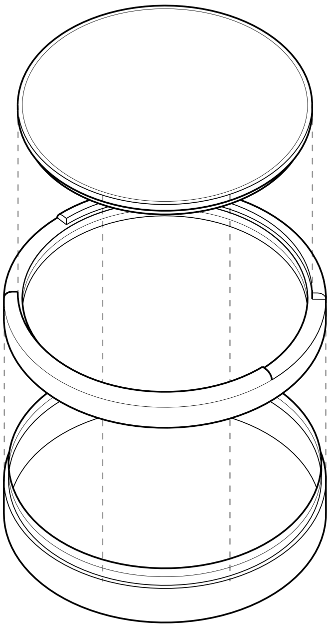

Life Cycle Assessment of snus cans in a cradle-to-grave study

A comparative Life Cycle Assessment of Swedish Match's snus cans.

Master's thesis in Industrial Ecology

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A comparative LCA of snus cans, aiming to determine environmental performance of packaging materials used by Swedish Match AB

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Cover:
Exploded view of a typical existing snus can. Illustrated by Emma Frykberg

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Abstract

This thesis investigates the environmental impact of four different packaging materials for snus cans by conducting a comparative Life Cycle Assessment (LCA). Two existing materials and two potential substitutes are assessed and compared. Current can materials are fossil-based polypropylene plastic and a wax coated recycled paper. Substitutes are bio-based polypropylene plastic and a hybrid can combining virgin paper and plastic. The thesis was conducted in collaboration with Swedish Match AB, a Swedish industrial company. The can is subject to regulations established by the Swedish Food Administration, and are therefore not possible to consist of recycled plastic.

The following research questions were established and set out to be answered:
What are the environmental impacts of Swedish Match's existing cans and what is the potential environmental impact of a substitute material which fulfills the same function?;
What processes contributes most to the environmental impact of the cans and is it possible to facilitate recycling rate and thus lower the environmental impact by selecting a different material?;
How can Swedish Match lower the environmental impacts from the snus cans?

Two waste management methods are assessed: incineration and recycling. The end-of-life scenarios forms a sensitivity analysis, to study how impacts from investigated material is affected by adjusted rates of recycling and incineration. An additional SA was conducted, with adjusted loss rates for cans at Swedish Match's factory. Five impact categories are considered in the Life Cycle Impact Assessment: abiotic resource use, acidification, climate change, eutrophication, and photochemical oxidation.

The conclusion of the LCA is that the studied hybrid can is preferable as a packaging material, in regards to impact categories. The largest contributor to emissions comes from material production, emphasizing the importance of minimizing losses and facilitate recycling of materials. Choice of origin for the materials affect the possible recycling rate and the possibility to be credited for material recovery. Existing consumer waste behaviour is favourable for the material composition of the hybrid can compared to the other cans.

Keywords: LCA, packaging, foodstuff, impact, End-of-life, consumer behaviour, comparative.

Sammanfattning

Denna avhandling undersöker miljöpåverkan av fyra olika förpackningsmaterial för snusdosor, i en jämförande livscykelanalys (LCA). Två befintliga dosmaterial och två potentiella ersättare utvärderas och jämförs. De befintliga materialen är fossilbaserad polypropenplast och ett vaxbelagt återvunnet papper. Potentiella ersättare är biobaserad polypropenplast, samt en hybriddosa bestående av papper och plast. Avhandlingen genomfördes i samarbete med företaget Swedish Match AB, ett svenskt industriföretag. Dosorna är reglerade av Livsmedelsverket, enligt vilket livsmedel ej får förpackas i återvunnen plast.

Följande frågeställningar fastställdes och besvarades:
Vad är miljöpåverkan av Swedish Matchs befintliga dosor och vad är den potentiella miljöpåverkan från ett alternativt material som uppfyller samma funktion?;
Vilka processer bidrar mest till dosornas miljöpåverkan och är det möjligt att underlätta återvinningsgraden och därmed sänka miljöpåverkan genom att välja ett annat förpackningsmaterial?;
Vad kan Swedish Match som företag göra för att reducera snusdosornas miljöpåverkan?

Två avfallshanteringsmetoder utvärderas: förbränning och återvinning. Tiden efter förbrukning bildar en känslighetsanalys, för att studera hur valt material på snusdosa påverkar miljökonsekvensen av justerad mängd återvinning och förbränning. Ytterligare en känslighetsanalys genomfördes med justerade förlustnivåer för dosorna i processen för fyllning och etikettering i Swedish Match's fabriker. Fem kategorier för miljöpåverkan undersöktes: abiotisk resursanvändning, försurning, klimatförändring, övergödning och fotokemisk oxidation.

Slutsatsen är att den studerade hybriddosan är att föredra som förpackningsmaterial efter utvärdering av tidigare nämnda kategorier i miljöpåverkan. Den största inverkan på miljön kommer från produktionen av råmaterialet vilket betonar vikten av att minimera förluster och underlätta återvinning. Observationer från studien är att återvinning sänker miljöpåverkan för alla dostyper. Materialens ursprung påverkar den möjliga återvinningsgraden och möjligheten att krediteras för materialåtervinning. Nuvarande konsumentbeteende, med avseende på mängd återvunnet material, är gynnsamt för hybriddosan jämfört med övriga dosor.

Keywords: LCA, förpackning, livsmedel, miljöpåverkan, känslighetsanalys, konsumentbeteende, jämförande.

Acknowledgements

The thesis has been educative, giving the possibility to deepen the knowledge modelling in LCA-software, search in databases and material understandings. We have learned great things in material knowledge and understanding of how choice of materials for packaging contributes to potential impact. For that we are thankful to Swedish Match for the opportunity to assess their packaging materials.

Firstly, we would like to thank company supervisors at Swedish Match's packaging development team Nina Henriksson, Lin Wang and Elisabeth Wising for providing us with useful data and information during the prevailing pandemic which prevented us from working at the production site. We would also like to send a thanks to Swedish Match's suppliers for answering questions about site-specific processes.

At the division of Environmental Systems Analysis at Chalmers University of Technology we would like to thank our examiner and supervisor Docent Matty Janssen. He was most supportive to us and had great inputs throughout the thesis, explaining thoroughly in correspondence whenever questions arose. Also a great thanks to the PhD students Frida Hermansson and Mudit Chordia, for taking time and helping us out when stuck in modeling.

The work and effort in the thesis is the result of a cooperation between the two authors where the workload have been equally divided.

Jacob Danielsson and Love Gidlund, Gothenburg, May 2021

List of Abbreviations

ADP	Abiotic resource depletion
AP	Acidification potential
CO_2 - eq.	Carbon dioxide equivalents
EC	European Comission
EoL	End-of-Life
EP	Eutrophication potential
EU	European Union
GHG	Greenhouse Gas
GWP_{100a}	Global Warming Potential over 100 years
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MOIR	Maximum Ozone Incremental Reactivity
NDA	Non Disclosure Agreement
O_3 - eq	Ozone equivalents
PO_4 - eq.	Phosphate equivalents
PP	Polypropylene
PP_1	Polypropylene can
PP_{bio}	Bio-Polypropylene can
RSS	Resources
SA	Sensitivity Analysis
Sb - eq.	Antimony equivalents
SM	Swedish Match AB
SO_2 - eq.	Sulfur Dioxide equivalents
US EPA	United States Environmental Protection Agency

List of Chemicals

CO	Carbon monoxide
CO_2	Carbon dioxide
$CaCO_3$	Calcium carbonate
D_{x1}	Dioxins heating value allocation
D_{x2}	Dioxins Cl allocation
HCl	Hydrochloric acid
Hg	Mercury
N	Nitrogen
NH_3	Ammonia
NO_X	Nitrogen oxide
P	Phosphorous
PAH	Polycyclic aromatic hydrocarbon
SO_2	Sulfur dioxide

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1

Introduction

1.1 Background

As mean global temperature rise, and increasing strain is put on natural systems, the world is changing. In response to global sustainability goals, such as the 17 sustainable development goals established by the United Nations, industry is transitioning towards a different approach. Goals established, along with increased consumer demands for "green" products, encourages industrial innovation. To increase awareness and facilitate conscious consumer choices, by assessing the impacts their products have on the natural environment, companies have started adopting different strategies to communicate sustainability. This is beneficial for both consumers and producers, as it bridges knowledge gaps and facilitates learning for both parts.

One company seeking to assess their products environmental impact is Swedish Match AB (SM). SM is a Swedish industrial company focused on a variety of products, spanning from matches to lighters (SwedishMatch, 2021b). A staple product of the company is nicotine and tobacco products, namely Swedish snus, which is distributed in cans. The focus of this study is the environmental impact of the cans, as a result of material selection. Current choice of material for the cans are either paper or plastic, depending on the type of snus. Portioned snus is generally sold in plastic cans made of fossil-based polypropylene (PP), while non-portioned snus is sold in paraffin coated paper cans made from recycled paper board. As of 2021, SM aims at phasing out the fossil-based PP used for cans, replacing it with a more sustainable choice of packaging material (SwedishMatch, 2021a).

With over a million snus consumers in Sweden (SwedishMatch, 2020), and a steady increase of environmental awareness, adaptation of products by producers is regarded a necessity. SM sees a growing interest on the market for more environmentally beneficial products, hence potential in developing a label on climate impact on their finalized products has been identified. Reduced dependency of virgin fossil-based plastic is further adressed by the European Comission in accordance with implementation of a circular economy in the European Union (European Comission, 2018). One step in this process is to find out potential environmental impacts, and what material choice gives rise to the least amount of environmental impact.

To quantify the material impact on the climate, a cradle-to-grave LCA is conducted. The scenario based end-of-life (EoL) forms the cradle-to-grave where the can is separated into open-loop recycling and/or incineration, with heat recovery (representing an average Swedish waste management system). This makes up the conducted cradle-to-grave study.

The LCA aims to get an overview of the total environmental impact the cans potentially have. The current supply chain of SM is such that the plastic cans are produced externally and purchased from other companies while the paper can is produced in SM's factory in Gothenburg. The plastic cans are transported to SM where they are labelled, filled, and lastly distributed to retailers. Therefore, the system is divided into a background system including background processes to extract and refine materials, a foreground system with a cradle-to-gate approach assessing the four can-material combinations, and a gate-to-grave assessing different scenarios for the products EoL. The gate-to-grave is to evaluate if the recycling rate can contribute to a lower impact and if a change of material can facilitate the recycling process.

1.2 Aim and Problem Definition

The aim of the study is to determine the environmental impacts of four snus cans for different materials. The study is done in collaboration with, and was initiated by SM. The study conducted seeks to provide additional support for further company decision-making, yielding a foundation for future course of action in achieving a more sustainable business.

As environmental impacts may be evaluated using a variety of different parameters, yielding different results, a set of impact categories was established. According to International Organization for Standardization, environmental impacts studied should be relevant to the geographical context and choice of impact categories should be justified ISO (2006a). Selected impact categories should further include impacts concerning resource use, human health, and ecological consequences.

The two current cans in use is the polypropylene (PP_1) can and the paper can. PP_1 is used as a baseline throughout the thesis where losses in production steps are considered for the other cans. Possible material alternatives investigated is a combination (hybrid) of the two existing materials produced in a different way, and a bio based polypropylene can (PP_{bio}) to possibly reduce the environmental impacts from extraction of fossil-based products and the use of scarce material.

Research questions can be found in section 2.3, and a more concentrated problem definition in Chapter 3.

2

Theory

The following chapter describes underlying theory for the thesis. This involves a description of the LCA procedure and the subject of study. It further provides an overview of software and database used for conducting the LCA, previous research on food packaging and lastly research questions answered in the paper presented in section 2.3.

2.1 Life Cycle Assessment

LCA is the process of mapping a products life cycle. It involves identifying and quantifying extracted natural resources used and emissions occurring over the life cycle. A full study from raw material extraction to waste management is referred to as a cradle-to-grave study (Baumann and Tillman, 2004). An LCA is performed in order to determine the environmental impacts associated with the manufacturing, use, and disposal of a product (Baumann and Tillman, 2004). According to the International Organization for Standardization, general characteristics of an LCA involves four distinct phases: goal and scope definition, inventory analysis, impact assessment, and interpretation (ISO, 2006a).

2.1.1 LCA Framework

The following section is an account of the four phases in an LCA.

Goal and scope definition

Goal and scope definition are decided on contextual, modelling, and procedural aspects of the study (Baumann and Tillman, 2004). Specific aspects are extracted from, and defined by, the aim and goal of the study. The goal definition seeks to establish the contextual aspects: why the study is conducted, how it is to be conducted, who the target audience is, and what the study contains. The scope decides the modelling aspects. This involves establishing boundaries for the system under investigation. The boundaries established determines which flows and processes are to be included in the assessment. It further establishes the functional unit, which is a quantitative measure used to describe the function of the studied product (ISO, 2006a).

Inventory analysis
Life cycle inventory analysis (LCI) is the construction of a system model based on defined goal and scope. The system model is a simplified model of the technical system involved in the cradle-to-grave activities associated with the production (and consequentially resource use) of studied object. According to Baumann and Tillman (2004), the inventory analysis can be split into three parts: construction of a flow model, data collection, and calculations. Construction of a flow model refers to a visual description of the system, using a flow chart. The flow chart should reflect the life cycle in terms of environmentally relevant flows (Baumann and Tillman, 2004). Data collection refers to quantification of established flows, in terms of inputs and outputs of resources and emissions to and from established processes. Calculations are simply the numeric determination of emissions and resource quantities in the system.

Life cycle impact assessment
Life cycle impact assessment (LCIA) translates the data gathered in the inventory analysis. LCIA is the conversion of inventory data into comprehensible information on environmental impacts via classification and characterization of environmental burdens. Choice of impact categories and possible indexes are determined by the goal and scope definition, in accordance with the aim and purpose of the study. LCIA begins with a classification of data collected in the inventory, where data is arranged in accordance with its contribution to stated environmental impacts. This refers to the environmental load being assigned to an impact category, such as global warming or abiotic resource use (Baumann and Tillman, 2004). According to the ISO (2006a) at least the following impact categories should be covered in an LCA: resource use, ecological consequences, and human health. Once the environmental loads have been classified, they are characterized. The characterization phase refers to the calculation of established environmental loads.

Interpretation
Interpretation refers to sense-making of the obtained LCA results. In the interpretation phase, results from the LCI and LCIA are constructed and explained in a comprehensible way. An important aspect to consider is that the results are to be understood as a representation of potential impacts, not actual impacts or risks associated to the assessed life cycle (Hauschild et al., 2018). Results from the inventory and impact assessment, in accordance with the goal and scope, are combined to support a conclusion. Presented results may be of either a qualitative or quantitative character, depending on purpose and target audience, or in some cases a combination of the two (Baumann and Tillman, 2004).

2.1.2 ISO14040-14044

ISO14040 is the international standard used for conducting an LCA. More specifically, it provides general principles and frameworks (ISO, 2006a). The standard is used as a foundation throughout the thesis, providing guidance in methodological choices made and in structuring the overall assessment. The ISO14040 is complemented by the ISO14044. The ISO14044 accounts for specific requirements and guidelines when conducting an LCA (ISO, 2006b). The main difference between the 14040 and the 14044 is that the former simply provides a general introduction, while the latter establishes specific requirements to meet.

2.1.3 Applications of LCA

The contextual aspects of an LCA may vary greatly. Applications of an LCA are hence plentiful. ISO-14040 identifies four alternative applications: identification of improvement possibilities, decision-making, market claims, and choice of environmental performance indicators (ISO, 2006a). In this study, as previously stated, the intended application of the LCA is strategic decision-making. An LCA may then provide guidance in selection of materials and/or manufacturing procedures for a product in regards to environmental performance and impact.

2.2 Previous Research

Previous studies have suggested that use of recycled waste plastics, rather than virgin, may drastically reduce a products environmental impact (Shen et al., 2010). Currently, recycled plastic is not an alternative however, as the snus contained in the cans is classified as foodstuff. According to the Swedish National Food Administration (Livsmedelsverket), which oversees and regulates production and facilitation of foodstuff, reused plastic may not be used for packaging (Livsmedelsverket, 2020). As a result, simply using recycled plastic from current plastic cans is not an alternative per current legislation. This results in an open-loop recycling system, where the recycled material goes to other products than packaging of foodstuff. Therefore, implementation of another type of packaging material may be of interest.

According to Raheem (2013), consumers wants packaging to be convenient, of high quality, safe, and recyclable. Already existing cans have no quantified climate impact. Previous studies mention kraft paper as a type of paper commonly used in similar applications (Netramai et al., 2016). Raheem (2013) also mentions that combinations with plastic and plastic coated paper are used today in products such as milk and dairy cartons. In Sweden, paper products is recycled to 82% while plastic recycling only reached 46% in 2018 (Hinde, 2020). Furthermore, as stated by Jain et al. (2012), several studies have shown that recycled paper consumes up to 57% less energy and environmental strain than virgin paper production. An exception is paper board, which requires up to 150% more energy than production of virgin paper.

Another possible alternative to lower the environmental impact could be to derive polypropylene from a renewable source, as it is characterized as carbon neutral (Masutani and Kimura, 2015). Bio-based plastics used for packaging materials already accounts for over 50% of total global bio-plastic production, and has started being adapted by the industry (Siracusa and Blanco, 2020). Although a bio-based polypropylene can is not yet commercially produced, investigating and comparing it with a currently available product by means of LCA is possible (Liptow and Tillman, 2012). However, simply selecting a renewable material over a non-renewable is not necessarily a one way solution. Other environmental loads, such as acidification or eutrophiaction, may increase as a result of replacing fossil-based polymers with bio-based counterparts (Hottle et al., 2013).

2.3 Research Questions

Based on previous research and the intended application of the study, the following research questions were established:

- *"What are the environmental impacts of Swedish Match's existing cans and what is the potential environmental impact of a substitute can material which fulfills the same function?"*

- *"What processes contributes most to the environmental impact of the cans, and is it possible to facilitate recycling rate, thus lower the environmental impact by selection of a different can material?"*

- *"How can Swedish Match lower the environmental impacts from their snus cans?"*

3

Goal & Scope Definition

The following chapter explains the goal and scope of the study. In scope definition, the investigated cans are presented, accompanied by a flow chart, and an explanation of selected functional unit. Explanations of boundaries, data collection, allocation procedures, impact categories, EoL scenario analysis, and sensitivity analysis are further presented. Lastly, assumptions and limitations are presented.

3.1 Goal

The goal of this LCA is to determine the environmental impacts of four snus cans made from different materials. The can types are either already in commercial use, or are possible substitutes for current cans. Can types are further described in section 3.2.1. The study is an attributional cradle-to-grave LCA, and covers all activities from raw material extraction to disposal and waste management. As commercially produced snus cans have relatively short lifetimes, and functions as packaging containers, they are considered disposable products. Hence, choice of waste management method for EoL is expected to play a central role in total environmental impact. A scenario based EoL study is therefore conducted, assessing the products sensitivity to type and rate of waste management method, and consumer disposal behaviour.

Primary purpose of the study is to provide SM with support for strategic decision-making, concerning material composition for snus cans from an environmental perspective. SM has expresssed the ambition to assess, and by extension reduce, their total environmental impact. This study sets out to assess specifically the snus cans.

3.2 Scope Definition

The following section defines the scope of the study.

3.2.1 Snus can

A snus can is a packaging container for snus. The general design involves a base that contains the actual snus, and a lid which seals the can. For a can containing portioned snus, the lid consists of two modules: a top lid and a disposal lid. For non-portioned (loose) snus, the lid does not contain an additional disposal lid. In this study, a snus can is defined by the containment of existing products, which is further elaborated on in section 3.2.2. The four snus can types under investigation are further presented and explained.

Polypropylene (PP_1) can

The following section describes the full cradle-to-grave life cycle of the PP_1 can. Modelling of the product system is further described in section 3.2.4. A full overview of data, calculation steps, and normalization to functional unit is presented in Appendix B. The modelled system for the PP_1 can is presented in Appendix A.1.

The PP_1 can is a can made from fossil-based polypropylene, a thermoplastic polymer. Polypropylene is produced by polymerization of propylene, a monomer derived from refined crude oil. The PP_1 can is generally used for packaging portioned snus (SwedishMatch, 2020). Both the base, lid, and disposal lid are made entirely in polypropylene.

The PP_1 can is considered as the baseline product for the study. The other three can types are completely, or partly, modelled according to the PP_1 can. This concerns: losses in supply chain, filling, labelling, distribution, use phase, and EoL. Although the PP_1 can cannot be recycled for production of new PP_1 cans, it is still a recyclable material for re-use in secondary products, by open-loop recycling.

