the aim of the study, the following research questions were created:

1. What are the environmental impacts associated with the end-of-life management for beverage packaging for the systems: deposit system, conventional recycling, and incineration with energy recovery?
2. What are the environmental hotspots in the end-of-life systems for PET and aluminium?
3. What could reduce the environmental impact of the different end-of-life systems?

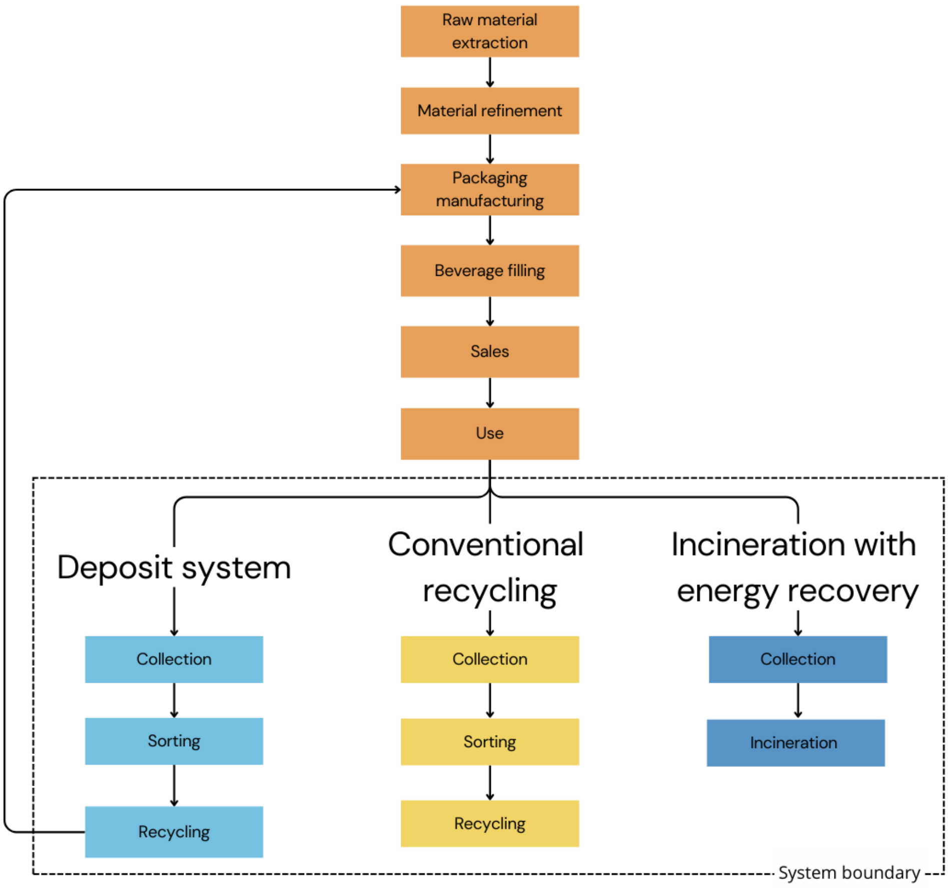


Figure 1.1: General and initial flowchart of three end-of-life systems for beverage packaging

The choice of LCA as the assessment method is based on its comprehensive and standardized framework for quantifying environmental impacts across multiple categories (Baumann & Tillman, 2004). This allows for an exploration and understanding of the environmental impact of the different EoL management systems. This method is particularly well-suited to the present study because it enables a comprehensive assessment of the environmental performance and improvement potential of systems that share similar functions but differ in their structure. Despite its strengths, the method has limitations related to data availability, quality, and the assumptions made regarding system boundaries and allocation.

The study is based on several key assumptions. Most importantly, access to detailed data primarily from Returpack is essential for modeling the deposit system with a high accuracy. Additionally, a combination of both primary and secondary data enables the modeling of the conventional recycling system and incineration with energy recovery. However, there are certain limitations associated with the study. The collection rate has not been fully quantified which should be considered in the interpretation of the results. Furthermore, the use of secondary data may affect the reliability of the results of the conventional recycling system and incineration with energy recovery.

The results of the study can be used to provide recommendations to Returpack on how to improve the performance of the deposit system. Furthermore, the study will identify areas where additional research is necessary to address data gaps, reduce uncertainties, and enhance the study's scope. This will enable a deeper and more accurate understanding of environmental impacts in future studies.

1.2 Earlier studies

Several studies have been conducted on the EoL management of beverage packaging. In Norway, a study published in 2023 examined the Norwegian deposit system in comparison to an alternative reuse system (NORSUS, 2023b). Norway has operated a deposit system similar to Sweden's since 1999. The aim of the study was to compare the deposit system for PET bottles and aluminum cans with an alternative system for reusable PET and glass bottles. The study also included the production of the packaging. Additionally, it focused on different modeling approaches, using Cut-off, Circular Footprint Formula (CFF), and System Expansion. The results varied depending on the chosen approach. The study evaluated four impact categories: climate change, cumulative energy demand, terrestrial acidification, and mineral resource scarcity. The study found that the single-use system performed better than the reuse system in the impact categories of climate change, cumulative energy demand, and terrestrial acidification. In contrast, the reuse system had the lowest impact in terms of mineral resource scarcity. When focusing solely on the deposit system, it was found that the high recycling rate led to significant avoided environmental burdens. Consequently, the high initial impact of producing materials such as aluminum is largely offset by the benefits of replacing virgin production through recycling.

NORSUS published another study which aimed to assess and compare the environmental impact of different beverage packaging production and collection systems for PET bottles and aluminium cans in Norway using an LCA approach (NORSUS, 2023a). The systems assessed were the Norwegian deposit system, the curbside collection system for plastic packaging, and residual waste incineration. The impact categories investigated included climate change, abiotic depletion, acidification, and eutrophication. The functional unit chosen was "Production, collection, and treatment of PET bottles and aluminium cans used for distributing 1000 liters of beverage to consumers." The results showed that the Norwegian deposit system had lower environmental impact than the curbside system due to its higher collection rate, while the incineration system performed the worst. When excluding the contribution from PET production, the deposit system outperformed the others in all categories except eutrophication, where the curbside collection performed better due to lower incineration emissions. In the categories of acidification and eutrophication, reverse vending machines contributed significantly within the deposit system because of the production of electronic components. Furthermore, achieving high collection rates for bottles was found to be crucial, since improved collection typically leads to better environmental outcomes for the systems. However, the authors importantly noted that collection and treatment activities accounted for less than 10% of the total environmental impact across all systems.

Returpack also conducted studies in 2018 aimed at examining the environmental impact of three waste management systems for handling aluminium cans and PET bottles, respectively (Bertils et al., 2018; Hemmingsson et al., 2018). The functional unit used in both studies was "the management of packaging for 1,000 liters of beverage." The impact categories investigated included climate change, acidification, ozone depletion, and eutrophication. Results from both studies showed that the deposit system performed better for aluminium cans across all impact categories, largely due to lower spill fractions compared to the other two systems. Similar results were found for PET bottles, except in the ozone depletion category, where the conventional recycling system and incineration with energy recovery demonstrated a greater degree of avoided environmental impact. However, since then, the management of the conventional recycling system has changed and is now overseen by a different producer responsibility organization.

Multiple studies have examined the environmental impact of different types of beverage packaging. In 2024, the Swedish Brewery Organization (Sveriges Bryggerier) published an LCA study conducted by RISE on beverage packaging (Löfgren et al., 2024). This study focused on the environmental impacts of various beverage packaging types, covering all phases of the packaging's life cycle. The assessed packaging types included glass bottles, PET bottles, aluminum cans, as well as bag-in-box, kegs, tanks, and Tetra Briks. The functional unit was defined as "distribution of 1 liter of beverage including packaging to the end consumer, including collection and recycling of the packaging." This study was an updated version of a similar assessment conducted in 2018. The systems analyzed included raw material extraction, packaging manufacturing, handling and transportation through the value chain to the consumer, as well as reuse and material recycling of the packaging. The results showed that the 150 cl PET bottle packaging solution demonstrated the best environmental performance for distributing 1 liter of beverage to consumers (including the drinking container), with the lowest climate impact per liter delivered. Additionally, the study found that during the distribution of the different beverage systems, as well as during collection and recycling, a larger share of renewable fuels with lower climate impact than diesel is used.

1.3 Outline of report

This thesis is structured to provide an impact based assessment of different EoL systems for beverage packaging, with a particular focus on their environmental impact. The report begins with an introduction which gives context to the study and is followed by an outline of the aim of the study, research questions and a review of earlier studies performed. Chapter 2 outlines the methodological approach with a focus on LCA in line with ISO standards 14040 and 14044. It highlights the four stages of an LCA. Furthermore, the method for collecting data, allocation principles and chosen sensitivity and scenario analyses are described.

The goal and scope is explained in Chapter 3 including the functional unit, system boundaries, limitations, data quality requirements and selected impact categories. The chapter ends with a technical background presenting information about the studied systems. Assumptions related to these systems are further detailed in the Life Cycle Inventory, Chapter 4, where data and assumptions for all systems are thoroughly described and evaluated.

Chapter 5 presents the numerical results of the investigated systems. The results are presented in relation to the avoided production of virgin material and heat and electricity. Furthermore, the results from the scenario and sensitivity analyses are presented in this chapter. Chapter 6 addresses the hotspots of the systems and outlines potential areas for improvements. A discussion of the methodology and future research suggestions are presented here. The report concludes in Chapter 7 with the key insights from the study.

2
Methodology

This chapter presents the methodology used to conduct the life cycle assessment (LCA) in this study. The methodology follows the international standards ISO 14040 and ISO 14044, which define the principles and framework for performing LCAs. This chapter also describes how the methodology was applied in practice.

2.1 Life cycle assessment methodology

Life Cycle Assessment (LCA) is a methodology used to assess the environmental impacts of products and services throughout their entire life cycle (Baumann & Tillman, 2004). An LCA evaluates the complete product system, from raw material extraction, production, and transportation, to use and end-of-life management, including material recycling. The environmental impacts are linked to specific products or materials, and the results are expressed in relation to the product's function. This functional basis enables fair comparisons between alternative products or systems that fulfill the same purpose.

2.1.1 Life cycle assessment framework

According to Baumann and Tillman (2004), the application of an LCA can be very broad. Common uses include identifying opportunities to improve the environmental performance of products, informing decision makers, selecting relevant indicators, and supporting marketing efforts (ISO, 2006a). Additionally, LCA serves as a valuable tool for gaining a deeper understanding of a product system and its interactions (Baumann & Tillman, 2004). This LCA follows the standards of ISO 14040 and ISO 14044. There are four stages in an LCA study (ISO, 2006a). These are the goal and scope definition, inventory analysis, impact assessment and interpretation, see Figure 2.1. These will be explained in more detail below.

2.1.2 Goal and scope definition

The goal and scope definition is the first stage of the LCA methodology. In this stage, the product to be studied and the purpose are decided on (Baumann & Tillman, 2004). According to ISO (2006a) the goal of an LCA contains the intended application, why the study is carried out, the intended audience and the use of the results. The last mentioned part also highlights whether the results are intended to be used for comparison and whether or not it should be disclosed to the public. The

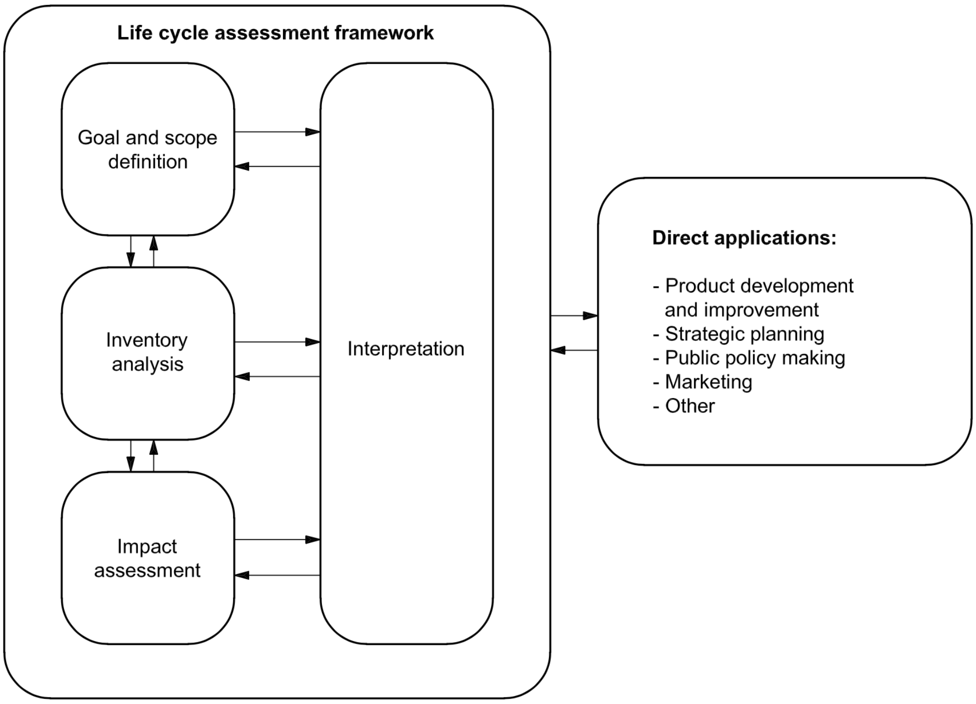


Figure 2.1: Stages of an LCA (ISO, 2006a)

goal of an LCA is important as it guides the aspects of the LCA which create the scope (Silva, 2021). Therefore, the goal should be clearly defined.

The scope involves detailed specification of various elements according to the study's goal (Silva, 2021). According to ISO (2006a), these elements include, but are not limited to, the functional unit, system boundaries, allocation procedures, and assumptions. In addition, impact categories are chosen as well as the methodology for impact assessment. The functional unit makes a quantification of the function of the product. It aims to act as a reference, and the input and outputs are related to it. The functional unit makes the results comparable as comparisons can be created on a common basis. The reference flow is also crucial and determined in relation to the functional unit. The reference flow is for example the amount of products needed to fulfill the decided function. The system boundaries chosen shape the system by deciding what processes are included.

2.1.3 Inventory analysis

The second stage of an LCA is the life cycle inventory (LCI) (ISO, 2006a). The LCI includes data collection and calculation procedures to quantify relevant input and output of the system. The data collection can include inputs and outputs such as energy, raw materials, products, and emissions. The collected data can be either primary data, obtained directly from specific processes (e.g., through measurements or site-specific information), or secondary data, which is typically sourced from literature or life cycle inventory databases such as Ecoinvent. As data collection can be a demanding process, constraints on the data collection should be discussed in the scope of the study and considered in the LCI. The data collection is succeeded by data calculations, which involve validation and relating the data to the unit processes and the reference flow or functional unit. The LCI also includes the allocation of flows, where a choice of allocation procedure needs to be made. This is particularly important when a system creates multiple products.

2.1.4 Impact assessment

The next stage of the LCA is the life cycle impact assessment (LCIA) (ISO, 2006a). In this step, the environmental impact of the system is evaluated. The impact assessment describes the environmental loads, from the inventory, into environmental impacts. The inventory data is connected to certain impact categories (Baumann & Tillman, 2004). These impact categories can be, for example, freshwater ecotoxicity, terrestrial acidification and climate change. These categories makes it easier to relate to the results and it increases comprehensibility and communication. According to ISO (2006a) the mandatory elements of an LCIA are: selection of impact categories, category indicators and characterization models, classification and characterization. An LCIA can also include normalization, grouping and weighing. When selecting impact categories, they must be justified and in line with the goal and scope of the LCA (ISO, 2006b). The ISO-standard gives the areas of protection: natural environment, resource use and human health. These are what are considered endpoints and are broken down into midpoint impact categories in the ReCiPe method (Huijbregts et al., 2017), see Figure 2.2. ReCiPe is a method used for the impact assessment and uses the midpoint and endpoints to derive characterization factors.

During classification, the LCI results are organized and assigned to different impact categories, where some environmental loads may be linked to multiple categories (Baumann & Tillman, 2004). In the characterization stage, these results are converted into common units within each impact category, resulting in a quantitative outcome (ISO, 2006b). Normalization involves relating the characterized values into reference information. The grouping is the sorting and ranking of the impact categories. Weighing is the last optional step where the results are weighted in relation to each other in regard to their relative importance.

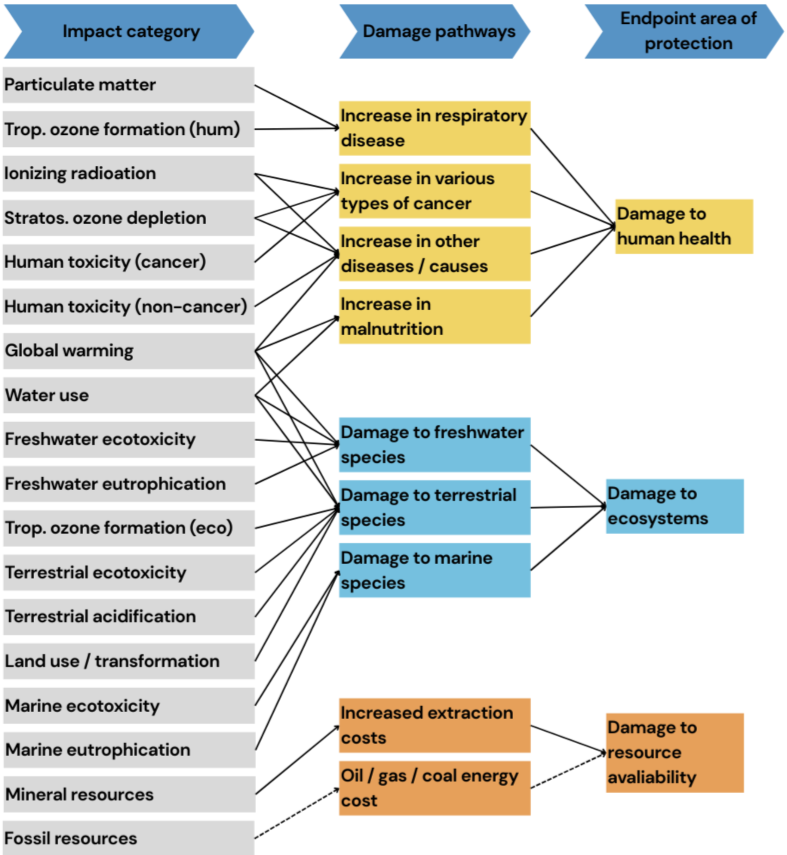


Figure 2.2: Overview of the impact categories that are covered in the ReCiPe 2016 methodology and their relation to the areas of protection. Image modified from Huijbregts et al. (2017), licensed under CC BY 4.0.

2.1.5 Interpretation

The last stage of the LCA is the life cycle interpretation. In this step the findings from the LCI and LCIA are considered and results are delivered in line with the goal and scope definition (ISO, 2006a). However, Baumann and Tillman (2004) also claim that results outside the scope and goal could be given attention as they show potential for learning. For example, although the production of recycling equipment can be excluded from the system boundaries of the current study, the life cycle inventory analysis may show that the energy consumption associated with the production of such equipment contributes significantly to the overall environmental impact. This suggests that upstream processes that were initially considered negligible may warrant further investigation and possible inclusion in future assessments. The findings of the interpretation can be presented in as conclusions and recommendations, often visualized in diagrams. The results can for example show the largest environmental loads or those which are particularly problematic. Different ways of presenting results can convey different messages and influence interpretation. Evaluation is another key part of the interpretation stage, as it helps to assess the robustness of both the results and the conclusions drawn. Sensitivity analysis involves changing input parameters and observing how the results respond. These methods are useful for testing the robustness of the LCA and determining whether the conclusions still hold despite changes in the underlying data.

2.2 Modeling and data collection

This section presents the methods used for data collection and life cycle modeling. It describes the sources of data, the software used for modeling, and the principles applied to allocation. Finally, it outlines how the robustness of the results was assessed.

2.2.1 Data collection

Data for this study was collected through a combination of direct contact with relevant stakeholders and review of existing reports and documentation. Sustainability reports, environmental reports, and other company and government documents have been analyzed to collect information on material flows, resource use, emissions, and energy use. In addition, email correspondence was conducted with companies, municipalities, and experts to supplement current and site-specific information where public data were unavailable. The main contributors are summarized in Table 2.1. When primary data was not available, the database Ecoinvent 3.9, cut-off by classification, was used. For several parts of the system, for example for fuel data (HVO, CBG, and LBG), specific life cycle inventory datasets were not available in Ecoinvent 3.9. Therefore, custom datasets were constructed using data compiled from various reports and literature sources. This included estimating resource use, emissions, and energy content based on reported values and assumptions. Overall, the data collection was the most time-consuming aspect of this study.

2.2.2 LCA software tool

Activity Browser is an open source software developed to facilitate advanced LCA (Steubing et al., 2020). It functions as a graphical user interface for the Brightway framework, which has been under continuous development since 2012 and is one of the most flexible tools for LCA modeling. Development of the Activity Browser began shortly after the release of Brightway version 2, with the aim of making common LCA tasks more accessible and intuitive. Activity Browser enables users to manage projects and databases, model life cycle inventories, and analyse results in a user-friendly environment. In addition, the software supports calculations for multiple functional units and impact categories simultaneously, making it a powerful tool for both research and applied environmental analysis.

2.2.3 Allocation principles

Allocation problems occur when several products share processes, requiring environmental loads to be divided between products (Baumann & Tillman, 2004). When-

	Contact person and role	Data insights
Returpack	Elin Wiklund, Sustainability Strategist	General data about the deposit system
	Sara Bergendorff, Head of Sustainability and Quality	General data about the deposit system
	Erik Ebbeson, Customer Manager	General data about the deposit system
	Henric Oskarsson, Head of Technology and Development	Reverse vending machines, deposit system
	Jan Wendelin, Logistics Developer	Transport in collection of beverage packaging, deposit system
	Annsofie Bäck, Transport and Production Planner	Train transportation, deposit system
	Kjell Petersson, Factory Manager	Data about the sorting process, deposit system
Svensk Plaståtervinning	Linnea Granström, Climate & Environmental Strategist	Supply chain, conventional recycling

Table 2.1: Individuals who assisted with data and information through personal communication

ever possible, allocation should be avoided by expanding the system or increasing the level of detail. If this is not possible, the allocation should be based on the physical relationship such as mass or energy. If physical allocation is not possible, economic allocation can be used instead. This involves allocating impacts based on the market value or selling price of products. In this study, efforts have been made to avoid allocation whenever possible. However, when allocation could not be avoided, it has been thoroughly described and can be found in Chapter 4.

2.2.4 Robustness of the results

Several sensitivity and scenario analyses were carried out to test the robustness of the results (Baumann & Tillman, 2004). Sensitivity analyses were used to assess how changes in critical input data, such as variable "A", influence the overall outcome. These analyses help identify which parameters the results are most sensitive to. Scenario analyses, on the other hand, were used to explore the effects of alternative assumptions or system conditions. Unlike sensitivity analyses, scenario analyses can involve simultaneous changes in multiple variables, allowing for comparison between the base case and alternative situations. The analyses performed in this study are summarized in Table 2.2 and described in more detail in Section 5.2.

Table 2.2: Overview of the sensitivity and scenario analysis.

Analysis	Short description
Sensitivity analysis 1, PET	Modification of transportation fuels to the recycling site in Germany, Conventional recycling system
Sensitivity analysis 2, PET	Including transport to Reverse Vending Machines, Deposit system
Scenario analysis, PET	Increase in the production of food grade PET flakes at Veolia, Deposit system
Sensitivity analysis 1, Aluminium	Change in distance to sorting facilities, Conventional recycling system
Sensitivity analysis 2, Aluminium	Reduction of electricity consumption by 10% in the recycling process, Deposit system
Scenario analysis, Aluminium	Altering of metals in recycling process, Conventional recycling system

2.2.5 Declaration of interest

This study was conducted on behalf of Returpack, which assigned an internal supervisor to the project. Throughout the project, Returpack was involved through informal interviews and provided access to the data used in the assessment. Returpack reviewed and provided input on sections of the report describing their operations and the use of their data, as well as sections defining the study's goals and scope. Importantly, Returpack encouraged a conservative approach in cases of uncertainty, favoring worst-case assumptions over optimistic estimates to avoid overstating environmental performance. Despite their involvement, the study was conducted with the aim of remaining objective and transparent.

3 Goal and scope

This chapter presents the first phase of the LCA, which is to define the goal and scope of this study. This includes defining the purpose of the assessment, the intended application, and the system boundaries. A third-party critical review of this study has been undertaken.

3.1 Goal

The goal of the study is to examine three end-of-life systems for PET bottles and aluminium cans in terms of their environmental impact. The findings will provide data which can be used by Returpack to communicate the environmental impacts of the deposit system. The communication is aimed at their stakeholders, including supermarkets, restaurants, event organizers, material purchasers and the general public. Additionally, the study aims to contribute to a broader understanding of the EoL management systems.

