THE CIRCULAR BIOECONOMY IN PRACTICE – ASSESSING THE END-OF-LIFE OPTIONS AND ITS ENVIRONMENTAL IMPACT FOR BIO-BASED POLYETHYLENE FURANOATE (PEF)

Final Thesis

Topic

A study to the potential end-of-life options of PEF plastics and assessing their environmental GHG-impacts – A research in cooperation with Avantium

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Abstract

PEF is an innovative bio-plastic with a number of superior characteristics compared to PET, which could lead to advantages in food packaging applications such as light weighting combined with an enhanced shelf life. Moreover, the contaminating influence from PEF on PET recycling is limited, which allows co-recycling in until at least up to 2% that could accelerate the market introduction of PEF. A promising production process has been developed by Avantium and is technically ready for implementation. However, the environmental advantages compared to existing fossil-based plastics are being discussed heavily when it comes to using biomass as a feedstock. Limited scientific research has been dedicated to the environmental performance of PEF and especially to its End-of-Life (EoL). This study investigates the environmental performance in terms of GWP-impact of different EoL-options that contribute to a circular bio-economy of PEF in higher detail compared to existing studies. The EoL-options for small bottles made from PET and PEF have been compared, as this is one of the specific applications where the technical characteristics of PEF enable improved performance. In the short-term (2020), mechanical recycling is the relevant EoL but for the long-term (2030-2035) both mechanical recycling and chemical recycling have been considered as prioritized EoL-options. While using the LCA methodology, the GWP-impact of the integrated EoL-options in representative Dutch waste treatments were assessed, starting at the collection of the bottles after consumer use. It was found that among the EoL-options mechanical recycling achieves the largest environmental benefits, although the results for chemical recycling might be improved if industrial scale data were available rather than only pilot plant scale data. When waste treatments of PET and PEF were mutually compared, no large differences were identified in the mechanical and chemical recycling processes themselves. Mechanical recycling of PEF is largely compatible with PET recycling and potential differences in chemical recycling could not be identified due to lack of available data and process details. In a second assessment, a cradle-to-grave LCA was done on a single small (250 ml) beverage bottle with a shelf life of 12 weeks, which takes into account the different bottle weights of PET and PEF needed to achieve this functionality. It was found that a PEF bottle delivers a GWP reduction per functional unit of 54-64% over the whole life cycle for short-term mechanical recycling, long-term mechanical recycling and long-term chemical recycling. The choice of the EoL appeared to be significant for the GWP-impact of a PEF bottle life cycle. Compared to incineration (with energy recovery), PEF mechanical recycling delivers in the short-term an advantage of 23% and in the long-term an advantage of 53%. Although no representative data is used for chemical recycling of PEF, the obtained benefit is still 24%.

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Acronyms and Abbreviations

APOS = at point of substitution
BHET = bis(2-hydroxyethyl) terephthalate
CBE = circular bio-economy
CO_2 = carbon dioxide
CR = chemical recycling
DMT = dimethylterephthalate
DKR = quality standards for sorted plastics from DerGrunePunkt
MEG = ethylene glycol
EoL = end-of-life
EFSA = European Food Safety Authority
ER = energy recovery
EPBP = European PET bottle platform
FENC = Far Eastern New Century (Taiwanese recycling company)
FDCA = furandicarboxylic acid
GHG = greenhouse gas
GWP = global warming potential
IEA = International Energy Agency
ILUC = indirect land use change
IPCC = Intergovernmental Panel on Climate Change
ISO = International Organization for Standardization
IV = intrinsic viscosity
KIDV = Kennis Instituut Duurzaam Verpakken
LCA = life cycle assessment
MR = mechanical recycling
MRF = material recovery facility
MSW = municipal solid waste
NREU = non-renewable energy use
O_2 = oxygen
OWS = Organic Waste System (Belgian company)
PE = polyethylene

PEF = polyethylene furanoate
PET = polyethylene terephthalate
PLA = polylactic acid
rPET = recycled PET
SSP = solid state polycondensation
TPA = terephthalic acid

1. Introduction

Recent scenario studies in climate modelling assign a key role to biomass to keep the global temperature increase at a maximum of two degrees compared to pre-industrial levels (J. Moreira, 2020 et al.; V. Daioglou et al., 2014; F. Creutzig et al., 2015; S. Rose et al., 2014; J. Rogelj et al., 2018; L. Clarke et al., 2014). For the global chemical sector, accounting for respectively 8% and 14% of the worldwide oil and gas use (IEA, 2018), biomass is one of the few options to replace their fossil feedstock with a renewable source (IEA, 2018; B. Dale, 2003). The size of the chemical sector has largely increased from 1970 during the rise of industrialization. Since then the production of plastics, which is one of the main outputs of the chemical industry, has multiplied by a factor of ten. That is a higher growth rate than any other group of bulk materials (IEA, 2018). In 2018, the global plastic production was amounting to 359 million metric tons production (Plastics Europe, 2019; European Bioplastics, 2019). The packaging industry accounted for 36% of the market worldwide and is thereby the most prominent end-use sector for plastics, leaving second and third largest sector respectively construction (16%) and textiles (15%), far behind (*Figure 1*) (OECD, 2018; R. Geyer et al., 2017). A continued growth of global plastic use is projected resulting in a forecasted production quantity of more than 1100 million metric tons in 2050 (Mc Kinsey, 2018; Ellen Mac Arthur Foundation, 2016). This makes the switch to biomass as feedstock for plastics such as cellulose, sugar, wood and starch, having a significant potential contribution to global climate targets. Despite the relatively strong growth of bio-plastics (European Bioplastics, 2019), bio-based plastics represents less than 1% of the current total volume of plastics commercially offered annually (European Commission , 2019).

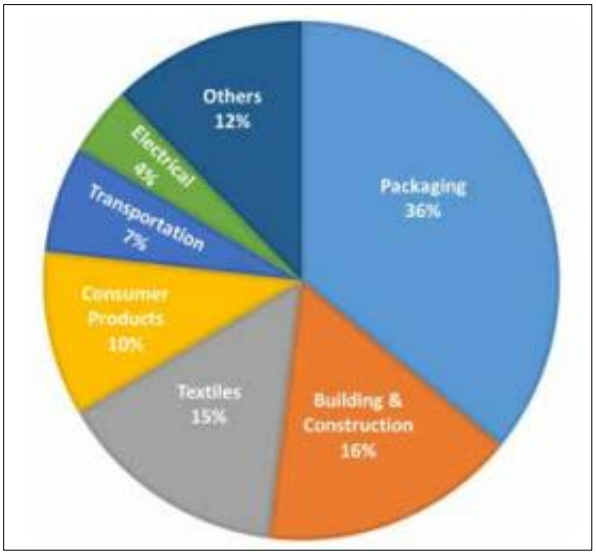

Figure 1. Global plastic use (non-fiber) by sector and polymer from 2015 (R. Geyer et al., 2017).

However, various publications about the bio-based economy highlight potential trade-offs and negative impacts, indicating that the environmental performance is not always inherently sustainable. The discussed potential negative impacts of the use of biomass range from pressures on the ecosystem, the competition with the food market and the actual greenhouse gas (GHG) emission reduction potential (CE Delft, 2010; K. McCormick & N, Kautto, 2013; S. Pfau et al., 2014; T. Searchinger & R. Heimlich, 2015). Yet, most scientists conclude that it is not a matter of whether or not modern biomass applications should become part of the energy and material mix, but how it can be produced and used sustainably (F. van Hilst et al., 2015). This is leading to an increased use of certification schemes to guide sustainable procedures (J. van Dam et al., 2008). The application of biomass used to substitute fossil resources for the production of plastics, is a widely accepted strategy towards sustainable development (R. Jain & A. Tiwari, 2015; V. Piemonte & F. Gironi, 2011; E. Arikan & H. Ozsoy, 2015), although still trade-offs on some climate categories exist between biopolymers and traditional polymers (T. Hottle et al., 2013; V. Piemonte & F. Gironi, 2011). A study of the environmental impacts over the life cycle of bio-based disposable plastic packaging applications confirmed that not all climate impacts automatically reduce due to their bio-based roots compared with their fossil-based counterpart (European Commission, 2018).