The can base and lid are made through injection moulding of polypropylene granulates. Injection moulding is the process of smelting a material into a liquid state, and then injecting it into a mould, where it is shaped and cooled to desired form. This is a common method for producing plastic containers all over the globe. The moulded can modules (lid and base) are transported to SM's factories, where they are assembled into the actual can. The can is then filled, labelled, stored, and distributed to retailers. After a can have been filled with content, it is kept refrigerated until distributed to consumer. This applies to both transports and warehousing, resulting in additional electricity use. The use phase consists of consumption of the content, after which it the can is discarded. Hence, the use phase does not affect the can in any signinficant way.

Paper can

The following section describes the full cradle-to-grave life cycle of the paper can. Modelling of the product system is further described in section 3.2.4. A full overview of data, calculation steps, and normalization to functional unit is presented in Appendix B. The modelled system for the paper can is presented in A.2.

The paper can is another type of can currently in use. The paper can is standard for using in packaging non-portioned snus (commonly referred to as loose snus). Unlike the PP_1 can, the paper can only contains a top lid, and no disposal lid. The lid is made from injection moulded PP granulate, using the same process as the PP_1 can. The base of the can is made from recycled paper board, supplied in sheets. The base is manufactured from the sheets at SM's factory, and is coated with paraffin wax to avoid absorption of moisture from the content of the can. Once coated, the base is combined with the polypropylene lid for a complete paper can. The can is subsequently filled and labelled, before being shipped and distributed to end consumer, according to the same procedure as PP_1 can.

The paper can base is not recyclable once it has been coated with paraffin wax. As a result, in difference to the other three can types, the base is not subject to recycling in the EoL scenario analysis. Only incineration is considered as an option, while the lid is considered recyclable. This means that the EoL scenarios only apply to the material used for the lid, while the rest is 100% incinerated.

Cardboard paper required for production of one can was modelled according to primary data on the mass for one can, presented in Appendix B.

Hybrid can

The following section describes the full cradle-to-grave life cycle of the hybrid can. Modelling of the product system is further described in section 3.2.4. A full overview of data, calculation steps, and normalization to functional unit is presented in Appendix B. The modelled system for the hybrid can is presented in Appendix A.3.

The hybrid can is a can made from a combination of paper and plastic. A design is not provided or suggested in the report, but rather based on a prototype not disclosed in the thesis. Unlike the paper can, it is not coated with paraffin wax, making it a possible subject for recycling. The EoL scenario analysis of the hybrid can will therefore be recyclable up to 100%, like the PP_1 can. According to the manufacturer of the prototype, it can be recycled in the same way as cardboard box for liquid products, such as the ones commonly used for dairy products in Sweden.

For the paper to be used as a container it needs to be coated with some other material, as in e.g. the use of paraffin wax for the paper can. For the hybrid can, a thin layer of polymers is applied to avoid the paper from absorbing moisture from the content. This is done before the injection moulding of the can. The hybrid can is manufactured externally from SM, before being filled and labelled at SM's factories. Downstream processes from SM's factory gate are the same as the PP_1 can.

Bio-polypropylene (PP_{bio}) can

The following section describes the full cradle-to-grave life cycle of the PP_{bio} can. Modelling of the product system is further described in section 3.2.4. A full overview of data, calculation steps, and normalization to functional unit is presented in Appendix B. The modelled system for the PP_{bio} can is presented in Appendix A.4.

The PP_{bio} can is made from bio-based polypropylene plastic, according to the same design as the PP_1 can. For a plastic to be considered bio-based, it can be said that it fulfills at least one of the following criteria: it is based on a renewable resource and is biodegradable, it is petroleum based but 100% biodegradable, or it is based on a mixture of petroleum and renewable material (Siracusa and Blanco, 2020). In this study, bio-based refers to the material being derived from a renewable source of biomass. The specific type of biomass assumed for production of the PP_{bio} can is cultivated sugar cane.

As current knowledge of the potential manufacturing processes for the PP_{bio} can is uncertain, and specific processes used in bio-refineries are complex and varied, refinement of sugar cane into bio-polypropylene relied on a literature review and secondary data. Moreover, commercially available routes for bio-polypropylene production are generally confidential at the time of this study (Siracusa and Blanco, 2020). A possible route for producing propylene from biomass is by refining bio-ethanol (Machado et al., 2016). A simplified pathway is illustrated in 3.1.

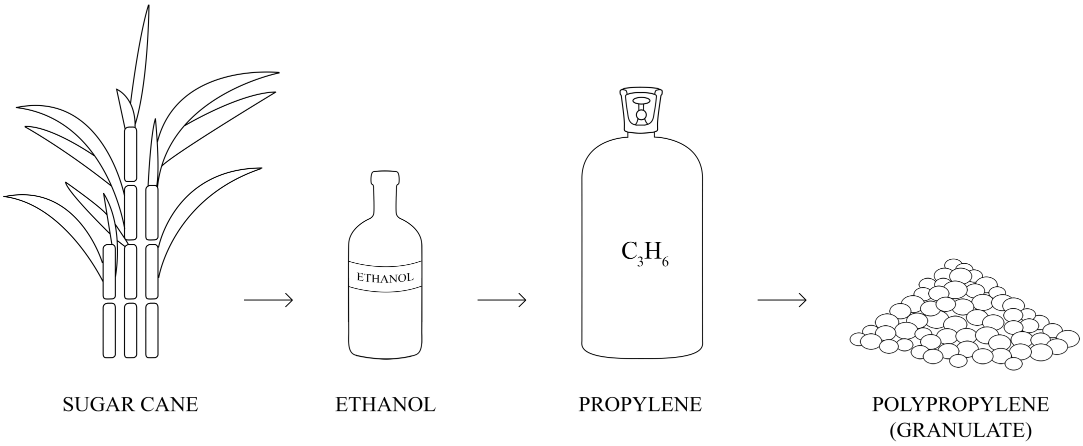

Figure 3.1: Schematic illustration of bio-polypropylene production from raw material. Illustration by Emma Frykberg

The only difference between the PP_{bio}- and PP_1 can, in terms of production, is raw material extraction. Downstream from produced granulates, it follows the same trajectory as the PP_1 can. This concerns injection moulding, filling, labelling, storage, distribution and disposal.

The product system design was further complemented by stoichiometric calculations in order to assess the inventory, explained in section 3.2.4.

Conceptual Flow chart

The system equations found in section B, in Appendix B, constructed from the LCI is extracted from the conceptual flow charts in figure 3.2, which includes the flow charts for all the cans. The flows described covers the material flows for the products in a generalized way. More detailed flow charts can be found in Appendix A. Materials or additives added earlier on in the processes are not taken into account in the conceptual flow charts, as they lack relevance in the system equations. In the conceptual flow chart (3.2) energy and resources (RSS) are generalized to all systems, and emissions are accounted separately for every system.

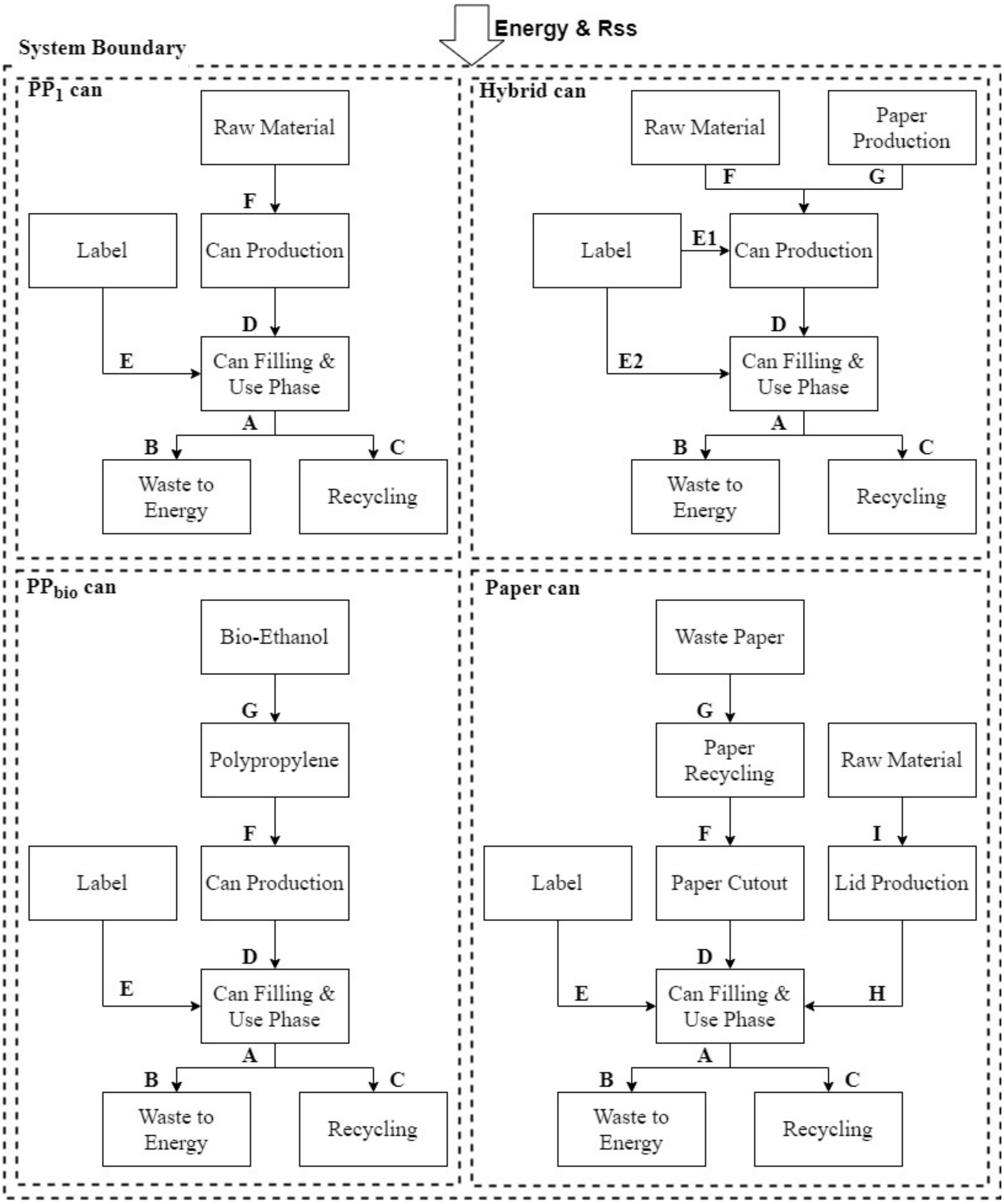

Figure 3.2: Conceptual flow chart for the cans under investigation.

The conceptual flow chart is a way of illustrating the flows of the materials through the system. It has also been used as a backbone to the system when modelled in openLCA (see section 3.2.4). The conceptual flow charts should not be considered as the actual system, but a general description, as the actual life cycle is far more complex.

3.2.2 Functional Unit

Functional unit for the study is set to "one snus can". The functional unit is used as a quantitative measure to define the order of flows upstream for the four can types. The functional unit itself describes the function of the system, which is to contain either 22 grams of portioned snus (obtained from ONE white) or 42 grams of non-portioned snus (obtained from General Classic loose). Selected functional unit was deemed reasonable as a basis for comparison, as the function of the product remains unaffected by the choice of packaging material.

3.2.3 Boundaries

Boundaries set for the studied system are further presented in different categories, concerning their type and characteristics.

System boundaries
The overarching system is divided into two sub-systems. One sub-system is a cradle-to-gate system, focusing on assessing production of the can types. Production of the can types is divided into a background system, with raw material extraction, and a foreground system including can manufacturing. The LCA covers cradle-to-grave, incorporating the EoL scenario analysis which completes the entire life cycle.

Regarding the natural system, both the agricultural system in Brazil and forestry production in northern Europe are included. This is due to the bio-polymer used for PP_{bio} can as it is derived from sugar cane cultivated in Brazil, and the paper and pulp products are derived from forestry production in northern Europe. Crude oil for plastic production is further included.

Geographical boundaries
The agricultural systems considered are sugarcane cultivation in Brazil, and forestry in northern Europe. Crude oil for plastic production is assumed to be extracted in Europe. As the LCA includes several parts of the world, the cradle-to-gate system was given a global geographical boundary. Transports were considered to and from the two SM production sites in the Gothenburg area (Gothenburg and Kungälv), respective to production volume. The second sub-system, including the EoL scenario analysis, is limited to Sweden.

Temporal boundaries
The temporal boundary is set to one year, as the contents expiration date will be exceeded within that time frame and then be discarded in its entirety.

Technical boundaries
The report does not cover labor and/or personnel affected in the processes. No associated social aspects are further considered in terms of production.

Cut-Off criteria
A cut-off will only be made if the decision does not affect the rest of the results, or interfere with the result between the can types. The impact from energy consumption in filling and labeling at SM's factories is considered negligible for the packaging and therefore allocated to the snus content, which is outside the scope. However, production of the paper base for the paper can (which occurs at SM's factories), is not considered part of filling and labelling. Energy consumption for the process is therefore accounted for.

The study does not cover any possible changes in extraction or refining of materials, nor changes in manufacturing processes. The LCA rather focuses on material selection and the differences in environmental impact from associated processes. The use phase is not considered, since no degradation of the can is expected during the time period. Indirect emissions from the use phase are considered irrelevant in regards to material selection for the thesis.

Furthermore, as the LCA is comparative, all cans have the same function regardless of can material. The EoL is considered to have two alternative pathways, which are scenarios based on Swedish waste management systems. Studied waste management methods are incineration and recycling in an open-loop system; no alternative pathways are considered.

3.2.4 Data Collection

The following section is an account of data collection. Specific modelling aspects of the snus cans are further explained for each can type. Data quality requirements for the study are presented in Appendix A.

The thesis methodology relied mainly on primary and secondary data. Primary data was provided by SM and external suppliers, concerning: quantities, materials used, manufacturing processes, and material losses. In cases when primary data was either unavailable or insufficient, secondary data was used. The main source of secondary data gathered was EcoInvent 3.7. In cases where data was insufficient or unavailable, data from previous research and literature was assessed.

Modelling of the product systems was done in openLCA, and started after the life cycle inventory had been established. OpenLCA is a software used for life cycle modelling and sustainability assessment, developed by GreenDelta (Ciroth, 2007).

The software is open source, free, and requires no license for use (Ciroth, 2007). OpenLCA is used to provide a comprehensive and readable model of studied system. It further allows for streamlined facilitation of large data sets, in comparison to manual handling of data.

To perform an assessment in openLCA, a database providing the system with information is required. In this study, the database EcoInvent 3.7 was implemented. EcoInvent 3.7 contains well documented and comprehensive data for products and processes, provided by companies and organizations around the world (Wernet et al., 2016). EcoInvent 3.7 was primarily used to bridge knowledge gaps between authors, literature, and product specific data acquired.

Frequently used processes from EcoInvent 3.7 are market processes. A market process accumulates every activity with the same reference product in a geographical region, and transfers it from one transforming activity to another, which consumes it (EcoInvent, 2021). The process may be described as a consumption mix of a certain product, including average transports and losses for the entire product system. For knowledge gaps with large uncertainties, such as polypropylene production or virgin paper production, market processes were used. The background system represents processes gathered from EcoInvent 3.7 and secondary materials used.

Polypropylene can
Manufacturing of the PP_1 can begins with refinement of crude oil into PP granulate, through a series of refinement processes. Pathway from raw material extraction to finished PP granulate are generalised with processes from EcoInvent 3.7.

Extraction of raw materials for the PP_1 can is limited to crude oil extraction. A unit process from EcoInvent 3.7 was used to account for background processes for production of the PP granulate, as shown in Appendix A.1 (E1). The flow of PP granulate was quantified in mass (g), according to the functional unit. Geographical location for granulate production was nationally determined and set to two providers in Europe. Energy mix used in granulate production could therefore be assumed according to a national standard, presented in Appendix A.1 (E19).

Produced PP granulate are transported to injection moulding. Location and distance gate-to-gate for the processes were established and measured. Both base, lid, and disposal lid are subject to the same injection moulding process. To account for injection moulding, an EcoInvent 3.7 unit process was used, presented in Appendix A.1 (E2). The unit process represent the conversion of plastics, accounting for energy and material use for converting calculated amount of granulate into moulded plastic. The unit process was complemented by primary data for energy use in the factory. Energy requirement was normalized to account for production of one PP_1 can.

The normalization was based on provided data of energy used (in kWh) for one hour of injection moulding on site, using a set quantity of polypropylene granulates (in kg). Provided this data, in addition to established mass for one PP_1 can, energy use for production of one can could be approximated. The calculation procedure is described and presented in Appendix B. As the process' geographical boundary was known, an energy mix was selected according to a national average, using a unit process showcased in Appendix A.1(E19).

For refrigerated transports mentioned in section 3.2.1, an EcoInvent 3.7 process for refrigerated transports was used, presented in Appendix A.1 (E13). For warehousing at retailers, primary data on specific coolers used was provided by SM. Assuming an average filling rate for the refrigerator (number of cans) and the time span for which a can remains refrigerated (60 days), an estimate of energy requirement for cooling could be estimated, and is represented by a national energy mix shown in Appendix A.1 (E18).

Paper can

Extraction of raw materials can be divided into three primary upstream categories: cardboard paper, polypropylene granulates, and paraffin wax. The cardboard paper used is derived from recycled waste paper, which comes from a mix of sources. It was modelled from an EcoInvent 3.7 unit process, which can be found in Appendix A.1 (E5). To account for primary data acquired, concerning types of waste paper used for production of recycled cardboard paper, process inputs of paper were adjusted according to Appendix A.1 (E3).

The paper can lid is made entirely from injection moulded PP granulate. The same process, from crude oil extraction to granulate production is applied for the lid of the paper can as for the PP_1 can, according to primary data from SM and suppliers. Due to differences in design, however, the paper can does not contain a disposal lid. The total mass of granulate used, and by extension upstream raw material extraction, is therefore less per functional unit than that of the PP_1 can.

Losses occurring over the production line, both at SM and supplier, was calculated and accounted for in determining the required amount of cardboard paper. Calculation steps are described in more detail in Appendix B. The paraffin wax used for coating the can is derived from crude oil refinement. A market process from EcoInvent 3.7 was used to account for the upstream activities associated to its production, and is presented in Appendix A.1 (E6).

Hybrid can

Extraction of raw materials used for the hybrid can is limited to crude oil and forestry products for virgin paper production. The hybrid can uses injection moulded granulate for its plastic components, which have relied on the same EcoInvent 3.7 process as the PP_1 can and paper can for comparability.

The paper coated is considered equal to kraft paper, as it is a common type of paper used in packaging of foodstuff according to Netramai et al. (2016). An EcoInvent 3.7 process for production of kraft paper has been used to represent the paper in the hybrid can and is shown in Appendix A.1 (E15). Injection moulding of the hybrid can applies the same unit process as the PP_1 and paper can. As in the case of PP granulate production, the geographical location differs however, affecting the transport distances. Furthermore, according to site-specific primary data acquired, the energy use for the process could be established. Specific energy use for injection moulding of one can could hence be calculated and used to modify the process, and is presented in Appendix B.

Bio-polypropylene can

Upstream from granulate, the study has assumed production of bio-polypropylene from bio-ethanol, as it is deemed a likely method for future commercial production of bio-polypropylene (Harmsen et al., 2014). Bio-ethanol, in turn, is assumed to be derived from sugar cane by sucrose fermentation, as described by Santos et al. (2019). The refinement process from sugar cane to finished granulate was partitioned into a set of three intermediate processes, to account for conversion rates and losses. The first process refers to refinement of sugar cane to bio-ethanol, and the second process refer to derivation of bio-propylene from bio-ethanol. The third process refers to production of granulate from bio-propylene. The three intermediate steps are calculated backwards from the amount of polypropylene granulate needed to injection mould a PP_1 can (accounted upstream for losses along the supply chain).

The PP_{bio} can life cycle is assumed to mirror that of the PP_1 can. This refers to every unit process downstream from polypropylene production, including filling, labelling, storage, and distribution. Geographical and technological characteristics of the processes remain equal to that of the PP_1 can, except for transportation and geographical location, which is in south America (Brazil). Waste management practices for the PP_1 can are further deemed representative for the PP_{bio} can, due to their shared design and material properties.