Although Returpack only communicates the results of one of the systems externally, it is still valuable to include the other two systems in the study. Investigating the other systems provides Returpack with important insights into how its own system performs in relation to others. This internal benchmarking can highlight strengths and areas for improvement, inform future development, and support strategic decision making. In addition, evaluating multiple systems with similar purpose, managing waste, contributes to a broader understanding of the systems in general.

The study will include both PET bottles and aluminium cans. The chosen volumes are 50 cl for PET bottle and 33 cl for aluminium can. Data from Returpack indicated that these two sizes were the most frequently collected in 2024 and will therefore be the subject of study (E.Wiklund, personal communication, 29 January 2025). The Swedish market share of the different sizes of bottles and cans can be found in Table 3.1.

Table 3.1: The Swedish market share of the different sizes of PET bottles and aluminium cans

Volume	Market share	Total market share
PET 33 cl	22.4%	100%
PET 50 cl	33.3%	
PET 150 cl	27.3%	
PET other sizes	17%	
Aluminium can 33 cl	65.2%	100%
Aluminium can 50 cl	20.8%	
Aluminium other sizes	14%	

3.2 The scope

The scope defines the boundaries of the system and the level of detail of the assessment. In this study, the scope was defined to ensure consistency with the goal and to enable a comprehensive evaluation of the systems' environmental performance.

3.2.1 Functional unit

The functional unit is defined as **end-of-life management of packaging for 1,000 liters of beverage**. The functional unit is chosen to provide a clear and consistent basis for quantifying environmental impacts related to the packaging's end-of-life management. The primary function of the packaging is to contain the beverage, and the packaging would not exist independently of the beverage. A reference flow was created for the 50 cl PET bottle and 33 cl aluminium can, respectively, to more easily convert and normalize the data to the functional unit. The reference flow is the amount of material required to contain 1000 liters of beverage. The reference flow was calculated by reviewing the weights of all 50 cl PET bottles and all 33 cl aluminium cans available on the market. An average weight was then calculated for each packaging type. This was done due to differences in bottle design and material use. For example, a 50 cl PET bottle for Fanta does not necessarily weigh the same as one for Coca-Cola, although containing the same volume of beverage. The weight for PET 50 cl only includes the bottle itself. Therefore, the total weight for the reference flow of PET 50 cl beverage packaging is the sum of the reference flow for the bottle and the cap. These weights can be found in Table 3.2.

Table 3.2: The calculated reference flow of material for 1000 liters of beverage

Volume	Reference flow	Number of bottles/caps/cans
PET bottle 50 cl	43.21 kg PET	2000
Cap for PET bottle	4 kg HDPE	2000
Aluminium can 33 cl	38.67 kg aluminium	3030

3.2.2 System boundaries

This study defines the system boundaries starting at the point of collection of beverage packaging. Processes prior to this stage, including the raw material extraction and use phase, are excluded, as they are not affected by the choice of end-of-life treatment. Transportation to the collection point is therefore also excluded. To ensure consistency and clarity, the system boundaries are drawn at the same point, the collection stage.

For this study, it is assumed that consumers return beverage packaging to the deposit system during routine grocery shopping trips. Therefore no dedicated transport is allocated to these returns. This assumption is supported by the fact that the vast majority of bottles and cans are returned at grocery stores. To ensure consistency and clarity, the system boundaries are drawn at the same point, the collection stage. This boundary choice may result in an underestimation of the environmental impact of the transport related emissions for the deposit system. These uncertainties are further addressed in the sensitivity analysis to evaluate their potential influence on the results.

The deposit system was modeled as a closed loop system, where collected materials are returned to the same or equivalent product system. In contrast, the conventional recycling system was modeled as an open-loop system, where recycled materials may be used in a variety of different applications. Therefore, manufacturing of the final products was not included in either system boundary. For PET, the recycled output was modeled as flakes or granulate, and for aluminium as rolled sheets which are quite common intermediate products. To avoid assuming specific downstream applications, the system boundary was consistently set at the point where recycled PET or aluminium re-enters the market as a recycled raw material. Consequently, the substitution of material was modeled by determining how much virgin material could be replaced by recycled material, accounting for physical and economic losses and quality degradation. This approach allows for a fair comparison of the environmental benefits between the systems without overestimating the advantages of either.

In this study, each end-of-life system is modeled based on the assumption that one reference flow of packaging material has already been collected. This means that the collection rate has been disregarded. In Sweden, the current collection rate is approximately 53% for plastic packaging in the conventional recycling system and 87% for bottles and cans in the deposit system (Svensk Plaståtervinning, 2023; Pantamera, 2025c). These real world collection rates are not considered in the modeling. Instead, the study evaluates the potential environmental impact of each system when handling one reference flow. This impact is however evaluated in the later parts of the report.

The study aims to reflect the environmental impact of existing EoL systems during the year 2025. The studied deposit system is situated in Sweden. This is where most processes occur and the study is mainly limited to Sweden. However, processes regarding the raw material extraction occur outside of Sweden, usually even outside of the EU. Some of the recycling processes occur in the EU.

Only clear PET has been considered in this study. This is not reality as approximately 7% of the PET is colored and can therefore not become a new bottle. This choice was justified by the reasoning that this study considers the deposit system as a closed loop system, i.e. the material becomes a bottle again. Colored PET is used as material in products such as PET straps (S. Bergendorff, personal communication, 30 January 2025). The labels and glue on the bottles are also excluded as their mass is significantly smaller than that of the PET bottles, and considered to have a limited impact on the entirety of the system. This applies to all three PET systems.

3.2.3 Limitations

This study does not examine other beverage containers such as liquid cartons and glass bottles. This is because these types of beverage containers are not included in the current deposit system. Consequently, the results of this study cannot be generalized to other types of packaging, as they may differ significantly in material composition and recycling pathways.

After careful consideration, it was decided that this study would not study aluminium cans in incineration with energy recovery. This is because aluminium does not burn, i.e. it does not generate electricity or heat. In Sweden, which is the geographical focus of this study, most incinerators today sort and remove metal from the ash (Avfall Sverige, 2023), which means that the aluminium that ends up in the incineration system is mainly returned to the conventional recycling system. Furthermore, after reviewing sorting analyses from different municipalities in Sweden, it became apparent that the amount of metal packaging in residual waste was very low. In Västerbotten, the average across 14 municipalities was only 0.06% metal in the residual waste (EcoRetur, 2023). Considering this low figure, examining aluminium cans in residual waste was assumed to be non-essential and therefore excluded from further analysis.

For PET, the end product of the deposit system was PET and HDPE flakes, whereas the end product of conventional recycling was PET and HDPE granulates. The goal was to produce the same end product. However, given the processes available in Ecoinvent 3.9, this was not possible. Given this information, the processes for recycling may differ slightly potentially influencing a potential comparison between the results. However, the main goal is not to compare the systems but rather explore and understand them individually.

This study is limited to the deposit system on the Swedish market, but some processes included in the life cycle assessment take place in other countries. For example, the recycling process occur in countries with different energy systems and electricity mixes. This introduces a degree of uncertainty, as the environmental impact of energy intensive processes is highly dependent on the electricity mix used. Countries with cleaner electricity mixes generally cause lower climate impacts in processes like recycling or production, while fossil-based mixes result in higher emissions. This will affect the size of the environmental impact of different processes.

Furthermore, this assessment uses Ecoinvent version 3.9, which lacks several updates introduced in newer versions. Version 3.11 includes for example more regionalized datasets for municipal waste treatment, as well as substantial updates to the plastic recycling sector (Ecoinvent, 2024). These include new, detailed datasets for the mechanical recycling of specific polymers such as PET and HDPE, developed in collaboration with Plastics Recyclers Europe. In addition, later versions improve data on key chemicals used in plastic production. These changes are likely to influence the environmental impact results and improve accuracy in representing PET and HDPE production and recycling. Therefore, results based on older datasets may differ from those using more current data.

Transportation of waste generated from the processes sorting and recycling in both the deposit system and conventional recycling was not included in the calculations due to an oversight. Although this represents a limitation, the overall impact is expected to be marginal and unlikely to significantly affect the comparative results.

3.2.4 Cut-off criteria

The system boundaries define which life cycle stages are included in the study, whereas this section clarifies which processes and flows were excluded within those boundaries, and on what basis. According to ISO14044 it is important to clearly establish cut-off criteria. Flows contributing less than 1% of the total input to a process, for which no reliable data could be found, were excluded from the modeling. This exclusion is considered acceptable as long as the total impact of the excluded input remains below 5% of the process's total input and they are not expected to significantly influence the overall environmental impact.

Excluded processes/inputs:

- Fuels for transportation in the deposit system, other than HVO100, CBG and LBG
- Infrastructural processes such as the construction of production facilities, roads, sorting stations and vehicles
- Labels and glue on PET bottles
- Balling of collected and sorted material
- Heating of intermediate storage
- Transportation to incineration for waste generated in deposit system and conventional recycling system
- Production and maintenance of machinery and equipment such as baling wire

In addition to the cut-off criteria for excluded flows, two different modeling approaches were used to handle the allocation of recycling. The primary modeling follows a simple cut-off approach, where recycled materials leave the system without credit. In a second version of the results, a cut-off + credit approach is applied, where environmental benefits from avoided production of virgin materials and recovered energy are included. This represents a form of system expansion and allows for comparison of net environmental performance across the end-of-life systems. Explanation of the reasoning for avoided production can be found in Chapter 4.

3.2.5 Data quality requirements

To ensure that the results are as relevant, reliable and accessible as possible, certain data quality requirements have been established. A main source of information are environmental reports as they often provide insights into emissions and resource use. These reports offer information that can complement more detailed and technical data where such information is unavailable. This type of data is assumed to be transparent as it is law to submit it to the County Administrative Board. The data used for modeling the deposit system is primarily collected through communication with Returpack and its stakeholders. Svensk Plaståtervinning and Stena Aluminium provided most of the data for the conventional recycling system, while municipalities and Avfall Sverige provided data for the incineration system with energy recovery. Given that the data was provided by individuals with extensive expertise in the respective systems, it was considered to be sufficiently reliable. On the other hand, relying on personal communication from companies as a primary data source may have limitations, such as reduced transparency or potential bias. Therefore, a combination of using documented data and personal communication is preferable. The aim is to use as current data as possible, with primary data collected through personal communication and reports aiming to be from no later than 2023. Where this is not available, older data may be used if it is still relevant.

For processes where primary data could not be obtained, the Ecoinvent 3.9, cut-off by classification, database was used. This version was selected as it is the most recent release compatible with the modeling tool employed in this study, Activity Browser. It is important to note, however, that newer versions of Ecoinvent, such as 3.10 and 3.11 contain substantial updates. These updates could potentially influence the outcomes of the assessment. While relying on version 3.9 may introduce some limitations, the choice was motivated by its accessibility, transparency, and the ability to ensure reproducibility. This consideration is addressed in the interpretation and discussion of the results.

3.3 Selected impact categories

An LCA should cover a wide range of impact categories to avoid problem shifting, i.e. solving one problem while unintentionally causing another (Baumann & Tillman, 2004). However, it is common practice to focus on a selection of key categories that are most relevant to the system under consideration.

Climate change was included because of its high relevance in both environmental and sustainability contexts. Carbon emissions are often the primary focus of climate reporting frameworks, such as the Corporate Sustainability Reporting Directive (CSRD) since it aims to reduce greenhouse gases (European Commission, 2022). Freshwater eutrophication and freshwater toxicity were chosen because the systems involve the use of chemicals and materials that can lead to the release of nutrients and toxins into aquatic environments. Terrestrial acidification was considered important because of the expected emissions from combustion and transportation activities.

The hierarchical perspective is used and it is based on scientific consensus regarding the time frame and plausibility of the impact mechanisms (Huijbregts et al., 2017). The name of the impact category package in Activity browser is ReCiPe 2016 v1.03, midpoint (H). The chosen environmental impact categories in this study is described in Table 3.3, with descriptions from the ReCiPe method. Normalization and weighting were not included in the study, as these steps often rely on value-based assumptions that can introduce subjectivity and influence the interpretation of the results.

Table 3.3: Description of the chosen impact categories (Huijbregts et al., 2017)

Impact category	**Characterization factor and unit**	**Environmental relevance**
Climate Change	Global warming potential (GWP1000), kg CO_2-eq.	Emissions of a greenhouse gas result in an increase in the atmospheric concentration of greenhouse gases, which in turn increases the radiative forcing capacity, leading to an increase in global mean temperature. This ultimately results in damage to human health and ecosystems. The main contributing emissions are CO_2, CH_4 and N_2O. Based on information from the IPCC report 5 (IPCC, 2013), Joos et al. (2013), Hanafiah et al. (2011) and De Schryver et al. (2009).
Freshwater Eutrophication	Freshwater eutrophication potential (FEP), kg P-eq.	Freshwater eutrophication occurs due to the release of nutrients into soil or freshwater and the subsequent increase in nutrient concentrations, primarily phosphorus and nitrogen. Environmental impacts follow a sequence of ecological responses, including increased nutrient uptake by autotrophic organisms such as algae and cyanobacteria, which alters ecosystem dynamics. This process can lead to oxygen depletion and ultimately leads to a relative loss of species. The main contributing emissions are P and ${PO_4}^{3-}$. Based on information from Helmes et al. (2012), Azevedo et al. (2013a), Azevedo et al. (2013b) and Azevedo (2014).

Table 3.3: Description of the chosen impact categories (Huijbregts et al., 2017)

Impact category	Characterization factor and unit	Environmental relevance
Terrestrial Acidification	Acidification potential (TAP), kg SO_2-eq.	Atmospheric deposition of inorganic substances, such as sulphates, nitrates and phosphates, causes a change in soil acidity. For almost all plant species there is a clearly defined optimal acidity level. Serious deviation from this optimal level is detrimental to the specific species in question and is called acidification. Consequently, changes in acidity levels will cause changes in a species' abundance. The main acidifying emissions are NO_X, NH_3 and SO_2. Based on information from Roy et al. (2014).
Freshwater Ecotoxicity	Freshwater ecotoxicity potential (FETP), kg 1.4-DCB-eq.	The human toxicity and ecotoxicity characterization factors represent a chemical's persistence in the environment (fate), accumulation in the human food chain (exposure), and toxicity (effect). The cause and effect pathway from release into the environment, through fate and exposure, to affected species and disease incidence, ultimately leading to damage to ecosystems and human health. The main contributors are Cu, Ni and Hg. Based on information from Van Zelm et al. (2009, 2013).

3.4 Technical background

This chapter presents the processes of the three end-of-life systems and explains their characteristics as a basis for understanding the environmental impacts of the systems.

3.4.1 Overview of the systems

The flowcharts in Figure 3.1 and 3.2 provide a more detailed yet accessible overview of the processes involved in the end-of-life systems for PET bottles and aluminium cans. Each chart visualizes the main steps from collection to final treatment, offering a clear structure of the material flows. A more in-depth description of each system and its respective processes is presented in this section.

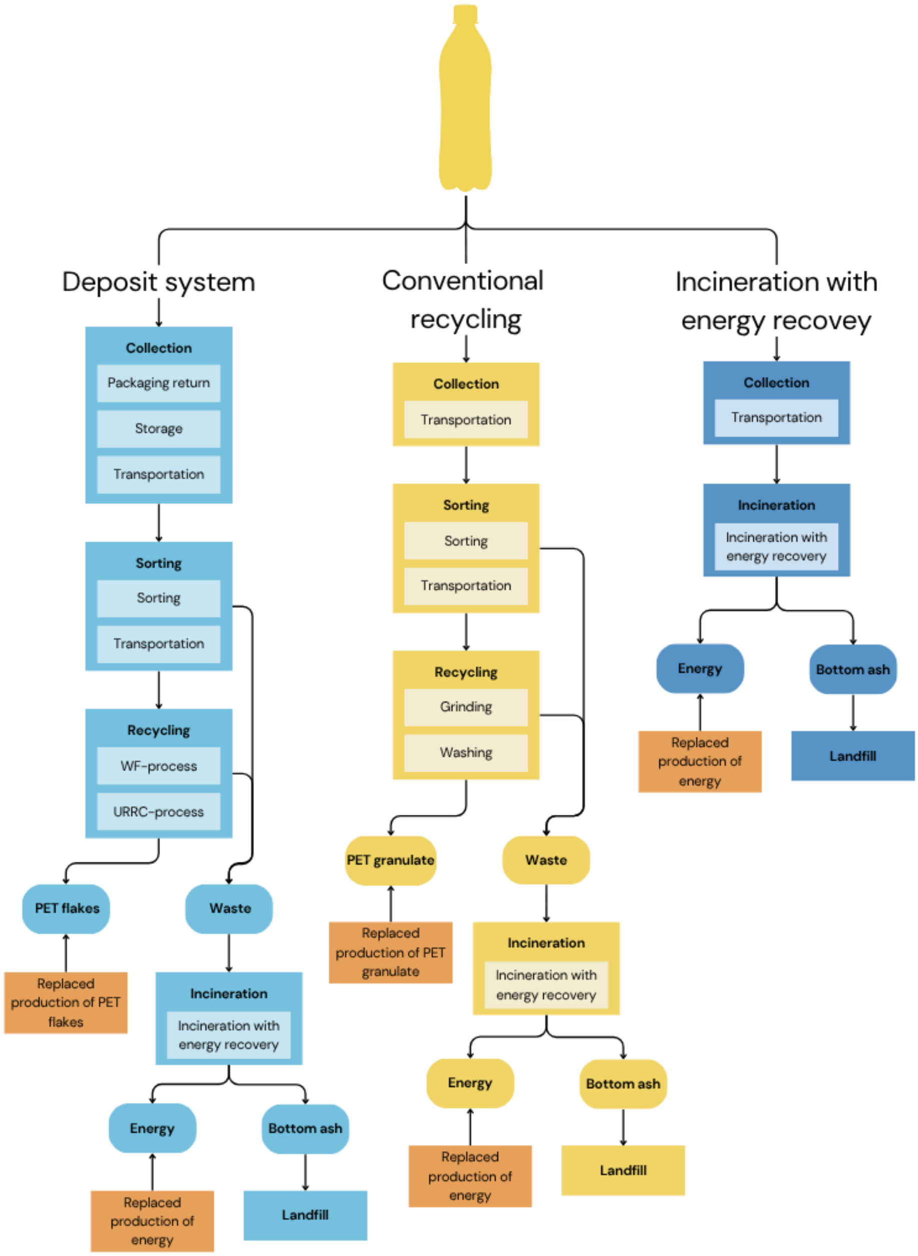


Figure 3.1: Flowchart for the PET bottle

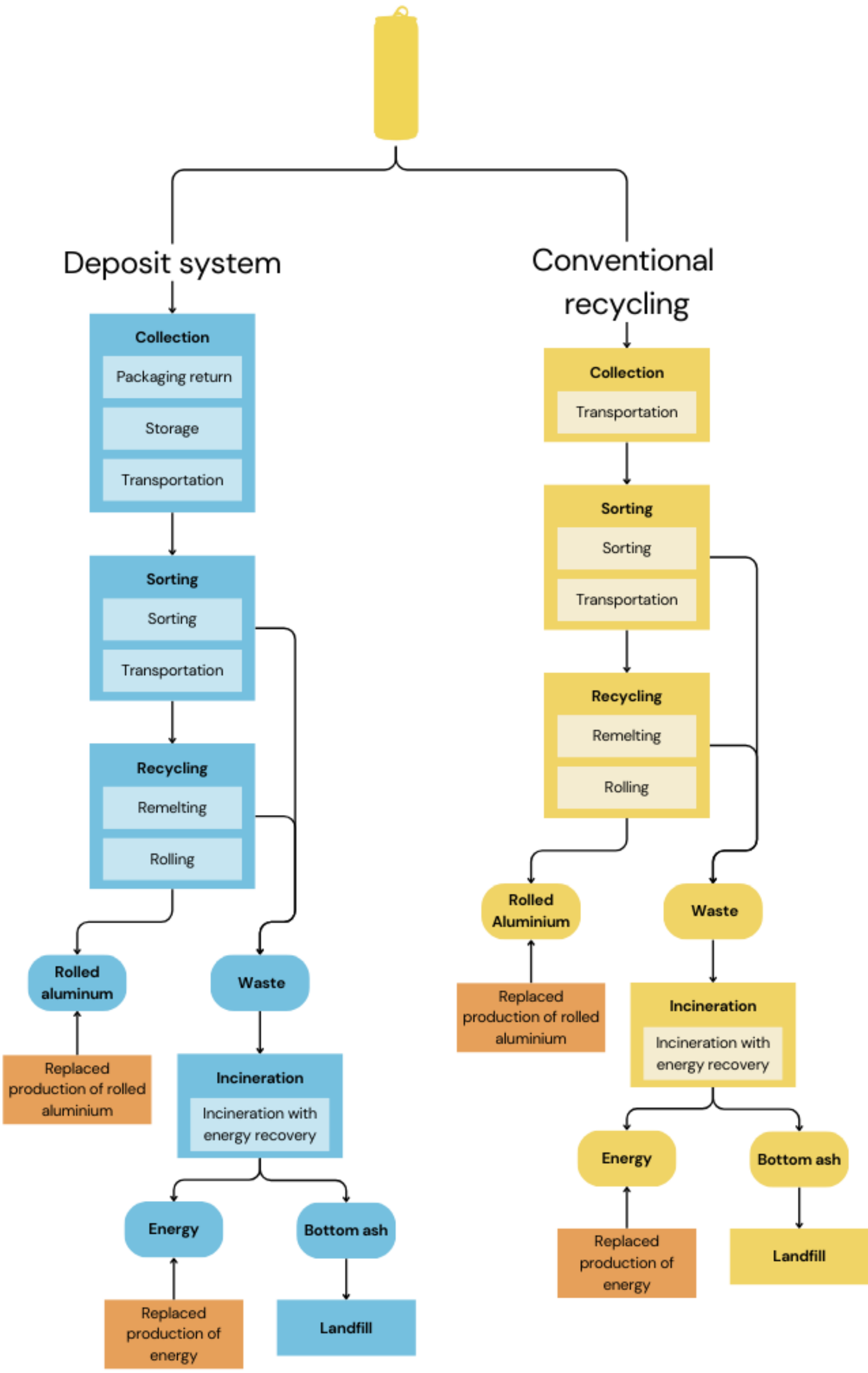


Figure 3.2: Flowchart for the aluminium can

3.4.2 Deposit system

The deposit system is designed to enable closed loop recycling, where returned bottles and cans become new beverage containers of the same type (Pantamera, 2025c). This system helps preserve material quality and reduces the need for virgin resources. By encouraging consumers to return used packaging, the deposit system plays an important role in achieving the goals of the circular economy.

3.4.2.1 Collection

Compressed material
The deposited packaging arrive at the sorting facility in Norrköping through four different flows. The largest flow, 92% of all collected deposit packaging in 2023, is called the bulk flow (E. Wiklund & E. Ebbeson, personal communication, 29 January 2025). These are the packaging that enters the system through a reverse vending machine (RVM). The packaging is manually inserted one by one into the RVM, sorted according to plastic or aluminium, compressed, and stored until it is picked up. More than 3100 supermarkets around Sweden have at least one RVM (Pantamera, 2025b). The second largest flow, 5.5%, is called the PEX flow (E. Wiklund & E. Ebbeson, personal communication, 29 January 2025). This flow is collected by PantaMera Express, larger RVMs located at recycling stations throughout Sweden. In PantaMera Express, bags of cans and PET bottles can be emptied into a large compartment, the rest of the process is similar to the bulk flow. These two compressed flows are transported to intermediate storage and reloaded for further transport to Returpack's facility in Norrköping, see Figure 3.3.

Uncompressed material
Flows from more temporary or seasonal activities, such as campsites, ski resorts, and festivals, called X-flows, are the smallest and account for 0.8% of all packaging collected (E. Wiklund & E. Ebbeson, personal communication, 29 January 2025). The X-flow also includes collecting carried out by sports clubs. The last flow is the flow that is later handled manually in the Returpack factory, hence the name manual flow and accounts for 1.7% of all collected packaging. Restaurants, cafes and small shops, among others, contribute to this flow. The X-flow and the manual flow are transported in sacks, uncompressed, to a depot warehouse awaiting transport to Returpack's facility in Norrköping, see Figure 3.3, where it later will be compressed.