To achieve a more resource-efficient biomass use, and thus increasing its sustainable potential, the concept of a circular bio-economy (CBE) increasingly found its way into European bio-economy strategies. The arising CBE builds on the synergies of the circular economy and bio-economy concepts (European Forest Institute, 2017) and is shown in *Figure 2*. The CBE could strongly contribute to a sustainable chemistry as it stimulates renewable carbon that is seen as key (nova-Institute GmbH, 2018); it enables the carbon to circulate in biomass as well as within the applications. An important element of the CBE is the recycling of biomass, which refers to the process of converting bio-based waste products into a new product that is used at least once more either for material or energy purposes (R. Essel et al., 2014). A comparative assessment of the most used plastic products in Europe between the bio-based and the fossil based version, concluded that the choice of an end-of-life (EoL) option (e.g. recycling) could have a significant contribution to the overall climate impacts of the bio-based products. The study pointed out that the influence is especially significant on the GHG-emissions (European Commission, 2018). In some bio-based sectors, recycling has already been established for many years before the term circular economy became mainstream policy as the textile and paper industries. However, recycle chains are often difficult to establish, especially for bio-based products that still have a comparably small market size (M. Carus & L. Dammer, 2018).

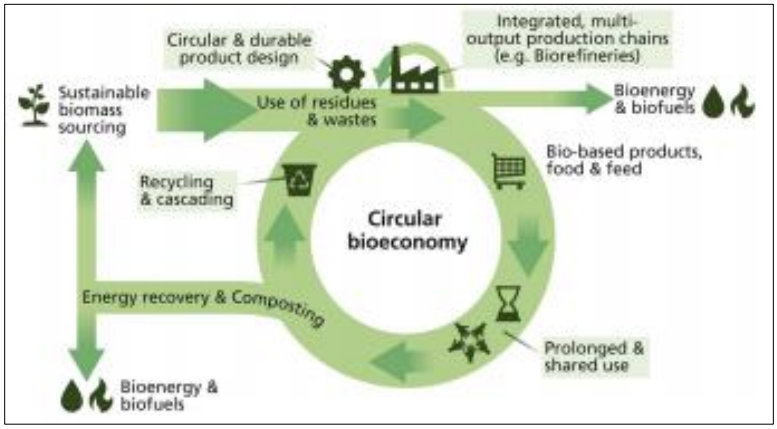

Figure 2. A visualization of the circular bio-economy (P. Stegmann et al., 2020).

This relates to another important drawback of the introduction of bio-based plastics that differ in chemical structure from fossil based ones (others than drop-in bio-based plastics such as bio-PE and bio-PET). This could disturb the existing recycling of plastics, which is undesirable given the current focus on a transition towards a circular economy (D. Briassoulis et al., 2019). With regards to circularity, plastics are already lagging behind compared to other packaging materials, mainly due to the heterogeneity in plastic compositions and the complexity of the recycling chain (KIDV, 2017). Whereas the circular economy has largely developed for most packaging materials (paper, board, glass and metal), the collection and recycling system for post-consumer plastic packaging waste is still relatively low developed (European Comission, 2015; J. Fellner et al., 2017; Afvalfonds, 2018). Although the size of the bio-plastic market is currently limited, a relatively small share in waste streams is currently viewed as contaminating in conventional waste streams (L. Alaerts et al., 2018; Valpak Consulting , 2010). For example, the remaining presence of small amounts of the bio-based plastic PLA (polylactic acid) is detrimental to the quality of recycled PET (polyethylene terephthalate) (L. Alaerts et al., 2018) while sorting out is at the expense of costs, time and efficiency (Valpak Consulting , 2010). Just like the expected increase of plastic production, the production of bio-plastics is also expected to increase both absolutely and relatively compared to general plastic production (European Bioplastics, 2019). This requires research to smooth the integration of bio-plastics into the evolving waste infrastructure to successfully secure the concept of a circular economy. Determining which end-of-life (EoL) option and which recycling chain is preferable from an environmental, economic and technical perspective is thus not always straightforward and often case specific.

The bio-plastic named PEF (polyethylene furanoate) is currently under development at Avantium (Avantium, 2020a). PEF is a polyester resin showing strong chemical and physical resemblance to PET but comprising furandicarboxylic acid (FDCA) instead of terephthalic acid (PTA) in the polyester backbone. Based on its technical characteristics that enable thinner packaging and increased shelf life, PEF could reach food packaging solutions that PET alone cannot reach (CE Delft, 2017; S. Burgess et al., 2015). As PET accounts currently for approximately 7.7% of the European plastic packaging market, mainly in bottle applications (Plastics Europe, 2019), the GHG-mitigation potential of the replacement by PEF is promising. In addition, preliminary studies to the co-recycling of PEF together with PET pointed out that PEF in low shares (up to 2%), does not hinder the quality of the recycled PET stream (EPBP, 2017), which is promising for a successful introduction of the material.

However, little information of the environmental performance of specifically PEF has been published in the scientific community. Until recently, only one paper was published regarding the environmental impact of PEF (T. Gomes et al., 2019). A. Eerhart et al. (2012) performed an analysis on PEF polymer resins and compared that with PET while using a life cycle assessment (LCA). The LCA showed promising savings of 40 to 50% on the consumption of non-renewable energy use (NREU) and GHG-emissions in a cradle-to-grave analysis. The only EoL-option taken into account was incineration without energy recovery. The authors argued that including energy recovery or mechanical recycling would make a little difference in the comparable assessment between PET and PEF as the caloric values differ only 10-20%. At that time, the polymer morphology of PEF was also not well understood. However, the inclusion of more circular EoL-options is expected to have a contribution to the environmental performance on GHG-emissions for PEF. Studies to the recycling of PET pointed to significant environmental benefits for recycling compared to incineration (A. Detzel et al., 2004; U. Arena et al., 2003). From the perspective of the CBE, incineration without energy recovery is also not desired. More recently, the European Commission proposed their draft results on the environmental impacts of the most commonly used plastic applications, in which the bottle of 0.5L was taken into account. The plastic bottle composed of PEF was also included in their methodology, where the EoL was based on the current average European EoL-methods, consisting of recycling (60%), incineration (21%) and landfilling (19%) (European Commission (Draft), 2020). Most importantly from the perspective of the goal of this paper, the study leaves room for improvement in the EoL as it was assumed the same for PEF and PET and no attention was paid to alternative EoL-options.

As an addition on the existing literature, this study focusses on the assessment of GHG-emissions of PEF during the EoL while taking into account different EoL-options that fit into the CBE. Another novelty of the study is that the focus for the GHG-performance is specifically assessed for the Netherlands. The EoL from PEF applied in a small bottle application will be addressed. The gas permeability of PEF on O_2 and CO_2 is respectively twelve and eighteen times lower, resulting in a more efficient relationship between material requirements and barrier properties compared to PET bottles (S. Burgess et al., 2015). The applicability of PEF is especially attractive in small bottle applications as in decreasing bottle sizes the relative material requirements per bottle become higher compared to the volume of the bottle. The emphasized characteristics of PEF in small beverage bottle applications make the small clear bottle containing 250 ml of beverage one of the prioritized initial applications to launch PEF for Avantium. The GHG-impact assessment is done on both the short and long-term. The long-term accounts for several developments in the evolving market of plastic recycling reflected by the ambitious targets set by Europe (European Commission, 2016). The Netherlands is used as a case study because the headquarters of Avantium are located here and it is one of the better performing countries in Europe on recycling (European Parliament,

2018). The GHG-emission impact is expressed in global warming potential (GWP). Therefore the research question of the subsequent study is:

- **What are the preferred EoL-options for small PEF bottles in the Netherlands in terms of practical feasibility and GWP-impact reduction while following the principles of the circular (bio)economy in the Netherlands?**

Both the EoL-options on the short-term and the innovative options on the long-term are assessed on their GWP-impact. The short-term includes the currently used EoL-options for small PET bottles as of 2020. The long-term scenario is set on the moment where PEF could be penetrated on such a significant scale that it is beneficial to recycle it separately from PET which could impact the collection, sorting and recycling performances. This year is calculated to lay between 2030 and 2035. Long-term potential EoL-options of PEF are identified at first. These EoL-options are then exposed to a quick screening to review the practical feasibility in terms of regulations, possible integration in the Dutch waste system and commitment to the principles of the circular economy. This results in the first two sub questions:

  - What are the potential EoL-options for small PEF and PET bottles in the short- and long-term?
  - What is the practical feasibility of these EoL-options in terms of regulations, possible integration in the Netherlands, and commitment to the principles of the circular economy?