For the first intermediate process, the study assumed a modern Brazilian sugar cane mill using sucrose fermentation to produce bio-ethanol according to data from an EcoInvent 3.7 unit process, presented in Appendix A.1 (E9). The process accounts for resource use and emissions from sugar cane cultivation to finished bio-ethanol.

The second intermediate process used was conversion of bio-ethanol to propylene. To determine the quantity of bio-ethanol corresponding to the amount of propylene required for production of one can, a stoichiometric calculation between the molecules of propylene and ethanol was made. The relationship was established for conversion of bio-ethanol into propylene. The chemical equilibrium established is presented in Equation 3.1.

$$3C_2H_6O \rightarrow 2C_3H_6 + 3H_2O \tag{3.1}$$

Using the stoichiometric equilibrium and secondary data on physical properties of elements, a mass ratio could be established, and the required bio-ethanol quantity manually calculated from propylene. Efficiency in the third intermediate process, propylene to polypropylene, was assumed ideal without any losses. Complete polymerization was assumed, meaning that the mass of polypropylene corresponds to the mass of propylene. Hence the prefix "poly", means "many".

3.2.5 Allocation Procedure

To partition inputs and outputs from processes, allocation is required. The study primarily relied on either mass allocation or system expansion, according to recommendations from the ISO (2006b). Mass allocation is used for e.g. the conversion of polypropylene granulates to can base and can lid, while system expansion is applied for EoL scenario analysis (recycling and incineration). In the case of producing a paper can (that is made in SM's factory in Gothenburg) an allocation have been made for the number of cans produced during 2020, between the factory in Gothenburg and Kungälv (see section 3.2.8). One can, independent of mass, have been fractioned by material and mass throughout the thesis to allocate emissions along the processes. Number of items delivered from suppliers to factories have been scaled to reach recent years production numbers with losses in filling and labelling per module (lid and base).

3.2.6 Impact Categories

As a foundation for the LCIA, a method package was selected for the LCIA. The method package used is CML2001 (superseded), a midpoint (problem-oriented) method (Department of Industrial Ecology, 2016). The superseded version was used in lack of a compatible newer version. CML2001 is a frequently used method developed by the University of Leiden. CML2001 includes commonly used categories for LCIA. Midpoint refers to the categories focusing on specific mechanisms early on in the cause-effect chain of environmental issues. A midpoint approach was deemed appropriate for the study, as the results are simpler to interpret and present, compared to that of an endpoint approach. The following paragraph is an account of selected impact categories, and why they were chosen.

Studied impact categories are: abiotic resource use, acidification, climate change, eutrophication, and photochemical oxidation. Abiotic resource use is of interest because three of the cans use fossil based raw materials in their design. Climate change was selected as greenhouse gas emissions (GHGs) are expected to occur over the life cycles. Acidification is chosen due to refinement of crude oil, as well as incineration of materials, causes emissions of gases such as NO_2 and SO_2. Eutrophication is of interest as three out of four can types use biological material in their design. Lastly, photochemical oxidation was considered to give some insight on the amount of potential creation of ground-level ozone, which is shown to have negative effects on human health.

The assessed impact categories were further arranged into additional main categories, which include: resource use, ecological consequences, climate change, and human health. These overarching categories was implemented to align the results of the study with categories recommended by the ISO (2006a). Selected categories are further described in this section, including selected indicators and units for measurement. A summary of impact categories, indicators, and units are presented in table 3.1.

Table 3.1: Table showcasing impact categories, indicators, and units

Selection of Environmental Impact Categories		
Impact category	Indicator	Unit
Resource Use		
Abiotic resource use	ADP	kg Sb - eq.
Ecological Conseq.		
Acidification	AP	kg SO_2 - eq.
Eutrophication	EP	kg PO_4 - eq.
Climate Change		
Climate Change	GWP_{100a}	kg CO_2 - eq.
Human Health		
Photochemical oxidation	MOIR	kg O_3 - eq.

Abiotic Resource Use
Abiotic resources refer to non-living resources that are either non-renewable or difficult to replenish, such as oil and coal (Biron, 2016). Due to the limited availability of these resources, and the dependency for both current cans production and suggested cans, an assessment on depletion was considered to be of interest. In this study, the indicator used is abiotic resource depletion (ADP), and is expressed in kg Sb - equivalents. Both fossil resources (such as oil and coal), and other abiotic resources (such as minerals and metals) are considered.

Acidification
Acidification is the reduction of pH in soil or a body of water, making it more acidic (USEPA, 2016). Acidification alters the chemical properties of the affected area, affecting biological life by e.g. disrupting reproductive functions and disintegrating shells and exoskeletons in aquatic environments (USEPA, 2019a). The indicator used is acidification potential (AP), and is further measured in kg SO_2 - equivalents.

Climate Change
Climate change represents an increase in temperature on earth as a consequence of GHG emissions. Emitted GHGs alter the radiative balance on earth by absorbing infrared radiation and trapping it in the atmosphere (IPCC, 2014). In this thesis, climate change is presented in terms of GWP_{100a}, which stands for global warming potential over 100 years. Carbon dioxide (CO_2) is the most common GHG and serves as the quantitative measure for the indicator global warming potential, using kg CO_2-equivalents (IPCC, 2014). There are a number of other GHGs contribut-

ing to global warming, such as carbon monoxide (CO), nitrous oxides (NO_x), and methane (CH_4). Other GHGs are accounted for in GWP_{100a}, in kg CO_2 - equivalents.

Eutrophication

Eutrophication may be described as excessive production of biological material on land or in bodies of water (Naturvårdsverket, 2021). Eutrophication in aquatic areas may cause loss of biodiversity and dissolved oxygen depletion. It is a naturally recurring mechanism which becomes accelerated as a result of surplus nutrients and minerals emitted from anthropogenic activities (World Resources Institute, 2021). The most common contributors are nitrogen (N) and phosphorus (P). Contributing activities are e.g. agricultural processes using fertilizers containing N and P. In this thesis, eutrophication is indicated by eutrophication potential (EP), and measured in kg PO_4 - equivalents.

Photochemical Oxidation

Photochemical oxidation (summer smog), can harm vital organs and is of importance to highlight in order to reduce emissions of volatile organic compounds (VOCs). VOCs are organic chemicals with high vapour pressure at room temperature and low water solubility (USEPA, 2019b). Numerous chemicals are classified as VOCs, and they can be derived from both natural and anthropogenic sources. VOCs are commonly emitted from anthropogenic activities such as use of fuels (fossil and bio-based) and incomplete combustion of biomass. Moreover, inks and coatings often contain VOCs, which may evaporate at even low temperatures. Emitted VOC's can harm the health of inhabitants in a certain area: causing breathing difficulties, damage to central nervous systems and organs, or cancer (USEPA, 2017). The indicator used in the thesis is "photochemical oxidation (summer smog) - MOIR", to quantify the amount of maximum ozone incremental reactivity (MOIR) emitted during a cans life cycle. Photochemical oxidation is measured in kg O_3 - equivalents.

3.2.7 Sensitivity Analysis

In this section, the scenario based EoL analysis is presented. Further, an additional sensitivity analysis concerning can loss rates at SM's factory is described.

EoL Scenario Analysis

The way the EoL scenario analysis is modelled forms a sensitivity analysis (SA). This will determine how sensitive the system is to changes in consumer behaviour concerning waste management. The scenarios EoL1-5 depicts a "what-if" scenario in the end phase of the products lifetime. The SA will cover predictions of how the change in waste management affects the total impact of the cans. The SA consist of five scenarios covering potential contributions to the environment from the investigated products.

The EoL phase of a can is largely unknown and subject to uncertainty. To assess the impact of disposal methods (by consumers), and choice of waste management type (incineration or recycling), the end-of-life phase of the LCA implemented a scenario analysis. Studied EoL treatments are incineration and recycling. These were selected on basis of being the most common treatment methods in Sweden (Avfall Sverige, 2020).

The scenario analysis assumed different ratios between the amount of cans going to recycling and incineration, respectively. Although the LCA examines the life cycle of just one can, which naturally is either recycled or incinerated (and practically not partitioned), the analysis has theoretically assumed a mix of the two to allow for up-scaling to any number of cans. A set of EoL scenarios were selected, based on different rates of recycling and incineration. The scenarios were then implemented in the model. The ratios refer to the total amount of cans ending up in each respective waste management system. Scenarios are presented in table 3.2.

Table 3.2: Table to show rate of incineration & recycling.

Model of EoL scenarios

Scenario	Recycling Rate (%)	Incineration Rate (%)
EoL1	100	0
EoL2	75	25
EoL3	50	50
EoL4	25	75
EoL5	0	100

The scenarios are dependent, and present a hypothetical partitioning applicable for any quantity of cans produced. The five selected scenarios were deemed appropriate for assessing the sensitivity of the cans in terms of the effects of waste management practices. For further implementation of recycling of materials, the impact might vary depending on what materials are used in the can. This opens up the possibility for SM to guide consumers in how to dispose of their empty cans in the future.

Adjusted Loss Rates

In addition the EoL scenario analysis, to conduct further sensitivity analysis of the studied cans, losses at SM's factory were addressed. The analysis only concern losses occuring at SM's factory in the filling and labeling process, losses in upstream activities are not adjusted. Different adjusted losses for the base and lid, in addition to assembled cans, were investigated. Losses were based on order *215684* on production line *K-550:2* in Kungälv factory. For the observed order, the can lid loss is 7.3 % and the can base loss is 3.8 %.

The reason for carrying out this sensitivity analysis is to assess impact reduction that SM can make in their own factories. In addition, this could possible lower the total impact upstream, by reducing amount of resources required for production.

3.2.8 Assumptions & Limitations

The following section is an account of specific data gaps identified in the study, and an explanation of how these gaps were managed. Limitations are further addressed.

General Assumptions and Limitations
Due to the prevailing pandemic at the time of the study, no access to production sites were possible. Naturally, this limited access to documentations and accurate site specific measurements for on-site material losses. A number of general assumptions were necessary.

An estimate of 60 days storage in refrigerator at retailer was made to calculate the contribution of energy consumption in the coolers. 60 days are based on an estimation of 120 days expiration time for the content, with delivery and time spent at end consumer subtracted.

It was assumed that the refrigerator model *"Star 15-6"* is representative for all the refrigerators at retailers, as it accounts for over 20% of the refrigerators used for snus in Sweden. *Star 15-6* is one of 46 snus refrigerators used on the market today. An assumption is made that a refrigerator is filled to 75% of maximum capacity.

Additives in the mixtures of materials are not considered in the thesis, and is assumed to have a negligible impact contribution. The assumption was made because no relevant and reliable data from material producer was available.

Labels
An acknowledged data gap in the study concerns labels attached to the cans. All studied can types are labelled at SM's factory, before being transported to storage. This is done to seal the can and protect the content. The labels were modelled using an EcoInvent 3.7 unit process, found in Appendix A.1(E10). The process ends with finished printed paper at factory gate, which in this study represents the final label. The mass was estimated by weighing a detached actual label and that same mass (1 gram) was used for every can type.

Specific data on content, upstream processes, transports, and material losses along the supply chain were not acquirable for the study. The labels, and consecutively impact contributions, hence solely relied on secondary data and assumptions. Due to the comparative nature of the study, it was deemed a reasonable solution however, as all the cans use the same labels. The impact contribution from the labels should hence be equal for the different can types.

PP_1 can
According to the corresponding amount of delivered PP_1 cans (both base and lid) to the two production sites, the quantity of losses in the filling and labeling process is considered equal to those of order 215684 filled and labelled on production line K-550:2 in Kungälv factory. Energy consumption at SM's factory is allocated to the content of the can entirely, and is therefore not contributing to emissions produced in the factories.

Paper can
To calculate energy consumption for manufacturing a paper can, existing numbers collected from SM were used. Energy consumption for manufacturing of the can is estimated by a differentiation between the plastic can and the paper can. Energy used in Kungälv factory (E_K), where PP_1 can accounts for the majority of produced cans, is subtracted from the energy consumed in Gothenburg factory (E_G). The energy was later divided by the number of paper cans produced in 2020 (n_{2020}) and then mass allocated between the content and the can itself (X_{paper}).

$$E_{paper} = \frac{E_G - E_K}{n_{2020}} \cdot X_{paper} \tag{3.2}$$

The same loss of cans and lids as for the PP_1 can is assumed to be representative for the paper can in the filling and labeling process.

Hybrid can
The hybrid can is assumed to replace the existing cans, both the paper can and the plastic can, for quantification during calculations. Losses in injection moulding and energy consumption for injection moulding is based on estimations provided by the supplier for their current products. The type of process is estimated to have a 30% lower energy consumption than traditional injection moulding, according to the supplier. The same loss of cans and lids as for the PP_1 can is assumed to be representative for the hybrid can in the filling and labeling process.

PP_{bio} can
The can made of bio-polypropylene is calculated in the same way as the already existing PP_1 can. Assumptions are made that mass and material loss are the same for the two can types. Conversion rate from ethanol to propylene, and propylene to polypropylene is assumed to be ideal, without losses in polymerization. This means that raw material extraction and refinement in combination with transports are the main differences between the PP_{bio} and PP_1 can.

Transports
For transports inside Europe, means of transport were selected according to the EURO 6 standard (European Comission, 2021). Vehicles used were assumed standard freight lorries for all gate-to-gate transports, as provided by EcoInvent 3.7. Capacity of the lorries, in metric tonnes, were set for each transport based on average values.

For transport distances, assumptions were made that lorry and sea transports takes the shortest possible route, as suggested by navigation from Google maps. Exact distances are presented in Appendix B. In instances where transport by sea was involved, mainly from Helsinki to Stockholm (206 km) or Puttgarden to Rödby (18.7 km), the use of ferries was assumed. In the case of supply chains acting outside Europe, as in the case of the bio-polypropylene from Brazil, container ships were used. This is assumed as no sugar cane cultivation plants are located in Europe, and that Brazil is the largest producer of sugar cane in the world. The largest sugar cane district in Brazil is in the southwest. From the center of the district to the closest harbour a distance of 300 km have been estimated.

Concerning the total amount of transports involved in the life cycle, the gate-to-grave sub-system relied on assumptions to a significant extent. Transports associated to the use phase: distribution to retailers, means of acquirement by consumers, and disposal, occur dynamically across all of Sweden. This results in difficulties identifying exact transport characteristics. For transports occurring between SM's factory and retailers, refrigerated trucks were assumed as the content of the can needs to be kept under cooling. A more accurate cooled transportation to SM's storage in Brunna could be established, where a distance from the factories could be calculated to 463 km.

Energy Consumption

For energy use (heat and electricity) in industrial processes over the life cycles, a mix of sources has been assumed. As specific energy sources are difficult to asses, mixes was deemed representative and appropriate. For processes with confirmed national location, a cut-off for the selected country was chosen.

Disposal and Waste Management

An assumption of average distance for household waste to incineration plant for municipal waste transportation have been estimated to approximately 71.08 km, according to an EcoInvent 3.7 unit process presented in Appendix A.1 (E14). Distances from household to unmanned recycling stations in Sweden is assumed to be 400 meter, according to (Wiqvist, 2018). 400 meter is considered walking distance for most people. For distances longer than 400 meters, as well as apartment complexes with waste sorting (distance considered 0 meters), adjustments were made. 50% of consumers with an average distance of 400 meters were assumed to use a car with an internal combustion engine. It was therefore deemed reasonable that a distance of 200 meters was set for transport by car.

4

Result & Discussion

In section 4.1, the LCI for recycling and incineration is presented, while the rest of the inventory is presented in Appendix B. Results from the LCIA is presented in the form of tables representing cradle-to-gate and cradle-to-grave separately, where the cradle-to-grave system shows the EoL-scenarios with five waste management options focusing on end consumer. The results are further presented in bar charts, in figure 4.9, expressed in percentages of one PP_1 can cradle-to-gate, as it represents the majority of the cans SM have available on the market. Complementing contribution graphs are presented and discussed along with the result from the sensitivity analysis. Closing out the chapter, a summary of the result and discussion is presented to give a holistic comparison and reflection.

4.1 Inventory Analysis

Due to non-disclosure agreements (NDA) with SM, data gathered during the thesis provided by SM, and suppliers, are subject to confidentiality to a large extent. A full inventory together with calculations are presented in Appendix B for transparency towards the company. Accompanying secondary data gathered from EcoInvent 3.7 is further presented in Appendix A.

End-of-Life Scenarios
In order to model established EoL scenarios, data on incineration was first collected. The study relied on secondary data for emissions produced from incineration of materials, presented in table A.2, which was provided by Baumann and Tillman (2004). The data was incorporated in the modelled system to account for emissions as a result of can incineration. Values used for emissions at incineration plants are presented in table A.2.

Incineration
To facilitate the calculation from the incineration of waste at the incineration plant, the constants from table A.2 were multiplied with the mass of the materials presented in the table and then added up to represent the entire can. "Paper" represents the paper used in the paper can and the hybrid can. "Plastic mixture" represents PP used for the PP_1 can, parts of the hybrid can, and the paper can lid. "Synthetic rubber" is used to represent the slack wax used for coating the paper can. Both slack wax and synthetic rubber are petroleum products, hence an estimate of the contribution at the incineration plant has been made.

Example of calculations made for CO_2 from incineration of a paper can:

$$m_{CO_2} = \frac{m_{paper} \cdot 1190 + m_{wax} \cdot 1460 + m_{lid} \cdot 2750 \cdot r_{inc.}}{1000} \tag{4.1}$$

Calculations are performed for all cans and components, and are presented in Appendix B.

The thermal and electrical energy is assumed to be used within the system. The credit for the heat and electrical energy is considered to be a Swedish electricity mix from a waste-to-energy plant, according to an EcoInvent 3.7 process presented in Appendix A.1 (E21).

Recycling
Recycling of the products depend on the products composition. The two waste treatment options makes up 100% of the can.

For the open-loop recycling of the PP_1 can, a second product made of recycled plastic was investigated and used as reference for material loss in recycling. According to an EcoInvent 3.7 process, presented in Appendix A.1 (E24), fleece shirts are made of waste plastic where 90% of the recycled material can be reused into fleece fabric. The process was deemed representative and equivalent to that of the PP_1 can. The PP_1 can is therefore considered to be credited for up to 90% if all distributed cans are recycled. A negative input of PP granulate of the calculated recycled mass have hence been used to quantify and calculate the credits for the recycled PP_1 can.

For the paper can, only the lid is subject to recycling while the base of the can is incinerated. The recycling rate is dependent on the rate of incineration, but the material loss rate is equal to the material loss rate for recycling the PP_1 can.

Regarding the hybrid can, the can is recycled as a liquid packaging board according to the supplier. A possible way of recycling the hybrid can is then to make a paper can out of it. Therefore, the same amount of material loss is used for material crediting the hybrid can. Losses equivalent to those at the paper recycling station have been used for recycling of the hybrid can, which is approximately 9.3% according to calculations in Appendix B. This is credited as a negative input of graphic paper (100% recycled), taken from an EcoInvent 3.7 unit process presented in Appendix A.1 (E3).

For the PP_{bio} can 50% of the amount of recycled granulate ,compared to the fossil based PP, are credited. The reason for the credit difference is because of lower material quality, ergo degradation of material properties, which equals 45% credit for the total recycled mass of fossil based PP.

4.2 Life Cycle Impact Assessment

In the following chapter, impact contributions from the can types (material extraction, production, and end-of-life) are presented and explained in combination with the EoL scenarios. LCIA of the full cradle-to-grave system for all cans, respectively, is further presented and discussed alongside with graphs depicting process contributions. An overall impact per can is presented in figure 4.9, and detailed showcases of all cans in EoL1 and EoL5 is presented in contribution graphs under the subsection for each can type. In the sensitivity analysis, a deeper discussion of the EoL scenarios and the result from the changed loss rates at SM factory is presented and elaborated on. For detailed numerical values in the cradle-to-gate system, see table A.3 in Appendix A. Full cradle-to-grave is presented in table A.4, including EoL2-EoL4, showcased in tables A.3.

4.2.1 PP$_1$ can

Figure A.5 shows the contribution for a PP$_1$ can in EoL1 with 100% recycling, and EoL5 with 100% incineration relative to the cradle-to-gate system. It was found that the environmental impacts decreases with an increased rate of recycling, regardless of impact category. Looking at the EoL scenarios in figure A.5 a recycling rate of 50% is required for the can to outperform the cradle-to-gate system. This is true for all impact categories except climate change, where a recycling rate of 75% is required to be lower than the cradle-to-gate system.

Figure 4.1 and 4.2 shows contributions from processes in the PP$_1$ life cycle for each impact category. The figure have been normalized to account for relative contributions in percentages of total impact.