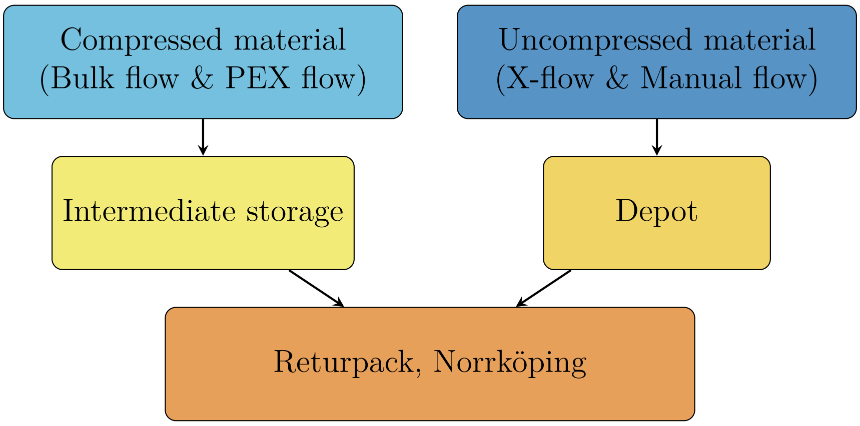


Figure 3.3: The transportation flows of compressed and uncompressed materials.

The packaging is transported to intermediate storage or depots, mainly by two-chamber rear loaded trucks (J. Wendelin, personal communication, 12 February 2025). All of the intermediate storage facilities in Sweden are unheated areas, most of the depots are unheated as well. To reload a truck, going to the sorting facility in Norrköping, a HVO-powered loader is used. From intermediate storage and depots, so-called volume trucks transport all material to the factory in Norrköping, see Figure 3.4.

Figure 3.4: Picture of a volume truck with trailer (Returpack - Pantamera, n.d.).

3.4.2.2 Sorting

When the packaging arrives at Returpack's facility in Norrköping, the compressed material is dumped into separate pits for each material, PET and aluminium (K. Petersson, personal communication, 29 January 2025). The uncompressed material is handled manually and passes through RVMs to be counted and compressed before it is sent to the pit. The purpose of counting the packaging is to enable the refund of the deposit to, for example, the restaurant that submitted it. From the pit, the packaging is transported on conveyor belts for further sorting.

PET

The PET bottles pass through a sieve to separate loose labels and caps and are then color sorted using sensors and compressed air (K. Petersson, personal communication, 29 January 2025). Color sorting is performed twice to ensure that the colored PET and the clear PET is separated. If the bottles had not been sorted by color, the color of the final recycled material would have been gray and not as clear as many buyers would like. Separating colored bottles from clear bottles improves the color quality of the clear fraction. The PET flow passes through magnets and separators to remove as much other material as possible, usually consisting of metal residues and debris. If PET or aluminium are wrongly sorted out, they are returned to their respective sorted flows. The sorted PET streams, clear and colored, are baled and transported by an electric truck to Veolia, the company next door, where PET bottles are recycled. Contaminated plastic bottles and other waste that cannot be returned to the sorted flows are sent to plastic recycling or incineration with energy recovery.

As for the cap and label material that detaches from the PET bottles, they pass through a water bath to separate the materials by density (K. Petersson, personal communication, 29 January 2025). Only the caps that detach at Returpack's facility are recycled there. The caps, made of HDPE, pass through a mill to become flakes, which are then washed, dried and packed in big bags. The labels are collected and packed in big bags.

Aluminium

The aluminium cans pass through magnets to remove steel scrap and eddy current separators to remove other contaminants such as wood and plastic (K. Petersson, personal communication, 29 January 2025). They are then baled into cubic meter-sized blocks. These are placed on trains and transported for recycling in Germany or France.

3.4.2.3 Recycling

PET

At Veolia, PET bales are first crushed and screened to remove smaller PET fragments and other unwanted materials. They are then passed through NIR sensors and a separator to eliminate small aluminium residues (Veolia, 2023). The sorted PET then enters the washing process, known as the WF process, short for washed flakes. In this process, the material is crushed again, tumbled to remove remaining labels and caps, washed in hot water, spray rinsed, and passed through a sink-float separation tank to separate PET from HDPE. After that, the material is milled and dried. The HDPE is packaged at this point, while the PET continues through several additional steps: chemical etching, a rotary oven, turbo washing, and optical colour sorting before final packaging. This process uses URRC technology (developed by the United Resource Recovery Corporation and patented by Veolia in Europe), which gives the process its name. The final PET flakes are sold to companies that produce new preforms from the recycled material. These preforms are then sold and transported to breweries, where they are blown into bottles and filled with beverages. Because the PET has undergone several washing steps, chemical etching, and thermal treatment, it is considered food-grade (or bottle-grade) and approved for use in food packaging.

Aluminium

Returpack has contracts with two different recyclers in Europe, where the baled aluminium is sent (A. Bäck, personal communication, 13 Mars 2025). One share is sent to Novelis in Nachterstedt, Germany (DE) and the other share is sent to Constellium in Neuf Brisach, France (FR). The compressed bales are first broken up and shredded into small pieces (Novelis Recycling, 2025). To remove the printed decoration, hot air is passed through the shredded pieces. Once the metal is cleaned, it is melted in a high-temperature furnace. The molten material is then poured into a casting pit where it begins to take shape. A curtain of water cools the metal, causing it to solidify into an ingot. These ingots are then moved to a rolling mill where they undergo an initial hot rolling process. Finally, they are cold rolled to achieve the exact thickness required for beverage can production, see Figure 3.5

Figure 3.5: Overview of the finishing line where aluminium is rolled (Novelis, 2019).

3.4.3 Conventional recycling

When a product is recycled into another product, it is called open loop recycling (Baumann & Tillman, 2004). This is typical of conventional recycling, where collected materials are processed and reused, but often for different types of products than the original. For some materials, quality losses are common due to mixing of materials or impurities, often resulting in low-quality products from the recycled material. In this system, this means that a bottle cannot become a bottle again, mainly because food-grade material cannot be produced, and a can cannot become a can again if the alloys are mixed with alloys from other products.

3.4.3.1 Collection

Packaging waste is collected close to most Swedish households, either by curbside collection or by recycling stations. Both collection routes contribute to the flow, which is called conventional recycling in this study. Consumers are required by law to sort their packaging (SFS 1998:808). Furthermore, as of January 1, 2027, all households in Sweden will be required by law to have curbside collection of paper packaging, plastic packaging, uncolored and colored glass, and metal packaging in separate fractions. When the material has been sorted, it is collected by the garbage trucks provided by the municipality. The plastic fraction is pressed into cubic meter bales to be sent to Site Zero in Motala (Svensk Plaståtervinning, 2025b). The metal fraction is also compressed and sent to Skrotfrag's facilities in Järna and Ulricehamn (NPA, 2025).

3.4.3.2 Sorting

PET
Site Zero, located in Motala, is currently the world's largest and most advanced sorting facility for plastic packaging and has been in operation by Svensk Plaståtervinning since November 2023 (Svensk Plaståtervinning, 2025c). With a total area of 60,000 square meters, 1000 packaging units per second are sorted into 12 different fractions. When the plastic bales arrive at Site Zero, the packaging is sorted by type of plastic and possibly by color (Svensk Plaståtervinning, 2025b). The sorting process at Site Zero is similar to the process at Returpack. The residual fraction that remains at the end of the sorting process consists primarily of non-plastic materials (Svensk Plaståtervinning, 2023). It also includes packaging that is not intended by its design to be recycled and very small pieces of plastic that are removed early in the process. Examples of packaging that cannot be recycled include black packaging, packaging made of several types of plastic, and packaging with all-over labels (Svensk Plaståtervinning, 2025a). The residual fraction is incinerated with energy recovery.

According to Svensk Plaståtervinning (2023), the recycling rate of all plastic packaging from Swedish households in 2023 was 23.7%. The recycling rate is the proportion of plastic packaging placed on the market that ultimately becomes recycled raw material. They are positive that the rate will have increased by 2024, as Site Zero was only operational for two months in 2023.

Aluminium
Cans, spray cans, tubes and caps are examples of metal packaging. The collected metal packaging is transported to sorting facilities. According to NPA (2025), collected metal packaging is transported to Skrotfrag's facilities located in Ulricehamn and Järna. There, the metal types are separated using magnets, similar to the sorting at Returpack. Water baths can also be used to take advantage of the differences in density of the metals (Stena Recycling, 2025). The sorted packaging is baled into cubes and transported to a recycling facility.

3.4.3.3 Recycling

PET
Plastics can be recycled in several ways, mechanical recycling is the most common, but chemical recycling is developing (Naturvårdsverket, 2025a). In mechanical recycling, sorted plastics are shredded into smaller pieces, then washed before being melted down into granulates that can be used to make new products (Plastics Europe, 2025). The cleanliness of the plastic is critical to maximize the quality of the recycled material (Naturvårdsverket, 2025a). Chemical recycling breaks down the polymer chain of the plastic into monomers or other smaller hydrocarbons that can then form new polymers. The advantage of chemical recycling is that it can recover complex plastic waste streams, such as films or laminates, that mechanical recycling cannot handle. However, it is much more energy intensive and has greater emissions than mechanical recycling (Naturvårdsverket, 2025b).

Aluminium
At the recycling facility, the sorted aluminium is washed to remove as much impurities as possible, and is melted down and shaped into ingots (Stena Recycling, 2025). The aluminium is then rolled into sheets, ready to become a new aluminium part or product.

3.4.4 Incineration with energy recovery

Incineration can be viewed as open loop recycling because the process recovers energy from the waste material into heat, which can then be used for district heating or electricity generation (Baumann & Tillman, 2004). However, unlike recycling where materials are reused to make products, incineration transforms the waste into energy, effectively "recycling" the energy content rather than the material itself. In Sweden, waste incineration is widely used to provide district heating across the country and, to some extent, generate electricity. In this section, only PET is included, as explained in section 3.2.3.

3.4.4.1 Collection

Residual waste is collected in a variety of ways, often depending on the type of dwelling (Avfall Sverige, 2023). Collecting waste in plastic bins is the most common, but vacuum and underground containers are becoming more common, especially in large cities and newly built areas. According to Avfall Sverige (2023), underground containers have several advantages. The temperature is lower, which prevents odors, and by placing containers underground, the need for space above ground is reduced.

Rear-loading garbage trucks dominate the collection transport, and multi-compartment trucks are becoming more common as more municipalities switch to multi-compartment containers (Avfall Sverige, 2023). The trucks run on fuel procured by the municipalities, and there is an increasing trend towards the use of HVO and biogas. Depending on municipality and the distance to the nearest incineration plant, the waste may be reloaded to make transportation to the plant more efficient.

3.4.4.2 Incineration

In Sweden, there are 35 incineration plants with energy recovery from residual waste, see Figure 3.6 (Avfall Sverige, 2023). The total capacity for energy recovery in Sweden is greater than the domestic supply of combustible waste, resulting in combustible waste being imported from other European countries.

Figure 3.6: Map of incineration plants with energy recovery i Sweden (Avfall Sverige, 2025).

There are two main technologies used for energy recovery in Sweden, roaster bed and fluidized bed technology (Avfall Sverige, 2022). In roaster bed incineration, which is the most common, waste is fed through a hopper and then moved down the roaster bed. Air is added during the process, and the waste is gradually mixed. In order for waste to be incinerated in a fluidized bed, the waste must be pretreated, such as through shredding and separating metals. The waste is fed into a bed of sand that floats, as air is blown in from below. Sand helps distribute air evenly, resulting in more uniform incineration of the waste. The main emissions from the incineration process are carbon dioxide and water vapor (Avfall Sverige, 2023).

Residues remain after incineration (Avfall Sverige, 2023). Bottom ash consists of materials that are not incinerated or do not vaporize during incineration. Examples of such materials include glass, scrap iron, and gravel. Aluminium is also one of these materials. The metals are often extracted from the bottom ash and can be recycled.

4
Life cycle inventory

This chapter provides an overview of the data and assumptions used in this study to assess the environmental impacts of the different systems considered. It outlines the key inputs, outputs, processes, and assumptions involved in the life cycle inventory, and highlights the sources of data used in the assessment. The chapter also identifies the limitations in the data, particularly where assumptions have been made or where data gaps exist. These limitations are assessed in terms of their potential impact on the results, specifically regarding whether they may lead to overestimation or underestimations of the environmental impacts associated with each system.

4.1 General data

This section focuses on the data and assumptions that apply for all three systems. Fuel and electricity assumptions are presented here, data for fuels can be found in Appendix A.

4.1.1 Fuels

Returpack use five different types of fuel for its trucks when transporting used beverage packaging to depots, intermediate storage and its sorting facility. The three main fuel types are Hydrotreated Vegetable Oil (HVO100), Compressed Biogas (CBG 100%), and Liquefied Biogas (LBG). The "100" in HVO100 and CBG 100% indicates that the fuel is entirely renewable with no mix of fossil fuels. These three fuel types accounted for more than 98% of the total distance traveled and 99.8% of the total energy consumption. Thus, the impact of the remaining fuels were not considered in the assessment.

There was no data set in Ecoinvent 3.9 representing HVO100, therefore it was manually created. The input was based on data from a study on HVO fuels in the Swedish market (Källmén et al., 2019). The chosen data was based on HVO from slaughterhouse waste. The choice of slaughterhouse waste was based on the reasoning that animal fats are the most common component used for HVO production in Sweden (Energimyndigheten, 2023). The HVO data was based on a well-to-wheel approach, which means that it takes into account the processes from extraction and production to combustion in the engine. The created process can be found in Appendix A.

Neither LBG nor CBG was available in Ecoinvent 3.9 and was therefore modeled in a similar manner to HVO. The data used reflects fuel characteristics from the Swedish market (Hallberg et al., 2013). Two parts of data was used. One data set covered the cradle-to-gate inputs and outputs for biogas and the other data set covered the tank-to-wheel emissions for CBG. Due to the lack of tank-to-wheel data for LBG, the same data set as for CBG was used instead. This likely leads to an underestimation of the impact of LBG. Due to lack of data, the only input data differing CBG and LBG was the energy use for liquefaction and compression. This data was therefore added to the data set. For CBG the electricity needed was 0.18 kWh/m^3 and for LBG it was 0.63 kWh/m^3 (Moghaddam et al., 2015).

The following allocation choices are embedded in the datasets and were not made in this study. For the HVO fuel, cut-off allocation was chosen to reflect the conditions in the EU Renewable Energy Directive (Källmén et al., 2019). In this case, slaughterhouse waste is considered waste and therefore none of the impact from the upstream processes are allocated to the slaughterhouse waste. Energy allocation was applied for the production of the HVO. In this case, the impact was allocated based on energy content of the produced products which were HVO, steam, electricity and biogasoline. For the combustion in the engine, no allocation was applied as all impact was assigned to the HVO.

For the production and combustion of biogas, no system expansion nor allocation was applied (Hallberg et al., 2013). This indicates that 100% of the inputs and outputs were allocated to the biogas and nothing to the digestate which is also produced. For the combustion of the biogas in the engine, the entire impact was allocated to the fuel. Therefore, neither fuel takes into consideration the avoided impact from using for example waste but rather reflects the impact of the fuel itself.

The data used for these fuels are from 2013 and 2019, which may introduce some uncertainty due to potential developments in production technologies or energy systems since then. However, as the data reflect conditions specific to the Swedish context, their use seemed appropriate for this study.

When modeling freight transport with the alternative fuels HVO100, CBG, and LBG, existing transport processes in Ecoinvent were used as a basis and modified accordingly. Returpack primarily uses EURO6-standard trucks (J. Wendelin, personal communication, 18 Feb 2025). This motivated the choice of EURO6 transport processes in the model. The original diesel fuel in these processes was replaced with HVO100, CBG, or LBG.

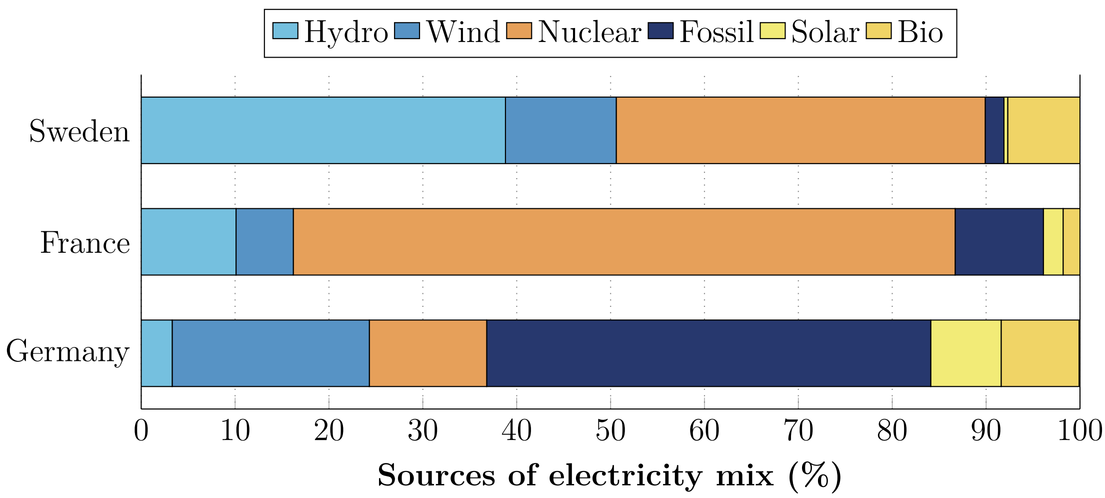
In the current activity for freight transport, the fuel is given in kilograms. The alternative fuels therefore needed to be converted from kilogram to MJ. To calculate the fuel requirement per tonnekilometer, the following heating values were applied: 44.1 MJ/kg for HVO100 and 43.3 MJ/kg for diesel (Källmén et al., 2019). Since the data source did not differentiate between the heating values of CBG and LBG, both fuels were assumed to have the same energy content in this study, with a value of

46.9 MJ/kg (Hallberg et al., 2013). These values were then used to recalculate the energy use per tonnekilometer, which was implemented in the dataset in Activity Browser.

When modifying the Ecoinvent processes, only the technosphere flows related to vehicle and infrastructure use (e.g. road maintenance and road wear) were kept. Biosphere flows, which were assume to reflect emissions and resource use associated with diesel combustion, were removed. As a result, the environmental impact of HVO100, CBG, and LBG may be underestimated, particularly if specific emissions related to their combustion were not kept. However, since the same approach was consistently applied across all transportation processes in the LCA, the comparability between scenarios remains valid.

4.1.2 Electricity

Many processes use electricity and its impact varies depending on the power sources used. Although the data used for electricity in Ecoinvent 3.9 are from 2019 and, therefore, not fully up to date, they still provide a useful picture of the general energy mix for each country. In 2019, the distribution of energy sources for Swedish electricity production was 38.8% hydropower, 11.8% wind power, 0.4% solar power, 7.7% bio energy, 39.3% nuclear power and 2% from fossil sources (Ember, 2025c). In France 2019, nuclear power accounts for 70.5%, bio energy for 1.5%, hydropower for 10.1%, wind for 6.1%, solar for 2.1% and fossil fuels for 9.4% (Ember, 2025a). In Germany 2019, the distribution was 47.3% fossil (28.6% coal, 15% natural gas, 3.7% other fossil sources), 7.5% solar, 21% wind, 3.3% water, 12.5% nuclear and 8.3% bio energy (Ember, 2025b). However, nuclear power has been phased out since 2019 in Germany.



4.1.3 Avoided production of virgin material

In this study, it has been assumed that the bottles and cans which enters the systems are produced from 100% virgin material. It is therefore assumed that by enabling these two systems, production of virgin material can be replaced. There is therefore no consideration taken to the current proportion of recycled material within the individual bottles or cans. To calculate the avoided production of primary material, degradation factors from the Product Environmental Footprint (PEF) method was applied (Joint Research Centre, 2019). Data from the PEF guide were used in this study, although the full PEF methodology was not applied. The figures are quality-assured and widely recognized within the EU context, supporting transparency and comparability across different methodological approaches. The processes in Ecoinvent used to model the avoided production of PET and HDPE were the market processes for PET granulate, bottle grade, and market for polyethylene, high density, granulate. For aluminium it was the market process for for aluminium, primary, ingot in Europe and sheet rolling aluminium, in Europe. Material being sent to incineration generates heat and electricity which has been accounted for in all systems. For more information regarding incineration, see Section 4.1.2.

PET Deposit system
In order to make a conservative assumption and to reflect the physical reality of some quality degradation happening, a degradation factor of 0.9 (10% loss in quality) was considered (as per PEF guidelines for mechanical recycling of PET), despite the fact that the recycled PET is currently more expensive than virgin one according to Returpack (S. Bergendorff, personal communication, 12 March 2025). However, 0.115 kg PET waste was generated per kilogram at Veolia. Therefore, 1.26 kg PET was needed to produce 1 kg recycled PET material. The same calculation was performed for the cap made of HDPE. Thus, the deposit system can enable the substitution of 0.7965 kg of virgin PET and HDPE per 1 kg of material entering the recycling process, accounting for process losses and degradation.

PET Conventional recycling system
To make a similar assumption for the PET conventional recycling system, the physical degradation was also set to 10% in accordance with PEF (Joint Research Centre, 2019). A 22% spill factor was apparent in the process for PET recycling and the same factor was applied for the HDPE caps. Combining these factors, 1.42 kg PET was needed to produce 1 kg recycled PET flakes. The same ratio was used for HDPE. Thus, the conventional recycling system can enable the substitution of 0.704 kg of virgin PET and HDPE per 1 kg of material entering the recycling process, accounting for process losses and degradation.

Aluminium Deposit system
In the case of aluminium in the deposit system, degradation was assessed based on data from the Product Environmental Footprint (PEF) guidelines. Both physical quality degradation and economic value loss were considered to be 0%, as the system represents a closed-loop recycling process where the recovered aluminium can be used to produce new cans of the same quality (Joint Research Centre, 2019). Consequently, it was assumed that the economic value of the material remains unchanged throughout recycling. However, some material losses still occur in the recycling process, 8.7% according to European Aluminium (2024). Thus, the deposit system can enable the substitution of 0.920 kg of virgin aluminium per 1 kg of material entering

the recycling process, accounting for process losses and degradation.

Aluminium Conventional recycling system
In order to reflect both physical losses and the economic consequences of quality degradation, a combined degradation factor was applied for recycled aluminium. According to the environmental report from Stena Aluminium, 1 kg of aluminium scrap yields 0.82 kg of recycled aluminium, based on incoming scrap and total production volume in 2024 (Stena Aluminium, 2024). Furthermore, when aluminium cans are mixed with other aluminium alloys during recycling, the quality of the material is reduced, making it unsuitable for producing the same high-quality products as before (Material Economics, 2020). To capture this loss in quality in the assessment, an economic degradation factor of 0.9 (i.e., a 10% reduction in value) was applied, in line with the findings from Material Economics (2020). Therefore, by combining the 18% physical spill and 10% economic degradation, a total of 1.36 kg of aluminium scrap is required to produce 1 kg of recycled aluminium. Thus, the conventional recycling system can enable the substitution of 0.735 kg of virgin aluminium per 1 kg of material entering the recycling process, accounting for process losses and degradation.

4.2 Deposit system

This section presents the data and assumptions related to the deposit system. Most of this data can be found in Appendix E and Appendix H, unless otherwise noted, where alternative sources are specified.

4.2.1 Collection

For the collection of bottles and cans, assumptions regarding reverse vending machines (RVMs) and transportation to Returpack have been included. Data for the RVMs can be found in Appendix B.

Reverse vending machines
The impact of the RVMs was considered in terms of material composition, weights and energy consumption. The decision to include the deposit machines in the LCA was due to the RVMs sole purpose of enabling the deposit system. Tomra T9 is the most common RVM connected to Returpack's system (H. Oscarsson, personal communication, 11 Feb 2025). A T9 has a minimum lifetime of 7 years. With maintenance, they often last longer than that. Its material composition was used as a reference for all RVMs, but the assembly process was not taken into account. The energy use of the RVMs was calculated to approximately 0.001615 kWh/packaging. This means that it was assumed that the energy use for one bottle in the RVM required the same amount of energy as one can. In this case, the energy consumption was calculated based on data on consumption for all different types of RVMs (E. Wiklund, personal communication, 22 Feb 2025). By averaging the energy use, both bigger and smaller RVMs contribution would be included. The calculation was

based on the average energy use for each type of RVM. Therefore, the PantaMera Express, the customer-owned RVMs, and the RVMs owned by Returpack were assumed to have the same energy consumption per packaging. This is a simplification that disregards the size and type of packaging. The process created in Activity Browser can be found in Appendix B, including the composition of the machine.

It was assumed that the compression of the collected deposit packaging only takes place inside the RVMs, which is a simplification of reality. Compactors are available at larger collectors and are used to further maximize the transportation of packaging. Energy and resource use in baling is also ignored for all three systems. As all intermediate storage facilities are unheated surfaces, all depots are assumed to be as well, mainly due to the lack of data. Due to an EU directive aimed at reducing littering in nature (SFS 2021:996), bottle caps are now attached to the bottle. Consequently, it is assumed that every collected bottle includes its cap.

Transportation from collection point to Returpack
After collection, the packaging is transported to intermediate storage or depots. As the activities in these facilities are disregarded in the LCA, the total distance from collection point to Returpack's sorting facility was calculated.