Next, the GWP-impact of the relevant EoL-options is assessed. For this assessment the full EoL-chain (ranging from collection until EoL-treatment) in the Netherlands is taken into account which are called subsequently waste treatments. As the Netherlands uses several collection systems with different chain efficiencies, the results give insight in the environmental impact of the different collection systems as well. The sub-processes involved along the waste treatments are identified and quantified in environmental inputs and outputs to obtain eventually the calculated GWP-emission impact. Both the impacts of the waste treatment for small PET and PEF bottles are assessed and compared. Based on this it could be decided which EoL-option is preferred from an environmental perspective. To put the impact of the EoL into perspective, a second assessment is done on the full life cycle of a single PET and PEF bottle. Different waste treatments are combined into representative EoL-scenarios for small bottles in the Netherlands. The production impact per bottle is plotted against the EoL-scenario to explore the significance of the EoL.

  - Which processes are involved in the different waste treatments of small PET and PEF bottles and what is the GWP-impact per process and eventually per waste treatment?
  - What is the influence of EoL on the GWP-impact for PET and PEF bottles over their full life cycle and how do the different EoL-choices compare to each other?

2. Introduction case study

Avantium is a chemical tech company headquartered in Amsterdam that develops innovative chemistry technologies across industry value chains in order to produce chemicals and materials based on renewable feedstock instead of fossil resources. The business unit, called Avantium Renewable Polymers, aims to commercialize the YXY plants-to-plastics technology. This technology converts plant-based sugars with help of catalysts into FDCA, which can be used to make materials such as the new plant-based plastic PEF. PEF is a 100% plant-based and 100% recyclable plastic with superior performance properties compared to todays widely used petroleum-based packaging materials (Avantium, 2020b). In *Table 1*, the technical characteristics of PEF are compared to the characteristics of PET. Especially, the superior gas barrier properties for O_2 and CO_2 of PEF make the material suitable for food-packaging applications as beverage bottles and food protection foils/films. Although PEF is produced from biomass, the plastic is not considered as biodegradable. According to European Standard EN 13432, materials are considered as biodegradable if 90% will be degraded under standardized circumstances within six months, or if 90% is degraded compared to cellulose exposed to the similar circumstances. In the latter case, the cellulose must be degraded at least for 70% in a maximum of six months to validate the test. (European Comission, 2002). From experimental results by the a specialized Belgian company Organic Waste System (OWS), which is an independent research laboratory, presented in *Figure 3*, it stands out that PEF does not satisfy the requirements to be labelled as biodegradable. However, it appears that PEF degrades much faster than PET under both weathered and unweathered conditions which, inhibits the lifetime of PEF. Although this might be disadvantageous after multiple recycle loops, this counteracts the accumulation of micro plastics in marine environments, which is at the moment a world-wide issue (S. Rezenia et al., 2018).

*Table 1. A comparison between important technical characteristics of PEF and PET (H. Nakajima et al. 2017). *Obtained from S. Burgess et al., 2015*

	PEF	PET
Density (g/cm^3)	1.43	1.36
O_2 permeability	0.0107	0.114
CO_2 permeability	0.026	0.46
T_g (◦C)	88	76
T_m (◦C)	210-230	250-170
E-modulus (GPa)	3.1-3.3	2.1-2.2
Yield stress (MPa)	90-100	50-60
Quiescent crystallization time (min)	20 - 30	2.0-3.0
H_20 permeability*	180	370

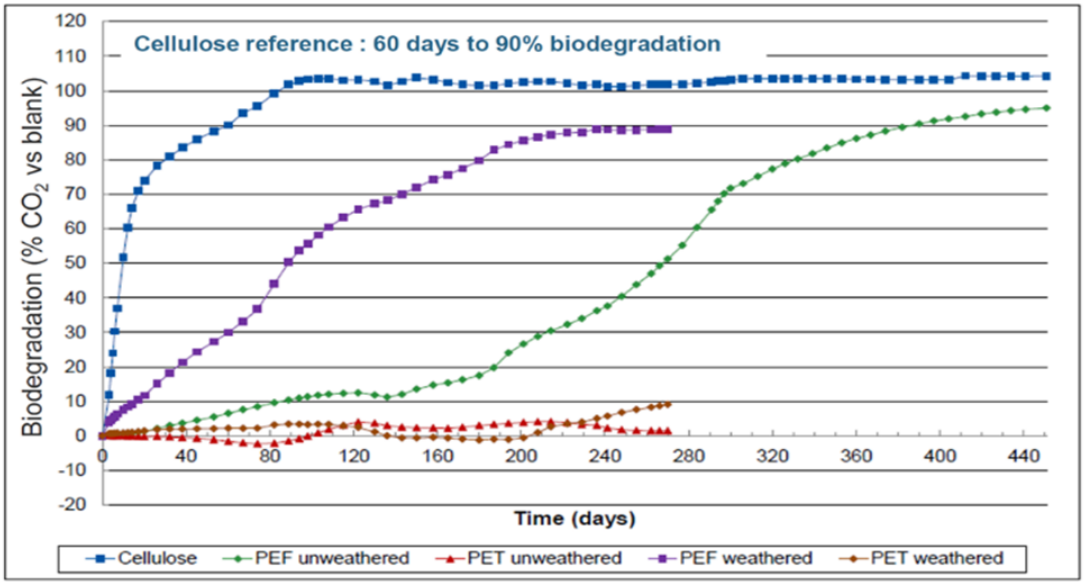

Figure 3. The biodegradability characteristics from PET and PET in both weathered and unweathered circumstances compared to cellulose over time (OWS, 2015)

From a technical perspective, the YXY technology producing PEF is proven in the pilot plant that is already running. However, from an economic point of view the technology needs to be proven yet. For a next step in the commercialization of PEF plastic, a plant using the YXY technology on a commercial scale with an output capacity of 5 kilotons per year is planned for construction in 2023 (Avantium, 2020b). If successful, from 2023 onwards Avantium will commercialize the PEF production at an industrial scale. European PET Bottle Platform (EPBP), which is an industrial association, already gave an interim approval for market penetration of PEF until 2% in PET recycling. The role of EPBP is to facilitate the integration of new PET bottle innovations in existing recycling processes in Europe. The approval is given with the understanding that the integration of PEF until 2% into the European PET recycling infrastructure does not hinder the quality of the recycling stream and thus sustains circularity (EPBP, 2017). It has even been technically proven that percentages of 5-10% are possible without reduced quality specifications (Synvina, 2017). From an environmental perspective, there exist many challenges for PEF as these are inherently related to bio-based products. For Avantium's (potential) partners and brand-owners in the commercial value chain the actual environmental performance of PEF compared to fossil-based plastics is critical. On top of that, in order to be considered for European subsidies that would enable further technical development, the effectiveness of GHG-emission reduction must be proven (European Union, 2020). In conclusion, a successful commercial introduction of PEF is largely dependent on its environmental performance in which the GHG-climate indicator is an important parameter.