Noticeable differences between full incineration and recycling concern that of credits received for recycling. Credits are given for each category when 100% recycling occurs. For 100% incineration, credits are given in regards to acidification and eutrophication. This is due to the negative impact from recovered heat and energy as a result of incineration. The differences in EoL1 and EoL5 suggest that recycling is preferable in regards to every impact category.

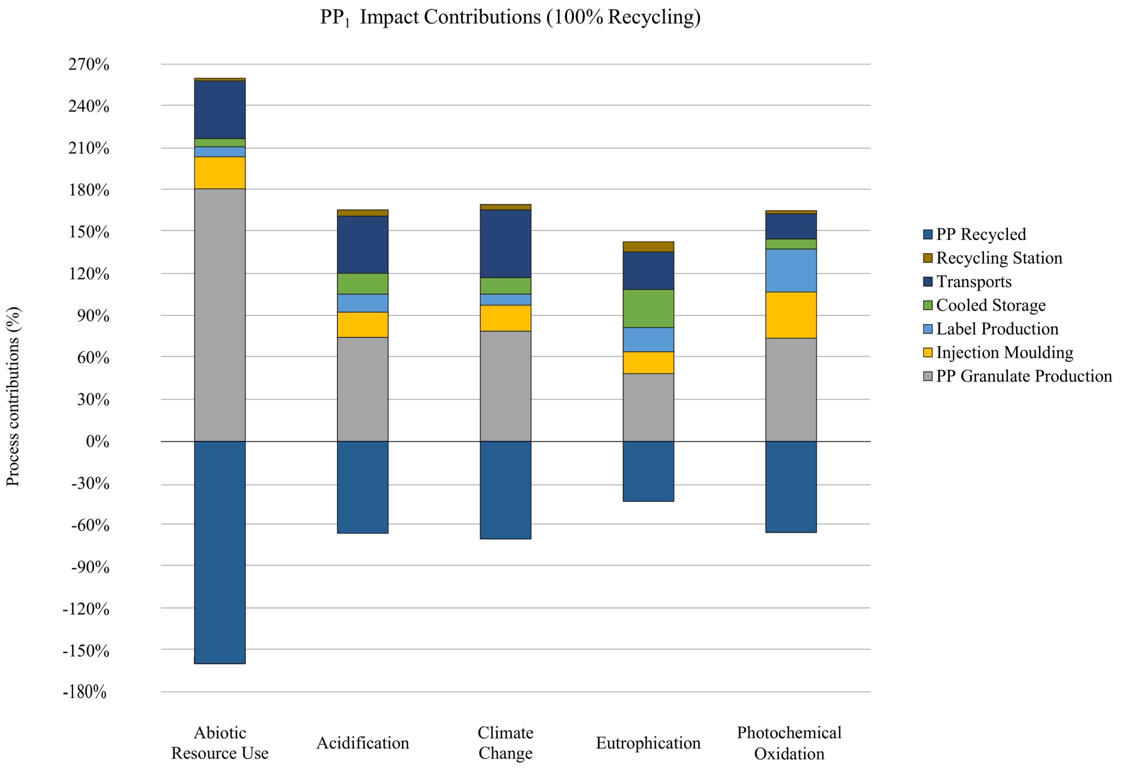

Figure 4.1: Impact contributions for the PP_1 can with 100% recycling.

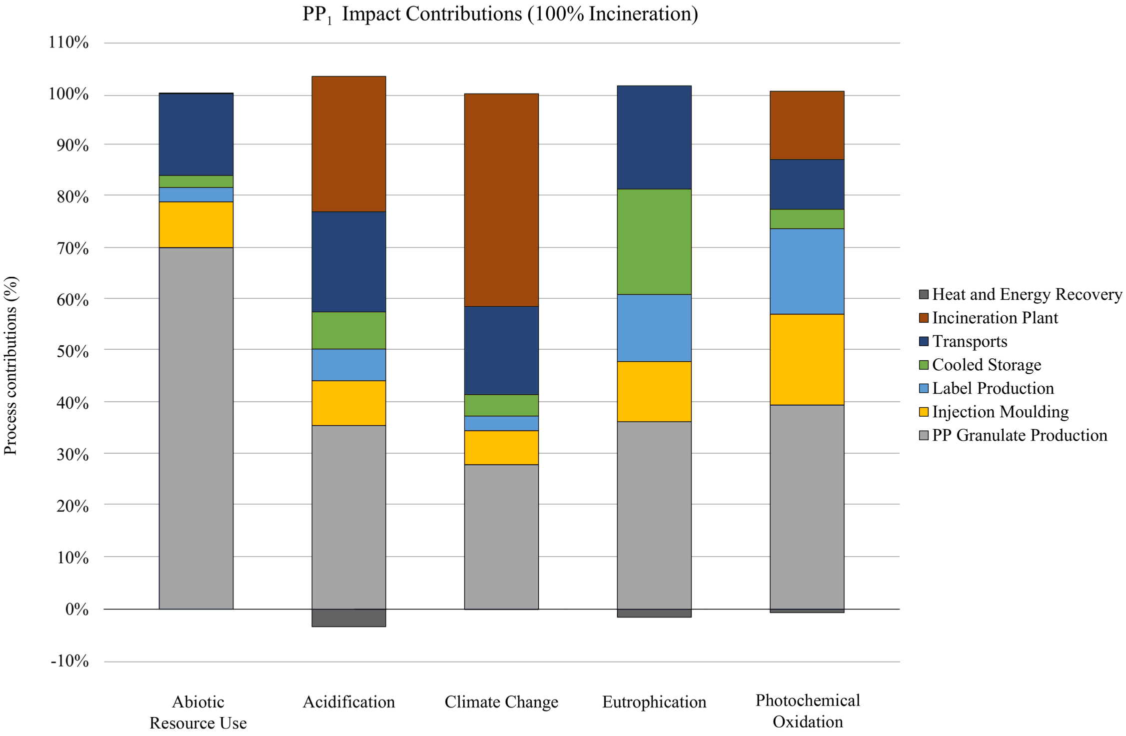

Figure 4.2: Impact contributions for the PP_1 can with 100% incineration.

Figure 4.1 and 4.2 suggests that production of PP granulate is the main contributor of emissions for the PP_1 can. For 100% incineration, acidification and climate change stands out as the process of incineration contributes significantly. The credit given in both of these categories are of further noticeable size if the can is recycled, and incineration is avoided. Abiotic resource use yields credit of the highest magnitude, which is to be expected as the majority of the materials extracted will remain within the industrial system.

The PP_1 can, which is the can used mostly for packaging SM's products, is highly recyclable. The problem with the plastic can is that the average Swedish recycling rate of plastics (except for PET) is only about 46% (Hinde, 2020). What contributes most to the impact categories is the raw material extraction and production of PP granulate, which is naturally difficult to avoid when using the material. Another way in which the impact from the PP granulate production can be reduced is facilitation of plastic recycling, making it easier and more convenient for consumers to recycle.

4.2.2 Paper can

Figure 4.9 shows the contribution for a paper can in EoL1 (100% recycling)[1], EoL5 (100% incineration), and cradle-to-gate presented relative to the cradle-to-gate system for a PP_1 can. The result from the impact assessment is that the cradle-to-gate processes for the paper can is lower for resource use, climate change and photochemical oxidation. A higher contribution to the impact categories eutrophication and acidification was observed. It was further observed that the environmental impact decrease with a higher recycling rate. For climate change, 100% recycling yields a larger impact than the cradle-to-gate system. This is due to the impracticability to recycle waxed paper. Therefore, a complete incineration of the waxed paper is considered even though EoL1 (100% recycling) is applied to the can. This is also seen in figure A.6, where the incline is less steep due to recycling impracticability, giving less material recycling credit.

Figures 4.3 and 4.4 shows contributions from processes in the paper can life cycle for each impact category. The figures have been normalized to account for relative contributions in percentages of total impact.

What is significant for the paper can is that it contributes more than the PP_1 can to acidification and eutrophication. The paper board recycling process is the largest contributor in terms of emissions. It is shown that recycled paper can be better than virgin paper in energy efficiency, however, for the paper can, paper board is used which is less energy efficient than using virgin paper (Raheem, 2013). The paper can is also a product with high material loss in the production phase. An alternative way to produce the paper can is to use some other type of paper that is recyclable, hence increasing the material credit from recycling.

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[1] 100% recycling for a paper can corresponds to 100% recycling of the lid and 100% incineration of the base.

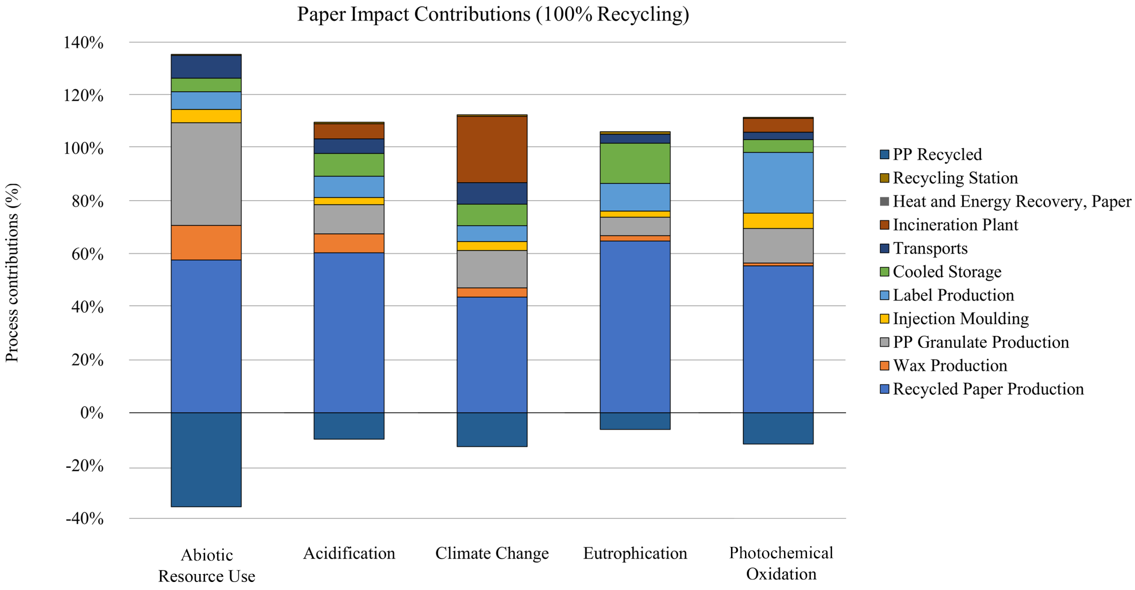

Figure 4.3: Impact contributions for the paper can with 100% recycling.

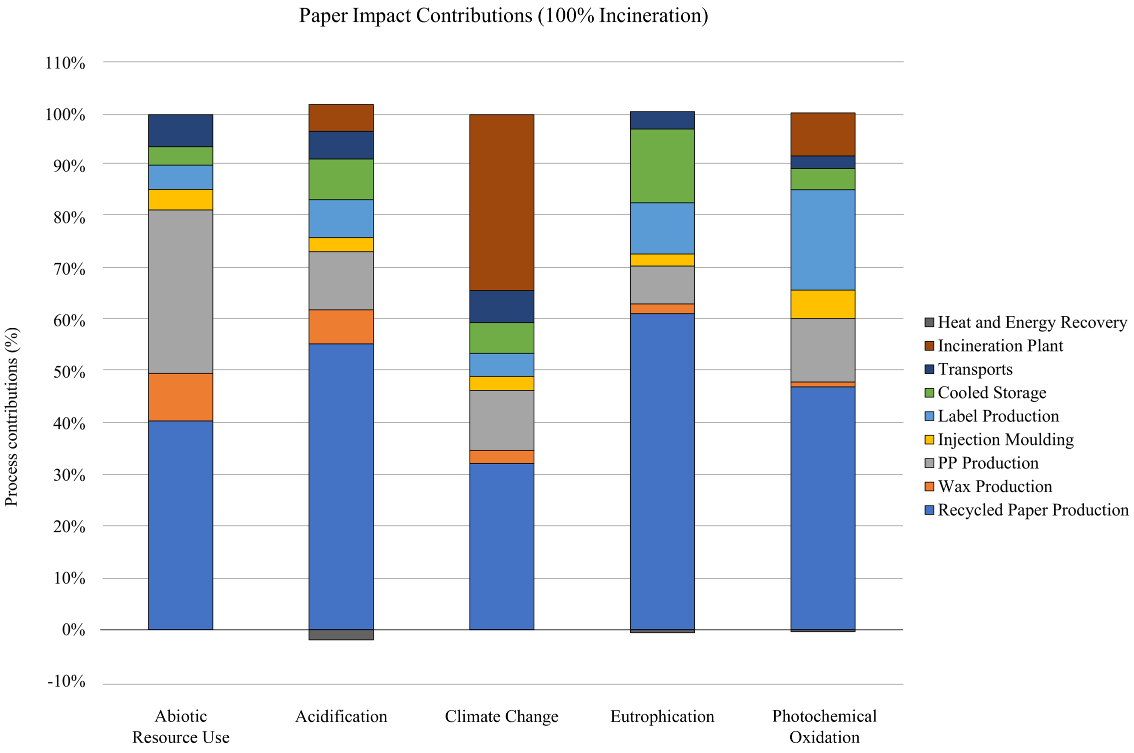

Figure 4.4: Impact contributions for the paper can with 100% incineration.

4.2.3 Hybrid can

The third part of figure 4.9 shows the contributions of the hybrid can in EoL1 (100% recycling), EoL5 (100% incineration), and cradle-to-gate relative to the cradle-to-gate of a PP_1 can system. The hybrid can outperforms the results of the PP_1 can in all impact categories, except for eutrophication. Observing the EoL scenarios in figure A.7, a steeper decrease in the hybrid cans' contribution to eutrophication in relation to an increased recycling rate can be noticed. The hybrid can further outperforms the PP_1 can if a recycling rate over 50% can be achieved and maintained.

In regards to 100% incineration, a variance in contributors for the separate categories can be noticed. Abiotic resource use and eutrophication are influenced by plastic and paper production. The total climate change impact is in large a result of the incineration process, which gives additional emissions of GHG. This applies similarly for the paper and PP_1 cans.

Recycling the hybrid can results in material credits for all categories. The largest negative contributions occur for acidification and eutrophication. This is due to avoided emissions of organic compounds (accounted for as SO_2 - equivalents) produced from burning of fossil fuels for acidification. For eutrophication, it concerns avoided production of biological material from forest cultivation for virgin paper production.

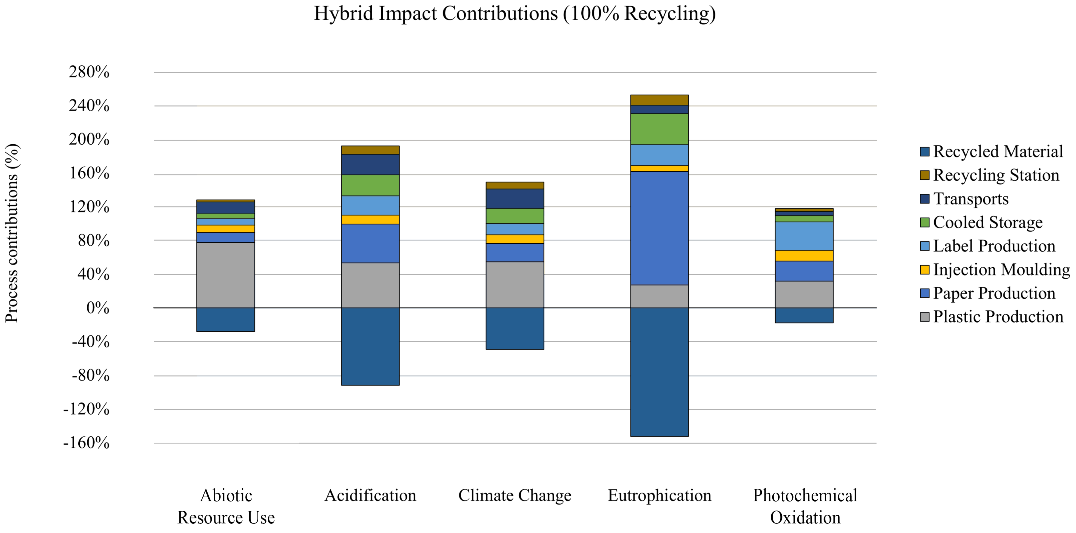

Figure 4.5: Impact contributions for the hybrid can with 100% recycling.

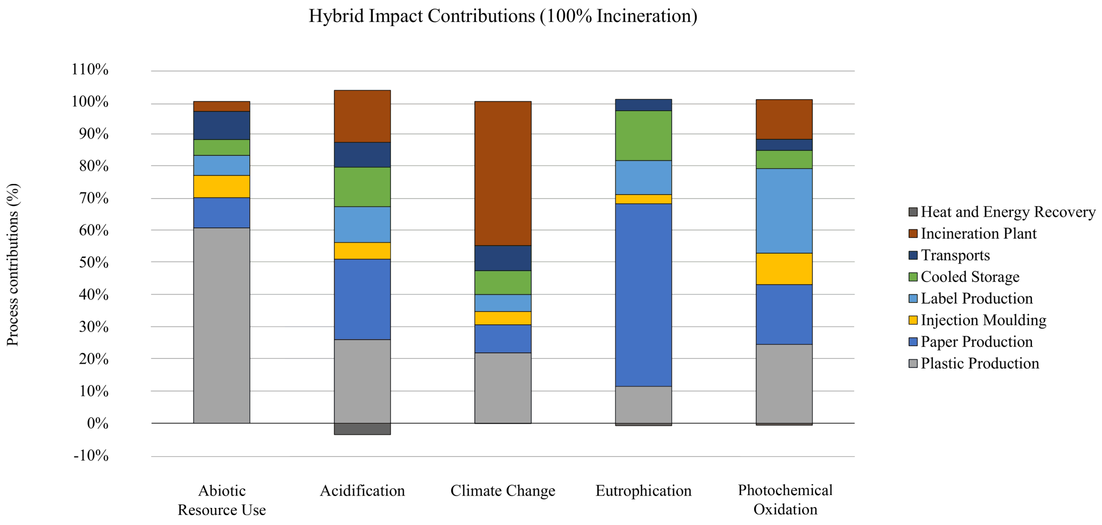

Figure 4.6: Impact contributions for the hybrid can with 100% incineration.

The hybrid can is a potential competitor to the existing can types. As the hybrid can outperforms the existing can types in assessed impact categories, except for eutrophication (where the largest contribution comes from paper production), it is considered a suitable alternative to existing can types. The possibility to recycle the can makes the material combination favourable in all cases, compared to the current paper can. The only can that yields a lower potential impact than the hybrid can is the PP_{bio} can, in terms of abiotic resource use. This is because of the fossil based plastic that is used in the hybrid can, which is why it contributes more to abiotic resource use. The PP_{bio} can only uses abiotic resources indirectly in production processes, not in its actual design. Since it is possible to recycle the can as a carton product, such as those for dairy product packaging, which goes under the material of paper products that, according to Hinde (2020) have a recycling rate of 82% of all the paper products. With a higher degree of habitual behaviour, where consumers recycle paper to a higher degree than plastic, a transition from plastic and paper to the hybrid can could likely prove even more environmentally beneficial.

4.2.4 PP_{bio} can

The last part of figure 4.9 shows the contribution for the PP_{bio} can in EoL1 (100% recycling), EoL5 (100% incineration), and cradle-to-gate relative to the cradle-to-gate of a PP_1 can system. What can be seen in the figure is that the contribution to climate change and abiotic resource use is lower than the PP_1 can. There is a trade-off when using biomass rather than fossil resources, however. Looking at figure A.8, a larger impact to the potentials acidification, eutrophication and photochemical oxidation can be observed, compared to the PP_1 can.

Figure 4.7 and 4.8 shows contributions from processes in the hybrid can life cycle for each impact category. The figure have been normalized to account for relative contributions in percentages of total impact.

Main contributor of emissions for the PP_{bio} can is sugarcane cultivation, for the impact categories acidification, eutrophication, and photochemical oxidation. The category sugarcane cultivation in figure 4.7 and 4.8 includes bio-ethanol refinement, as well as polymerization of bio-polypropylene, and accounts for 50% of total impact. Sugarcane cultivation being the primary impact contributor to acidification, eutrophication, and photochemical oxidation is true for both EoL1 and EoL5. Climate change showcase a similar trend to the other can types, that incineration of the can contributes to a significant amount of total emissions. Abiotic resource use occurs primarily as a result of transports, due to shipping distance for granulates to injection moulding. A significant credit is given for abiotic resource use. This is explained by the fact that the negative impact from recycling credits a fossil-based counterpart due to the open-loop recycling system.