The average distance to Returpack was calculated using different approaches depending on the packaging flow. To calculate these distances, data obtained from Returpack was used. The data included the type and amount of fuel used on each route, the volume of a truck, and the amount of material collected (J. Wendelin, personal communication, 18 Feb 2025). For the compressed material to intermediate storage, the number of trips was known. The distance was divided by the number of trips, resulting in an average distance for compressed and uncompressed material. To create an average distance, each distance was multiplied by the proportion of compressed and uncompressed material collected. Trucks were always assumed to be full in the assessment. The reference flow is assumed to contain 97.5 % compressed and 2.5% uncompressed material.

For the remaining flows, the number of trips was not available and therefore another approach was taken. By knowing how much material was collected and the volume capacity of truck, the number of trips was calculated. It was assumed that a volume truck with trailer of the capacity of 160 m^3 transported all flows (J. Wendelin, personal communication, 18 Feb 2025), see Figure 3.4 for picture of the volume truck. PET and aluminium differ in their density both when compressed and uncompressed (K. Petersson, personal communication, 21 Feb 2025). Therefore, the density of the materials was obtained from Returpack and used to calculate the number of trucks needed to transport all the collected material. Then, by dividing the total distance by the number of trucks, an average distance was obtained for each type of material and for each distance. These distances were similarly to above, multiplied with the percentage for compressed and uncompressed material. The calculated distances can be seen in Table 4.1.

Table 4.1: Calculated transportation distances, in km, to Returpack's sorting facility

	Distance with allocation factor [km]	Total distance [km]
PET Collection - Intermediate storage/Depot		
Compressed material	221.27	
Uncompressed material	4.45	225.73
PET Intermediate storage/Depot - Returpack		
Compressed material	363.20	
Uncompressed material	3.12	366.32
Aluminium Collection - Intermediate storage/Depot		
Compressed material	221.27	
Uncompressed material	8.91	230.18
Aluminium Intermediate storage/Depot - Returpack		
Compressed material	363.20	
Uncompressed material	6.23	369.43

Data on the fuel types used for different flows were obtained from Returpack (J. Wendelin, personal communication, 18 February 2025). By examining the total distance driven, the percentages for each fuel type were calculated. After some minor adjustment to obtain 100%, it was determined that CBG accounted for 50.8% of the distances, HVO100 for 38.6%, and LBG for 10.6%, see Figure 4.1. It was also assumed that all domestic transports in the deposit system used these fuel shares. The process for these calculation is further described in Section 4.1.1.

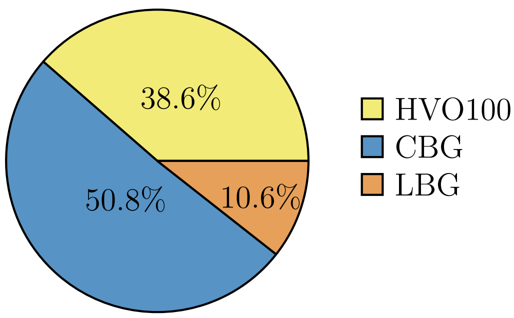


Figure 4.1: Shares of transportation fuel to Returpack

The manual flow is picked up via backhaul transport, which means that they are picked up during other trucks' deliveries or pick-ups, mainly from brewery and food deliveries. Therefore, the environmental burden was assigned to the truck deliveries rather than the collection of the packaging. This means that the environmental impact of the transport of the manual flow to the depot was considered to be zero, seen as a grey arrow in Figure 4.2.

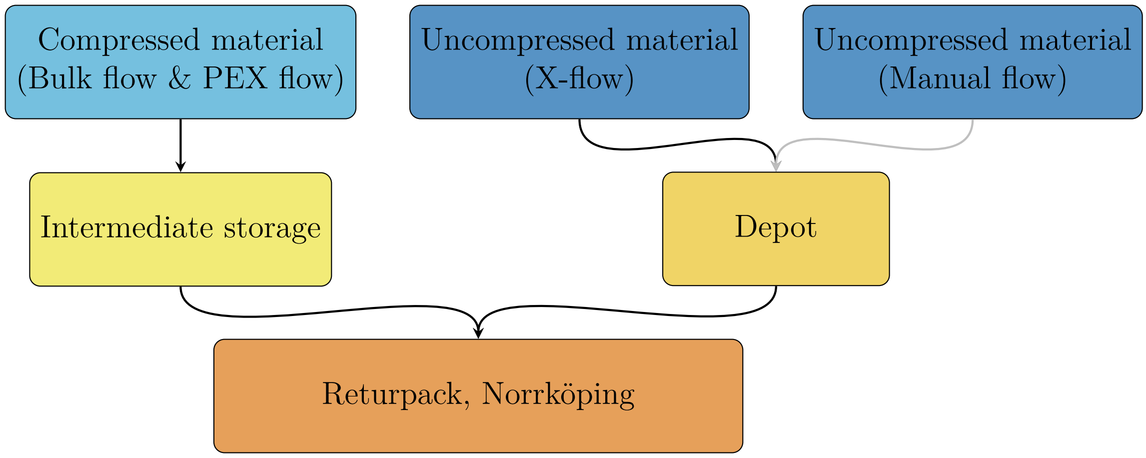


Figure 4.2: Schematic view of Returpack's transportation flows. The transports for the manual flow are marked as gray as it is not estimated to have any environmental impact.

4.2.2 Sorting

The sorting process for both PET bottles and aluminium cans takes place at Returpack's facility in Norrköping. Data on energy and district heating were provided by Returpack (K. Petersson, personal communication, February 28, 2025). Electricity consumption for lighting in the facility, ventilation and charging of industrial trucks was divided equally between PET and aluminium. The reason for this is that these were not considered to be affected by the volumes of the different packaging. The same was done for district heating. However, individual energy consumption was collected for the PET flow and the aluminium flow, and these were assigned individually to each process. When modeling the electricity mix, specific data for Returpack's electricity mix was used. The facility uses 13% solar power from photovoltaic panels. The remaining 87% is wind power. The electricity mix was modeled by altering the Swedish electricity mix, medium voltage in Ecoinvent and can be found in Appendix C. The transmission losses were accounted for in the dataset.

When sorting the different types of beverage packaging, unintended waste may accidentally be included. The waste which is not PET or HDPE is therefore sorted out in Returpack's facility. This waste is assumed to be sent to incineration with energy recovery as municipal residual waste.

Transportation to aluminium recycling facilities

Once the aluminium is sorted, it is sent to recycling facilities in Nachterstedt, Germany and Neuf-Brisach, France (A. Bäck, personal communication, 16 Feb 2025). The total weight of aluminium sent to the different recycling facilities was available. The trucks transporting aluminium to Germany had a capacity of 60 tonnes, while trucks bound for France had a capacity of 24 tonnes. The route to France covered a total of 1793 km, of which 550 km was covered by HVO100-fueled trucks and the remaining by train. To Germany, the total distance was 1257 km, of which 136 km was driven by HVO100 trucks and 1121 km by train. The distances and load capacity are summarized in Table 4.2. These distances were estimated using Google Maps and are based on the road network rather than the railway, meaning that in reality, these distances may vary somewhat. The train transports are fully transported by electricity (J. Wendelin, personal communication, 4 April 2025). The calculated transportation distances were multiplied with the reference flow for aluminium cans to obtain the unit tonnekilometers. This data can be found in Appendix D.

Destination	Truck, km	Train, km	Load capacity, ton
France	550	1243	24
Germany	136	1121	60

Table 4.2: Transportation distance and load capacity to France and Germany

4.2.3 Recycling

PET

Veolia currently has a capacity of producing 41% food grade material. According to Veolia (2023), this capacity has almost been reached. Thus, for the assessment, it is assumed that they produce 41% food grade PET flakes. The remaining PET material passes through the WF process alone and can therefore not be used for food packaging. At Veolia, the electricity is assumed to be medium voltage, Swedish electricity mix, as the company operate medium-scale industrial activity. The waste generated at Veolia is assumed to be PET and HDPE rather than municipal waste since a thorough sorting has already taken place at Returpack.

Since all PET from Returpack is sold to Veolia, the data from their environmental report was used. The data for the two processes, WF and URRC, are not separated in Veolia's environmental report, the data is just summarized (Veolia, 2023). Information regarding electricity, heat, water and chemical use for the individual processes was unknown. Instead of guessing the quantities in each process, all of the impact was allocated to the URRC process, producing food grade flakes. This decision was based on the understanding that the URRC process is more resource-intensive than the WF process (K. Petersson, personal communication, 24 February 2025). However, this approach likely results in an overestimation of the actual impacts associated with the URRC process.

Aluminium

At the recycling facilities in both France and Germany, aluminium is remelted and rolled into new sheets. Used beverage cans follow a separate stream, which prevents quality degradation, allowing them to be recycled back into beverage can sheets. The data for the remelting and rolling process was obtained from a report from European Aluminium (2024). This data can be found in Appendix H. The process requires 1.087 tonnes aluminium for the production of 1 tonne recycled aluminium. This means that it has a spill fraction of approximately 8.7%. This number is likely an overestimation as Returpack's fraction generally is quite clean (S. Bergendorff, personal communication, 29 Jan 2025). The electricity has been assumed to be high voltage as the companies operate large-scale industrial activity. The added electricity are German and French mixes. The reason to include both energy mixes is to be consistent with the amount of material which goes to either recycling facility. For the natural gas, the same reasoning was used.

4.3 Conventional recycling

This section focuses on the data and assumptions related to the conventional recycling system. Most of these data can be found in Appendix F and Appendix I, unless otherwise noted, where alternative sources are specified.

4.3.1 Collection

To estimate the distance driven for collection of household waste, data was gathered from 17 municipalities in Sweden. These municipalities were selected to provide a representative sample of the country, with variation in factors such as size, population, and geographical location. Data on the amount of waste collected in a year and the total distance were multiplied to determine how far one ton of waste is transported. The data was then averaged and weighted based on the population density of each municipality. It was decided to assume the same distance for the collection of sorted plastic and metal packaging. The distance from collection to reloading station was estimated to 23 km. This assumption is supported by Liljenström and Finnveden (2015), which calculated a distance of the same order of magnitude.

An assumption was made that half of the collection transports were fueled by HVO100 and the other half by CBG. This was based on information from several municipalities highlighting their use of fossil-free fuels. This shift towards fossil-free transport is also emphasized as a national trend by Avfall Sverige (2023). However, this assumption may not apply to all municipalities, as the choice of fuel can vary depending on local procurement contracts. Consequently, the environmental impact of collection transport may be underestimated. This fuel assumption applies to the collection of both waste destined for incineration and plastic and metal packaging sent to sorting facilities for recycling.

To estimate the average transportation distance per ton of plastic waste, the distances from the 50 largest cities in Sweden to Svensk Plaståtervinning's facility Site Zero in Motala were estimated and weighted by population. This is based on the assumption that the population generates the same amount of waste per person. This distance was assumed to be 230 km.

To estimate the average transportation distance for the aluminium scrap to Skrotfrag's facilities in Järna and Ulricehamn, the same distance as to Motala was assumed. This assumption is based on both Ulricehamn and Järna's quite central locations in the country, similarly to Motala. However, since there are two locations for the aluminium sorting, this distance is likely slightly overestimated. Distances and fuel types are summarized in Table 4.3.

Transport	Distance, km	Fuel
Collection	23	50% HVO100, 50% CBG
to Recycling	230	50% HVO100, 50% CBG

Table 4.3: Transportation distance and fuel used for the collection transports for teh conventional recycling system

4.3.2 Sorting

PET
The use of district heating at Site Zero was calculated by converting the emissions reported by Svensk Plaståtervinning for district heating in 2023 (Svensk Plaståtervinning, 2023). According to the 2023 sustainability report, district heating resulted in emissions of 42 tonnes of CO_2-eq. By using Vattenfall Motala's key figures for district heating, the total use of district heating was calculated to be 1586.7 MWh (Vattenfall, 2025). Of all the plastic that arrives at Motala and Site Zero, 8.8% is PET, which can be recycled (NPA, 2023). Therefore, 8.8% of Site Zero's energy use is allocated to PET in this study. The cap is assumed to be attached to the bottle and therefore included in the 8.8%. Of the 8.8%, 27% are sorted out and sent to incineration. As for Returpack's waste, the same assumption has been made here, the waste is considered as municipal residual waste. This means that the recycling rate of the collected PET packaging at Svensk Plaståtervinning is 73%.

Aluminium
Specific data for sorting at Skrotfrag's facilities were not available. Therefore, the process for sorting metal scrap in Ecoinvent 3.9 was used. The electricity used was switched from European to Swedish electricity mix. After sorting, the metal scrap was sent to Stena Aluminium in Älmhult. An average distance was therefore calculated between Ulricehamn and Älmhult and Järna and Älmhult, this distance averaged to 320 km. Due to lack of data on fuel type and mode of transportation it was assumed to be similar to the collection of the scrap. Therefore, fuel types were assumed 50% CBG and 50% HVO100 on a lorry 16-32 tonnes.

4.3.3 Recycling

PET
Svensk Plaståtervinning sells the sorted PET plastic to several different recyclers in Europe, but specific recyclers are confidential (L. Granström, personal communication 2025). According to Liljenström and Finnveden (2015), about 50% of the sorted Swedish plastic is sent to Germany. One large recycling plant is located outside Leipzig in Germany. This plant recycles PET specifically into granulate. The distance from Site Zero to the plant is 1,143 km, as estimated using Google Maps. It is assumed that the proportional split between truck and rail transport

for this distance is the same as for aluminium recycling in Germany. Since Motala and Norrköping are located near each other, as are Nachterstedt and Leipzig, this assumption was considered reasonable. 10% is assumed to be truck transport and the remaining 90% is assumed to be train transport. The assumed fuel for the truck transport is diesel. This assumption is based on the fact that nearly 100% of the heavy-duty truck fleet in Sweden operates on diesel or gasoline (Svenskt Näringsliv, 2024). Therefore, it was assumed that no procurement of fossil-free fuels had been made, unlike Returpack's transports. Standard freight trains in Germany, which operate on a mix of diesel and electricity, were chosen for the same reason. Due to the lack of primary data for plastic packaging recycling, Ecoinvent data for general PET recycling was used in the model.

Aluminium
When the aluminium scrap reaches Stena Aluminium, the metal is melted and elements are added to produce new ingots. According to their environmental report, they add mainly copper, but also smaller quantities of magnesium, zinc and sodium, after customer demands (Stena Aluminium, 2024). These specific ratios were unknown, therefore half of the quantity of "other alloying elements" were assigned to copper and the rest was divided equally between the remaining elements. The electricity used in the recycling process was assumed to be high voltage similarly to the smelters in France and Germany but with Swedish electricity mix. The waste was sent to incineration with energy recovery.

Stena Aluminiums ingots are used in a range of different applications. To make the results of the different systems comparable, a process needed to be added after the production of recycled ingots at Stena Aluminium. Therefore, the same rolling process as used in the deposit system was added after the production of aluminium ingots. The data for the rolling process was based on European averages, which made it reasonable to apply to a Swedish context. Therefore, the electricity and heat was assumed to be Swedish rather than French or German. Since Stena Aluminium's buyers use the ingots for various applications, it is difficult to determine where further processing takes place. Therefore, the rolling process was assumed to occur at Stena Aluminium's facility in Älmhult. Consequently, no additional transportation was included, which likely underestimates the overall impact, as rolling typically does not occur at Stena Aluminium's site.

4.4 Incineration with energy recovery

This section describes the data and assumptions related to the incineration system for PET. Most of this data can be found in Appendix G, unless otherwise noted, where alternative sources are specified.

4.4.1 Collection

The distance from each transfer station to the nearest incineration plant was calculated by comparing the coordinates of all postal codes in Sweden with those of the incineration plants. For each postal code, the closest plant was identified, and the corresponding distance was determined. The median distance calculated was 18 km. The use of median distance was chosen due to it not being as sensitive to outliers as the mean value is. Due to the large number of postal codes and significant variation in geographic distribution, using the median provided a more representative estimate of the typical transport distance. This approach ensures that extreme cases, such as remote locations, do not disproportionately affect the result. After communicating with municipalities, it became apparent that waste is not always transported to the nearest incineration plant due to procurement decisions, and this was not accounted for in the calculations. However, the distance is also calculated as a linear distance based on coordinates. Therefore, this distance might be slightly underestimated. The total distance from collection to the incineration plant was estimated to 41 kilometers since the collection route was estimated to be 23 km, see Subsection 4.3.1. HVO100 and CBG were assumed to be the fuels used for transportation. This assumption was based on the previous communication with municipalities where the most common fuels used were HVO100 and CBG. It was therefore assumed that the transportation to the incineration facilities were also facilitated by the municipalities, using the same modes of transportation and fuels. Distances and fuel types are summarized in Table 4.4.

Transport	**Distance, km**	**Fuel**
Collection	23	50% HVO100, 50% CBG
to Incineration	18	50% HVO100, 50% CBG

Table 4.4: Transportation distance and fuel used for the collection transports for incineration

4.4.2 Incineration

After the plastic packaging has been transported to an incineration plant, it is assumed that all plastic is incinerated. The small fraction that remains is assumed to be landfilled. This is accounted for in the Ecoinvent dataset. When plastic burns, electricity and heat is generated in the plant. This study assumes that all plastics are incinerated and converted to energy and ash, where the ash is landfilled. PET has a heat value of 23 MJ/kg (Sánchez et al., 2007). This value was used for the calculation of energy generation.

The replaced electricity was set to a Swedish electricity mix at medium voltage.
For district heat, a process based on the Swedish fuel mix was set up. According to Energiföretagen Sverige (2023), 2% of the fuel mix is fossil, about 45% of the heat comes from wood fuels and bio-oils, 30% from waste, most of which is biogenic, and 10% is industrial residual heat. Since there was no process in the Ecoinvent database

that could be equated with industrial waste heat, this process, and the other small fuels that add up to 100%, were divided between bio fuels and waste as fuel sources. The shares can be found in Table 4.5. In 2023, 88% of the energy recovered from incineration became district heating and 12% to electricity (Avfall Sverige, 2023). In Ecoinvent, the transmission and distribution losses were accounted for in the datasets.

Fuel	**Share**	**Process in Ecoinvent 3.9**
Biofuels	59%	heat production, hardwood chips from forest, at furnace 1000kW (CH)
Waste	39%	treatment of municipal solid waste, incineration (SE)
Fossil fuels	2%	light fuel oil, at industrial furnace 1MW (Europe without Switzerland)

Table 4.5: Shares of energy sources in Swedish district heat

5

Life cycle impact assessment

5.1 Results

The results presented in this chapter address the research question: "*What are the environmental impacts associated with the end-of-life management for beverage packaging for the systems: deposit system, conventional recycling, and incineration with energy recovery?*" To answer this question, one main figure is presented, showing the environmental impact per system. To clarify and highlight specific aspects of the results, two complementary visuals build on this figure: one focusing on the total impact of each system, and one illustrating the net impact after accounting for avoided burdens. In the first environmental impact category, climate change, transport to recycling is included within the sorting process, as illustrated in the previous flow charts. However, since this activity has a significant impact on certain environmental impact categories, it is presented as a separate process in the following figure. For the remaining categories, the results are therefore presented with transport to recycling treated as a distinct process. In the deposit and conventional recycling systems, rejected and residual material is sent to incineration. This incineration is included within the sorting and recycling processes like in the flowcharts and is not marked separately, unlike the transportation to recycling. All results presented are per functional unit. The Sankey diagrams available in Activity Browser were analyzed to identify the contributing processes. All numerical data underlying the figures are provided in Appendix J.

5.1.1 PET

Climate Change

The recycling process is clearly the largest contributor to climate change in both the deposit system and conventional recycling, see Figure 5.2. According to the results for the deposit system, the climate change impact in the recycling process is largely due to the incineration of rejected PET and waste fractions. Sorting and collection contribute to a lesser extent. In the conventional recycling system, significant impact arise from electricity use and incineration of rejected material. Recycling processes and transportation to the recycling facility also contribute notably to the total impact. In Figure 5.1, the activity of transport to recycling is included within the sorting process, as shown in the previous flowcharts. However, since this activity has a significant impact in certain environmental impact categories, it is presented as a separate process in Figure 5.2. In the following section of the results chapter, the results are therefore shown with transport to recycling treated as an individual process. For the incineration with energy recovery system, nearly all impact is attributed to the incineration process itself.

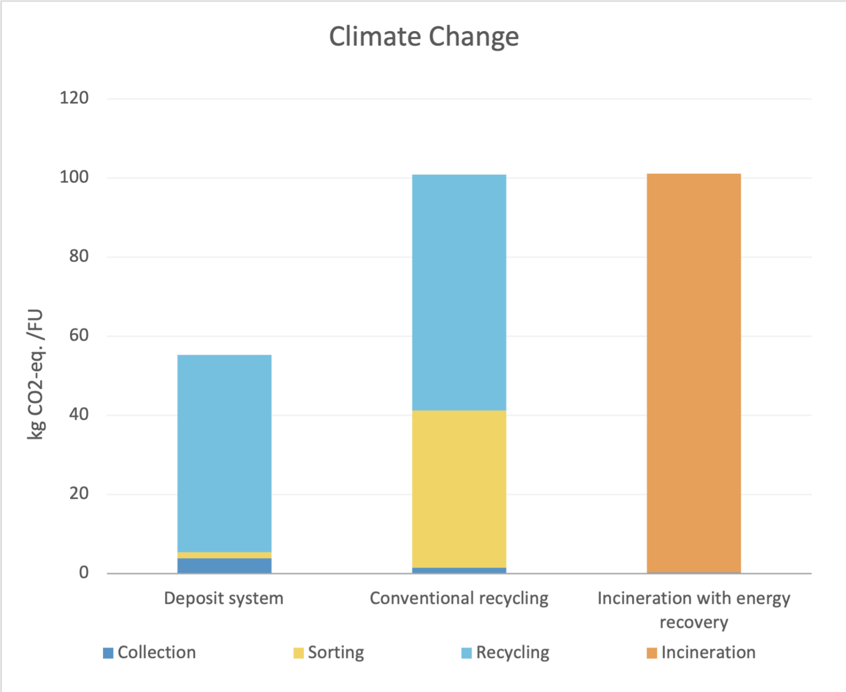


Figure 5.1: GWP100 from the three EoL systems, PET, version 1.

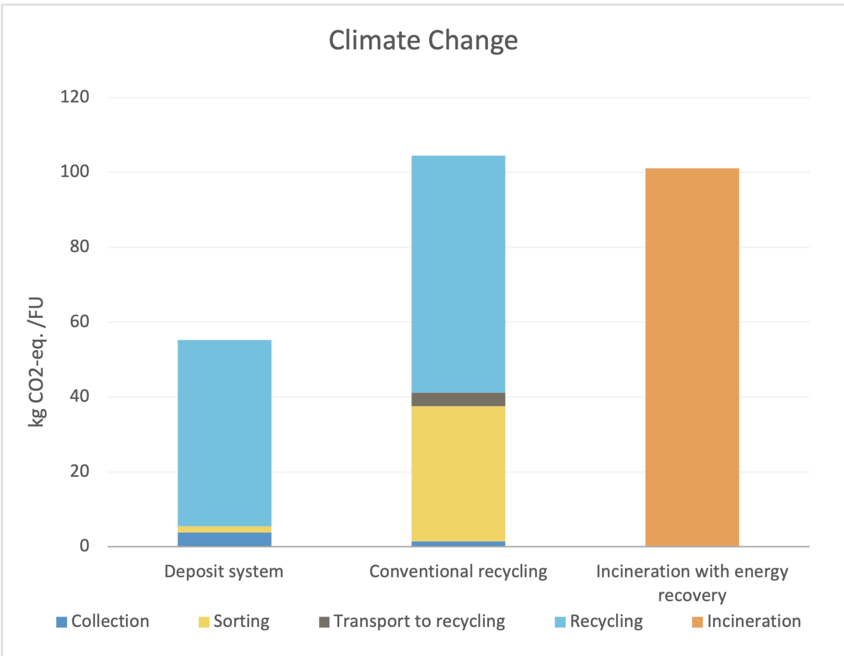


Figure 5.2: GWP100 from the three EoL systems, PET, version 2

The three systems also contribute to the avoided production of virgin PET and the production of heat and electricity. When environmental burdens and credits are added together, see Figure 5.3, the net effect is negative for the deposit system and for conventional recycling, see Figure 5.4. The main difference arises from the avoided production of primary materials, which means that for incineration, where no materials are recovered, does not contribute to environmental benefits. However, the avoided production of electricity and heat in incineration with energy recovery, has a significant impact on climate change.