In 2017, nova-institute GmbH, a German based research institution, did an assessment on the environmental impacts of PEF that was commissioned by Avantium. They did a general assessment of the environmental impacts over the full life cycle of PEF in the targeted applications being the small bottle and multilayer film. The initial study showed promising results of significant GHG-reductions over the whole life cycle compared to alternative packaging materials (nova-Institute GmbH, 2017). Although these results are useful, the included EoL-phase leaves room for improvement as only two EoL-options were covered being mechanical recycling and incineration. To complement on the existing literature and Avantium's knowledge, this study will focus on different EoL-options in different time frames and aims to determine the corresponding GWP-mitigation potential. This study should provide more insight in the comparison of environmental performance related to the different EoL-options.

3. Methodology

The methodology is split into four parts. *Section 3.1* focusses on the identification of feasible EoL-options for PEF that stimulate a circular economy. This part includes the first two sub questions and is mainly qualitative. *Section 3.2* provides the goal/scope definition and the inventory analyses on both assessments covered in the last two sub questions. The first assessment thus evaluates the GWP-impact of the waste treatments including different EoL-options. The second assessment assesses a combination of different waste treatments, representing EoL-scenarios for small PET and PEF bottles in the Netherlands and adds the associated GWP-impact to the production impact of one bottle and is thereby covering the life cycle impact. The subsequent study is thus based on a bottom-up approach in which first the EoL-options are explored and then combined into waste treatments into representative EoL-scenarios. These scenarios are plotted against the production (*Figure 4*). In the inventory analysis the processes involved in the waste treatment and EoL-scenarios for PET are identified and quantified in order to perform the environmental impact assessment. *Section 3.3* summarizes the identified waste treatments and EoL-scenarios for PET embedded in the Dutch waste system to give an overview of the inventory analyses. *Section 3.4* describes the differences for PEF. Based on the inventory analyses of PET and the quantitative differences, the results of the PEF waste treatments and life cycles are modelled and calculated.

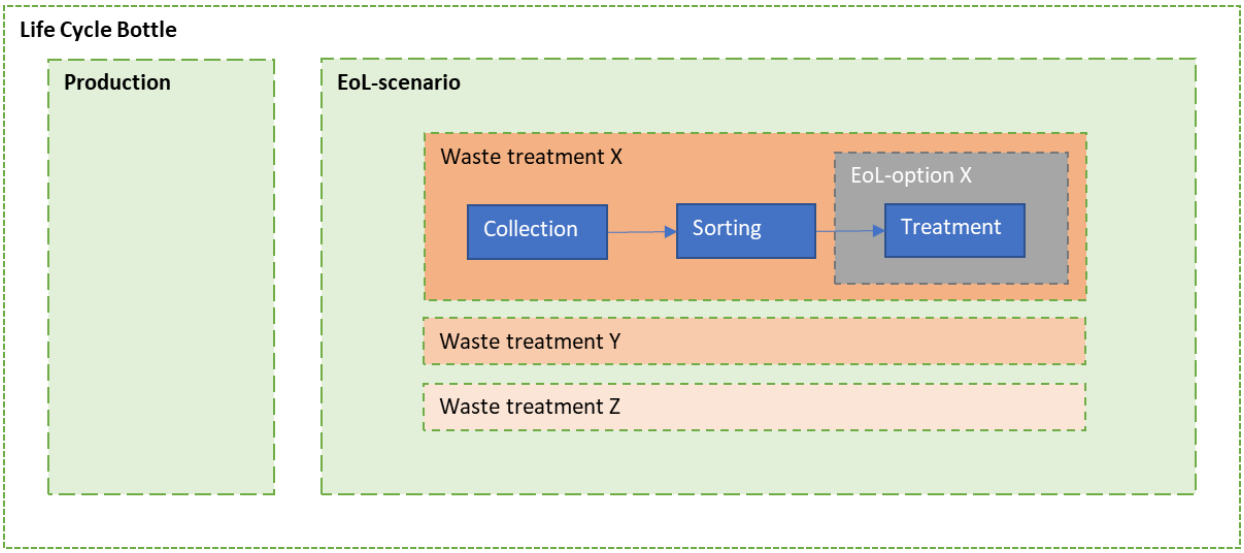

Figure 4. Schematic overview of the different assessments in this study. It also serves as a clarification on the terminology used.

3.1. Identifying potential EoL-options

Potential EoL-options for bio-based products are found in literature (D. Briassoulis et al., 2019; European Bioplastics, 2017). Prioritized according to the European waste hierarchy (European Union, 2008), the EoL-options are 1) reuse, 2) mechanical recycling, 3) chemical recycling, 4) industrial composting and anaerobic digestion (also known as organic recycling), 5) incineration with energy recovery, 6) incineration without energy recovery, and 7) landfilling. Theoretically littering is also a possible destination for plastic and therefore added here, although it is by definition not a desired EoL-option.

3.1.1. Short-term EoL-options

The short-term EoL-options in the Netherlands consist of mechanical recycling complemented by incineration for energy recovery (CBS, 2018). During incineration with energy recovery waste is converted

into electricity, heat and/or steam. For plastics, landfilling and incineration without energy recovery is not taking place at the moment. Landfilling of combustible and biologically decomposable waste materials is prohibited in the Netherlands since 1995 due to lack of space and growing public environmental awareness (E. Dijkgraaf & R. Gradus, 2014). Already from at least 2014 no incineration without energy recovery is taking place because of the efficient incineration facilities in the Netherlands; due to the high efficiencies of these facilities and the competitive gate fees, all the waste destined for incineration was used for energy recovery (R. Gradus et al., 2017). Although, no publically available data is found on small bottle littering in the environment, littering is assumed to be insignificant as well. From an estimation of (KIDV, 2017) in 2017 8.3 metric tons packaging plastics, a fraction of approximately 1.5% of the total marketed packaging plastics, end up as litter from which also an unknown fraction will be recaptured by public cleaning services carried out by municipalities and regional water authorities (CE Delft, 2019a). However it remains unclear what fraction is taken by the small plastic bottles as divergent numbers are used in literature. A study from CE Delft assumes that small plastic bottles and cans are responsible for approximately 40% of the littering volume based on littering rates in other European countries (CE Delft, 2017), whereas findings of Zwerfafvalmonitor state that only 2.7% consists of small bottles (and 6.2% of the cans) in the Dutch littering waste (Rijkswaterstaat, 2016). The latter value is equivalent to 1.5% of the amount of sold cans and small bottles, indicating that the remaining 98.5% is properly disposed (R. Gradus et al., 2017). Tiny fractions of plastic bottles that end up in nature could already influence significantly some climate impact categories as soil toxicity for example. However, in this study the GWP-impact is only considered. Regardless of the exact amount of small bottles ending up in the environment, the GWP-impact of littering is assumed to be insignificant as the emissions are spread out over many years. Although this could lead to differences between PEF and PET due to the faster biodegradability of PEF, this difference is expected to be small. Therefore littering as an EoL-option is not considered in this study and implies the assumption that all small plastic bottles are collected in the Netherlands. Besides the low GWP-impact of littering, a suitable methodology is also not yet available to quantify the environmental impacts (KIDV, 2017).