Bio-polypropylene is the material which has the lowest potential impact in regards to abiotic resource use. This is somewhat self explanatory, as it uses biomass for refining bio-ethanol refining and polypropylene polymerization. A potential increase in eutrophication is due to intensified agriculture in Brazil, which uses various fertilizers. Photochemical oxidation is a result of the energy mix used in Brazil, which differs from the one used in Europe (where material extraction and refinement occurs in Europe). This, in combination with the longer transport distance (from Brazil to Sweden), contributes to emissions in the impact categories acidification, eutrophication and photochemical oxidation.

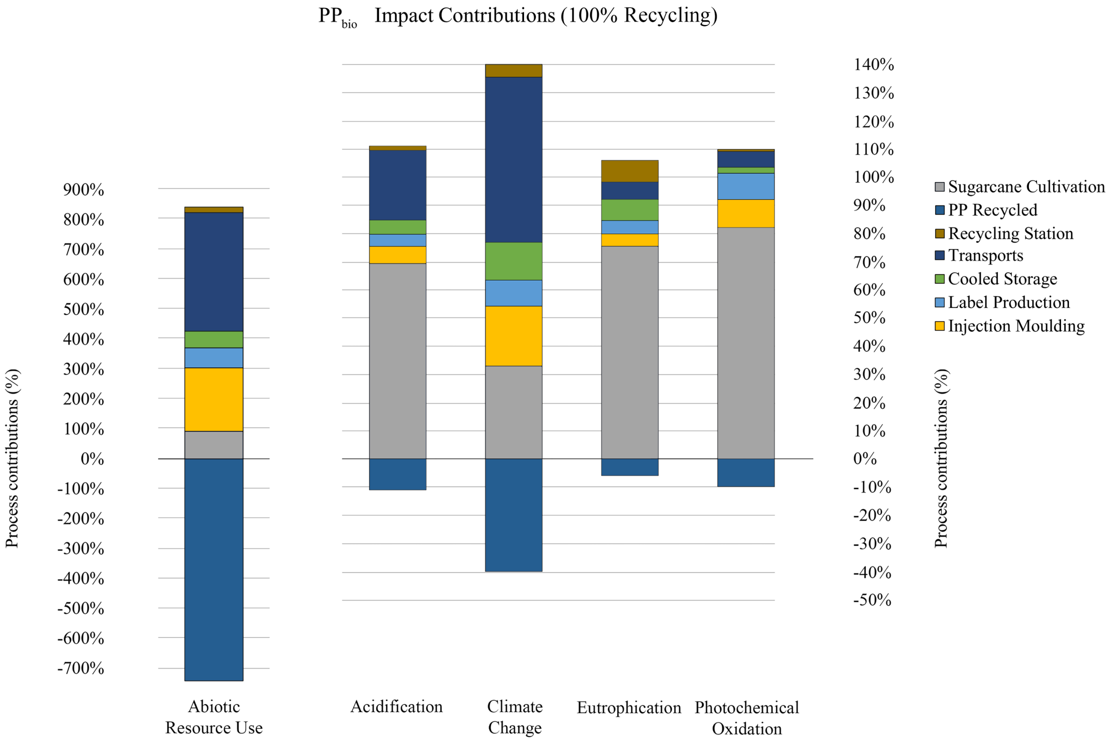

Figure 4.7: Impact contributions for PP_{bio} with 100% recycling.

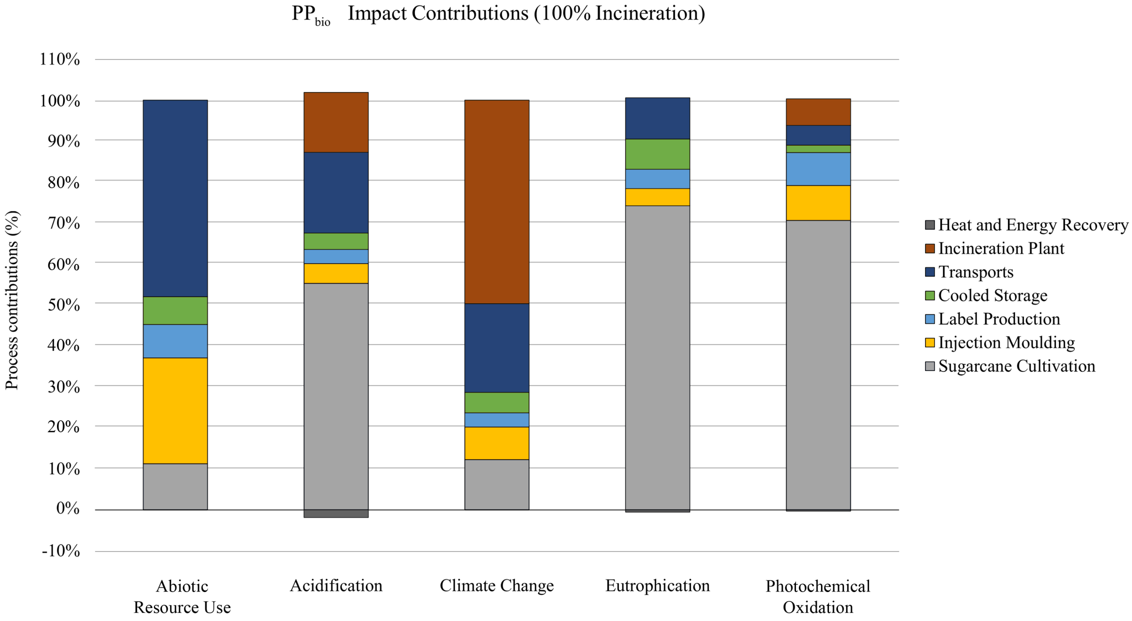

Figure 4.8: Impact contributions for PP_{bio} with 100% incineration.

If the cultivation of sugar cane was less intense, and took place in another region, it is expected that total impact could be reduced. A possible alternative route is production of bio-ethanol from sugar beets, as suggested by Marzo et al. (2019) in northern Europe, which could be subject to crop rotation or intercropping. This has shown feasible for wheat and sugar beets with low or adequate phosphorous (Hajiboland et al., 2018). By shortening transport distances and an increased agricultural management control, a reduction in impact from the bio-based PP could be achieved.

4.3 Comparative Life Cycle Impact Assessment

The way in which the cans are disposed of plays a significant role to total environmental impact. In this section, the quantified result from the calculations in the software openLCA is presented in table A.3. The table presents the results for all cans, EoL-scenarios, and impact categories. The results are further showcased in a bar chart and explained separately for every can.

Figure 4.9 reflects total impact contribution from can production of each can type. The results have been normalized to one PP_1 can, as it serves as baseline for the study. This was done to facilitate interpretation and understanding of relative differences between the cans, in accordance with the comparative nature of the study (see section 2.1.1).

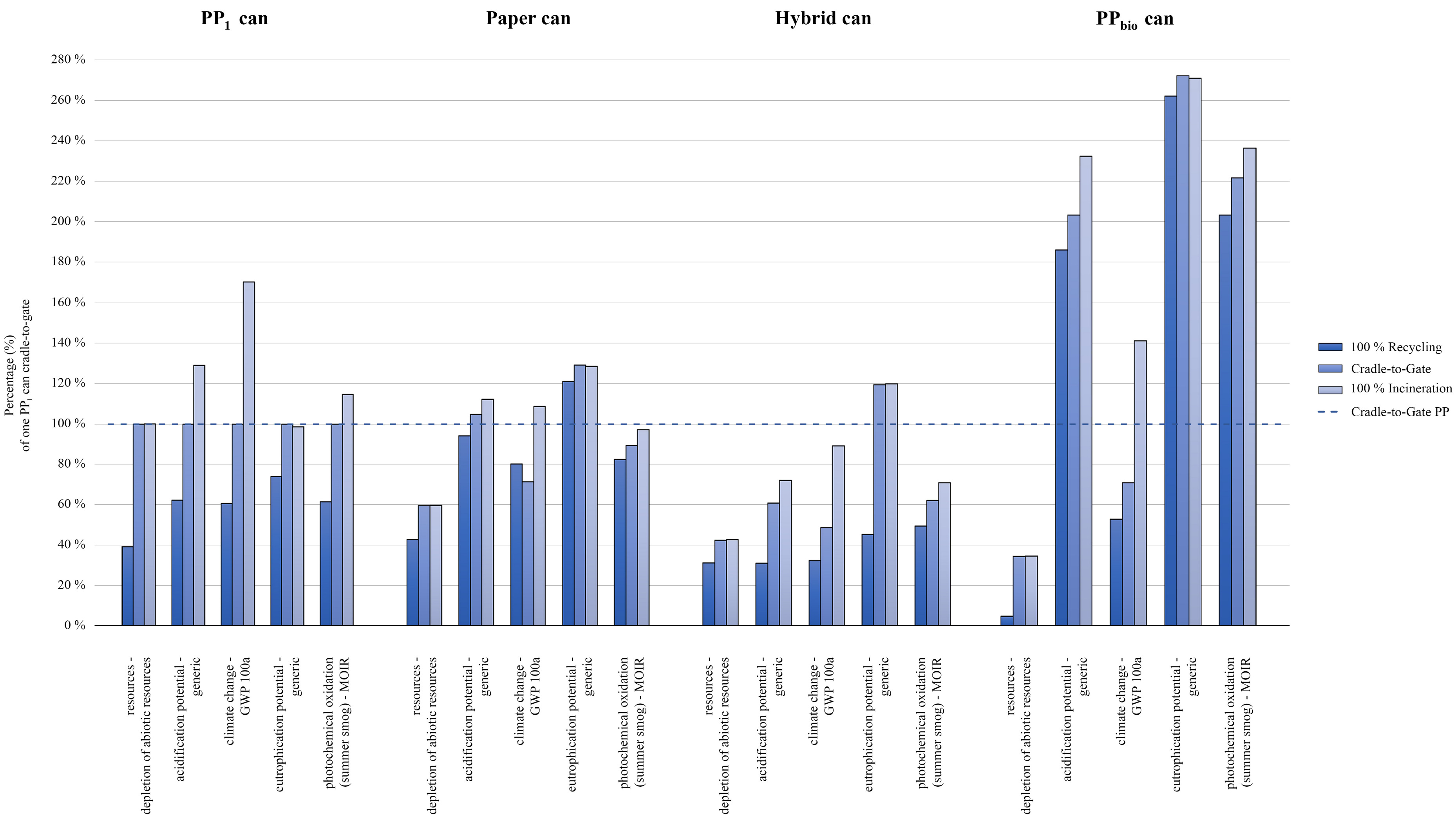

Figure 4.9: Bar chart depicting all four cans in 100% recycling, cradle-to-gate and 100% incineration. The dashed line represents the cradle-to-gate for a PP$_1$ can that acts as a baseline for the cans.

4.4 Sensitivity Analysis

EoL Scenario Analysis

Studying figure A.5, the PP_1 can is the can most sensitive to the EoL scenarios. The paper can is the can least sensitive to the EoL scenarios, showcased in A.6, due to the inevitable incineration of the can base regardless of recycling rate. The PP_{bio} can shows a high sensitivity to recycling, which is due to the possibility to recycle the product, resulting in a recycled material credit. Recurring for all can types is the impact reduction from an increased rate of recycling. This may be used as a guideline for influencing consumer behaviour in selection of disposal method, supporting a feedback loop that results in an even higher rate of recycling, enhancing the cans environmental performance additionally.

Adjusted Loss Rate

As stated in the impact contribution assessment, a majority of emissions are directly linked to can production, which ends at SM's factories. Losses in can manufacturing, and supply chains to the factories, directly affects the amount of material required for production of one can. This results in SM being in a position to directly impact supply chains upstream, as amount of material required (and by extension substances emitted) may be reduced from streamlining manufacturing and identifying specific production hot-spots.

For the sensitivity analysis for adjusted loss rate a set of terminated losses were implemented to determine impact contributions and reduction of total impact for each impact category. As the loss rate of the can modules, the base and the lid, differ in the studied system, they were addressed separately in terms of adjusted rates. Adjustments for the two parts separately can be seen in Appendix A.5. An analysis for adjusted loss rate of assembled can was further conducted.

The PP_1 can shows a varying sensitivity between 3- 4.7%, depending on impact category, which can be seen in figure 4.10 where the reduced impact from the adjusted loss rate for PP_1 is shown. Abiotic resource use is most sensitive to the loss of can material in filling and labeling performed in SM's factories. What is interesting is that the loss rate for the can lid is significantly higher than the loss rate for the can base for the order representing the system under investigation even though the lid stands for the highest mass rate of the two parts. For example by eliminating the loss of lids a reduction of almost 3% of the total impact on climate change can be reduced. This is shown in the separated figures in Appendix A.5.

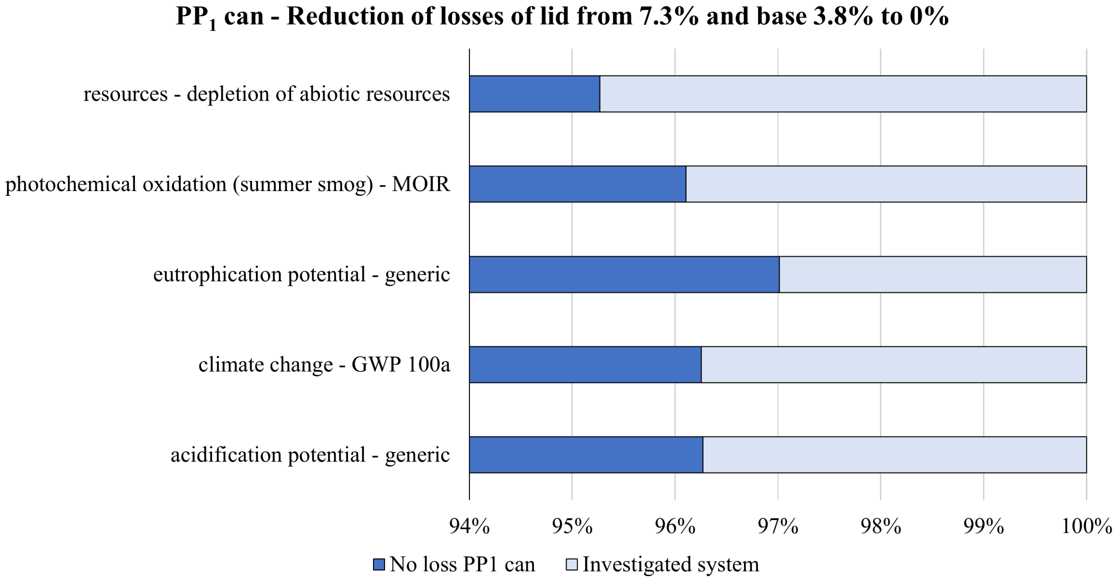

Figure 4.10: PP_1 can: can loss terminated at SM factory compared to studied system

In figure 4.11 the reduced impact from the adjusted loss rate for the paper can in SM's factory are shown. The paper can shows a lower sensitivity to losses in the filling and labeling process than the PP_1 can. This is probably because the losses of paper are already much higher when cutting out the paper in an earlier process. Almost all of the sensitivity is dependent on the loss of lid for the paper can which can be seen in Appendix A.5.

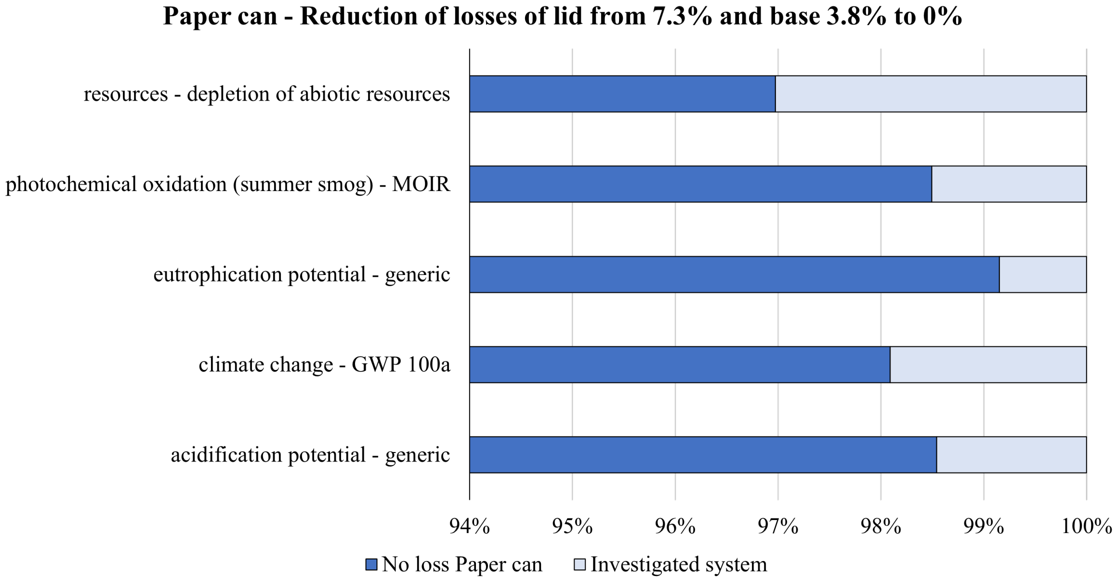

Figure 4.11: Paper can: can loss terminated at SM factory compared to studied system

In figure 4.12 the reduced impact from the adjusted loss rate for the hybrid can in SM's factory can be seen. The hybrid can have a lower sensitivity. The loss rate of can base and lid contributes similar to impact reduction. Appendix A.5.

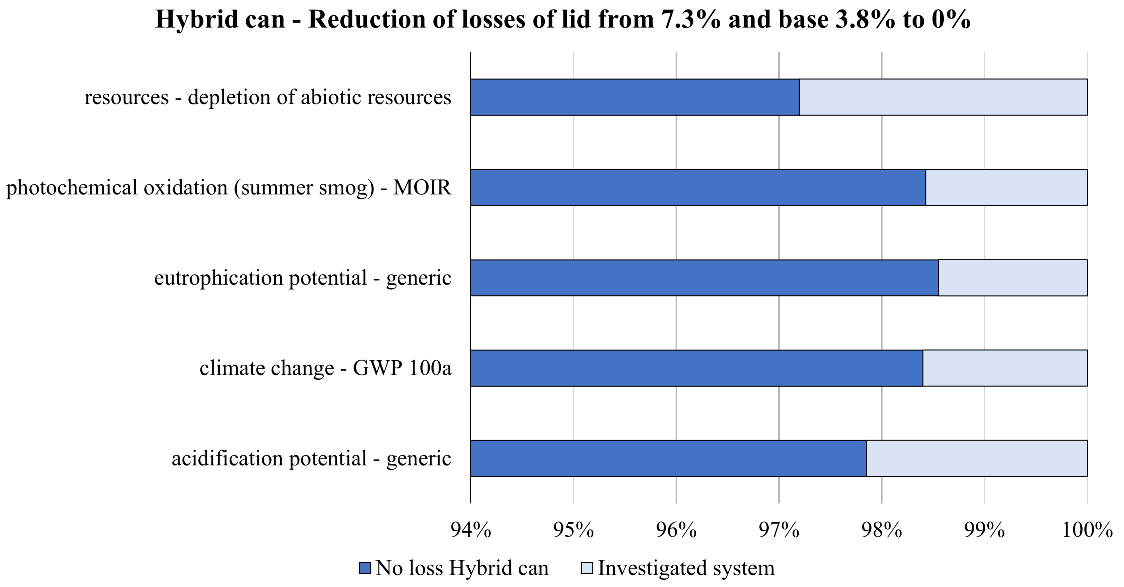

Figure 4.12: Hybrid can: can loss terminated at SM factory compared to studied system

In figure 4.13 the reduced impact from the adjusted loss rate of PP_{bio} can in SM's factory can be seen. The loss rate of the lids are as important as the lids for the PP_1 can as the mass ratio between base and lid is the same. For the reduction per part see Appendix A.5.