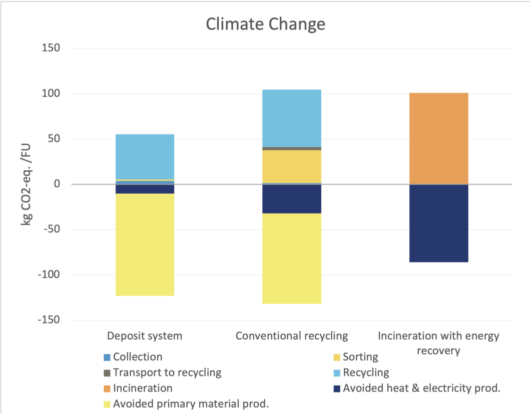


Figure 5.3: Total GWP100 from the three EoL systems, PET

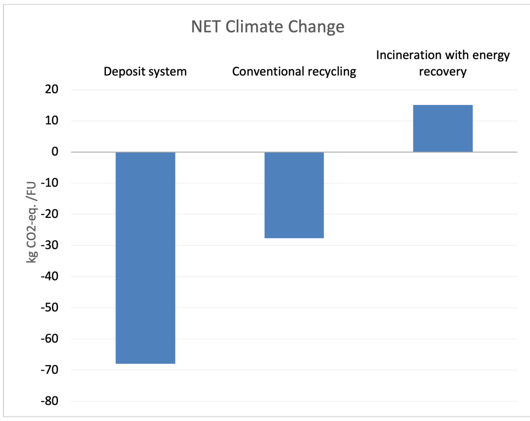


Figure 5.4: Net GWP100 from the three EoL systems, PET

Freshwater Eutrophication

The impacts in the category of freshwater eutrophication show relatively low values across all three systems. It is clear that the recycling process is the main contributor in both the deposit system and conventional recycling, see Figure 5.5. In the deposit system, the primary source of impact is the production of sodium hydroxide used in the recycling process, whereas in the conventional recycling system, electricity use is the dominant contributor. Impacts from transportation to Returpack are also evident in the collection stage. Transportation to recycling and sorting processes show a noticeable impact in the conventional recycling system compared to the deposit system. This is mainly due to the long distance to the recycling plant and the incineration of the discard material. Similarly to the other impact categories, the system incineration with energy recovery accounts nearly all its impact to the process of incineration.

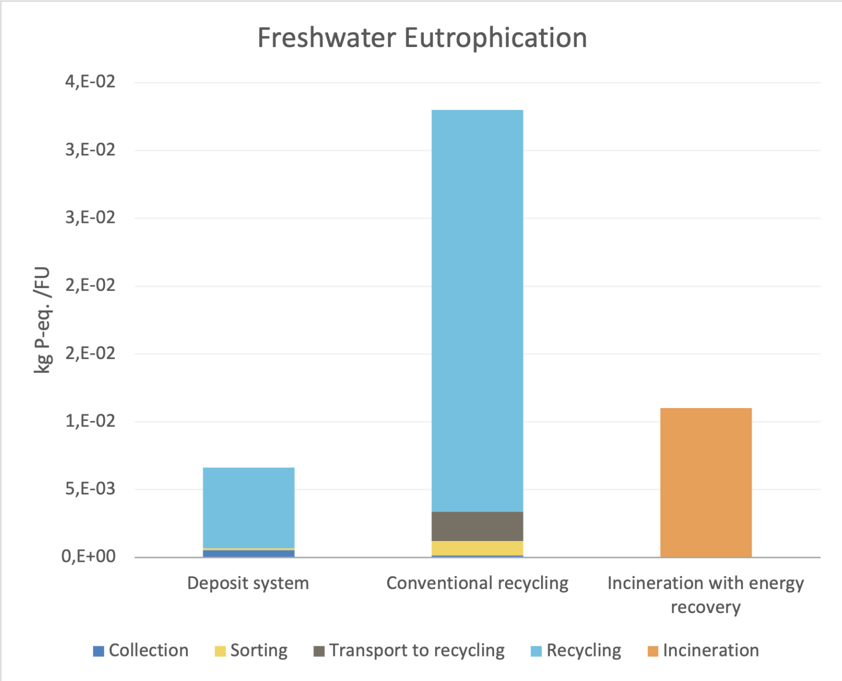


Figure 5.5: FEP from the three EoL systems, PET

The low impact of the deposit system and its avoided production of primary materials means that the deposit system has a net negative effect, while the other systems have a net positive effect, see Figures 5.6 and 5.7. The impact of the recycling process in conventional recycling is much greater than the gain from avoided production of materials, which is the main reason why the result is positive. The avoided production of heat and electricity has an effect on the incineration system, but is minimal in the other EoL systems.

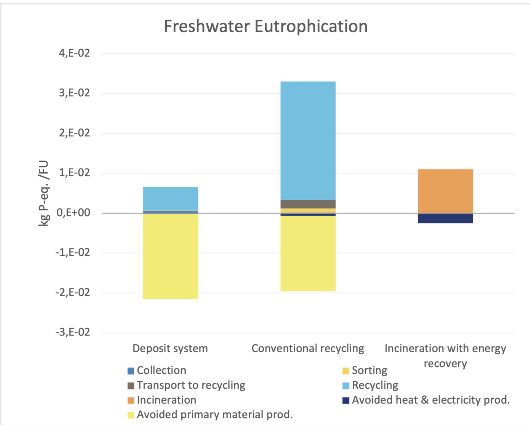


Figure 5.6: Total FEP from the three EoL systems, PET

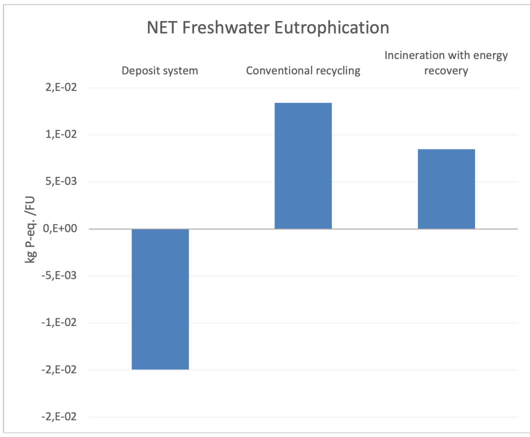


Figure 5.7: Net FEP from the three EoL systems, PET

Terrestrial Acidification

For terrestrial acidification, it is again the recycling processes in the deposit system and conventional recycling which shows the greatest impact, see Figure 5.8. In the deposit system, the use of sodium hydroxide (used for etching) and the fuels associated with the transportation for the collection processes show the biggest impacts on terrestrial acidification. For the conventional recycling system, the electricity use and incineration of waste contribute the most to terrestrial acidification. For incineration with energy recovery, it is once again the incineration process itself which has an impact on this impact category.

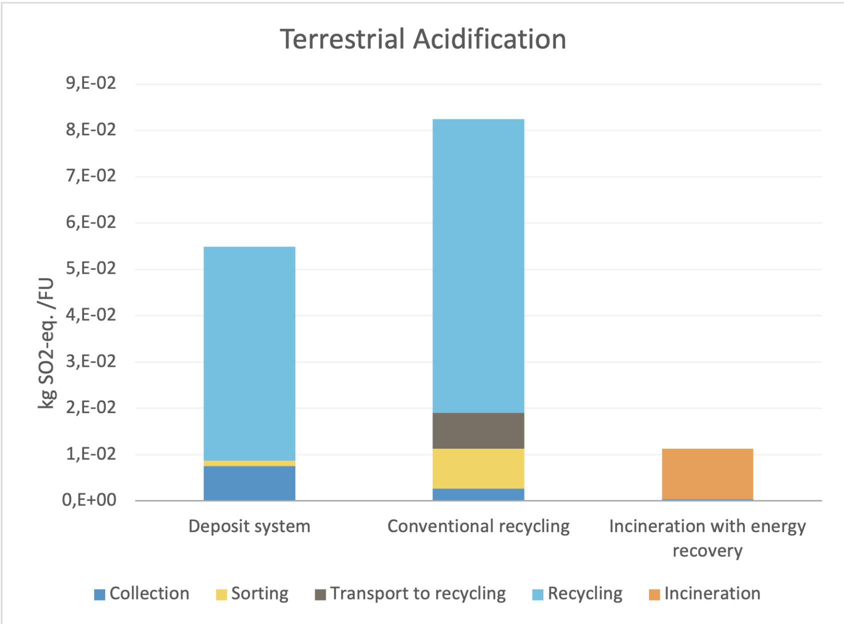


Figure 5.8: TAP from the three EoL systems, PET

All EoL systems are net negative, see Figure 5.10. This is largely due to the avoided production of electricity and heat, especially in the case of the incineration system, see Figure 5.9. As in the other categories, the main reason is the avoided production of primary materials. In this case, however, the avoided production of electricity and heat also has a significant impact on terrestrial acidification.

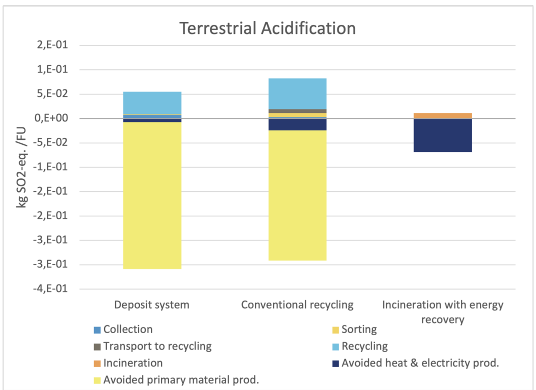


Figure 5.9: Total TAP from the three EoL systems, PET

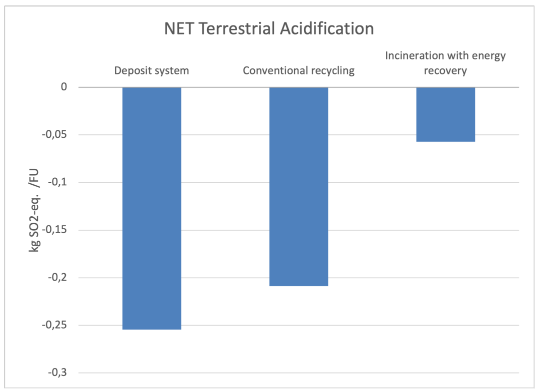


Figure 5.10: Net TAP from the three EoL systems, PET

Freshwater Ecotoxicity

In the deposit system and the conventional recycling system, the recycling process shows the greatest contribution in the category of freshwater ecotoxicity, see Figure 5.11. In the deposit system, the incineration of waste and PET is the greatest contributor. Similarly, in the conventional recycling system incineration of waste and PET are the largest contributors especially in the sorting process. The electricity used for the recycling process in Germany also show an impact. Regarding the incineration with energy recovery, the processes for incineration show almost the entirety of the impacts.

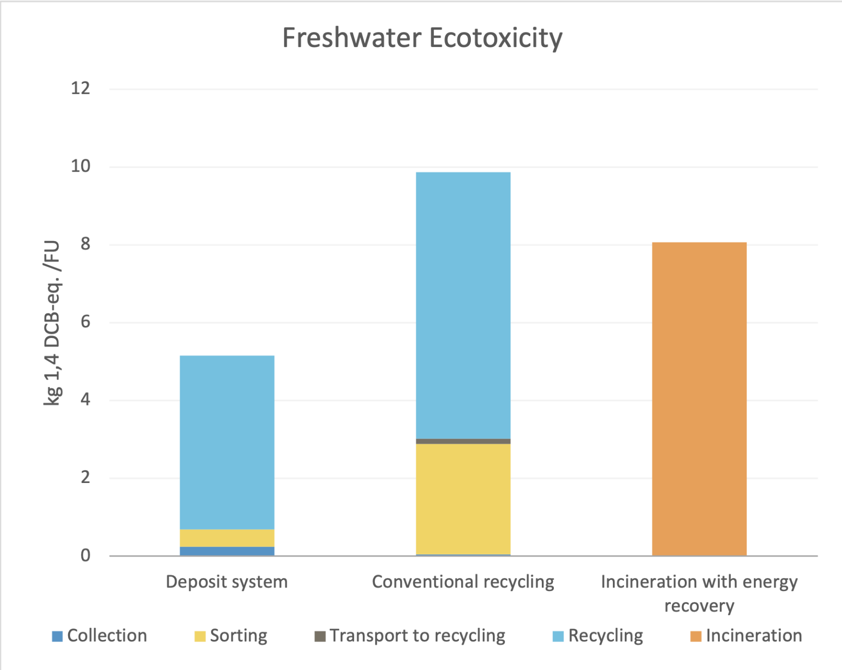


Figure 5.11: FETP from the three EoL systems, PET

All three systems show a net positive effect, see Figure 5.13. For the deposit system, this is very small in comparison to the other two systems. The incineration show the largest positive effect as the impact from the avoided production of electricity and heat is small in this category, see Figure 5.12. The avoided production of PET and HDPE material shows a big impact on the net effect as seen in the deposit system and the conventional recycling system.

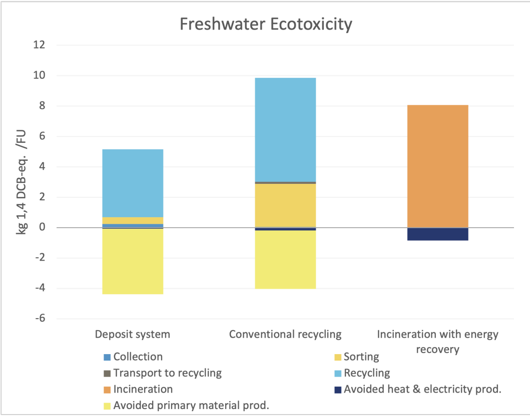


Figure 5.12: Total FETP from the three EoL systems, PET

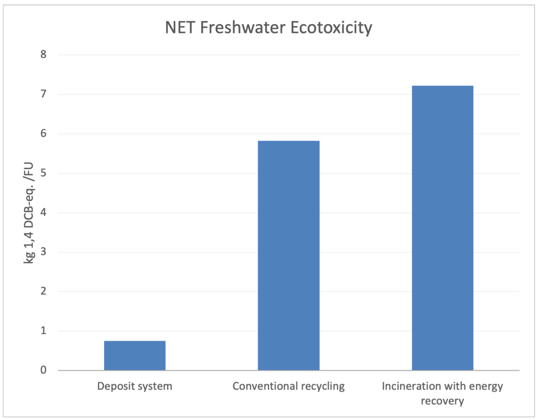


Figure 5.13: Net FETP from the three EoL systems, PET

5.1.2 Aluminium

Climate Change

For both the deposit system and the conventional recycling system, the recycling process shows the largest impact on global warming potential, see Figure 5.14. For the deposit system, electricity and natural gas in the recycling process are the largest contributors. Whereas transportation to Returpack is the largest contributor in the collection stage, its impact is comparable in magnitude to that of transportation related to recycling in Germany and France. The use of silicon is a major contributor to the global warming potential in the conventional deposit system, while the use of petroleum and oxygen gas also contributes notably.

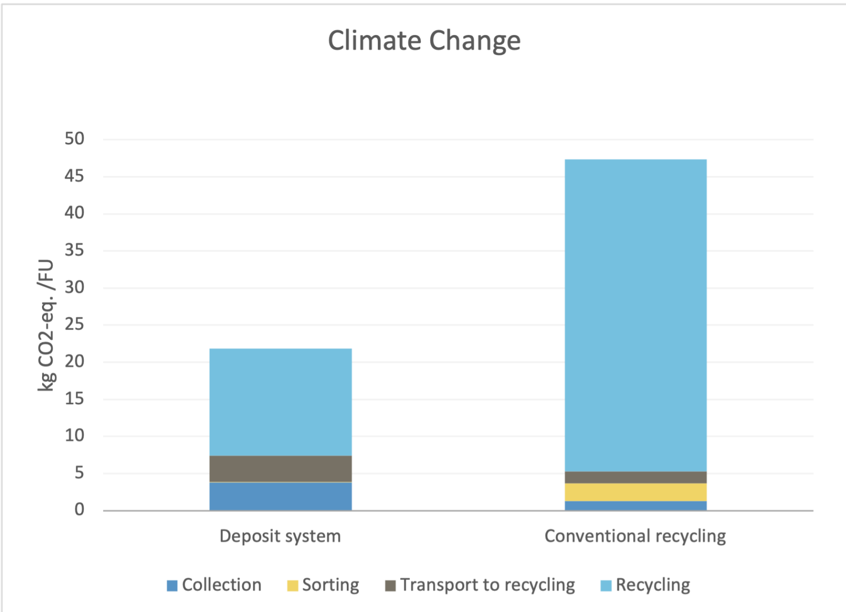


Figure 5.14: GWP100 from the two EoL systems, Aluminium

The results for climate change are net negative since the avoidance of primary material production is high, see Figure 5.15 and 5.16. The avoidance of heat and electricity production is almost negligible in this category.

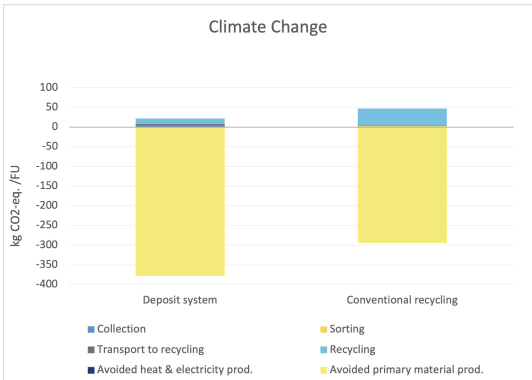


Figure 5.15: Total GWP100 from the two EoL systems, Aluminium

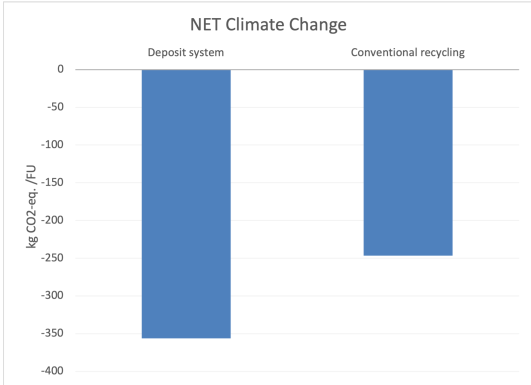


Figure 5.16: Net GWP100 from the two EoL systems, Aluminium

Freshwater Eutrophication

Once again, the recycling process shows the biggest impact in both of the systems in regard to freshwater eutrophication as well, see Figure 5.17. For the deposit system, the electricity use in recycling and the transport to recycling in Germany and France are the largest contributors to freshwater eutrophication. For the conventional recycling system, it is the use of silicon and copper as well as the use of oxygen in the recycling process which are the largest contributors to freshwater eutrophication. The other processes in conventional recycling are very small.

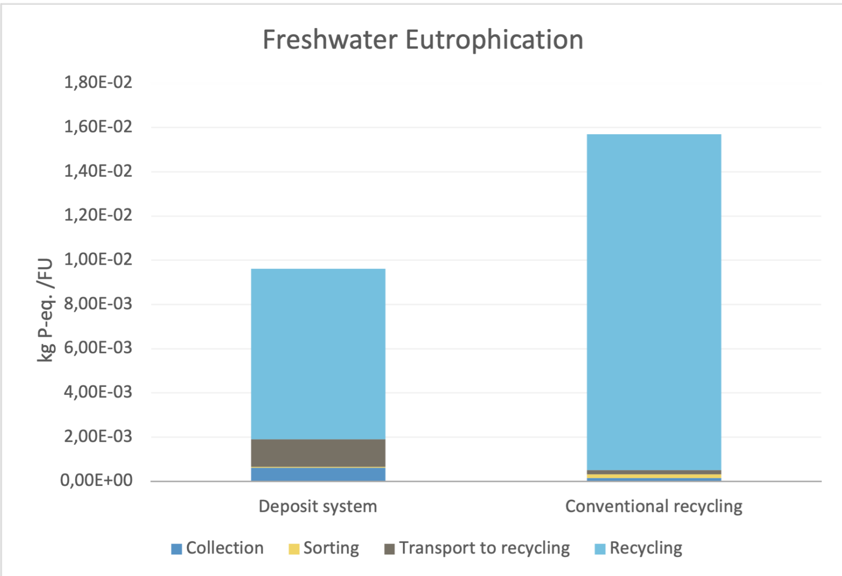


Figure 5.17: FEP from the two EoL systems, Aluminium

As with climate change, it is the avoided production of primary materials that makes both systems net negative, see figure 5.24 and 5.25.

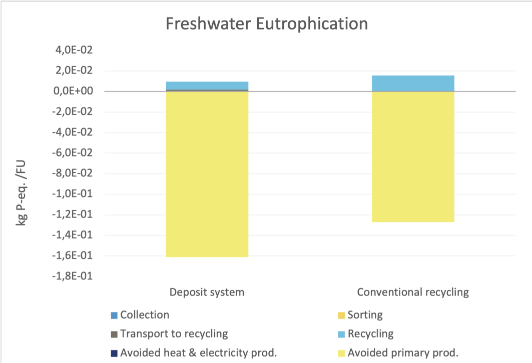


Figure 5.18: Total FEP from the two EoL systems, Aluminium

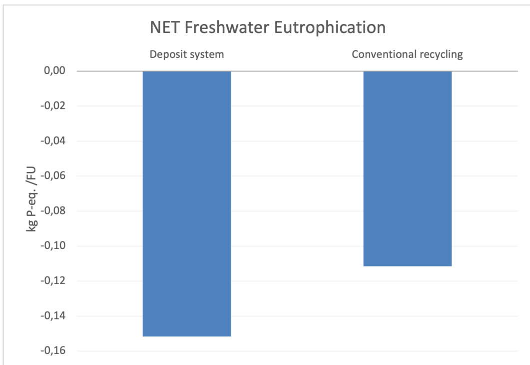


Figure 5.19: Net FEP from the two EoL systems, Aluminium

Terrestrial Acidification
The total impact for both systems are relatively low with the recycling process showing the largest contribution to terrestrial acidification in both systems, see Figure 5.20. For the deposit system, electricity and natural gas in the recycling process as well as transportation to Returpack and to recycling are the largest contributors to this impact category. For conventional recycling, again, it is silicon and copper use which shows the biggest impact on terrestrial acidification.

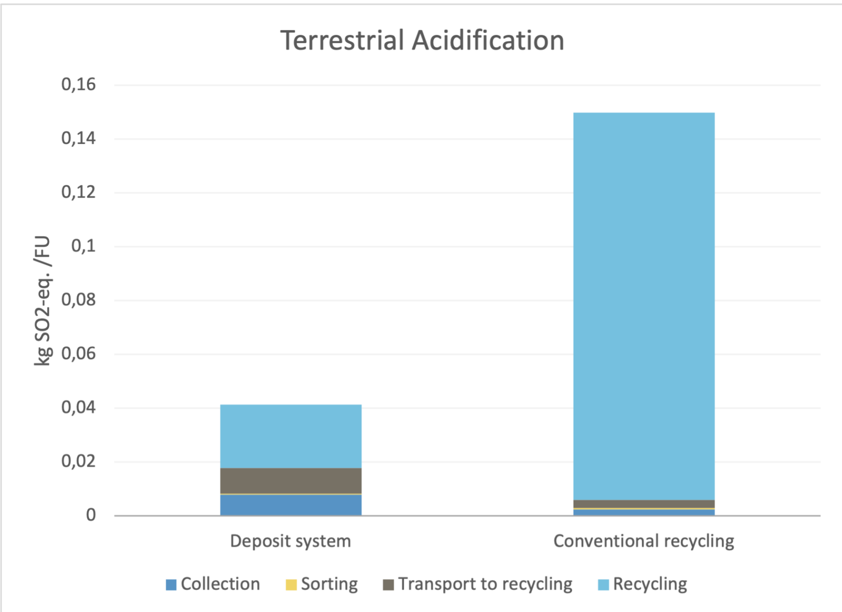


Figure 5.20: TAP from the two EoL systems, Aluminium

The results for terrestrial acidification are also net negative, mainly due to the significant avoided burden from primary material production, see Figure 5.21 and 5.22. In contrast, the contributions from avoided heat and electricity production are negligible within this impact category.

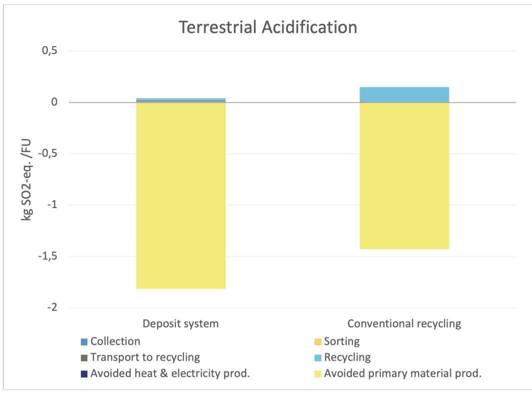


Figure 5.21: Total TAP from the two EoL systems, Aluminium

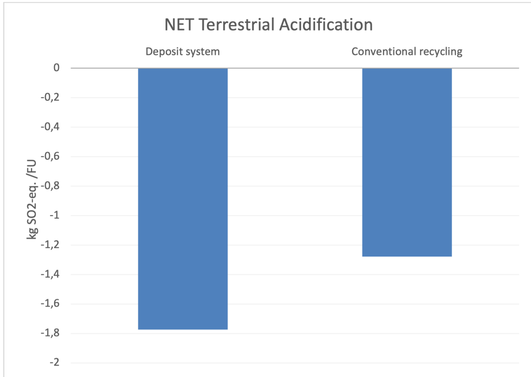


Figure 5.22: Net TAP from the two EoL systems, Aluminium

Freshwater Ecotoxicity

For freshwater ecotoxicity, the recycling process is once again the largest contributors to both systems see Figure 5.23. For the deposit system, the electricity in recycling process, electronics in the deposit machines and the transport to recycling in Germany and France are the largest contributors to freshwater ecotoxicity. This is similar to the conventional recycling system which also shows electricity use as a large contributor as well as the use of copper and silicon in the recycling process.