3.1.2. Long-term EoL-options

For the long-term a selection of the EoL-options was made and considered for further investigation. At first reusing is not taken into account in this study. From 2006 the reusable PET bottle has been abolished by the Dutch government, due to complaints of the involved companies in relation to the high costs of the required collection infrastructure (mainly the soft drink industry) (M. Verweij, 2014; N. van der Naald, 2006). Besides the abolishment, the current value proposition of PEF in reusable bottles is not discriminating compared to PET. Reusable bottles require strength and solidity and therefore thick material that already provides adequate gas barrier characteristics in the case of PET. However, due to renewed interest in the reusable bottle according to Avantium, this market should be kept in mind for the future, once the price of PEF is comparable with the price of PET. Neither the organic recycling options are considered as a relevant EoL-option. Since PEF is not biodegradable (OWS, 2015), this disables the option for industrial composting and anaerobic digestion (L. Alaerts et al., 2018). As argued before, landfilling, incineration without energy recovery and littering of small bottles are barely taking place in the Netherlands at the moment. Therewithal these EoL-options are not desirable in a CBE point of view. It is also expected that the introduction of a deposit system on clear PET bottles ≤ 0.5 would decrease the littering of plastic bottles even more (CE Delft, 2017). As incineration with energy recovery is low in the waste hierarchy, and therefore not foreseen as a goal in the European view of the circular economy (European Comission, 2020), it will not be investigated as a prioritized EoL-option. Incineration with

energy recovery is considered as an essential addition in a circular economy, however it should not be a purpose on itself (European Comission, 2020). This is the reason why the Dutch government is handling taxes for incineration to dissimulate this (Rijksoverheid, 2020). However, just as in the short-term waste management, it will be considered as a relevant EoL-option for complementary purposes. The two remaining EoL-options, mechanical recycling and chemical recycling will be used as the prioritized EoL-options for PEF in the long-term. Especially in the future the need for circular uses of plastics will be desired, which stimulates the production of high-quality secondary material improving the relevance of chemical recycling. In the Netherlands, the Transition Agenda for Plastics is set up that includes the ambition by 2030 to achieve 10% chemical recycling of plastics (KIDV & CE Delft, 2018). Also the producers' demand for recycled plastic with a quality similar to that of virgin plastics is growing (KIDV & CE Delft, 2018). In *Table 2*, the argumentation on the potential EoL-options is summarized.

Table 2. The set-up of the short-term scenario and the long-term scenarios.

Short-term EoL-options	Long-term EoL-options	Objection	Feasible long-term EoL-options
Mechanical recycling and incineration with energy recovery	Reuse	No prioritized market & abolished in NL	**Mechanical recycling** complemented by incineration with energy recovery
	Mechanical recycling	→	
	Composting	PEF is not biodegradable	
	Anaerobic digestion	PEF is not biodegradable	
	Chemical recycling	→	**Chemical recycling** complemented by incineration with energy recovery
	Incineration with ER	Doesn't fit into circularity goals	
	Incineration without ER	Doesn't fit into circularity goals	
	Landfilling	Doesn't fit into circularity goals	
	Littering	Doesn't fit into circularity goals	

3.2. Life Cycle Assessment

To assess the environmental impact, a life cycle assessment methodology (LCA) is used. An LCA is often used including versatile processed biomass products. Assessments bio-based energy systems (D. Tonini & T. Astrup, 2012), biochemical processes (P. Supawanicha et al., 2015) and specific bio-based products (European Commission, 2018) have been published. Due to the increasing use of the LCA in the starting from the late 90's, and the versatility of the methodology, the International Organisation for Standardisation (ISO) provided the first generation of guidelines in 1997 to ensure consistency between studies (ISO, 1997). According to the most recent standards in the ISO 14040 and 14044, an LCA is carried out in four distinct phases shown in *Figure 5*; goal and scope definition, inventory analyses, impact assessment and interpretation (I. Manickam & V. Muralikrishna, 2017).

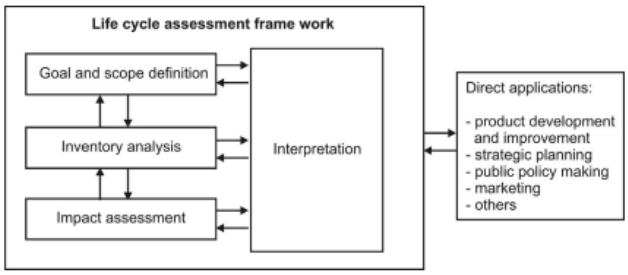

Figure 5. Stages of an LCA (I. Manickam & V. Muralikrishna, 2017)

In this part of the methodology, the goal and the scope definition of the LCA will be defined and the inventory analyses will be done. For setting up the inventory analyses, data for conventional PET recycling is found in existing databases of Ecoinvent and literature. The remaining gaps are complemented by interviews with experts. The data for PEF recycling is acquired qualitatively where possible and complemented quantitatively by Avantium. SimaPro software is used to model eventually the impact assessment. In the interpretation phase a sensitivity analyses on the most important uncertainties will be done to be able to draw conclusions.

3.2.1. Goal and scope definition

3.2.1.1. Goal and background

The goal of this case study is to assess and to compare the environmental impact in terms of GWP-emissions for different EoL-options of small clear beverage PET and PEF bottles. In the first assessment, the environmental performance of the EoL-options integrated into waste treatments suiting in the Dutch waste infrastructure is determined to support decision-making. Different collection systems are running in parallel in the Netherlands with own recycle rates. The recycle rate is defined here as the amount of collected bottles that are eventually processed into new applications on a weight basis. Besides the different impact in the EoL-options, the results generate insight into the differences per collection system as well as a consequence of the difference in losses and required steps. The environmental impact is assessed on both the short and the long-term to anticipate developments occurring in the evolving plastic waste management. By comparing the GWP-impacts of the different waste treatments for PEF, the preferred EoL-option could be found from an environmental perspective. Moreover, it could be pointed out from these results where and how large the differences are when waste treatments of PEF and PET are compared. In the second assessment, the GWP-impact of the EoL are put into perspective against the GWP-impact of the full life cycle of one bottle. The waste treatments are here combined into representative EoL-scenarios for small bottles in the Netherlands. By considering the full-life cycle of the small PEF and PET bottles, the relevance of EoL-choices could be assessed.

3.2.1.2. Scope

The geographical scope for the disposal of bottles is the Netherlands. Consequently, the Dutch waste system is used as the stage of the EoL for the bottles. Two temporal scopes are included. Short-term includes the current waste treatments of small bottles in the Netherlands as of 2020. The long-term is defined as the moment in which PEF has penetrated on such a significant scale that plastic sorters are willing to collect the PEF separately from the sorted PET fraction. According to interviews with Suez, a commercial company acting as a main waste handler, it will become economically feasible to equip sorting facilities with a separate recycle stream, if collected plastic waste would contain between 5 to 10% of one type of the bio-based plastic (CE Delft, 2017). In addition, CE Delft has a published study on PLA showing that only from a market penetration of 2-5% it is economically viable to start sorting PLA out as a separate stream depending on the market price (CE Delft, 2019b). Based on the projections of Avantium on the exploitation of PEF, the production of PEF will be respectively approximately 200 metric tons and 600 metric tons in Europe. In 2017, Avantium has received an (interim) approval for PEF resin penetration in Europe of 2% compared to PET, equivalent to 50-70 metric tons (EPBP, 2017). Assuming a homogenous distribution of PEF disposal in Europe, and a global plastic growth rate of 4.5% per year between 2017 and 2030 (Ellen Mac Arthur Foundation, 2016), it follows from a rough calculation that a viable fraction of PEF will be achieved within 2030-2035. As many sustainability goals are targeting on 2030, including the Dutch climate regulations (Rijksoverheid, 2019), several assumptions are taken based on this timeframe. The collection and recycling performances in the current Dutch EoL-chain are used for assessing the short-term waste treatments (2020). Two foreseen important developments on waste processing in the Netherlands are considered in the long-term. A deposit collection scheme for clear PET bottles ≤ 0.5 L will be introduced in the Netherlands (Rijksoverheid, 2020) and will therefore be used in the long-term scenario. It is anticipated that PEF bottles will be included in the deposit collection scheme. Moreover, the projected European electricity production mix as of 2030 is added (European Comission, 2017).