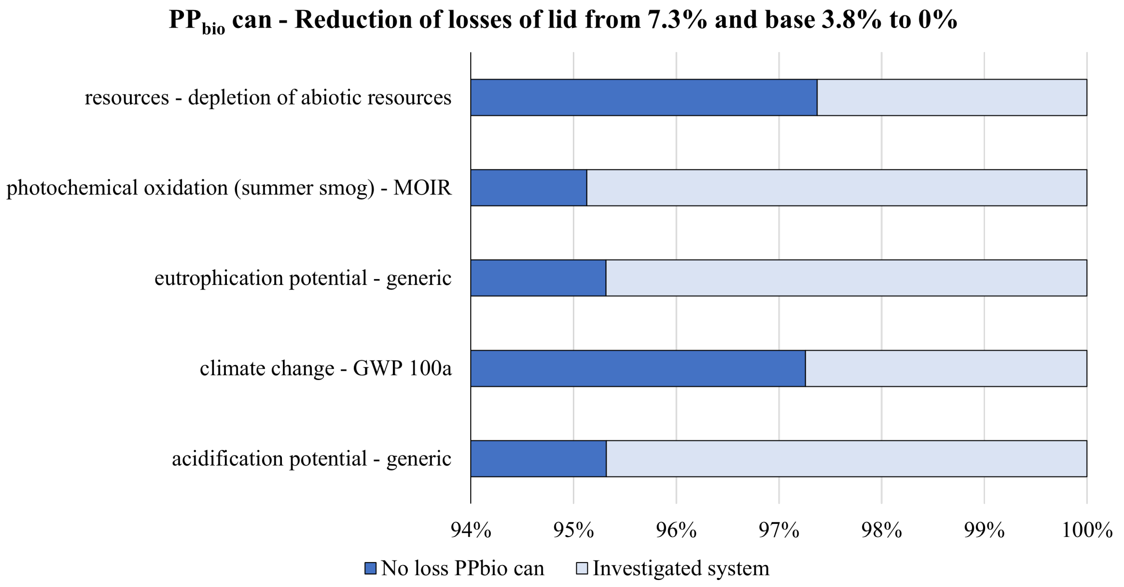

Figure 4.13: PP_{bio} can: can loss terminated at SM factory compared to studied system

4.5 Result Summary

According to chapter 4.2, the PP_1 can showcased the highest values in terms of climate change and abiotic resource use. The PP_{bio} can showed the highest values in terms of eutrophication and acidification. The results suggest that the hybrid can has the lowest impact values in general. Exceptions to this were the categories abiotic resource use and eutrophication, as stated in 4.9. The values for this categories were still marginally lower than the highest in each separate category.

Incorporating the waste management scenario analysis, some observations can be made. The paper can generally showcase the lowest sensitivity on basis of an adjusted incineration and recycling rate. This opens up for an interesting product attribute, which is further elaborated on in the discussion. The PP_1 can, PP_{bio} can, and hybrid can all demonstrate large differences depending on choice of waste management method. Their total impact potentials, however, vary. The PP_1 can have a larger potential impact than the other can types in most categories. The exceptions are eutrophication, acidification, and photochemical oxidation, where the PP_{bio} can revealed the highest values. In summation, the hybrid can signify the lowest potential impacts over all.

The sensitivity analysis conducted on the can loss in SM's factory in the process of filling and labeling shows that the two types of PP cans are most sensitive to losses. The environmental impact could possibly be reduced for several of the impact categories by improved management of the filling and labeling process.

5

Conclusion

The results show that existing cans, the PP_1 can and paper cans, have different contributions to different environmental impacts, which is a natural consequence of design and material selection. Depending on choice of waste management method, the PP_1 can may result in larger environmental benefits from open-loop recycling than the paper can. On the other hand, increased emissions from incineration are not as prevalent for the paper can, as it is more resilient to changes in waste management. An assessment on EoL for current cans would provide additional valuable information on current state of impact.

Although the PP_{bio} can shows potential in reducing abiotic resource use, it appears to be of concern in other regards. Its potential implementation requires clear trade-offs, regarding contributions to different types of emissions, and by proxy other environmental aspects than its fossil-based counterpart. The issue of currently not being subject to a closed-loop recycling system, as in the case of the PP_1 can, would remain for the PP_{bio} can, regardless of which raw material is used.

Based on the results, the hybrid can appears to be a suitable substitute to both the PP_1 can and paper can. From a holistic perspective, all impact categories considered, it shows potential in decreasing emissions in snus can production regardless of waste management method. If an increased rate of recycling can be accomplished, emissions are expected to decrease even further.

Choice of material composition is of great importance to avoid unwanted emissions from production and waste treatment of the products, as raw material extraction is one of the largest contributors to total environmental impact, regardless of can type. It is important to foresee and avoid great material loss in the production of a can to avoid extraction of excess material, since that process is the largest contributor to environmental impact, regardless choice of material. This also reflects EoL, where a higher rate of recycling yields a lower environmental impact.

Looking closer at the losses in SM's factory, where the lid stands for a higher loss rate (7.3%) than the base (3.8%), the hybrid can seems to be more stable than the rival cans. To improve the result and lower the climate impact on the cans a reduction in cans at the factories should be considered. If the loss rate in SM's factories are higher for the lid by rule, a different design may be considered where the heaviest and most material dense part is the part being filled (by placing the disposal lid on the bottom of the can).

In conclusion, the results indicate that hybrid can has the lowest potential environmental impact of the four cans investigated, and is deemed most environmentally beneficial from a holistic perspective. Production not only results in less emissions, but it is also a material that is recycled to a larger extent in Sweden as of today. By changing from the polypropylene and paper can, it can be assumed that a higher rate of recycling may be achieved by extension.

Questions For Further Research

Based on the result, a number of further research questions were established, which could assist in reducing SM's environmental impact from the snus cans:

- Is it possible to lower the environmental impact by change in design?
- The labels and print are contributing to the overall impact of the can and is therefore subject to further research.
- The hybrid can is suggested as the most environmental beneficial can in the report, is it possible to replace the virgin paper with a recycled paper?
- If a change in material is not of relevance, a collaboration with other companies should be considered, where a recycling system such as the once for PET-bottles could be implemented on the PP_1 can.

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A

Appendix A

A.1 Data Quality Requirements

Presented in the following section are specific data quality requirements for the study. The data quality requirements are based on guidelines and requirements provided by ISO (2006b).

Temporal Coverage

The study has not set an explicit time restriction on data. Generally, more recent data has been preferred over older data, due to significant differences in knowledge gaps between involved processes.

Geographical Coverage

Data gathered was geographically dependent to the extent possible. Geographically bounded data was selected when available. If not, a global and independent set was selected. The inventory analysis involved geographical location of upstream processes by assessing the supply chain, which were subsequently determined and modelled accordingly.

Technological Coverage

Concerning the technology used in the product systems, the procedure used for assessing product system design emanated from primary data provided by suppliers. Average options were selected in cases where the specific technology used could not be confirmed. The choice of technology used was hierarchically ordered according to availability of data. Information on site-specific technologies were hence preferred and selected over average technologies when deemed reliable. For technologies with a large degree of uncertainty, such as transports and energy production, geographically bounded technology mixes and continental transport patterns were used.

Precision, Completeness, and Representativeness

In terms of completeness, the product systems were consecutively backtracked in order to account for material losses and waste production in industrial processes. Consequences from losses due to process efficiencies are hence accounted for in cases where data was available. Incineration of snus cans are not considered to be highly contributing to the total impacts at an incineration plant and therefore average data is used instead of marginal data.

Consistency and Reproducibility
The report will be transparent to a possible extent. Appendix B, which includes inventory data, locations to suppliers, name of suppliers and exact calculations, will not be accessible due to confidentiality agreement between the authors and SM. The report will be published without Appendix B, but is reviewed by supervisors from SM and examiner from Chalmers University of Technology. Unit processes from EcoInvent 3.7 in the background system.

A.2 Flow charts

Flow charts presenting systems for all can materials.