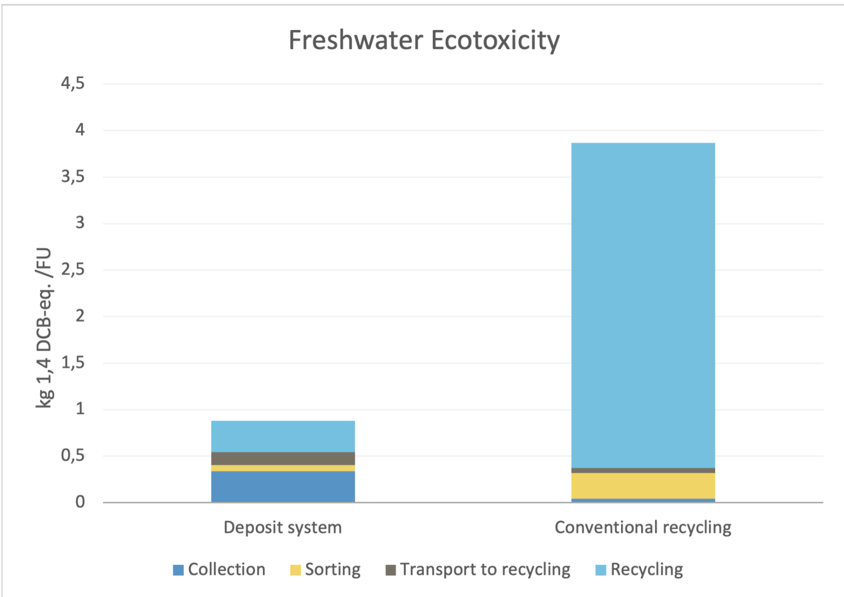


Figure 5.23: FETP from the two EoL systems, Aluminium

For both systems, the total is net negative when the avoided production of primary materials and the avoided production of electricity and heat are added, see figure 5.24 and 5.25. The avoided production of electricity and heat is negligible.

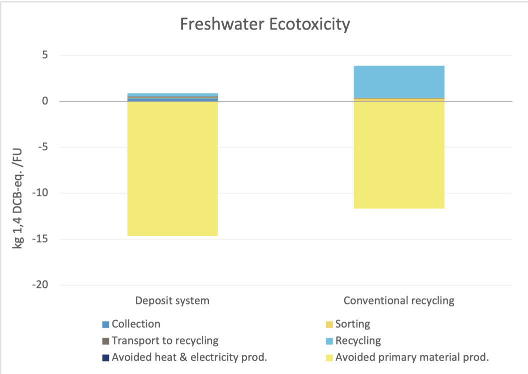


Figure 5.24: Total FETP from the two EoL systems, Aluminium

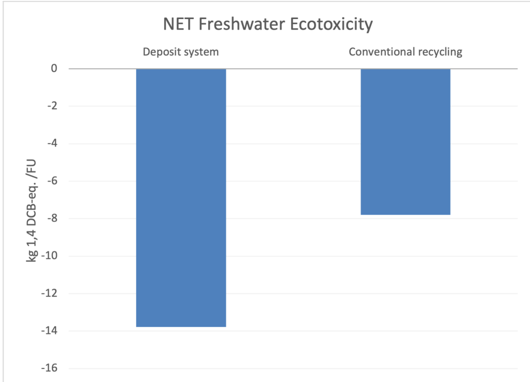


Figure 5.25: Net FETP from the two EoL systems, Aluminium

5.2 Sensitivity and scenario analysis

This section explores the results from the LCA with the use of sensitivity and scenario analyses.

5.2.1 PET

Sensitivity analysis 1: Modification of transportation fuels to the recycling site in Germany, Conventional recycling system
Diesel was assumed as the fuel for trucks, and a combination of diesel and electricity for trains transporting sorted PET to the recycling facility in Germany. These assumptions reflect the most commonly used fuels for such transport. To evaluate the effect of alternative fuel scenarios, a sensitivity analysis was conducted using electric trains and HVO100-fueled trucks. Transport distances were kept constant across scenarios. The results are presented in Figure 5.26.

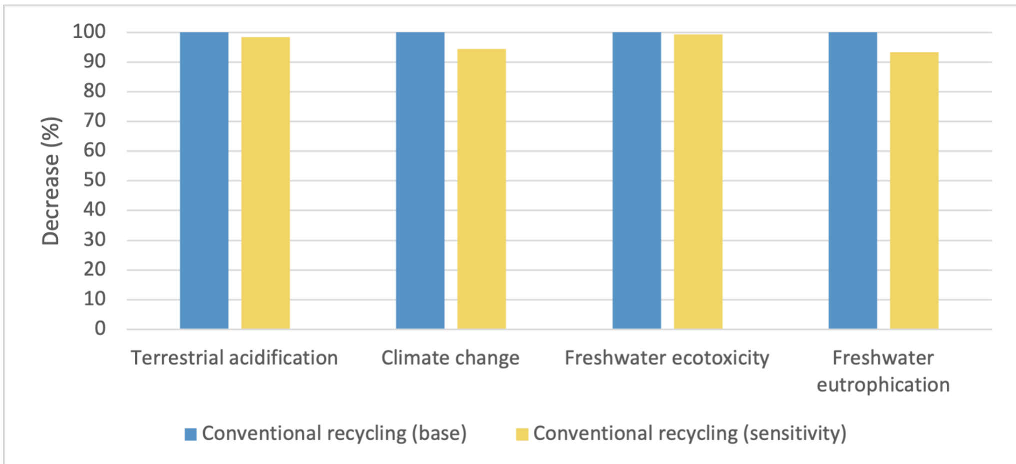


Figure 5.26: Results from sensitivity analysis, PET 1, modification of transport fuels in the conventional recycling system

The impact of the fuel types on the system as a whole were small. The two greatest reductions were found in the impact categories global warming potential and freshwater eutrophication. These reductions were 6% and 7% respectively. Terrestrial acidification showed a 2% reduction and freshwater eutrophication 1%.

Sensitivity analysis 2: Including transport to Reverse Vending Machines, Deposit system

In this study, the transportation to the collection point for the deposit system was not included in the base scenario, since it was assumed that these trips typically occur in connection with grocery shopping. This assumption is explained in the system boundaries section. To test the effect of assigning some of the transportation burden to the deposit system, a sensitivity analysis was performed. It was assumed that a car drives 3 km to a grocery store with RVMs. This distance was assumed to be the average distance to a store in Sweden. Each deposit trip was assumed to include 30 PET bottles. Since the reference flow for PET in this study is 2,000 bottles, this results in approximately 67 deposit trips (2000/30 $\approx$ 67). The transport process used was *transport, passenger car, medium size, diesel, EURO5* from Ecoinvent 3.9.

Two different scenarios were created:
Scenario 1 (S1, 10%): In the first scenario, 10% of the car trips were attributed to the deposit system, representing the assumption that 1 out of every 10 grocery trips were made primarily to return bottles.
Scenario 2 (S2, 25%): In the second scenario, 25% of the car trips were assigned to the deposit system, therefore 1 out of every 4 grocery trips were made primarily to return bottles.

The results are presented in Figure 5.27.

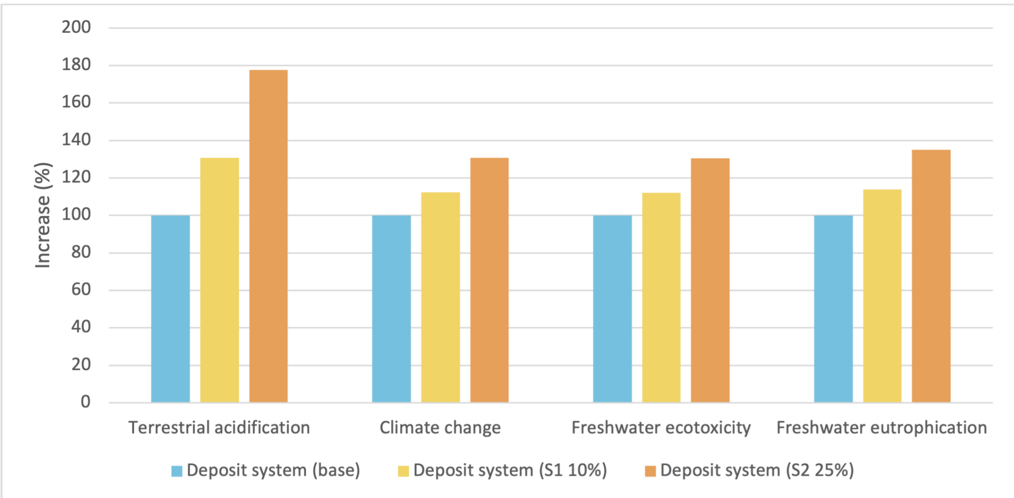


Figure 5.27: Results from sensitivity analysis, PET 2, including transportation to RVMs

The results show that attributing the transportation to the collection point for the depositing of bottles has a quite large impact in all impact categories. For both scenarios the greatest change is seen in the category terrestrial acidification. For the 10% case there is an increase of 30% in comparison to the base scenario. For the 25% case, the increase is 77%. For the three remaining categories, the increases are very similar. For the 10% case, an approximate 12% increase is observed in all categories, and approximately 30% for the 25% case. The attributing of transportation to collection therefore shows a quite big impact on the entirety of the deposit system.

Scenario analysis: Increase in the production of food grade PET flakes at Veolia, Deposit system

Currently, within the deposit system, Veolia can recycle 41% of its PET into food grade PET flakes (Veolia, 2023). In the upcoming year, the company plans to increase this capacity, allowing for the production of 66% food grade PET flakes. This would be done adding a new type of process, called Starlinger extrusion, and not with the URRC process (Veolia, personal communication, 22 April 2025). To assess the environmental impact of this capacity increase, a scenario was created to incorporate this change.

It was assumed that the capacity increase would act linearly, meaning that the spill factor and district heating were kept constant. However, with the increase in production capacity, electricity consumption is expected to rise by 50% as Starlinger extrusion is an electric process (Veolia, personal communication, 22 April 2025). This additional electricity demand was accordingly factored into the process. The results are presented in Figure 5.28.

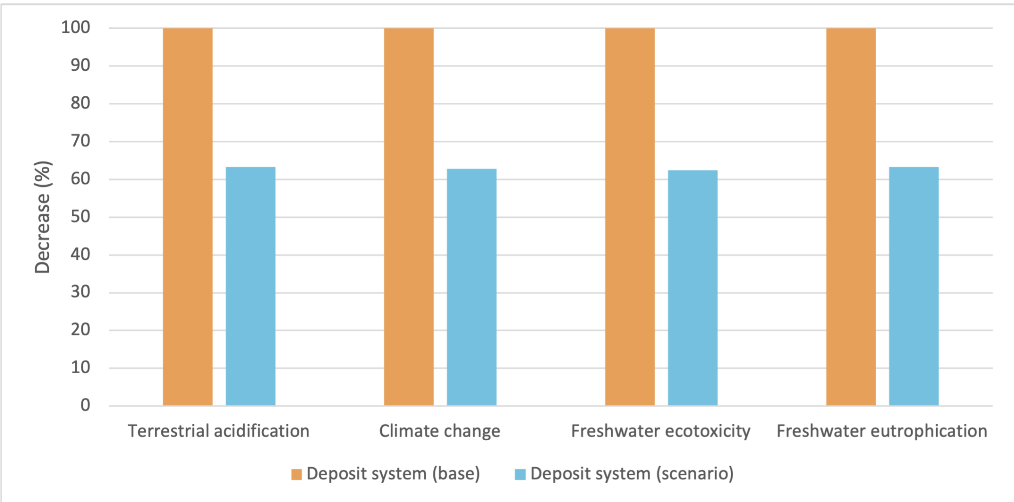


Figure 5.28: Results from scenario analysis, PET, increase in the production of food grade PET flakes

The results show changes in all impact categories. All impact categories show a reduction by approximately 37%. Therefore, when the output of food grade flakes increase per kilogram input material, the environmental impact is lowered in these four categories.

5.2.2 Aluminium

Sensitivity analysis 1: Change in distance to sorting facilities, Conventional recycling system

In the initial analysis, the distance between the collection point for aluminium scrap and the sorting facilities in Ulricehamn and Järna was assumed to be the same as for PET, where the material is sorted in Motala. Since aluminium sorting occurs at two different locations in Sweden, this distance may have been slightly overestimated. In theory, it could mean that the distances are shorter when there are two facilities to transport to. To evaluate the potential impact of this approximation, a sensitivity analysis was conducted by reducing the distance by 100 km. Thus, instead of a total distance of 253 km, the distance was set to 153 km.

The same fuel types were used for the transportation, with 50% of the distance driven on CBG and 50% on HVO100. The results of the sensitivity analysis for the conventional recycling system are presented in Figure 5.29.

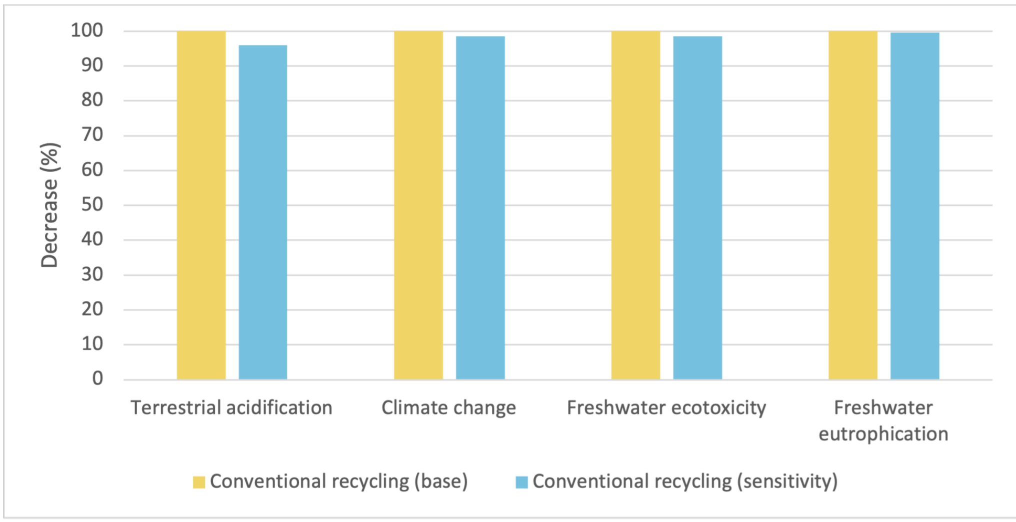


Figure 5.29: Results sensitivity analysis, Aluminium 1, Change in distance to sorting facilities

Decreasing the distance by 100 km has little impact on the results. The biggest change is seen in the category of terrestrial acidification where the results show a reduction of 4%. The climate change and freshwater ecotoxicity categories show reductions of approximately 2% whereas freshwater eutrophication shows less than 1% reduction. The effect of changing the distance driven did therefore not greatly affect the results on the entirety of the conventional recycling system.

Sensitivity analysis 2: Reduction of electricity consumption by 10% in the recycling process, Deposit system

The second sensitivity analysis examined the impact of electricity on the recycling

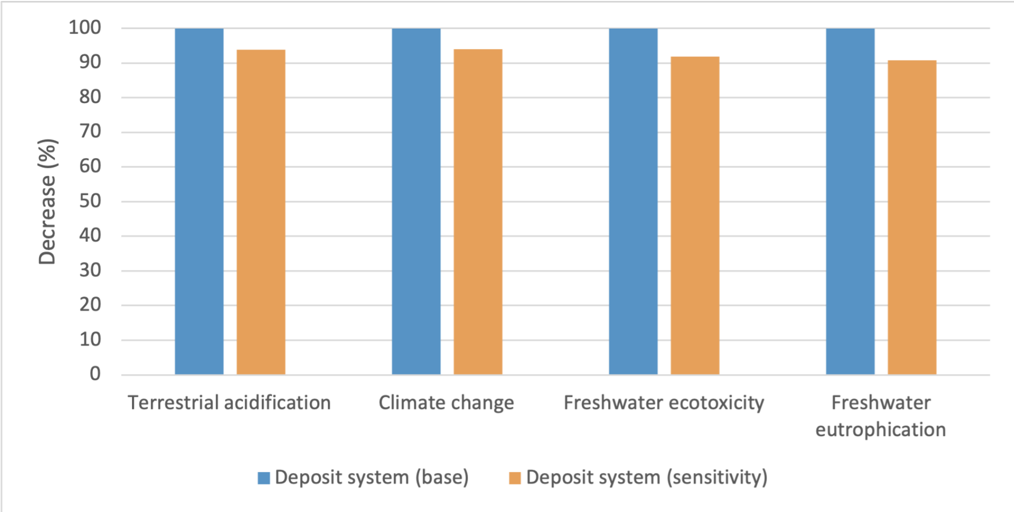


Figure 5.30: Results from sensitivity analysis, Aluminium 2, Reduction of electricity consumption by 10% in the recycling process.

process. The analysis was conducted since electricity plays a key role in the aluminium recycling process within the deposit system. In addition, there is a European Parliament decision to reduce the EU's final energy consumption by at least 11.7% by 2030 (European Union, 2024).

Therefore, in this sensitivity analysis, electricity consumption was decreased by 10% in the analysis for both remelting and rolling, from 112 kWh and 532 kWh to 100.8 kWh and 478.8 kWh. The results are presented in Figure 5.30.

The results show that electricity use in the recycling process contributes to all impact categories, particularly freshwater eutrophication. A 10% reduction in electricity consumption, considered a minor change, resulted in a 6–10% change in the total results. This indicates that the deposit system is quite sensitive to changes in energy supply and that electricity is an important parameter influencing the overall environmental performance.

Scenario analysis: Altering of metals in recycling process, conventional recycling system

The impact of copper and silicon was significant on multiple impact categories. Therefore two scenarios were created.

- **Scenario 1, No added metals:** The aluminium deposit system is closed loop, whereas the conventional recycling system is usually open loop. Through its recycling process, Stena Aluminium produces different alloys for different customers. In this scenario, both systems were modeled as closed loop systems, excluding the addition of metals to the recycling process. In this scenario, the inputs of silicon, copper, magnesium, and zinc were set to zero.
- **Scenario 2, Using recycled copper:** In Stena Aluminium's, it was unknown whether they used recycled or virgin copper. The base scenario includes virgin copper, including its production. Therefore, in this scenario recycled copper

was used instead, using Ecoinvent's process *"copper scrap, sorted, pressed, Recycled Content cut-off | GLO"*. Whereas the remaining metals were kept the same as in the base scenario.

The results are presented in Figure 5.31.

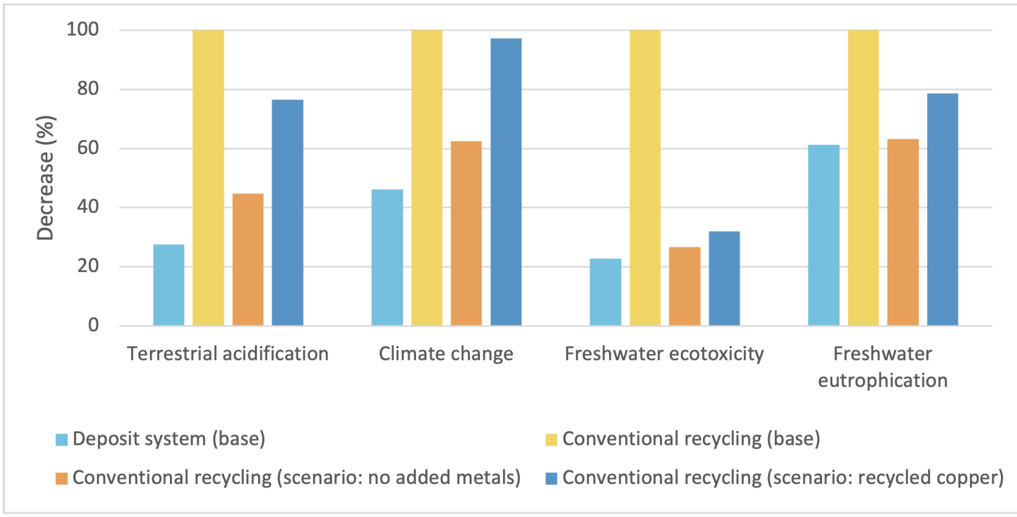


Figure 5.31: Results from altering metals in recycling process, conventional recycling system

For the first scenario, the impacts of the deposit system and the conventional recycling system appear more similar when no additional metals are added. The largest change is observed in the freshwater ecotoxicity category, which shows a 73% reduction in the no-metals scenario. Terrestrial acidification exhibits the second largest reduction, at 55%. Both categories climate change and freshwater eutrophication decrease by approximately 37%. In comparison to the deposit system scenario, the freshwater eutrophication results are nearly identical, with the deposit system showing only a slightly lower impact.

For the second scenario, the largest impact is once again observed in the freshwater ecotoxicity category. This category saw a 68% reduction. The terrestrial acidification category showed a reduction of approximately 24%. However, the reduction in climate change was slight. Silicon production is still the largest contributor to climate change, which was not affected by the use of recycled copper.

6

Life cycle interpretation

This chapter addresses the two remaining research questions. The first question relates to the identification of environmental hotspots in the end-of-life systems for PET and aluminium, based on the results presented in the previous chapter. The second builds on these hotspots by outlining potential areas for improvement. Furthermore, the sensitivity analyses are explored. The chapter concludes with a discussion of the applied methodology and suggestions for further research.

6.1 What are the environmental hotspots in the end-of-life systems for PET and aluminium?

The environmental hotspots identified in each end-of-life (EoL) system for PET and aluminium are summarized in Tables 6.1 and 6.2. These tables provide an overview of which processes and components contribute most significantly to environmental impacts across four impact categories: climate change (GWP100), terrestrial acidification (TAP), freshwater eutrophication (FEP), and freshwater ecotoxicity (FETP). In the tables, bullet points are used to indicate whether a specific hotspot is among the main contributors within each environmental impact category. The absence of a bullet point indicates that the hotspot has a minor contribution in that impact category.

One key observation across all systems is that the recycling process tends to be the dominant contributor to environmental impacts. For PET, this is mainly due to the use of sodium hydroxide in the washing process, while for aluminium, the high electricity demand in melting and rolling processes is a major contributor. Electricity use is particularly relevant when it comes to aluminium recycling, as it is an energy-intensive process, and the environmental burden is highly dependent on the electricity mix used. For example, Sweden's electricity mix is largely renewable and more similar to the French mix and significantly cleaner than the German one. This means that the same recycling process would have a higher environmental impact if carried out in a country with a fossil-based energy system, such as Germany. This geographical aspect is clearly reflected when comparing aluminium recycling across the systems, where the same process performed in different countries shows different levels of impact. Despite the total environmental impact of the conventional recycling system for aluminium being higher than that of the deposit system, it should be noted that the conventional system relies on the Swedish electricity mix and consumes less energy in the recycling stage. However, these advantages are largely overshadowed by other major impact contributors within the system, which means that the environmental benefits of lower electricity use are not strongly reflected in the overall results.

Collection generally plays a smaller role in all systems, although transport distance does influence results. The general trend in Sweden tends to be is to use fossil-free fuels in waste management, which reduces the overall impact of transport. Moreover, transport distances in the deposit system are based on exact data whereas transport distances in the conventional recycling and incineration systems are more uncertain and based on assumptions. However, a sensitivity analysis was performed on an estimated distance that did not reveal any significant differences.

In the conventional recycling system, a larger share of PET material is rejected during sorting compared to the deposit system. This rejected material is sent to incineration, which contributes significantly to the overall environmental impact. This highlights a key difference between the systems, where the quality and composition of collected material influence how much is ultimately recovered versus lost to incineration.

While each EoL system has its own unique hotspots, they also offer insights that can inform improvements in each other. For example, the importance of a clean, homogeneous material input in the deposit system can be linked to the lower sorting losses and thus reduced incineration related impacts. Similarly, ensuring high material quality and high recycling rates has proven to generate substantial benefits, particularly through the avoided production of virgin materials.