3.2.1.3. Function and functional unit

Two assessments were done in this study with each assessment having its own functional unit. As the EoL is only assessed, the first functional unit is set on the treatment of 1kg of collected small plastic bottles. The functional unit of the small bottle itself is based on the study of nova-Institute to provide consistency between the studies. The bottle containing 250 ml for beverage applications is aimed with barrier properties that must provide a determined shelf life of at least 12 weeks (nova-Institute GmbH, 2017). Bottle caps, neck rings and labels are not included in the functional unit. In a transparent PET bottle containing 0.5L, the collective weight of these accessories already take almost 15% of the total weight (E. Thoden van Velzen et al., 2016). In our case of a smaller bottle with a volume of 250 ml which is also made of the lighter PEF, this share will rise and could impact significantly the results. Moreover caps, neck rings and labels are typically made of polyolefins, which have a density lower than 1kg/dm^3, meaning they could be sorted out easily by a water floatation separation step that is typically part of the sorting chain (E. Thoden van Velzen et al., 2016). Therefore the functional unit defined of the waste treatment is:

The treatment in the Netherlands of 1kg of collected clear plastic bottles used for beverage applications each containing 250 ml and providing a shelf life of 12 weeks

The functional unit of the second assessment covers the whole life cycle of one bottle where the EoL consists of different EoL-scenarios. To take the different material requirements into account for small PET and PEF bottles, the functional unit used here is one small bottle. According to the nova-Institute one bottle of PEF containing 250 ml weights 10 gram and the PET variant with an equal function weights 26 gram (nova-Institute GmbH, 2017). Nova-Institute calculated the weights based on the permeability values to obtain a 12 week shelf life for a carbonated soft drink in a 250mL bottle. It is assumed that the production of the bottle takes place in Europe and the EoL in the Netherlands. To be consistent, also no bottle accessories are included in this functional unit. The functional unit of the second assessment is:

The life cycle of one bottle used in beverage applications containing 250 ml and providing a shelf life of 12 weeks produced in Europe and disposed in the Netherlands

3.2.1.4. Product systems

Two different plastic bottle compositions will be treated in this study. The product systems contain the small bottle made of PET and PEF bottle. The bottle thermoforming and PET granulate production both takes place in Europe. The production of PET granulate starts with the esterification of PTA and MEG (ethylene glycol) to BHET (bis(2-hydroxyethyl) terephthalate). As a next step, the molecules are sent to melt poly-condensation under vacuum conditions and high temperature to crystallize PET resulting in higher molecular weights. Finally the obtained PET is exposed to SSP in order to extent the molecular chains so it can be used as bottle-grade PET. PEF bottles are thermoformed in Europe from PEF granulate that is produced in the North-West of Europe. The PEF granulate production route is based on the results of nova-Institute. PEF granulate is produced from starch that is obtained from wheat yielded in France, Belgium and the Netherlands. The starch is converted into fructose which is again turned into FDCA with the YXY-technology. Then the purified FDCA is reacted with bio-MEG to polymerize the obtained PEF. Finally the PEF is treated with SSP. The system boundaries of the PET and PEF granulate production could be found in *Appendix A*. Multilayer PET bottles will not be treated in the LCA as they are not common in the Netherlands. They only take a share of 0%-0.6% in the deposit waste fraction and 1-2% in the sorted PET waste fraction (E. Thoden van Velzen et al., 2016). Due to the environmental unfriendly image, a trend could be observed towards the replacement by monolayer material (K. Kaiser et al., 2017).

3.2.1.5. Research boundaries

Chemical recycling is included as one of the long-term scenarios as this might be relevant for the future. *Figure 6* shows common technologies used for chemical recycling of PET being hydrolysis, methanolysis, glycolysis, ammonolysis, and aminolysis (G. Karayannidis & D. Achilias, 2007).

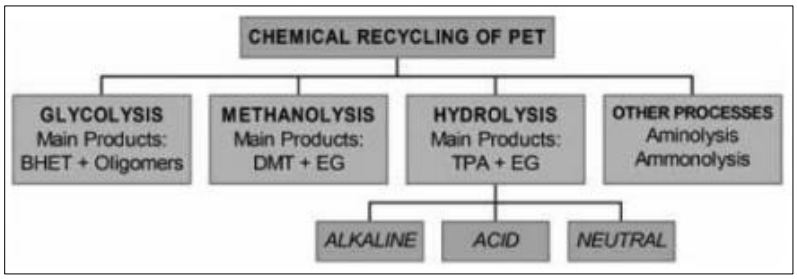

Figure 6. Different technologies to chemically recycle PET (G. Karayannidis & D. Achilias, 2007)

According to Avantium, these technologies could apply in a similar way to PEF, as both polymers consist of polyester functional groups. Due to time constraints and the goal of this study, only one technology has been considered. Avantium pronounced that the most relevant technology for them was the glycolysis process due to its simplicity and least-capital investment requiring process (L. Bartolome et al., 2014). This technology is therefore, already commercially applied (L. Bartolome et al., 2014; S. Park & S. Kim, 2014; G. Karayannidis & D. Achilias, 2007; A. Raheem et al., 2019). Methanolysis is also used on a commercial scale at the moment. However, compared to glycolysis, besides the higher cost, the main disadvantage of methanolysis comes from the fact that the molecules obtained, DMT (dimethylterephthalate) and EG, do not match the molecules required in the most commonly used production route of PET using TPA (terephthalic acid) and MEG as feedstock. The process based on the DMT route is being phased out due to superior qualities of the TPA route in terms of conversion efficiency and capital investments (A. Eerhart et al., 2012). The BHET obtained during glycolysis may directly be used as a raw material without significant major modification of the production facility based on both DMT and TPA based PET manufacturing routes (S. Park & S. Kim, 2014. It is mentioned as well that glycolysis is the most suitable in terms of efficiency and flexibility among the chemical PET recycling technologies mainly due to the fast depolymerization rate and broad range of possible reaction temperatures (M. Khoonkari & A. Haghighi, 2015; S. Park & S. Kim, 2014). Based on a review to the technical performance, glycolysis is mentioned as the most successful among the PET chemical recycling methods. (A. Raheem et al., 2019).

Although different climate impact categories are important for the assessment of bio-plastics, the environmental performance of the systems are only tested on global warming potential (GWP) due to time constraints of this study. Although many LCA studies to PET have assessed other impact categories as acidification potential and ozone depletion (F. Gironi & V. Piemonte, 2011; S. Madival et al., 2009; S. Papong et al., 2014), the GWP indicator is the most common one (T. Gomes et al., 2019). According to (E. Lindgreen & G. Bergsma, 2018), other studies have demonstrated that when it comes to energy and plastics, the assessment on carbon footprint is the dominant environmental impact and is a good approximation for differences in overall environmental performance. Moreover this climate impact indicator is considered as the most important one for Avantium's potential partners in the value chain and for the application for the European subsidies (European Union, 2020). However, the impact of indirect land use change (ILUC) emissions will be discussed. The GWP indicates the influence of a process or product on climate change expressed in $kgCO_2$-equivalent per functional unit. The GWP of a product is calculated by summing all anthropogenic GHG's multiplied with the specific global warming potential of the respective substance. In SimaPro is worked with the assessment method called 'IPCC 2013 GWP 100 a' which contains the climate change factor of the IPCC (Intergovernmental Panel on Climate Change) with a time frame of 100 years.