PP_1 can

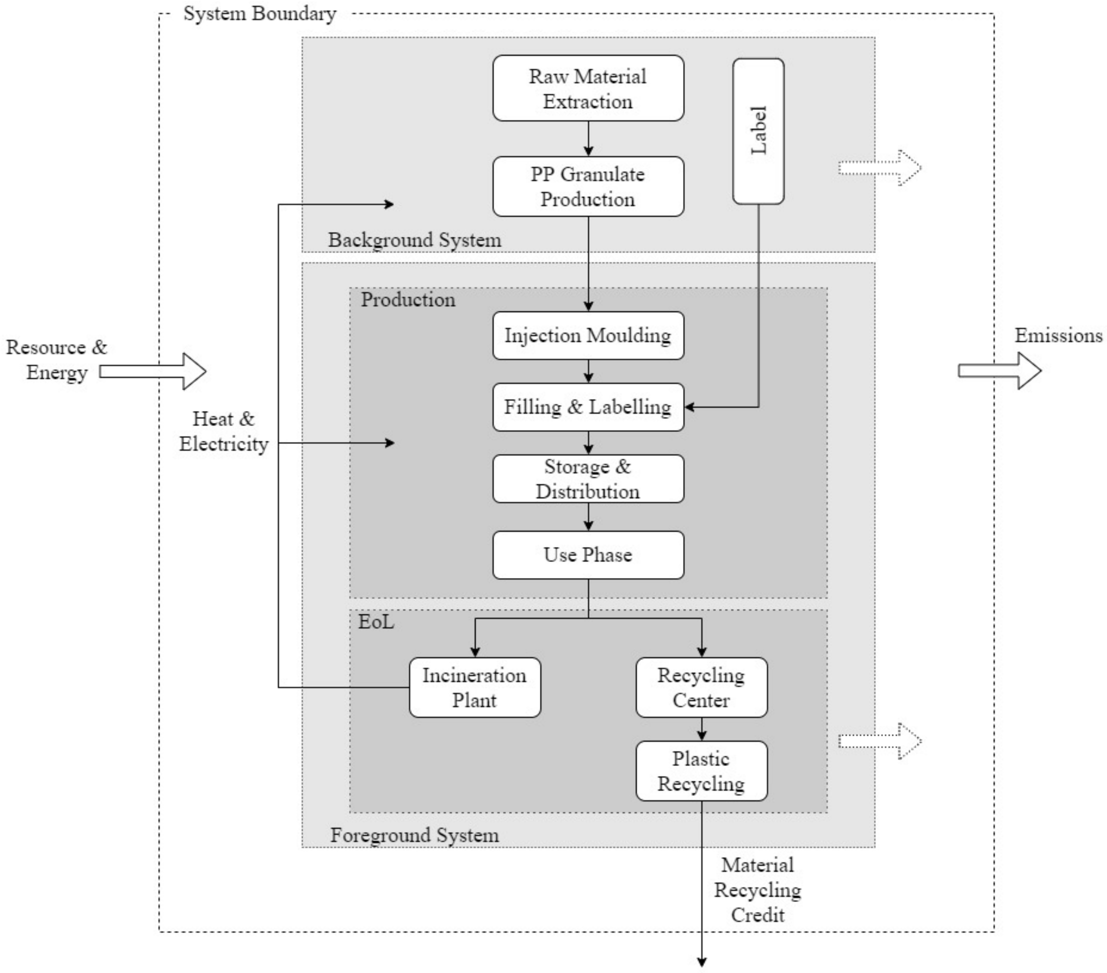

Figure A.1: Flow chart of PP_1 can

Paper can

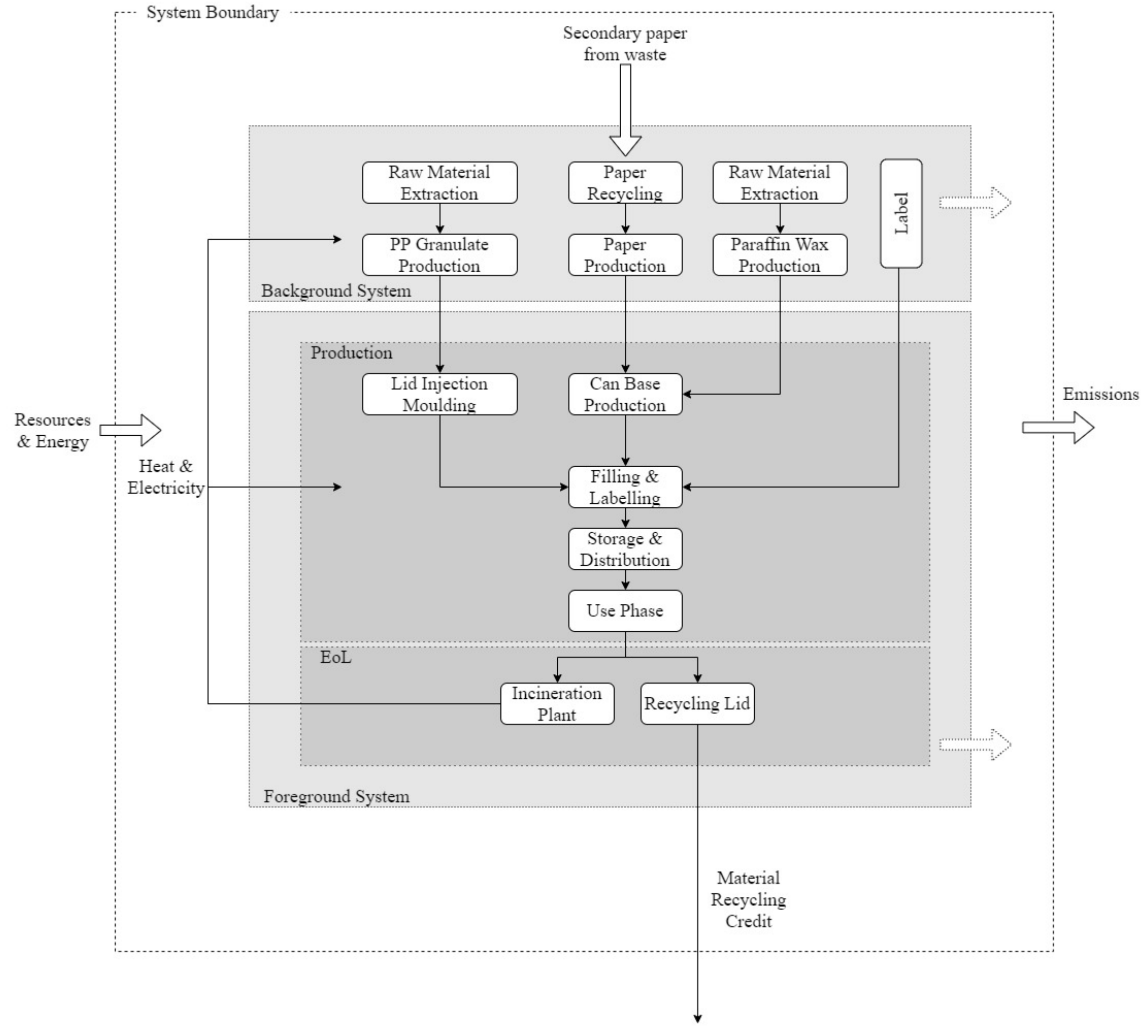

Figure A.2: Flow chart of paper can

Hybrid can

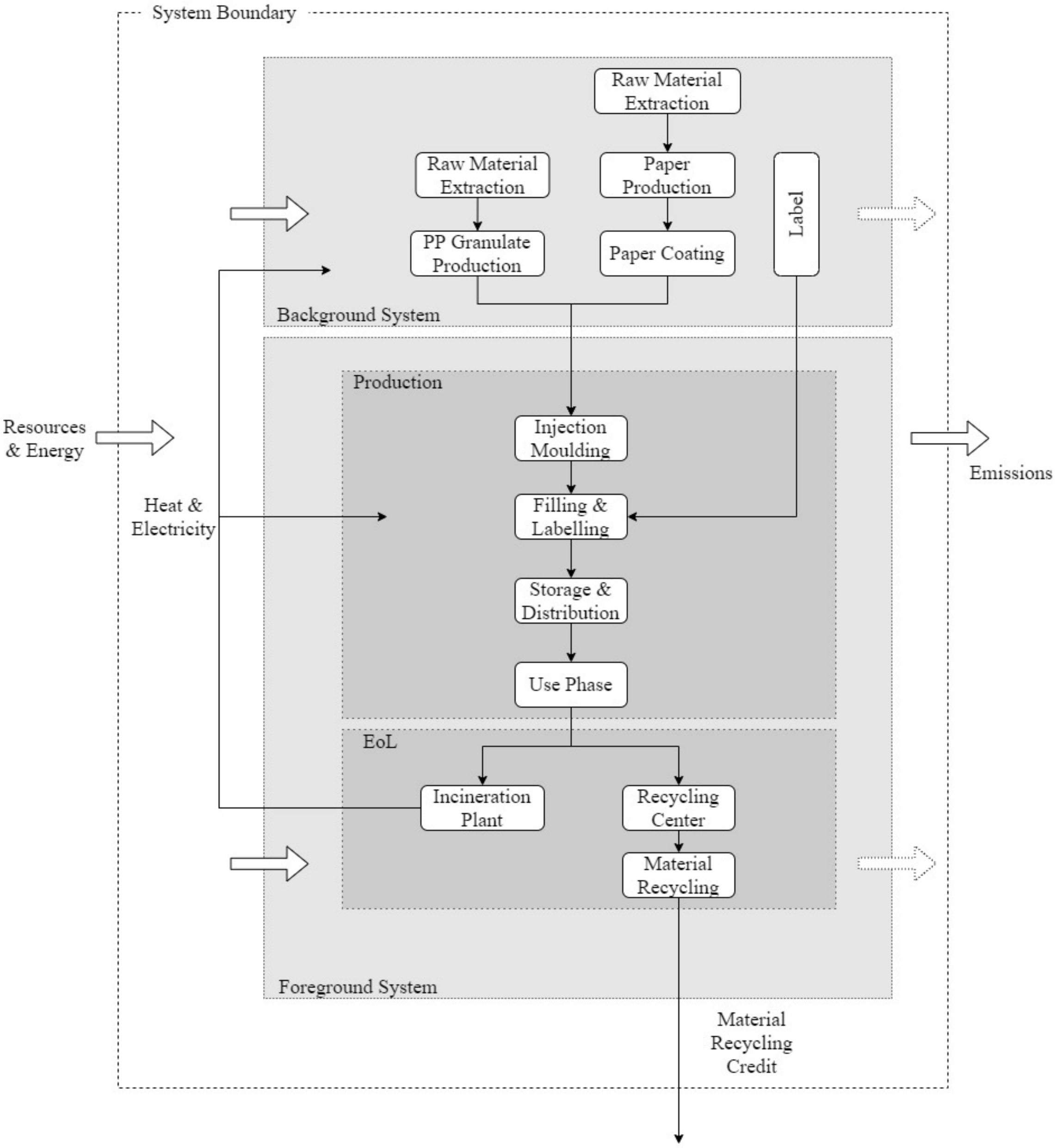

Figure A.3: Flow chart of hybrid can

$\mathbf{PP}_{bio}$ can

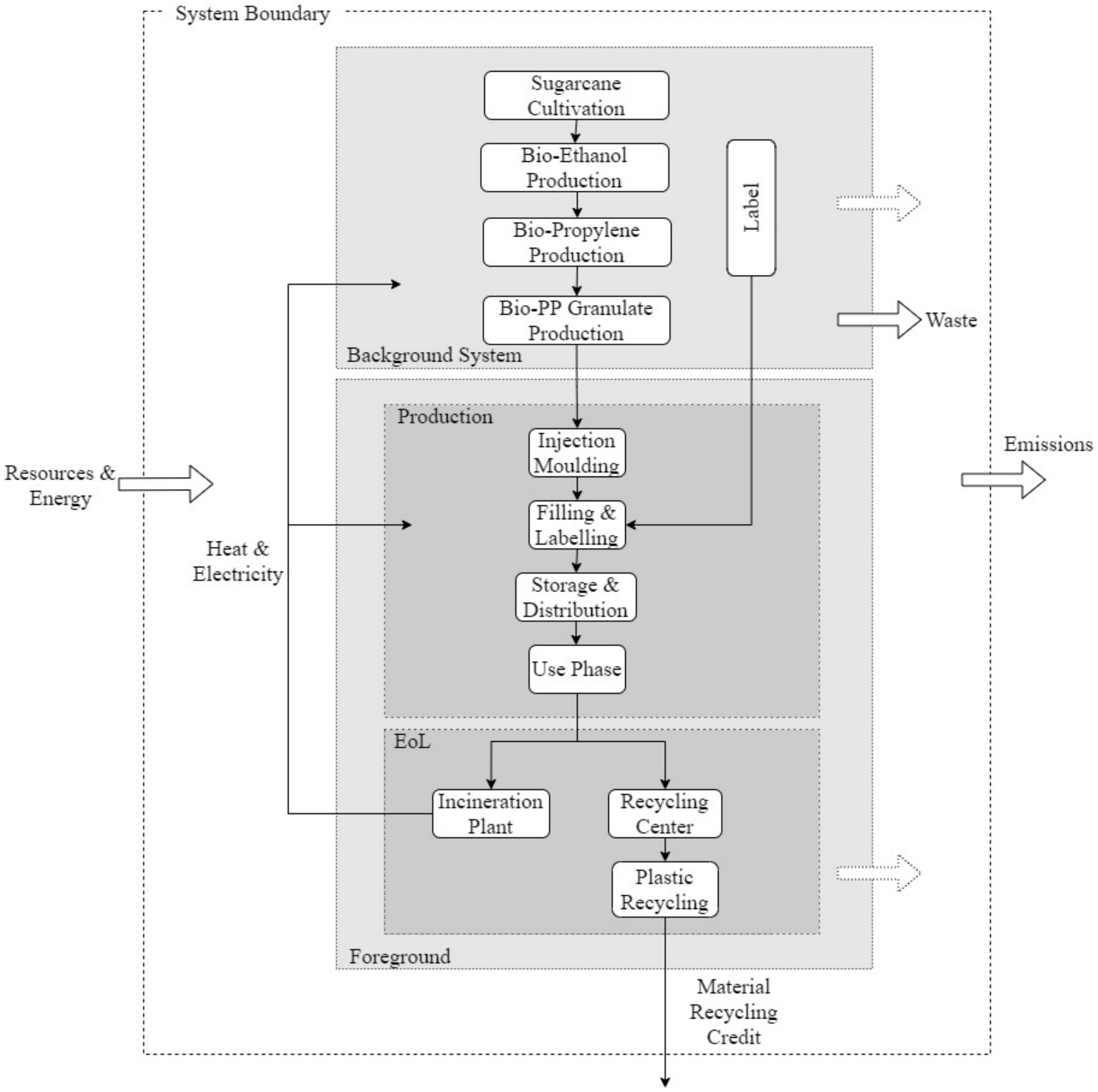

Figure A.4: Flow chart of PP_{bio} can

A.3 Tables

Table A.1: EcoInvent 3.7 background processes used in models

EcoInvent 3.7 Unit Processes

Reference	Process UUID	Last Changed
$\mathbf{PP}_1$		
E1	f7ade173-6fcc-3b2a-b784-452d2036d3c2	2020-10-01
E2	a08e906b-638e-3797-9dee-6cbfa9f44123	2021-03-17
Paper can		
E3	d64aad3a-7b0b-3d96-ae78-808f6aa13b6c	2020-10-01
E4	3c7c835d-7dee-36f0-9e74-b5da3e61b2f0	2020-10-01
E5	9558eaf5-7e67-38cf-a674-c9838ca11024	2020-10-01
E6	a09a7ea5-5c7c-3b77-b7df-3a2997572cb6	2020-10-01
Hybrid can		
E7	21aad1f8-7acc-3774-aa29-445624c270ff	2020-10-01
E8	2e6f4fe8-d96f-3f58-9da8-27dbec112546	2020-10-01
$\mathbf{PP}_{bio}$		
E9	b146aed8-4019-3a49-a384-985275f759d5	2021-10-01
Labels		
E10	adf11a24-bae2-3da2-b509-de03076575fa	2020-10-01
Transportation		
E11	567f982b-2f47-3049-be3f-84a3f130610f	2020-10-01
E12	82b77853-6735-3088-81cb-a5dc6cd3e9f1	2020-10-01
E13	48e8bf58-d87b-347d-ae85-bafb2f86de8c	2020-10-01
E14	ff431498-21c3-34ef-9835-7e13bb09dac0	2020-10-01
E15	3d13e021-0c45-3ecf-83b2-461e44edc4ee	2020-10-01
E16	4cc818f5-6919-36dd-a01e-362da8575eca	2020-10-01
E17	a1ebb82a-6d2b-3d34-be3e-240f7e7a8799	2020-10-01
Electricity Mix		
E18	07bc39db-3f1d-3541-9260-46c711c7a208	2020-10-01
E19	27d3a1fd-86bb-339a-8ec8-3cde7f1b402b	2020-10-01
E20	95cb308d-1418-3c12-9584-8ada668365cd	2020-10-01
End-of-Life		
E21	e01167ad-6cf8-47a7-8df9-e89bf35cb704	N/A
E22	d460a7eb-a15c-3c39-89e6-1bd87c964b83	2020-10-01
E23	dd248c9f-7abb-39a0-8ec5-5eafa63bf3f4	2020-10-01
E24	39686f3c-5526-338a-8d70-8bec2e3142fb	2020-10-01

Table A.2: Emissions from incineration of municipal waste (Baumann and Tillman, 2004) 1),2),3)

Emissions **Resource consumption** **Energy production** **g/kg waste component** **MJ/kg waste component**	**Waste component** **Paper**	 **Plastic Mixture**	 **Synthetic Rubber**
Emissions and waste products			
CO_2	1190	2750	1460
SO_2	0.15	0.20	1.50
HCl	0.077	4.52	1.54
Hg	$3.75 \cdot 10^{-5}$	$5.0 \cdot 10^{-5}$	$5.63 \cdot 10^{-5}$
CO	1.55	3.58	1.90
PAH	$1.01 \cdot 10^{-5}$	$2.34 \cdot 10^{-5}$	$1.24 \cdot 10^{-5}$
Dioxins *(heating value allocation)*	$6.41 \cdot 10^{-9}$	$1.78 \cdot 10^{-8}$	$9.16 \cdot 10^{-9}$
Dioxins *(Cl allocation)*	$2.10 \cdot 10^{-10}$	$1.23 \cdot 10^{-8}$	$4.21 \cdot 10^{-9}$
NO_x	1.16	0.806	2.88
Dust	0.75	0.5	1.88
Fly ash	21.8	14.5	54.4
Slag	52.5	35.0	131
Resource consumption4)			
$CaCO_3$	3.53	67.8	46.3
NH_3	0.456	0.316	1.13
Energy production			
Thermal Energy	7.7	21.4	11.0
Electrical Energy	3.5	9.72	5.0

1) Modelled for specific waste composition
2) No difference made for CO_2 origins
3) Dioxins emissions given according to two different allocation methods
4) Used for flue gas cleaning

Table A.3: Impacts in a cradle-to-gate system presented for all cans.

	Environmental impacts				
	Resource use **ADP**	Acidification **AP**	Climate Change **GWP_{100a}**	Eutrophication **EP**	Photochemical oxidation **MOIR**
Can	kg Sb eq.	kg SO_2 eq.	kg CO_2 eq.	PO_4 eq.	kg O_3 eq.
PP_1	$7.37 \cdot 10^{-4}$	$1.76 \cdot 10^{-4}$	$5.79 \cdot 10^{-2}$	$4.91 \cdot 10^{-5}$	$9.98 \cdot 10^{-6}$
Paper Can	$4.40 \cdot 10^{-4}$	$1.85 \cdot 10^{-4}$	$4.15 \cdot 10^{-2}$	$6.38 \cdot 10^{-5}$	$8.95 \cdot 10^{-6}$
Hybrid Can	$3.13 \cdot 10^{-4}$	$1.07 \cdot 10^{-4}$	$2.83 \cdot 10^{-2}$	$5.91 \cdot 10^{-5}$	$6.24 \cdot 10^{-6}$
PP_{bio}	$2.53 \cdot 10^{-4}$	$3.59 \cdot 10^{-4}$	$4.12 \cdot 10^{-2}$	$1.35 \cdot 10^{-4}$	$2.23 \cdot 10^{-5}$

Table A.4: Table showing impacts from all cans for all waste management scenarios.

		Environmental Impact Categories				
		Resource use **ADP**	Acidification **AP**	Climate change **GWP_{100a}**	Eutrophication **EP**	Photochemical oxidation **MOIR**
Can	**EoL**	kg Sb eq.	kg SO_2 eq.	kg CO_2 eq.	kg PO_4 eq.	kg O_3 eq.
PP_1	EoL1	$2.88 \cdot 10^{-4}$	$1.09 \cdot 10^{-4}$	$3.51 \cdot 10^{-2}$	$3.63 \cdot 10^{-5}$	$6.14 \cdot 10^{-6}$
	EoL2	$4.01 \cdot 10^{-4}$	$1.39 \cdot 10^{-4}$	$5.11 \cdot 10^{-2}$	$3.94 \cdot 10^{-5}$	$7.47 \cdot 10^{-2}$
	EoL3	$5.13 \cdot 10^{-4}$	$1.68 \cdot 10^{-4}$	$6.70 \cdot 10^{-2}$	$4.24 \cdot 10^{-5}$	$8.80 \cdot 10^{-6}$
	EoL4	$6.26 \cdot 10^{-4}$	$1.98 \cdot 10^{-4}$	$8.29 \cdot 10^{-2}$	$4.54 \cdot 10^{-5}$	$1.01 \cdot 10^{-5}$
	EoL5	$7.38 \cdot 10^{-4}$	$2.27 \cdot 10^{-4}$	$9.89 \cdot 10^{-2}$	$4.85 \cdot 10^{-5}$	$1.15 \cdot 10^{-5}$
Paper can	EoL1	$3.15 \cdot 10^{-4}$	$1.66 \cdot 10^{-4}$	$4.67 \cdot 10^{-2}$	$5.98 \cdot 10^{-5}$	$8.26 \cdot 10^{-6}$
	EoL2	$3.47 \cdot 10^{-4}$	$1.74 \cdot 10^{-4}$	$5.08 \cdot 10^{-2}$	$6.07 \cdot 10^{-5}$	$8.63 \cdot 10^{-6}$
	EoL3	$3.78 \cdot 10^{-4}$	$1.82 \cdot 10^{-4}$	$5.50 \cdot 10^{-2}$	$6.17 \cdot 10^{-5}$	$9.00 \cdot 10^{-6}$
	EoL4	$4.10 \cdot 10^{-4}$	$1.90 \cdot 10^{-4}$	$5.92 \cdot 10^{-2}$	$6.26 \cdot 10^{-5}$	$9.37 \cdot 10^{-6}$
	EoL5	$4.41 \cdot 10^{-4}$	$1.98 \cdot 10^{-4}$	$6.33 \cdot 10^{-2}$	$6.36 \cdot 10^{-5}$	$9.74 \cdot 10^{-6}$
Hybrid can	EoL1	$2.30 \cdot 10^{-4}$	$5.45 \cdot 10^{-5}$	$1.88 \cdot 10^{-2}$	$2.24 \cdot 10^{-5}$	$4.95 \cdot 10^{-6}$
	EoL2	$2.51 \cdot 10^{-4}$	$7.28 \cdot 10^{-5}$	$2.71 \cdot 10^{-2}$	$3.16 \cdot 10^{-5}$	$5.50 \cdot 10^{-6}$
	EoL3	$2.73 \cdot 10^{-4}$	$9.10 \cdot 10^{-5}$	$3.54 \cdot 10^{-2}$	$4.09 \cdot 10^{-5}$	$6.04 \cdot 10^{-6}$
	EoL4	$2.94 \cdot 10^{-4}$	$1.09 \cdot 10^{-4}$	$4.37 \cdot 10^{-2}$	$5.01 \cdot 10^{-5}$	$6.58 \cdot 10^{-6}$
	EoL5	$3.16 \cdot 10^{-4}$	$1.28 \cdot 10^{-4}$	$5.20 \cdot 10^{-2}$	$5.94 \cdot 10^{-5}$	$7.13 \cdot 10^{-6}$
PP_{bio}	EoL1	$3.30 \cdot 10^{-5}$	$3.29 \cdot 10^{-4}$	$3.06 \cdot 10^{-2}$	$1.30 \cdot 10^{-4}$	$2.04 \cdot 10^{-5}$
	EoL2	$8.84 \cdot 10^{-5}$	$3.49 \cdot 10^{-4}$	$4.35 \cdot 10^{-2}$	$1.31 \cdot 10^{-4}$	$2.12 \cdot 10^{-5}$
	EoL3	$1.44 \cdot 10^{-4}$	$3.70 \cdot 10^{-4}$	$5.64 \cdot 10^{-2}$	$1.32 \cdot 10^{-4}$	$2.21 \cdot 10^{-5}$
	EoL4	$1.99 \cdot 10^{-4}$	$3.90 \cdot 10^{-4}$	$6.93 \cdot 10^{-2}$	$1.33 \cdot 10^{-4}$	$2.29 \cdot 10^{-5}$
	EoL5	$2.55 \cdot 10^{-4}$	$4.11 \cdot 10^{-4}$	$8.21 \cdot 10^{-2}$	$1.34 \cdot 10^{-4}$	$2.37 \cdot 10^{-5}$

A.4 Complete EoL-scenarios

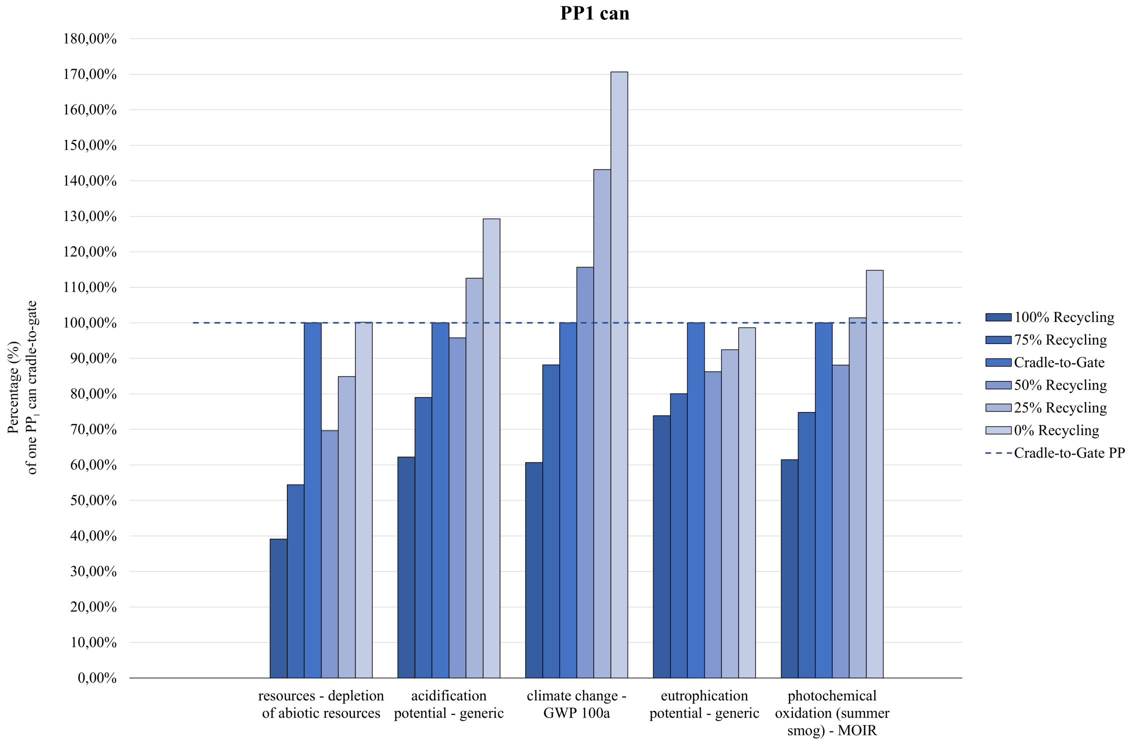

Figure A.5: Bar chart depicting the PP$_1$ can in cradle-to-gate and through all EoL-scenarios expressed in one PP$_1$ can in a cradle-to-gate.

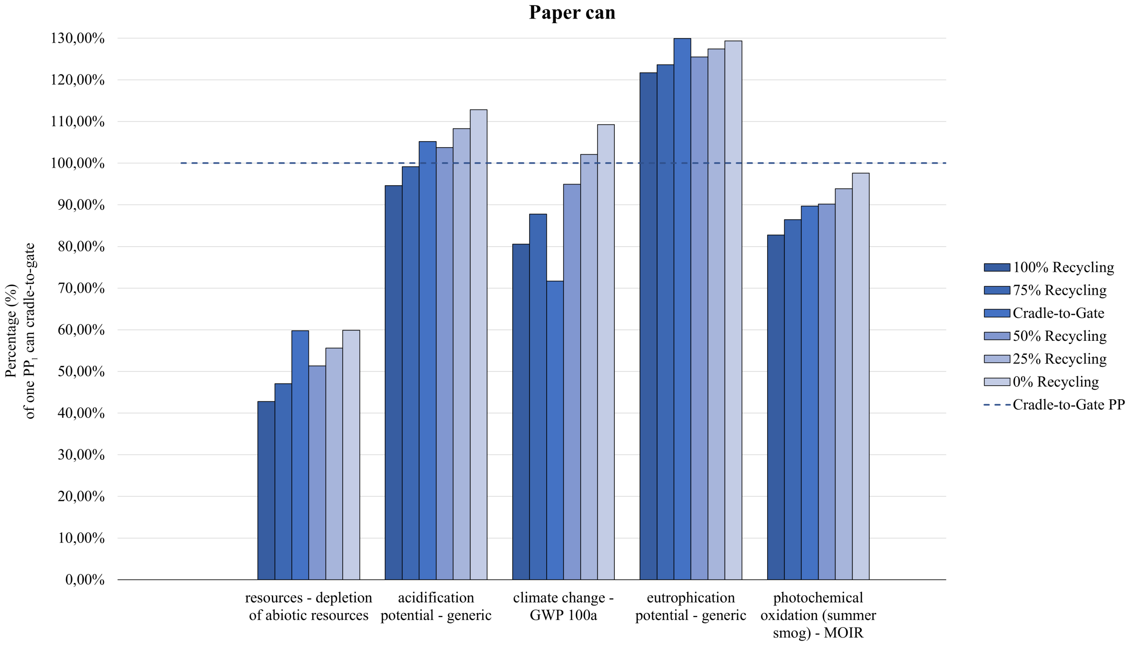

Figure A.6: Bar chart depicting the paper can in cradle-to-gate and through all EoL-scenarios expressed in one PP$_1$ can in a cradle-to-gate.

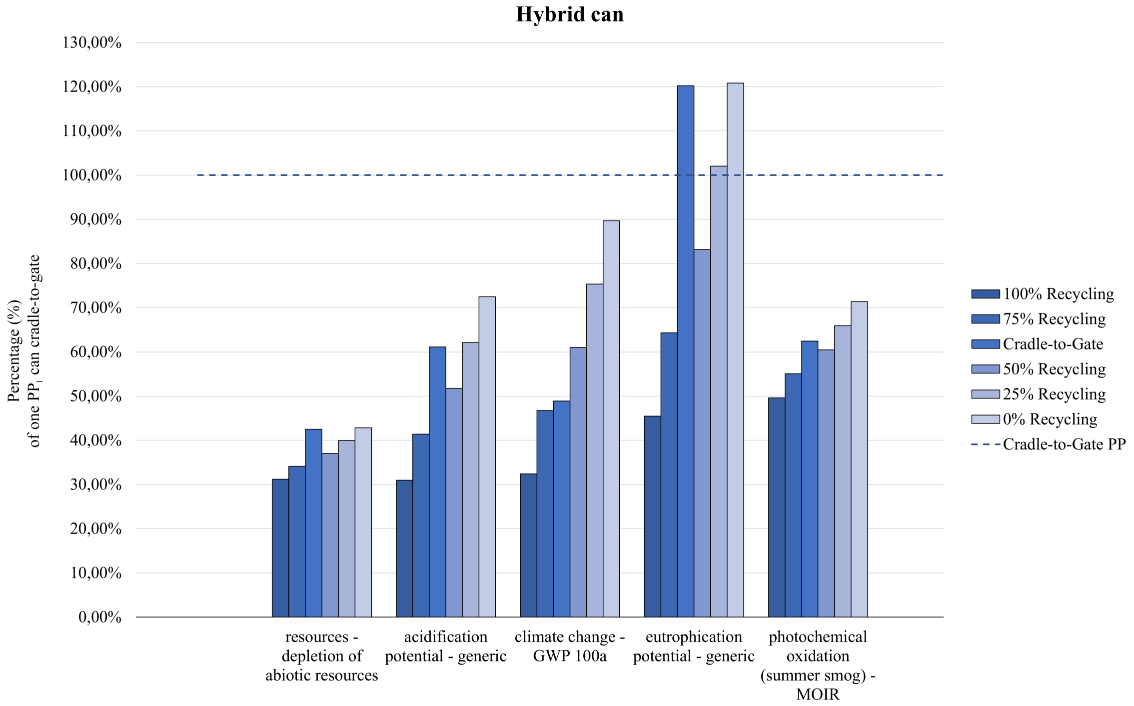

Figure A.7: Bar chart depicting the hybrid can in cradle-to-gate and through all EoL-scenarios expressed in one PP$_1$ can in a cradle-to-gate.