Hotspot	**Process**	**GWP100**	**TAP**	**FEP**	**FETP**
PET Deposit System					
Transportation to Returpack	Collection		•	•	
Incineration of waste/spill	Recycling	•	•	•	
Sodium hydroxide use	Recycling		•	•	
PET Conventional Recycling System					
Incineration of waste/spill	Sorting	•	•		•
Electricity use	Recycling	•	•	•	•
PET Incineration with Energy Recovery					
Incineration	Incineration	•	•	•	•

Table 6.1: Summary of environmental hotspots for PET end-of-life systems

Hotspot	Process	GWP100	TAP	FEP	FETP
Aluminium Deposit System					
Copper in electronics parts of RVM	Collection				•
Transportation to recycling in DE & FR	Sorting	•	•	•	•
Natural gas use	Recycling	•	•		
Electricity use	Recycling	•	•	•	•
Aluminium Conventional Recycling System					
Electricity use	Recycling		•		
Petroleum and oxygen gas use	Recycling	•		•	
Use of silicon and copper as alloying elements	Recycling	•	•	•	•

Table 6.2: Summary of environmental hotspots for aluminium end-of-life systems

6.2 What could reduce the environmental impact of the different end-of-life systems?

PET

The sodium hydroxide used in the recycling process to produce food grade PET flakes in the deposit system is a significant contributor to the terrestrial acidification and freshwater eutrophication impact categories. Sodium hydroxide is used in relatively large quantities in the recycling process, especially during chemical etching. The production of this industrial chemical is energy intensive and can result in emissions of nitrogen and sulfur compounds that contribute to acidification. In addition, emissions related to its upstream processes may contain nitrogen-based compounds that contribute to nutrient loading in aquatic environments. By reducing the use of sodium hydroxide or exploring alternative chemicals with lower impacts in the acidification and eutrophication categories, emissions from the recycling process in the deposit system could potentially be reduced.

Transportation to Returpack was identified as a hotspot for terrestrial acidification and eutrophication, and also showed a minor contribution to climate change. However, the overall impacts in the first two categories are generally quite low. The environmental impact from transportation arises primarily from fuel use, as it is modeled using a Well-to-Wheel approach that accounts for emissions from fuel extraction to combustion in the engine. It thus becomes apparent that, although fossil-free fuels are used, they are not entirely without environmental impact. This highlights the importance of critically evaluating not just the fuel type, but the entire fuel life cycle. By making sure that trucks are always full and that transport routes are optimized to avoid unnecessary mileage. However, despite the environmental impact associated with the collection phase, it remains significantly lower than that of producing virgin material, making it worthwhile to continue increasing efforts of collecting the packaging.

The incineration of waste, PET, and HDPE contributed significantly to the environmental impact of the recycling process in both of the recycling systems. Reducing the amount of material sent to incineration represents a key area for improvement with the potential to obtain environmental benefits. In the deposit system, the largest share of waste sent to incineration was identified at Veolia's recycling facility, suggesting that this is a targeted area with potential for improvement. The material being sent to incineration is likely other plastic material which is not suitable for bottle-to-bottle recycling. Improving this process could therefore be achieved by finding new purposes for these spill products.

In the conventional recycling system, the sorting process at Site Zero was identified as the stage generating the largest amount of waste. Here, a lot of waste which is wrongly sorted by consumers, including private individuals and companies, has to be sent to incineration. Therefore there is a need for encouraging consumers' sorting behavior at source. In addition, increasing efforts to direct non-plastic materials toward appropriate recycling streams, rather than incineration, could further reduce the environmental impact of the system. In the deposit system, where the sorting process has a small impact on the entirety of the system, it proves to be quite effective.

Furthermore, the large amounts sent to incineration may need to be addressed at the root of the problem. A comparison between the sorting processes in the deposit system and conventional recycling reveals significant differences. In the deposit system, only PET bottles are collected and processed, resulting in a relatively clean and homogeneous material stream. In contrast, Site Zero handles several different plastic fractions, often attached to the same product. This complexity makes the sorting process more difficult and less efficient. Therefore, designing packaging with material compatibility and ease of separation in mind is crucial. By reducing the number of different plastic types used in a single product and avoiding inseparable combinations, the efficiency of sorting and recycling processes can be significantly improved. This, in turn, could decrease the amount of material that ends up being incinerated and support a more circular plastic system.

Electricity use has been identified as another hotspot in the PET recycling process. In the scenario analysis found in Figure 5.28, electricity consumption increased due to the additional processing required to produce a larger share food grade flakes. However, the environmental impact still decreased across all categories. This is because the scenario also results in a higher yield of recycled material, meaning that less input is needed per functional unit. This way the efficiency gains in material output could lead to environmental benefits, even when energy use increases.

Aluminium

Regarding the collection of packaging, the copper used in RVMs showed a significant impact on terrestrial acidification and freshwater eutrophication. In the analysis, it was assumed that each RVM has a lifespan of at least seven years. To minimize environmental impact, it is therefore important that these machines are used and properly maintained throughout their intended lifespan, in order to avoid premature replacement and the associated demand for new copper in the manufacturing of electronic components. RVMs are, of course, also included in the PET deposit system. However, their relative contribution is less pronounced there, as other activities and processes dominate the environmental impact.

In both of the EoL systems, it is clear that the environmental benefits from avoided aluminium production are highly significant. Therefore, further increasing the collection rate is important to ensure that all packaging is recovered. While the collection stage in the deposit system does contribute to the overall impact, it is still much lower than the impact associated with producing virgin material. This suggests that even materials that are difficult to collect are worth the extra effort when considering the environmental impact of the system as a whole. Therefore, increasing the recycling rate and going the extra mile to collect it is considered beneficial.

Electricity use in the recycling process was identified as the largest contributor to environmental impact within the deposit system. This represents a key area for potential improvement, as demonstrated in the sensitivity analysis presented in Figure 5.30. The analysis simulated a 10% reduction in electricity consumption, which resulted in environmental improvements across all four impact categories. These results provide a basis for Returpack to engage with their downstream recycling partners and encourage them to reduce electricity use in their operations. Potentially by supporting these efficiency improvements or, perhaps, considering alternative partners with lower impact processes if possible. A significant part of the impact is linked to the electricity mix used in the recycling countries, which is generally less clean than in Sweden. However, by sending the material abroad, Returpack makes sure that the recycling loop is closed since these recyclers produce can sheets.

The main hotspot in the conventional recycling system was the use of silicon and copper to produce new aluminium alloys at Stena Aluminium. A scenario was illustrated in Figure 5.31, where excluding the input of additional alloying elements led to a significant reduction in environmental impact across all four categories. This result highlights the benefits of maintaining materials in a closed loop system. However, closed loop recycling is not always possible especially for companies which handle large amounts of scrap from many different sources, as the conventional recycling system does. In such cases, reducing the use of additional inputs like silicon and copper can still offer substantial environmental improvements. Furthermore, using recycled copper was shown to reduce environmental impact in all categories to varying degrees. Although the copper recycling process was not included, these results demonstrate the advantages of using recycled material instead of producing new copper.

6.3 Comparison

There are challenges associated with comparing the systems due to significant differences in data availability and quality. These differences are further discussed in Section 6.5. Therefore, the following comparison should be interpreted with some consideration.

PET

Firstly, in terms of the EoL systems for PET, the deposit system shows an advantage over the other two systems across all assessed impact categories. However, when it comes to terrestrial acidification, both the deposit and conventional recycling system show very similar performance. The conventional recycling system generally performs second-best in all categories, although the difference between this system and incineration with energy recovery is marginal in the category of freshwater eutrophication, based on the net impacts. The main reason for the notable difference between the deposit system and the conventional recycling system lies in the significantly higher recycling rate at Returpack's sorting facility compared to that of Svensk Plaståtervinning's Site Zero. More material is sent to incineration in the conventional recycling system than in the deposit system. It can be seen in the different impact categories that this shows a significant difference in the sorting process. Regarding incineration with energy recovery, since no material can be recovered after this EoL treatment option it decreases the overall resource recovery potential and performance of the system.

Aluminium

Secondly, in terms of the EoL systems for aluminium, the deposit system once again demonstrates the lowest environmental impact across the four investigated categories. The difference between the systems is lowest in the category of climate change and highest in freshwater ecotoxicity. The transportation to recycling shows higher environmental impact in all categories when being compared to conventional recycling. Whereas the recycling process itself is significantly higher in the conventional recycling system. As previously discussed, freshwater ecotoxicity is closely linked to the use of copper and silicon. Consequently, when examining the scenario analysis, it becomes apparent that the deposit and conventional recycling systems are much more similar when both operate on a closed loop basis. In this scenario, the environmental impacts across the categories show comparable results, despite the systems being implemented in different geographies. This highlights one challenge of comparing open and closed loop systems.

Material comparison

This study examined the EoL management of both PET bottles and aluminium cans. The results show that the deposit system involving aluminium cans leads to lower environmental impacts compared to PET bottles, when related to the functional unit. This is largely due to the system's ability to avoid primary aluminium production, which brings significant environmental savings. Furthermore, aluminium can be recycled repeatedly without large quality degradation, while PET suffers more losses in quality and material due to and degradation and spill, leading to more incineration. However, it is important to note that this study does not assess the entire life cycle of the beverage packaging, and therefore conclusions about which beverage packaging has a lower environmental impact is beyond the scope of this study.

6.4 Insights from sensitivity analysis

The robustness of the results were evaluated using sensitivity analyses for both PET and aluminium.

PET
To further evaluate the robustness of the results regarding PET, two sensitivity analyses were performed. The first focused on the conventional recycling system, where the fuel types used for transportation to recycling facilities in Germany were altered. Despite these changes, the results remained relatively stable across the assessed impact categories. The changes were quite small, but the largest change was seen in the impact category climate change. This shows that the impact from transportation was quite small in comparison to other processes.

The second sensitivity analysis performed included the transportation to RVMs within the deposit system. In contrast to the above described analysis, this parameter showed a bigger impact on the results. These results showed that the transportation to the RVMs, often located in supermarkets, have a large impact on the overall result of the deposit system. This indicates that transportation to RVMs is a parameter with high potential to significantly affect the results, and it should therefore be carefully considered in system modeling and interpretation.

Aluminium
In the case for aluminium, two additional sensitivity analyses were carried out. The first analysis explored the influence of changing the distance to sorting facilities in the conventional recycling system. These changes had a quite small impact on the overall results. These results suggest that the impact of transport distance is relatively minor in the context of the conventional recycling system, indicating that the overall conclusions of the system's environmental performance remain robust despite uncertainties in transport parameters.

The second sensitivity analysis focused on reducing electricity consumption by 10% in the recycling process in the deposit system. The results indicated that the recycling phase, particularly the electricity consumption, plays a significant role in determining the environmental impact of the aluminium recycling system. A 10% reduction in electricity use led to a 6-10% change in the results, suggesting that the system is somewhat sensitive to variations in energy use. This is therefore a parameter with an influence on the overall environmental impact of the system.

6.5 Discussion of methodology

LCA is highly dependent on the availability and quality of input data. In this study, some processes were modeled using generic data from the Ecoinvent 3.9 database, which may not fully represent the specific regional or technical conditions of the system under study. A combination of primary data from stakeholders and secondary data from databases was used, depending on data availability and accessibility. Primary data were given priority, but generic datasets were necessary in areas where direct information could not be obtained. However, mixing data sources of different quality and specificity can lead to inconsistencies in the assessment. For example, primary data may reflect more accurate and current conditions, while generic data are often based on average assumptions, which can affect comparability and increase uncertainty. It should also be noted that primary data has clearer sources and documentation, while generic data may have limited transparency. One such example from this study is that Veolia's environmental report to the County Council had detailed data for all emissions to water, while this data is not available for PET recyclers in Germany. Therefore, it is necessary to take this into account if comparisons of the systems are made.

One limitation of the study is that it does not consider packaging losses prior to collection, since collection rates are not included in any of the systems. Since the deposit system generally achieves a higher collection rate than the conventional recycling system, the results do not fully reflect its environmental benefits. Additionally, differences in collection performance between systems are not accounted for, which limits the ability to evaluate the environmental impact of inefficient collection. Including collection rates would make the comparison more realistic and better reflect system performance under actual conditions.

Obtaining primary data from companies proved difficult, as not all stakeholders able to share detailed information. In addition, the limited time frame of the project did not allow for follow-up and data requests that took several weeks to process. These limitations introduced additional uncertainty and may have led to simplifications and assumptions in parts of the assessment.

Uncertainties arising from limited data availability highlight that the purpose of the study is not to generate exact numerical results for each system or process. Instead, the focus is on identifying which processes and life cycle stages contribute more or less to the overall environmental impact of the systems. In addition to data limitations, the study's scope is further narrowed by including only one specific packaging size for each material. Consequently, the findings are not as representative as they would have been if a mix of sizes had been assessed. This limits the findings' generalizability, particularly in relation to the real packaging flows. It also adds to the overall uncertainty, as different sizes of packaging may affect life cycle stages differently. For instance, larger packaging might occupy more space during transport or require more energy during sorting and handling.

The definition of system boundaries has a major impact on what is and is not included in the analysis. For example, this study may not capture downstream processes beyond collection, sorting, recycling and incineration, such as leaching in landfills. These exclusions may result in an incomplete picture of environmental impacts. One example was seen in the sensitivity analysis of including the transportation to collection sites for the deposit system. This clearly illustrated how the results can vary significantly depending on the chosen system boundaries. In particular, this exclusion is likely to disadvantage the incineration with energy recovery system. Collection through residual waste streams is generally efficient. By not accounting for this, the environmental performance of the incineration system may be underestimated in the results.

Related to the defined system boundaries, the selection of impact categories also influences the broadness of the assessment. The choice of the impact categories may not cover all potential environmental or social impacts. As a result, issues such as microplastic pollution, land use or social impacts of waste management are overlooked.

Because this study compares five EoL systems in parallel, the level of detail for each system is therefore limited. The broad scope allows for a comprehensive comparison, giving an overview of the different systems. However this approach does come with certain trade-offs. Simplifications and assumptions had to be made where data was not easily available. Therefore, some elements in the analysis may be underrepresented or generalized in this study which potentially could impact the interpretation of the results. The trade-off is however taken into consideration in the interpretation, as the aim is not to provide exact impact values for each system, but rather to highlight relative differences and identify key contributors to environmental impact.

The functional unit chosen for this study is the end-of-life management of packaging for 1,000 liters of beverage. This functional unit was selected to enable a fair comparison of different EoL systems. Defining the functional unit in terms of beverage volume rather than the number of packaging accounts for differences in packaging size and material while ensuring the same quantity of product is handled in each system. It is important to note that the scope of this study is limited to the EoL phase of the packaging's life cycle. As such, upstream processes like production and distribution are excluded. Therefore, the conclusions drawn apply specifically to the waste management stage and should not be generalized to the packaging's full life cycle impacts.

6.6 Comparison with previous literature

The results of this study are largely in line with findings from earlier assessments of deposit and recycling systems for beverage packaging. Similar to the NORSUS studies, this study finds that high recycling rates are a key driver of environmental benefits (NORSUS, 2023a, 2023b). These benefits are primarily achieved by avoiding the production of virgin materials and reducing the amount of material sent to incineration.

The observed environmental hotspots in the recycling processes, such as the use of electricity, chemicals like sodium hydroxide, and the contribution of incineration are consistent with the results presented by (Bertils et al., 2018; Hemmingsson et al., 2018). Interestingly, these findings suggest that the types of processes driving environmental impacts have remained largely unchanged since Returpack's 2018 study, although their relative contributions have changed over time. This highlights the persistent importance of addressing energy and chemical use, as well as improving sorting efficiency to minimize incineration. Furthermore, the identified impacts from copper in reverse vending machines (RVM) in this study align with the findings from (NORSUS, 2023a), where the electronics in collection of packaging to ecotoxicity. This highlights the importance of accounting for the electronics used in the collection infrastructure.

It is also worth noting that, according to NORSUS (2023a), collection and treatment activities accounted for less than 10% of the total environmental impact across all assessed systems. This emphasizes that while improvements in collection and sorting may be important for efficiency and material quality, the most significant environmental outcomes are typically driven by processes further downstream, production activities. This is reflected in the results of this study, which show that avoiding the production of virgin materials contributes most substantially to overall environmental benefits. Additionally, Löfgren et al. (2024) found that, particularly during collection and recycling, a relatively high share of renewable fuels with lower climate impact than diesel was used, which contributed to lower emissions in the climate change impact category. In the present study, transportation emerged as a hotspot in certain processes. However, its contribution was relatively minor within the climate change category. This highlights how the significance of a process can vary depending on the choice of impact categories.

6.7 Future research suggestions

Although this study provides insights into the environmental aspects of the current systems of the three EoL systems, there are several areas that could be further explored. These suggestions can help refine future analyses and expand the system boundaries for a broader understanding.

First, transportation to the collection point is an area of uncertainty. These include transportation to RVMs in the deposit system and collection stations or similar in the conventional recycling system. The current sensitivity analysis for PET, which includes transportation, is based on general assumptions such as distance to collection point and vehicle type. A consumer survey could reveal how and when people return their beverage packaging to the deposit system. The sensitivity analysis performed highlighted the impact of assigning the transport to RVMs as quite significant to the results in the deposit system. However, assigning the environmental burden of this transport to the deposit system may be questionable as these trips often occur in combination with grocery shopping. Therefore, it is important to critically evaluate whether this transportation should be fully attributed to the deposit system or considered as a shared activity with other daily activities. Understanding behavioral patterns could improve the accuracy of the transport-related emissions in this assessment.

Secondly, the use of a more recent life cycle inventory databases, such as Ecoinvent version 3.11 or later, can improve the accuracy and fairness of environmental burdens. Updates to datasets often include more specific and regionally relevant information, which can affect the results. Therefore, for future studies it is recommended to use the latest database.

Thirdly, this study focused on clear PET bottles. A comparative analysis between clear and colored PET could provide further insight into the differences in circularity of the materials and ultimately influence packaging design decisions. Since clear and colored PET bottles have different EoL pathways, investigating both would give a more comprehensive view of the deposit system.

Moreover, this study has mainly considered the impacts up to the point where the material is recycled. Investigating the processes beyond that point would provide an even more complete picture, but it would be necessary to investigate what kind of products become of the recycled PET and aluminium. Investigating the impact of also recycle HDPE caps in a closed loop system could provide recommendations for future packaging design and optimization of the recycling system.

One limitation of the study is the exclusion of the collection rate from the analysis of the systems studied. Further work could include the collection rate because it plays a crucial role in determining the environmental impact of the EoL systems. Including collection rates would allow for a more accurate comparison of systems since differences in the efficiency of material recovery and return to EoL systems can significantly impact the results. Without accounting for this parameter, the assessment could underestimate or overestimate the benefits of certain systems, especially those with lower real-world collection rates.

One other important area is the assumption that the replaced PET bottle consists of 100% virgin PET. It could therefore be relevant in future research to investigate how much virgin material is actually avoided when replacing a bottle that already contains recycled content. This would help give a more accurate picture of the environmental benefits from increased recycling and material substitution.

Finally, current LCA methodology may not fully capture the benefits of maintaining closed loop material cycles compared to open loop recycling. While LCA provides valuable insights into environmental impacts, it does not always reflect the long-term retention of material value or the system-level benefits of keeping materials within the same product cycle. Therefore, additional methods may be needed to better capture the value of material retention and closed-loop performance at the system level.

7
Conclusion

This study set out to assess the environmental impacts of three end-of-life systems for PET bottles and two end-of-life systems for aluminium cans in Sweden. The systems include the deposit system, conventional recycling, and incineration with energy recovery. The findings indicate that the deposit system generally exhibits the lowest environmental impact, primarily due to its closed loop nature, which maintains high-quality materials in circulation for as long as possible.

One significant finding to emerge from this study is that incineration consistently results in substantial environmental impacts across most impact categories, despite the recovery of energy. This emphasizes the importance of minimizing the amount of packaging and waste sent to incineration. Improving collection and recycling rates is therefore essential to ensure that more materials enter recycling streams, particularly into closed loop systems like the deposit system.

The study also highlights that conventional recycling suffers from greater material losses and quality degradation, often resulting in down cycled products. This down cycling leads to lower material quality and reduced market value, which increases the demand for virgin material and consequently reducing the environmental benefits from avoiding new production. In contrast, the deposit system maintains material quality, allowing recycled PET and aluminium to become new beverage packaging. To further reduce environmental impact, efforts should focus on increasing collection rates, continue improving transportation activities, and encourage reductions in energy use in recycling processes.

Several factors can significantly influence the results, such as whether transport to collection points is included, or whether virgin or recycled metals are used in open loop recycling. Therefore, transparent and consistent boundary setting is crucial for drawing valid conclusions. By identifying key environmental hotspots across systems, this study highlited the most critical stages and processes.

Overall, the findings of this study can provide valuable insights for Returpack by clarifying the environmental impact of their current system and identifying potential areas for improvement. By examining other types of end-of-life systems, Returpack gains a broader perspective on their own system's strengths and limitations, which can support continued development towards greater circularity and reduced environmental impact.

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A

Fuels

Table A.1: Flow table and specific flow documention biogas, EURO6, Cradle-to-gate (Hallberg et al., 2013)

Flow table and specific flow documention biogas, EURO6, Cradle-to-gate					
Direction	Flow type	Environment	Substance	Quantity	Unit
Input	Product	Technosphere	Primary energy	0.39	MJ
Output	Emission	Air	Carbon dioxide (fossil)	8,90E-03	kg
Output	Emission	Air	Methane (biogenic)	1,09E-04	kg
Output	Emission	Air	Nitrous oxide	0,00E+00	kg
Output	Emission	Air	Carbon monoxide	0,00E+00	kg
Output	Emission	Air	Nitrogen oxide	6,54E-05	kg
Output	Emission	Air	Sulfur dioxide	3,10E-06	kg
Output	Emission	Air	NMVOC	2,80E-06	kg
Output	Emission	Air	Particles, unspecified	1,50E-06	kg
Output	Product	Technosphere	Biogas from manure	1	MJ

Table A.2: Flow table and specific flow documention CBG, EURO6, Tank to Wheel (Hallberg et al., 2013)

Flow table and specific flow documention CBG, EURO6, Tank to Wheel					
Direction	Flow type	Environment	Substance	Quantity	Unit
Input	Product	Technosphere	Compressed biogas (CBG)	1	MJ
Output	Emission	Air	Carbon dioxide (fossil)	0,00E+00	kg
Output	Emission	Air	Methane	5,56E-05	kg
Output	Emission	Air	Nitrous oxide	5,56E-06	kg
Output	Emission	Air	Carbon monoxide	4,44E-04	kg
Output	Emission	Air	Nitrogen oxides	5,11E-05	kg
Output	Emission	Air	Sulfur dioxide	8,52E-07	kg
Output	Emission	Air	NMVOC	1,78E-05	kg
Output	Emission	Water, fresh	Particles, unspecified	1,11E-06	kg

Table A.3: Flow table and specific flow documention for HVO, Cradle-to-gate (Källmén et al., 2019)

Flow table and specific flow documention HVO Cradle-to-gate						
Direction	Flow type	Environment	Substance	Quantity	Unit	Note: Net Calorific Value [MJ/kg]
Input	Resource	Ground	Crude oil	2,06E-02	MJ	42.3
Input	Resource	Ground	Hard coal	1,64E-02	MJ	26.3
Input	Resource	Ground	Lignite	8,70E-03	MJ	10
Input	Resource	Ground	Natural gas	3,92E-01	MJ	44.1
Input	Resource	Ground	Uranium	2,12E-02	MJ	544284
Output	Emission	Air	Carbon dioxide (fossil)	2,91E-02	kg	
Output	Emission	Air	Carbon dioxide (biotic)	4,63E-04	kg	
Output	Emission	Air	Carbon monoxide	1,79E-05	kg	
Output	Emission	Air	Nitrogen oxides	3,23E-05	kg	
Output	Emission	Air	Dinitrogen monoxide	5,14E-07	kg	
Output	Emission	Air	Sulphur dioxide	2,61E-05	kg	
Output	Emission	Air	Methane (fossil)	8,82E-05	kg	
Output	Emission	Air	Methane (biotic)	4,07E-07	kg	
Output	Emission	Air	NMVOC	1,12E-05	kg	
Output	Emission	Air	Particles (> PM10)	2,64E-06	kg	
Output	Emission	Air	Particles (PM2.5-PM10)	6,68E-07	kg	
Output	Emission	Air	Particles (PM2.5)	2,57E-06	kg	
Output	Emission	Water, fresh	Ammonium / ammonia	2,08E-08	kg	
Output	Emission	Water, fresh	Nitrate	5,22E-07	kg	
Output	Emission	Water, fresh	Phosphate	8,04E-07	kg	
Output	Product	Technosphere	HVO - Slaugtherhouse waste as residue	1	MJ	

Table A.4: Flow table and specific flow documention HVO, Tank-To-Wheel (Källmén et al., 2019)