3.2.1.6. System boundaries

The first assessment only includes the waste treatment of small plastic bottles, which is end user-to-cradle. The production phase and the consumer use phase are thus excluded. The EoL-stage of plastic packaging waste consist of a complex chain which can generally be distinguished in three stages; collection, sorting and treatment (M. Jansen et al., 2015; K. Kaiser et al., 2017). The functional unit of the waste treatment is defined at the collection stage. During sorting not all bottles will end up in the desired recycle stream and during the recycling not all the materials will be converted into second generation material causing losses in the waste treatment. These material losses, however, will not leave the system boundaries as they will be incinerated (with energy recovery). Transport between and within the stages is also included. In conclusion, the system boundaries of the waste treatments (EoL) are illustrated in *Figure 7*. It can be observed that on the one hand the operation throughout the waste treatment and EoL-scenarios requires energy and materials contributing to GHG-emissions. On the other hand, the materials incinerated and recovered as a result of recycling save GHG-emissions by substituting the production of respectively energy and virgin material**.**

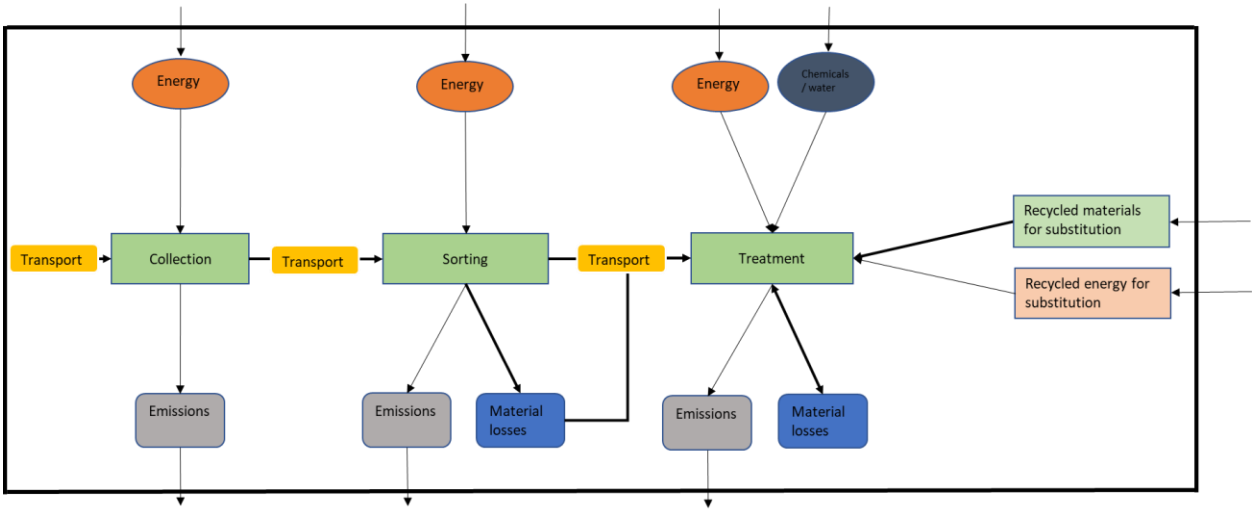

Figure 7. System boundaries of the first assessment covering the waste treatment of PET and PEF

In the second assessment, the whole life cycle of the bottle is included within the system boundaries. The system boundaries now reach from the production phase to the EoL-phase. The EoL-stage here consists of different waste treatments representing certain EoL-scenarios of the Netherlands. As littering is considered to be insignificant in quantity and quality, it is assumed that all bottles will be collected at the collection stage in the EoL-scenarios. Although there might be a difference in the fuel use in transport during the use phase due to the lower relative weight of PEF bottles, the related impact is expected to be small as the weight/volume ratio of empty bottles is low. Also in the case of filled bottles the fuel use caused by the bottles itself is small based on a weight allocated approach, causing negligible differences in PEF and PET during the use phase. Overall the impact of the use phase is neglected as this is expected to be minor compared to the production phase. The production of plastic bottles consists of two foreground processes that are granulate production and stretch-blow moulding (Plastics Europe, 2020). The system boundaries could be found in *Figure 8*.

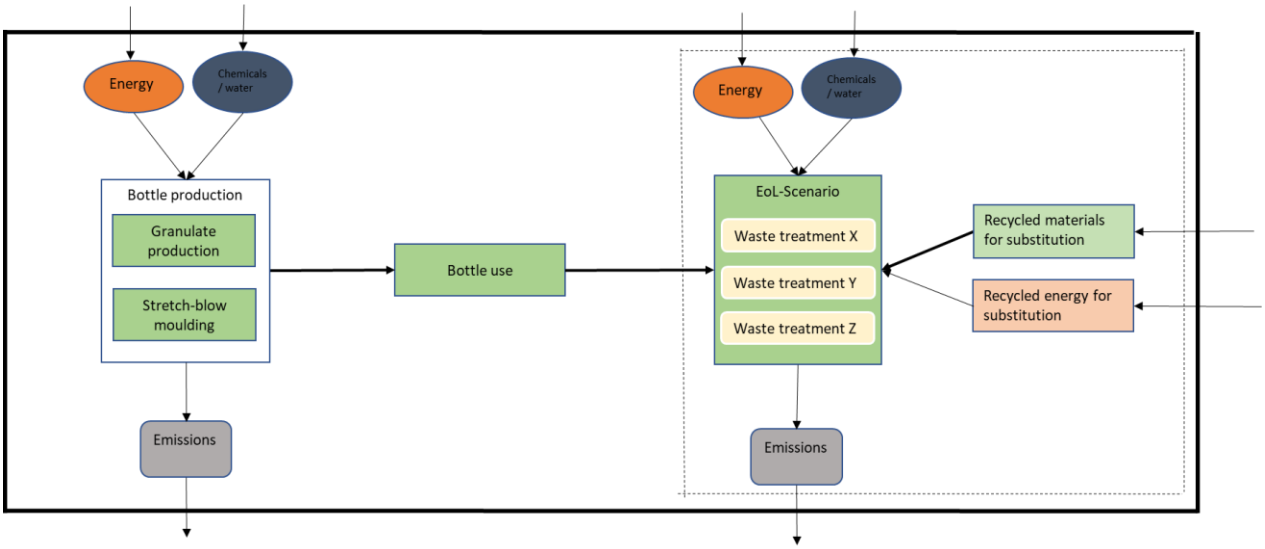

Figure 8. System boundaries of the second assessment covering the life cycle of one small bottle containing 250 ml and providing a shelf life of 12 weeks made of PET of PEF. The surface within the dashed lines is covering the system boundaries of the first assessment.

3.2.2. Life cycle inventories

In this part the processes involved in the EoL for the product systems are mapped. First the current Dutch post-consumer plastic waste management including the recycling is generally explained to give the reader an overview. With help of this, the pathway of the small PET bottles in the current and long-term waste system in the Netherlands is mapped. Based on this several, waste treatments are identified. As 250 ml plastic bottles are currently barely used in the Netherlands, no data was found on the behaviour of specifically this application in the waste system. Therefore, a note should be made that most of the data found, applies on small plastic bottles containing 500 ml. Next, the processes and their environmental impacts involved in the waste treatments are inventoried. In *Section 3.4* is explained how these processes differ for PEF bottles which lead to different EoL-impacts compared to the PET waste treatments.

3.2.2.1. Current waste system in the Netherlands

The plastic packaging chain is more complicated compared to chains of other packaging materials like paper and glass for several reasons (KIDV, 2017). At first many different plastic types are being used for many different packaging applications, which could in turn also consist of multiple plastic types. Therefore the recycling requires many different parties along the whole recycling chain like packaging designers and sorters which that should be aligned harmoniously. The fact that different collection systems are running in parallel, makes this even more challenging. Moreover, the fluctuating oil price strongly relates to the price of virgin plastics so with the price of recycled plastics causing unstable markets for recycled plastics. Moreover, an additional pressure has been associated with the use and the production of plastics due to the global littering problem and the related plastic soup pollution.

Plastic that is recycled in the Netherlands, is collected in three different ways: by source separation, by post-consumer separation, and through a deposit system. Since 2015 municipalities are kept responsible for the collection of packaging plastics. Some municipalities have chosen for the collection of plastics by a separate collection system (source separation). Others manage the plastic collection together with the municipal solid waste from which the plastics could later be sorted out in a material recovery facility (MRF)

which is known as post-separation. To make it even more complicated some municipalities have a combination of both collection systems (VNG, 2019). Currently the only plastic packaging application which is collected through the deposit system, is the clear PET bottle > 0.5 L (CE Delft, 2017). This fraction is directly going to the PET processor in order to generate mechanically recycled PET granulate. Recently, the extension of the deposit system to clear PET bottles ≤ 0.5L has been announced to be introduced by July 2021 (Rijksoverheid, 2020), and is therefore included in the long-term waste treatments.