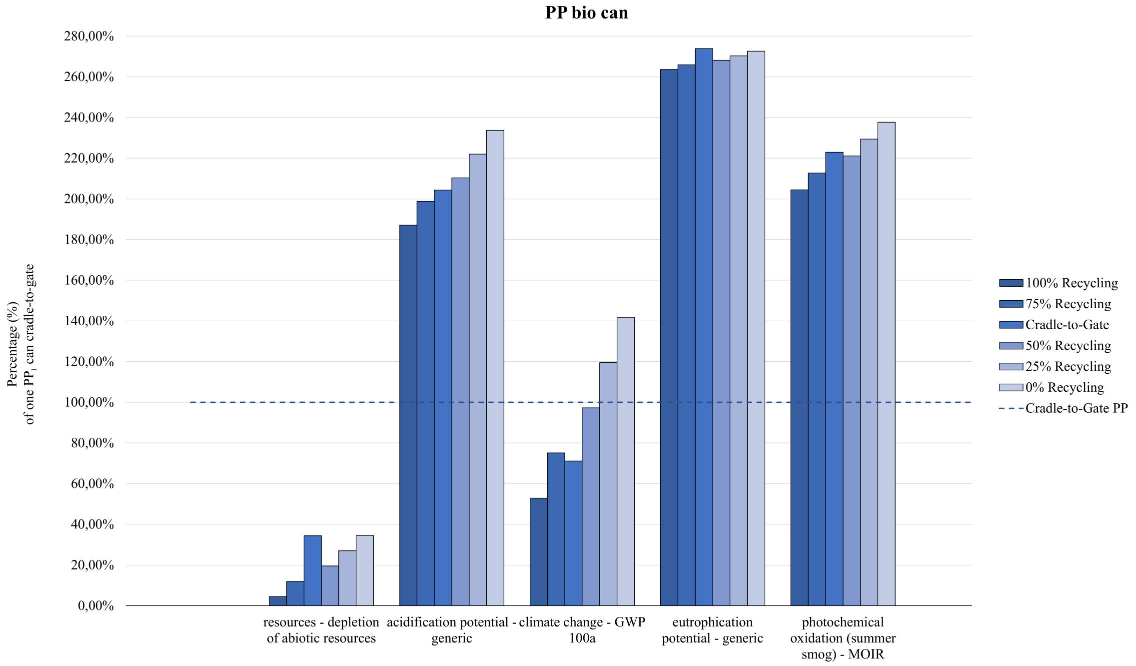

Figure A.8: Bar chart depicting the PP$_{bio}$ can in cradle-to-gate and through all EoL-scenarios expressed in one PP$_1$ can in a cradle-to-gate.

A.5 Loss rates at SM factory

Polypropylene can

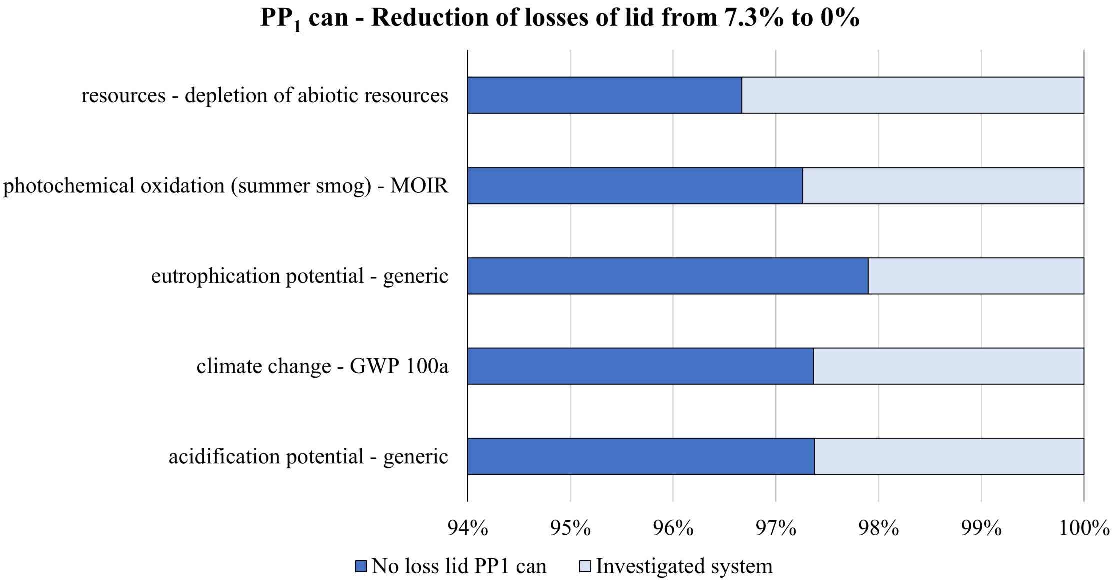

Figure A.9: Terminated lid loss for the PP_1 can at SM factory compared to studied system

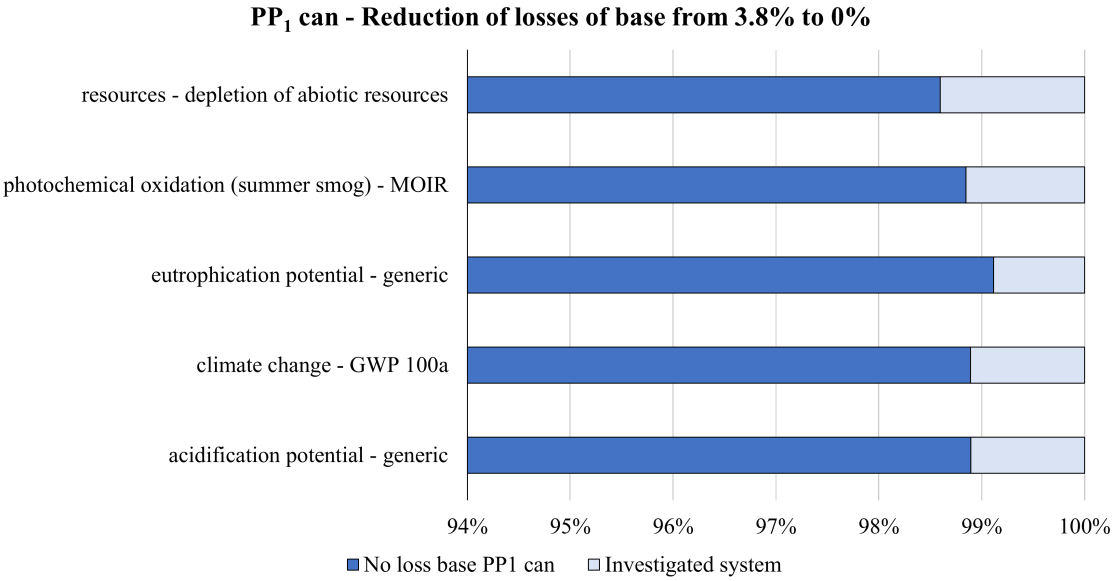

Figure A.10: Terminated base loss for the PP_1 can at SM factory compared to studied system

Paper can

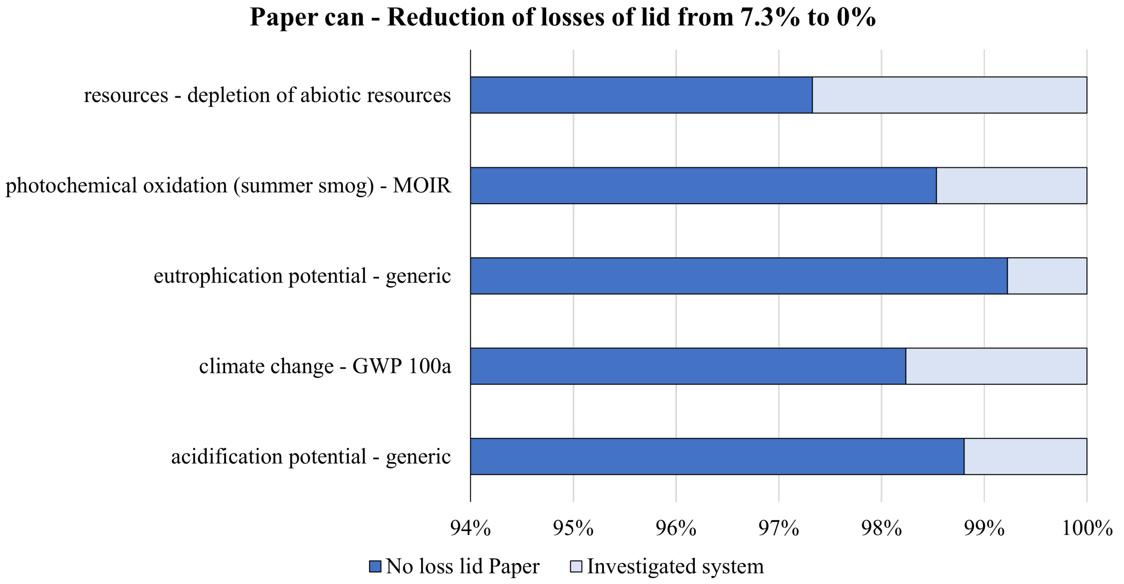

Figure A.11: Terminated lid loss for the paper can at SM factory compared to studied system

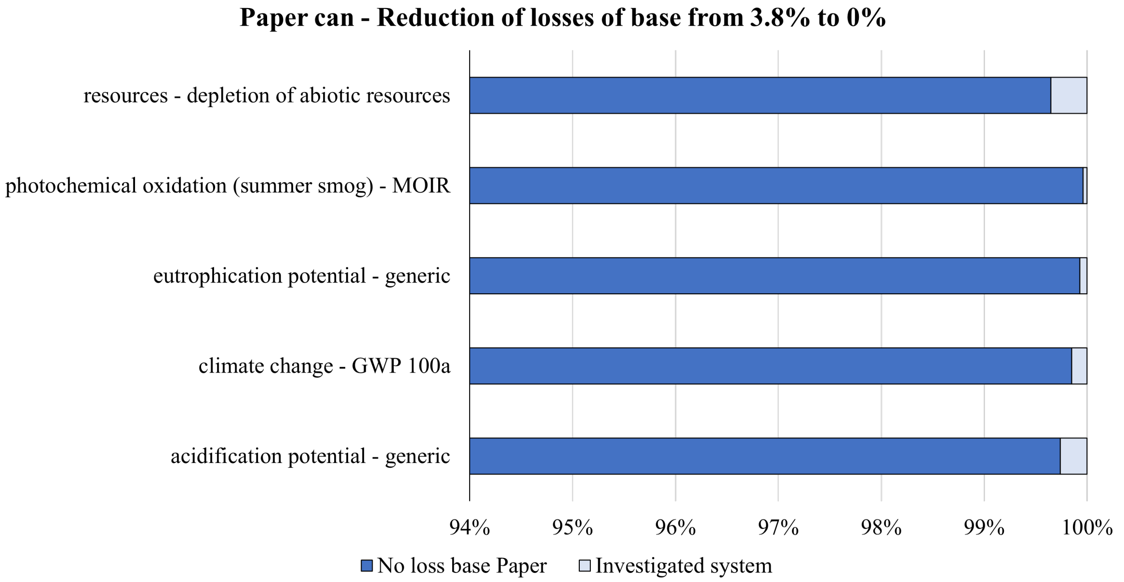

Figure A.12: Terminated base loss for the paper can at SM factory compared to studied system

Hybrid can

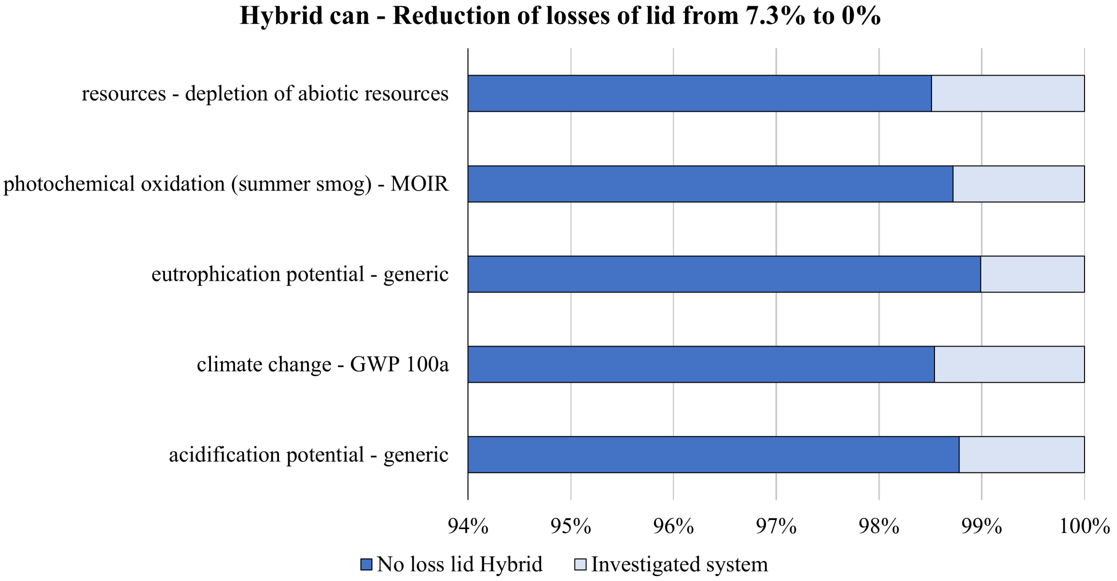

Figure A.13: Terminated lid loss for the hybrid can at SM factory compared to studied system

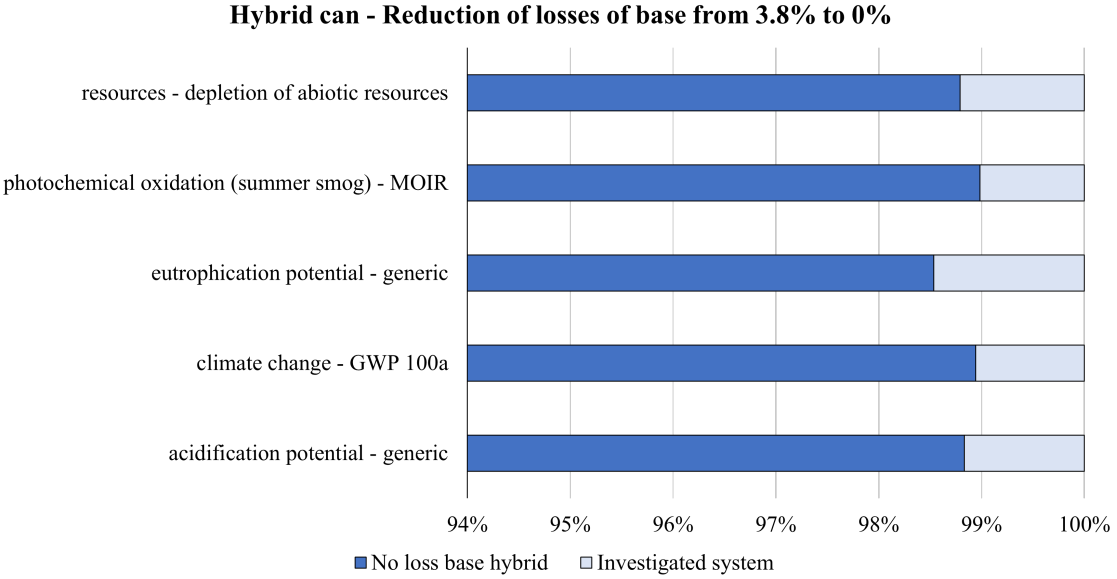

Figure A.14: Terminated base loss for the hybrid can at SM factory compared to studied system

Bio-Polypropylene can

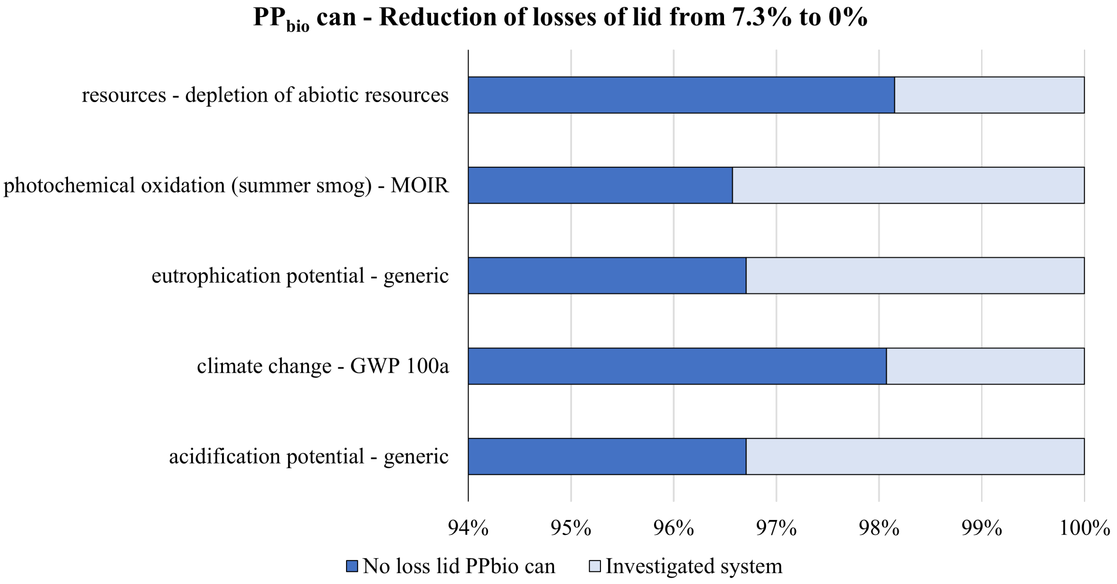

Figure A.15: Terminated lid loss for the PP$_{bio}$ can at SM factory compared to studied system

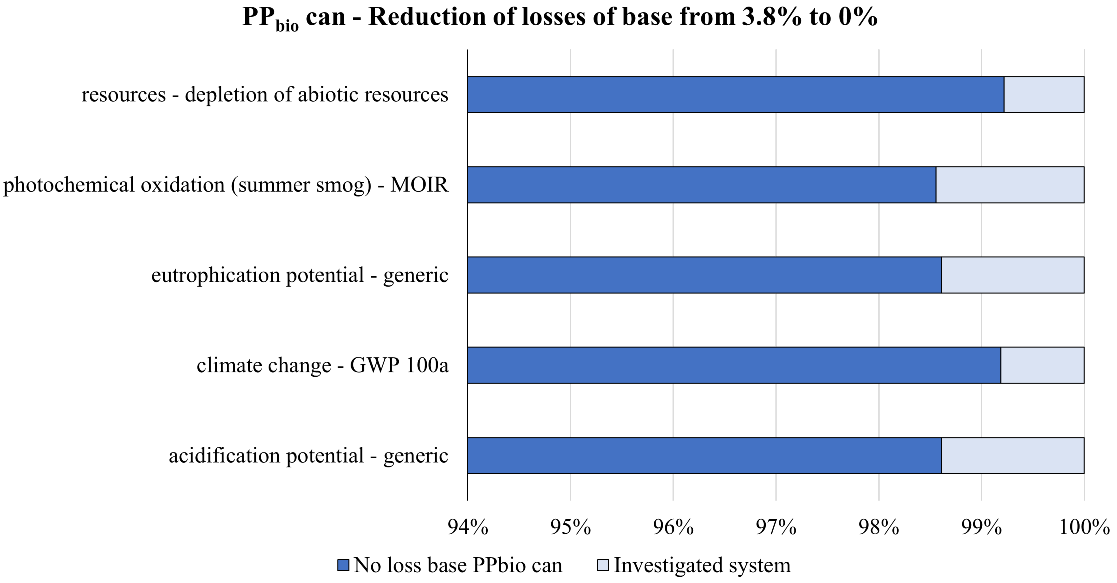

Figure A.16: Terminated base loss for the PP$_{bio}$ can at SM factory compared to studied system

B

Appendix B - Hidden

Appendix II is excluded in this version of the thesis, due to confidential content. It has been reviewed and approved by the Chalmers examiner.

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