Flow table and specific flow documention for HVO, Tank-To-Wheel					
Direction	Flow type	Environment	Substance	Quantity	Unit
Output	Emission	Air	Methane	1,96E-06	kg
Output	Emission	Air	Nitrous oxide	6,11E-06	kg
Output	Emission	Air	Carbon monoxides	4,89E-04	kg
Output	Emission	Air	Nitrogen oxides	5,62E-05	kg
Output	Emission	Air	Sulfur dioxides	1,36E-07	kg
Output	Emission	Air	NMVOC	1,76E-05	kg
Output	Emission	Air	Particles, unspecified	1,22E-06	kg

B

Reverse vending machine

Table B.1: Reverse vending machine, input and output data for deposit of one packaging

Flow	Amount	Unit	Provider	Source	Note
Input					
Aluminium	2.4375E-05	kg	market for aluminium, primary, ingot | Area EU27 & EFTA	Ecoinvent 3.9	Data from Tomra for one machine with a 7 year lifespan
Steel	7.123E-04	kg	market for municipal waste incineration to generic market for heat, district or industrial, other than natural gas	Ecoinvent 3.9	
Zink coat	1.3E-09	m^2	zink coating, coils | RER	Ecoinvent 3.9	
Glass	3.25E-05	m^2	market for flat glass, uncoated | RER	Ecoinvent 3.9	
Plastics	7.31E-05	kg	market for polypropylene, granulate | GLO	Ecoinvent 3.9	
Wood	1.25E-08	kg	market for plywood | RER	Ecoinvent 3.9	
Paper	1.056E-04	kg	market for paper, woodfree, uncoated | RER	Ecoinvent 3.9	
Electronics	3.25E-05	kg	market for electronics, for control units | GLO	Ecoinvent 3.9	
Electricity	1.616E-03	kWh	market for electricity, low voltage | SE	Ecoinvent 3.9	
Output					
Deposit machine	1	usage			

C

Electricity mix Returpack

Table C.1: Table of electricity mix for Returpack

Electricity mix Returpack				
Flow	**Amount**	**Unit**	**Provider**	**Source**
Input				
Sulfur hexachloride, liquid	1,13E-07	kg	Market for sulfur hexafluoride, liquid	
Transmission network, electricity, medium voltage	1.8628E-08	km	Market for transmission network, electricity, medium voltage	
Electricity, high voltage	0.8613	kWh	Electricity production, wind, >3MW turbine, onshore	Returpack (2025)
Electricity, low voltage	0.13	kWh	Electricity production, photovoltaic, 3kWp slanted roof installation, single-Si, panel, mounted	Returpack (2025)
Output				
Returpack Electricity	1	kWh		
Sulfur hexachloride	1.13E-07	kg	Sulfur hexafluoride | ('air')	

D
Aluminium transport

Table D.1: Data input and output for Transportation to France

Transport to FR				
Flow	**Amount**	**Unit**	**Provider**	**Source**
Input				
Truck transport Norrköping-Katrineholm	50	km	HVO transport, freight, lorry 16-32 metric ton, EURO6 | RER	Returpack (2025)
Train transport Katrineholm-Duisburg	1243	km	market for transport, freight train | Europe without Switzerland	Returpack (2025)
Truck transport Duisburg-Bishem	500	km	HVO transport, freight, lorry 16-32 metric ton, EURO6 | RER	Returpack (2025)
Output				
Transport to FR	1	unit		

Table D.2: Data input and output for Transportation to Germany

Transport to DE				
Flow	**Amount**	**Unit**	**Provider**	**Source**
Input				
Truck transport Norrköping-Oxelösund	74	km	HVO transport, freight lorry, >32 metric ton EURO6 | RER	Returpack (2025)
Train transport Oxelösund-Nachterstedt	1121.43	km	market for transport, freight train | Europe without Switzerland Note: 5% of the route	Returpack (2025)
Truck transport Oxelösund-Nachterstedt	61.568	km	HVO freight lorry HVO100, >32t Note: 5% of the route	Returpack (2025)
Output				
Transport to DE	1	unit		

E

PET Deposit system

Table E.1: Data input and output for PET Deposit system

PET: Deposit system				
Collection				
Flow	**Amount**	**Unit**	**Provider**	**Source**
Input				
Bottles	1	kg		
Deposit machine	40.12	usages	Appendix A	
Transport to Returpack, HVO	228.53	km	HVO transport, freight, lorry 16-32 metric ton, EURO6 | RER| Appendix B	
Transport to Returpack, CBG	300.76	km	CBG transport, freight, lorry 16-32 metric ton, EURO6 | RER | Appendix B	
Transport to Returpack, LBG	62.76	km	CBG transport, freight, lorry 16-32 metric ton, EURO6 | RER | Appendix B	
Output				
Collected bottles	1	kg		
Sorting				
Flow	**Amount**	**Unit**	**Provider**	**Source**
Input				
Collected bottles	1	kg		Returpack (2025)
Electricity PET	0.05589	kWh	market for electricity, medium voltage | SE	Returpack (2025)
Electricity HDPE	0.029	kWh	market for electricity, medium voltage | SE	Returpack (2025)

District heat	0.05892	MJ	heat, from municipal waste incineration to generic market for heat district or industrial, other than natural gas | SE	Returpack (2025)
Output				
Waste for incineration	0.02361	kg	treatment of municipal solid waste, incineration | SE	Returpack (2025)
Balled PET	0.97692	kg		Returpack (2025)
Grinded HDPE	0.09257	kg		Returpack (2025)
Recycling				
Flow	**Amount**	**Unit**	**Provider**	**Source**
Input				
Balled PET	1	kg		Veolia (2024)
Electricity	0.19974	kWh	market for electricity, medium voltage | SE	Veolia (2023)
District heat	0.07374	MJ	heat, from municipal waste incineration to generic market for heat district or industrial, other than natural gas | SE	Veolia (2023)
Light fuel oil, EO32	0.00355	kg	market for light fuel oil | Europe without Switzerland	Veolia (2023)
HVO for the industrial truck	0.01904882	MJ	Appendix B	Veolia (2024)
Water	0.002837	m^3	Water, unspecified natural origin | ('natural resource - in water')	Veolia (2023)
Sodium cloride	0.0012536	kg	sodium chloride production, brine solution | RER	Veolia (2023)
Sodium hydroxide	0.02751	kg	market for neutralising agent, sodium hydroxide-equivalent | GLO	Veolia (2023)
Sulfite	1.04665E-05	kg	sodium sulfite production | RER	Veolia (2023)
Sulfite acid	1.47261E-03	kg	sulfuric acid production | RER	Veolia (2023)
Surfactants	1.34538E-04	kg	alkylbenzene sulfonate production, linear, petrochemical | RER	Veolia (2023)
Output				
Clean PET flakes	0.52215	kg		Veolia (2023)

Bottle grade PET flakes	0.36285	kg		Veolia (2023)
Caps HDPE	0.09257	kg		Veolia (2023)
Waste for incineration	0.115	kg	market for waste polyethylene terephthalate | SE	Veolia (2023)
Water	0.002837	m^3	market for waste polyethylene terephthalate | SE	Veolia (2023)
Bod5	9.6672E-03	kg	BOD5, Biological Oxygen Demand | ('water',)	Veolia (2023)
TOC	5.3235E-03	kg	TOC, Total Organic Carbon | ('water',)	Veolia (2023)
Ntot	2.9153E-05	kg	Nitrogen, organic bound | ('water',)	Veolia (2023)
Ptot	1.5982E-05	kg	Phousphorus | ('water',)	Veolia (2023)
Susp. solids	1.2933E-03	kg	Suspended solids, unspecified | ('water',)	Veolia (2023)
Pb	3.5082E-08	kg	Lead II | ('water',)	Veolia (2023)
Cd	3.8980E-10	kg	Cadmium II | ('water',)	Veolia (2023)
Cu	2.17120E-07	kg	Copper ion | ('water',)	Veolia (2023)
Cr	1.6372E-07	kg	Chronium VI | ('water',)	Veolia (2023)
Hg	3.8980E-10	kg	Mercury II | ('water',)	Veolia (2023)
Ni	6.2758E-08	kg	Nickel II | ('water',)	Veolia (2023)
Ag	3.8980E-10	kg	Silver I | ('water',)	Veolia (2023)
Zn	6.385E-07	kg	Zinc II | ('water',)	Veolia (2023)

F

PET Conventional recycling

Table F.1: Data input and output for PET Open loop recycling

PET: Open loop recycling				
Collection				
Flow	**Amount**	**Unit**	**Provider**	**Source**
Input				
Bottles	1	kg		
Transport to sorting, HVO	126.5	km	HVO transport, freight, lorry 16-32 metric ton, EURO6 | RER| Appendix B	
Transport to sorting, CBG	126.5	km	CBG transport, freight, lorry 16-32 metric ton, EURO6 | RER | Appendix B	
Output				
Collected plastic packaging	1	kg		
Sorting				
Flow	**Amount**	**Unit**	**Provider**	**Source**
Input				
Collected plastic packaging	1	kg		Svensk Plaståtervinning (2024)
Electricity	Conf.	kWh	market for electricity, medium voltage | SE	Svensk Plaståtervinning (2024)
District heat	0.3268	MJ	heat, from municipal waste incineration to generic market for heat district or industrial, other than natural gas | SE	Svensk Plaståtervinning (2024)
HVO for industrial truck	0.0007975	MJ	Appendix B	Svensk Plaståtervinning (2024)

Transport to recycling, truck, HVO	114.3	km	HVO transport, freight, lorry 16-32 metric ton, EURO6 | RER | Appendix B	
Transport to Returpack, train	1028.7	km	market for freight transport, freight train | Europe without Switzerland	
Output				
Waste for incineration	0.27627	kg	treatmnt of municipal solid waste, incineration | SE	Svensk Plaståtervinning (2024)
Balled PET	0.73	kg		Svensk Plaståtervinning (2024)
Recycling				
Flow	**Amount**	**Unit**	**Provider**	**Source**
Input				
Balled PET	1.25	kg		
Recycling process PET	1.25	kg	polyethylene terephthalate production, granulate, amorphous, recycled | Europe without Switzerland	
Recycling process HDPE	0.1368	kg	market for polyethylene, high density, granulate, recycled | Europe without Switzerland	
Output				
PET granulate	1	kg		
HDPE granulate	0.1368	kg		

G

PET Incineration with energy recovery

Table G.1: Data input and output for PET Incineration with energy recovery

PET: Incineration with energy recovery				
Collection				
Flow	**Amount**	**Unit**	**Provider**	**Source**
Input				
Plastic packaging	1	kg		
Transport from collecting point to incineration facility, HVO	20.5	km	HVO transport, freight, lorry 16-32 metric ton, EURO6 | RER| Appendix B	
Transport from collecting point to incineration facility, CBG	20.5	km	CBG transport, freight, lorry 16-32 metric ton, EURO6 | RER | Appendix B	
Output				
Collected plastic packaging	1	kg		
Incineration				
Flow	**Amount**	**Unit**	**Provider**	**Source**
Input				
Collected plastic packaging	1	kg		
Incineration process PET	1	kg	market for waste polyethylene terephthalate | SE	
Incineration process HDPE	0.093023	kg	market for waste polyethylene | SE	
Output				
Electricity	0.7667	kWh		Sánchez et al. (2007)

District heat	20.24	MJ		Sánchez et al. (2007)

H

Aluminium Deposit system

Table H.1: Data input and output for Aluminium Deposit system

Aluminium: Deposit system				
Collection				
Flow	**Amount**	**Unit**	**Provider**	**Source**
Input				
Cans	1	kg		
Deposit machine	82.2	usages	Appendix A	
Transport to Returpack, HVO	231.45	km	HVO transport, freight, lorry 16-32 metric ton, EURO6 | RER | Appendix B	
Transport to Returpack, CBG	304.60	km	CBG transport, freight, lorry 16-32 metric ton, EURO6 | RER | Appendix B	
Transport to Returpack, LBG	63.56	km	LBG transport, freight, lorry 16-32 metric ton, EURO6 | RER | Appendix B	
Output				
Collected cans	1	kg		
Sorting				
Flow	**Amount**	**Unit**	**Provider**	**Source**
Input				
Collected cans	1.00064	kg		Returpack (2025)
Electricity	0.02547	kWh	market for electricity, medium voltage | SE	Returpack (2025)
District heat	0.02768	MJ	heat, from municipal waste incineration to generic market for heat district or industrial, other than natural gas | SE	Returpack (2025)
Transport to DE	Conf.	unit		Appendix C

Transport to FR	Conf.	unit		Appendix C
Output				
Waste for incineration	0.000641	kg	treatment of municipal solid waste, incineration | SE	Returpack (2025)
Balled Aluminium	1	kg		Returpack (2025)
Remelting				
Flow	**Amount**	**Unit**	**Provider**	**Source**
Input				
Aluminium scrap	1.087	kg		European Aluminium (2024)
Light fuel oil	0.013	MJ	heat production, light fuel oil, at industrial furnace 1MW | Europe without Switzerland	European Aluminium (2024)
Natural Gas	3.095	MJ	heat and power co-generation, natural gas, combined cycle power plant, 400 MW electrical | DE / FR	European Aluminium (2024)
Electricity	0.112	kWh	market for electricity, high voltage | DE / FR	European Aluminium (2024)
Argon	0.0018	kg	market for argon, liquid | RER	European Aluminium (2024)
Nitrogen	0.0011	kg	market for nitrogen, liquid | RER	European Aluminium (2024)
Chlorine	0.0001	kg	market for chlorine, liquid | RER	European Aluminium (2024)
Calcium oxides	0.0006	kg	market for calcium carbonate, precipitated | RER	European Aluminium (2024)
Process water	0.0006	m^3	Water | 'water'	European Aluminium (2024)
Cooling water	0.0013	m^3	Water, cooling, unspecified natural origin | 'natural resource', 'in water'	European Aluminium (2024)
Output				

Unscalped rolling ingots	1	kg		European Aluminium (2024)
Dross/ skimming	0.052	kg		European Aluminium (2024)
Chlorine	7.0E-07	kg	chlorine | 'air'	European Aluminium (2024)
Hydrochloric acid	7.8E-07	kg	hydrochloric acid | 'air'	European Aluminium (2024)
Nitrogen dioxide	0.0001816	kg	nitrogen oxides | 'air'	European Aluminium (2024)
Total gaseous organic carbon	0.0000191	kg	NMVOC, non-methane volatile organic compounds | 'air'	European Aluminium (2024)
Sulfur oxide	0.0000461	kg	sulfur oxides | 'air'	European Aluminium (2024)
Hazardous waste for landfilling	0.001	kg	market for hazardous waste, for underground deposit | RER	European Aluminium (2024)
Hazardous waste for incineration	0.0003	kg	market for hazardous waste, for incineration | Europe without Switzerland	European Aluminium (2024)
Non-haz waste for landfilling	0.0013	kg	treatment of inert waste, inert material landfill | Europe without Switzerland	European Aluminium (2024)
Rolling				
Flow	**Amount**	**Unit**	**Provider**	**Source**
Input				
Unscalped rolling ingots	1	kg		European Aluminium (2024)
Light fuel oil	0.012	MJ	heat production, light fuel oil, at industrial furnace 1MW| Europe without Switzerland	European Aluminium (2024)
Natural Gas	1.608	MJ	heat and power co-generation, natural gas, conventional power plant, 100MW electrical | SE	European Aluminium (2024)

Electricity	0.532	kWh	market for electricity, high voltage | SE	European Aluminium (2024)
Nitrogen	0.0089	kg	market, for nitrogen, liquid | RER	European Aluminium (2024)
Filter earths	0.0014	kg	Silicon production, metallurgical grade | NO	European Aluminium (2024)
Process water	0.0015	m^3	Water | 'water'	European Aluminium (2024)
Cooling water	0.0011	m^3	Water, cooling, unspecified natural origin | 'natural resource', 'in water'	European Aluminium (2024)
Output				
Aluminium rolled sheet	1	ton		European Aluminium (2024)
Dust/Particles	1.0E-07	kg	particulate matter, >2.5 μm and < 10 μm| 'air'	European Aluminium (2024)
Hydrochloric acid	3.9E-09	kg	hydrochloric acid | 'air'	European Aluminium (2024)
Nitrogen dioxide	0.000171	kg	nitrogen oxides | 'air'	European Aluminium (2024)
Sulfur oxides	6.0E-06	kg	sulfur oxides | 'air'	European Aluminium (2024)
Hazardous waste for landfilling	0.0014	kg	market for hazardous waste, for underground deposit | RER	European Aluminium (2024)
Hazardous waste for incineration	0.0012	kg	market for hazardous waste, for incineration | Europe without Switzerland	European Aluminium (2024)
Non-haz waste for landfilling	0.3	kg	treatment of inert waste, inert material landfill | Europe without Switzerland	European Aluminium (2024)

I

Aluminium Conventional recycling

Table I.1: Data input and output for Aluminium Open loop recycling system

Aluminium: Conventional recycling system				
Collection				
Flow	**Amount**	**Unit**	**Provider**	**Source**
Input				
Aluminium packaging	1	kg		
Transport to Sorting, HVO	126.5	km	HVO transport, freight, lorry 16-32 metric ton, EURO6 | RER |Appendix B	
Transport to Sorting, CBG	126.5	km	CBG transport, freight, lorry 16-32 metric ton, EURO6 | RER |Appendix B	
Output				
Aluminium packaging, unsorted	1	kg		
Sorting				
Flow	**Amount**	**Unit**	**Provider**	**Source**
Input				
Aluminium packaging, unsorted	1.024	kg	treatment of metal scrap, mixed, for recycling, unsorted, sorting | Europe without Switzerland	
Transport to Recycling	160	km	HVO transport, freight, lorry 16-32 metric ton, EURO6 | RER |Appendix B	
Transport to Recycling	160	km	CBG transport, freight, lorry 16-32 metric ton, EURO6 | RER |Appendix B	
Output				

Balled aluminium	1	kg		
Waste to incineration with energy recovery	0.024	kg	treatment of municipal solid waste, incineration | SE	
Recycling				
Flow	**Amount**	**Unit**	**Provider**	**Source**
Input				
Balled aluminium	1.33	kg		Stena Aluminium (2024)
Silicon	0.05679	kg	silicon production, metallurgical grade | NO	Stena Aluminium (2024)
Other alloying elements	1.79E-03	kg	market for copper, cathode | GLO	Stena Aluminium (2024)
Other alloying elements	5.97E-04	kg	market for magnesium| GLO	Stena Aluminium (2024)
Other alloying elements	5.97E-04	kg	market for zinc| GLO	Stena Aluminium (2024)
Other alloying elements	5.97E-04	kg	market for sodium| GLO	Stena Aluminium (2024)
Sodium chloride	0.0857	kg	sodium chloride production, powder| RER	Stena Aluminium (2024)
Bicarbonate	3.84E-03	kg	market for sodium bicarbonate |GLO	Stena Aluminium (2024)
Activated charcoal	4.3E-04	kg	activated carbon production, granular from hard coal | RER	Stena Aluminium (2024)
Nitrogen gas	1.21E-03	kg	market for nitrogen, liquid | RER	Stena Aluminium (2024)
Oxygen	0.121	kg	market for oxygen, liquid | RER	Stena Aluminium (2024)
LPG	0.000686	MWh	market for liquefied petroleum gas | Europe wiyhout Switzerland	Stena Aluminium (2024)

Electricity	0.000131	MWh	market for electricity, high voltage | SE	Stena Aluminium (2024)
District heat	0.0000121	MWh	heat, from municipal waste incineration to genericmarket for heat district or industrial, other than natural gas | SE	Stena Aluminium (2024)
Process water	0.000096	m^3	Water | 'water'	Stena Aluminium (2024)
Cooling water	0.000196	m^3	Water, cooling, unspecified natural origin | 'natural resource', 'in water'	Stena Aluminium (2024)
Output				
Aluminium ingots	1	kg		Stena Aluminium
Sulfur dioxide	8.84E-06	kg	Sulfur dioxides | 'air'	Stena Aluminium (2024)
Benzene	0.000011	kg	Benzene | 'air'	Stena Aluminium (2025)
Cadmium	9.71E-011	kg	Cadmium II | ('air',)	Stena Aluminium (2024)
Methane	0.00001	kg	methane, fossil | ('air')	Stena Aluminium (2024)
Chlorine	6.38E-07	kg	Chlorine | ('air') air	Stena Aluminium (2024)
Copper	1.25E-08	kg	Copper ion | ('air',)	Stena Aluminium (2024)
Fluorine	6.38E-07	kg	Fluorine |('air')	Stena Aluminium (2024)
Mercury	4.16E-12	kg	Mercury II | ('air',)	Stena Aluminium (2024)
NMVOC	0.0000126	kg	NMVOC, non-methane volatile organic compounds| 'air'	Stena Aluminium (2024)

Lead	1.11E-09	kg	Lead II | ('air',)	Stena Aluminium (2024)
Zinc	1.53E-08	kg	Zinc II | ('air',)	Stena Aluminium (2024)
Copper	3.39E-08	kg	Copper ion | ('water',)	Stena Aluminium (2024)
Zinc	8.55E-08	kg	Zinc II | ('water',)	Stena Aluminium (2024)
Hazardous waste for landfilling	5.55E-08	kg	market for hazardous waste, for underground deposit | RER	Stena Aluminium (2024)
Hazardous waste for incineration	1.8E-08	kg	market for hazardous waste, for incineration | Europe without Switzerland	Stena Aluminium (2024)
Non-haz waste for landfilling	4.26E-06	kg	treatment of inert waste, inert material landfil | Europe without Switzerland	Stena Aluminium (2024)
Waste, wood	0.00079	kg	treatment of waste wood, untreated, municipal incineration | CH	Stena Aluminium (2024)
Waste	0.00079	kg	market for municipal solid waste | Europe without Switzerland	Stena Aluminium (2024)

J

Results

Table J.1: Numerical Results, PET systems

	Process	**Deposit system**	**Conventional recycling**	**Incineration with energy recovery**
Global warming potential [kg CO_2-eq.]	Collection	3.8694	1.4356	0.22321
	Sorting	1.5318	36.1754	
	Transport to recycling		3.565	
	Recycling	49.8228	63.279	
	Incineration			100.9270
	Avoided prod. of electricity & heat	-10.348	-32.044	-86.036
	Avoided primary production	-112.83	-100.04	
Eutrophication, freshwater [kg P-eq.]	Collection	5.27E-04	1.59E-04	2.58E-05
	Sorting	1.36E-04	1.04E-03	
	Transport to recycling		2.16E-03	
	Recycling	5.97E-03	2.96E-02	
	Incineration			1.10E-02
	Avoided prod. of electricity & heat	-2.153-04	-6.65E-04	-2.55E-03
	Avoided primary production	-2.13E-02	-1.89E-02	
Terrestrial acidification potential [kg SO_2-eq.]	Collection	7.55E-03	2.66E-03	4.39E-04
	Sorting	1.09E-03	8.60E-03	
	Transport to recycling		7.75E-03	
	Recycling	4.62E-02	6.35E-02	
	Incineration			1.09E-02
	Avoided prod. of electricity & heat	-7.82E-03	-2.42E-02	-6.85E-02
	Avoided primary production	-3.01E-01	-2.67E-01	
Freshwater ecotoxicity potential [kg 1.4 DCB-eq.]	Collection	0.2466	0.0507	0.0082
	Sorting	0.4417	2.8371	
	Transport to recycling		0.1268	
	Recycling	4.4609	6.8495	
	Incineration			8.0638
	Avoided prod. of electricity & heat	-0.0638	-0.1974	-0.8513
	Avoided primary production	-4.333	-3.842	

Table J.2: Numerical Results, Aluminium systems

	Process	**Deposit system**	**Conventional recycling**
Global warming potential [kg CO_2-eq.]	Collection	3.7961	1.2848
	Sorting	0.0759	2.3987
	Transport to recycling	3.5225	1.6250
	Recycling	14.4564	42.0124
	Avoided prod. of electricity & heat	-0.0993	-0.8778
	Avoided primary production	-377.83	-293.1
Eutrophication, freshwater [kg P-eq.]	Collection	6.24E-04	1.43E-04
	Sorting	3.45E-05	1.81E-04
	Transport to recycling	1.25E-03	1.80E-04
	Recycling	7.71E-03	1.52E-02
	Avoided prod. of electricity & heat	-2.15E-06	-1.90E-05
	Avoided primary production	-1.61E-01	-1.27E-01
Terrestrial acidification potential [kg SO_2-eq.]	Collection	7.90E-03	2.38E-03
	Sorting	3.18E-04	5.26E-04
	Transport to recycling	9.56E-03	3.01E-03
	Recycling	2.36E-02	1.44E-01
	Avoided prod. of electricity & heat	-7.56E-05	-6.68E-04
	Avoided primary production	-1.81E+00	-1.43E+00
Freshwater ecotoxicity potential [kg 1.4 DCB-eq.]	Collection	0.3409	0.0453
	Sorting	0.0636	0.2716
	Transport to recycling	0.1390	0.0574
	Recycling	0.3384	3.4956
	Avoided prod. of electricity & heat	-0.0006	-0.0057
	Avoided primary production	-14.655	-11.662

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