The plastics being collected by source separation will be delivered at the sorter where they will be separated based on plastic type into fractions. A standard sorting process consists of shredders, wind-sifting, magnetic separators, eddy-current separator, near infrared technologies and manual sorting (K. Kaiser et al., 2017). In the Netherlands six main sorting fractions for plastics are currently distinguished that must comply with certain DKR (Der Gruener Punkt) standards adopted from Germany: PET (DKR 328-1), PET-trays (DKR 328-5), PE (DKR-329), PP (DKR-324), Film (DKR-310) and mixed plastics (DKR-350) (M. Jansen et al., 2015; M. Brouwer et al., 2019). In municipalities that handle post-separation, the plastics in municipal solid waste (MSW) first have to be recovered in a pre-sorting step performed by a MRF before the plastics are sorted into the DKR-fractions.

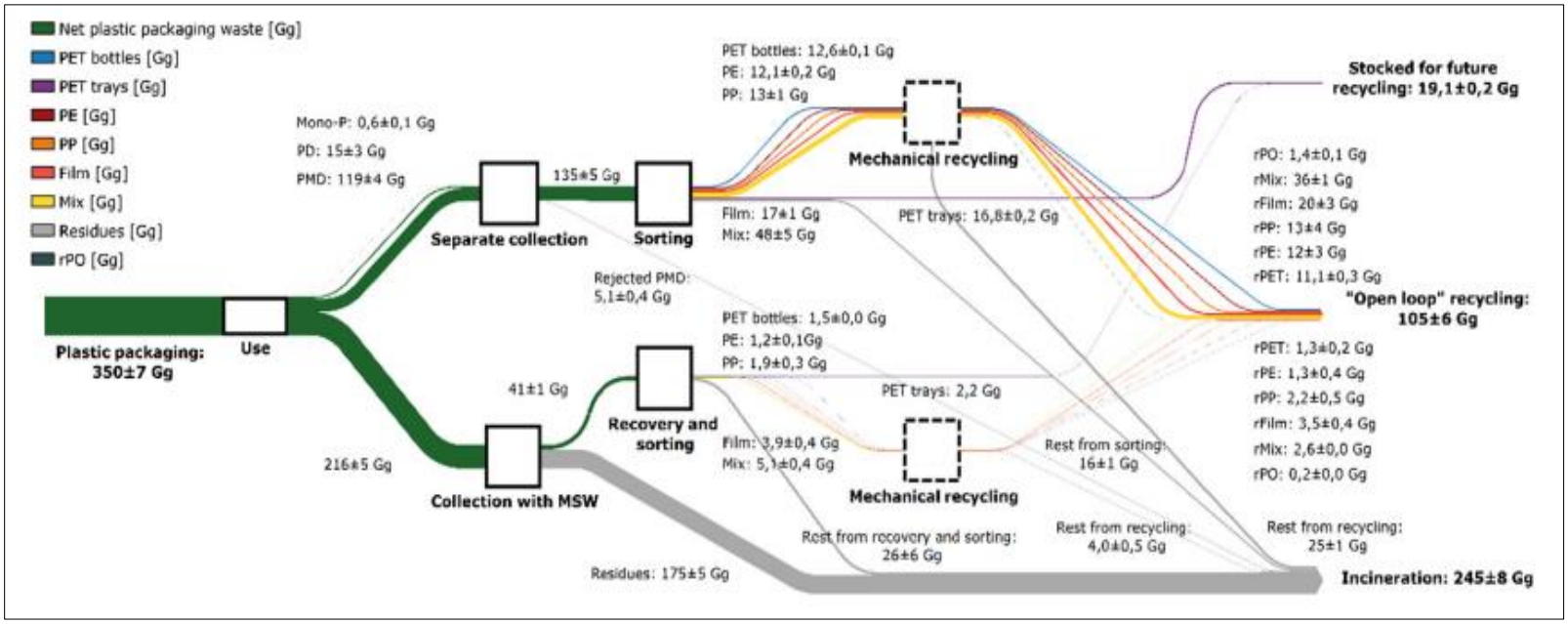

Figure 9. Sankey diagram of plastic packaging waste recycling network in the Netherlands from 2017. This diagram is excluding the deposit system plastic stream. Furthermore, please note that a Gg is one metric ton (M. Brouwer et al., 2019).

The plastics sorted according to the DKR-standards are then mechanically recycled. First the streams undergo some purification steps to improve the quality. These steps differ per plastic type, but could typically be distinguished as shredding, screening, washing, density separation, centrifugation and drying (TU Eindhoven, 2015). Thereafter the melt extrusion of the purified flakes and the homogenization into pellets takes place (EuRIC AISBL, 2019). In *Figure 9*, an overview is shown of the plastic packaging waste recycling network in the Netherlands including quantitative flows from 2017 (M. Brouwer et al., 2019).

3.2.2.2. Allocation

Ecoinvent offers allocation cut-off by classification, allocation at the point of substitution (APOS) and consequential substitution to meet the demand of different types of studies. The former two systems can be used for attributional studies. Allocation by cut-off and APOS differ solely in the way they treat waste and recyclable materials. APOS is an allocation approach that uses expansion of product systems to avoid allocating within treatment systems. It was designed to avoid allocations in general by taking average data of valuable by-products of treatment systems together with the main activity. Average means that the model doesn't use constrains due to markets and technology. A cut-off approach is often used in studies where the impact of a recycled product is assessed, because it avoids the necessity for primary production data. However in both assessments of this study, the impact of the first generation product is assessed (which is including the substitution of virgin granulate production). The system boundaries of the first life are not transcended in this study which avoids the need to cut-off the boundaries between first generation and second generation which is done during the cut-off approach. The credits of recycling are here assigned to the first generation instead of the recycled product in the second generation. In fact, applying the cut-off approach would generate inconsistent background data. Therefore, the APOS allocation method is used.

3.2.2.3. Energy sources

During modelling the energy requirements in the processes involved in the recycling processes are linked to the Dutch energy sources to represent the right system boundaries of this study. The electricity requirements for the relevant processes are therefore linked to the electricity mix from the Netherlands described by the Ecoinvent data process named '*Electricity, high voltage {NL}| production mix | APOS, U*'. This electricity production mix is based on data from IEA (International Energy Agency) and contains electricity shares in the Netherlands originating from the year 2015 (IEA, 2017). The Dutch medium voltage and low voltage production mixes described in Ecoinvent were linked to the Dutch high voltage production mix and used accordingly. In the long-term waste treatments the included electricity sources must represent the appropriate electricity mix. Therefore, the high voltage electricity data set from Ecoinvent has been replaced by the projected European electricity mix and adjusted further downstream in the medium voltage and low voltage production mixes as well. The modern electricity mix is based on the EUCO27 scenario of the European Commission on the European electricity sector as of 2030 (European Comission, 2017). The updated electricity production mixes are linked to the relevant long-term processes in SimaPro. For Ecoinvent data, this was just a matter of replacing the electricity production mix by the updated production mix as this data was made transparently. However the Plastics Europe data sourcing used only for the (substituted) virgin PET granulate production was not made transparently. To account for the modern electricity production mix, an alternative accounting method is used, which is described in *Appendix B*. Furthermore, the heat requirements are set on the data base named '*Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace low-NOx >100kW | APOS, U*' where the gas use is adjusted to Dutch natural gas. The specifications of the used electricity and heat database can be found in *Appendix D*.

3.2.2.4. Collection

Work from CE Delft (2019) contains information about plastic packaging collection in the Netherlands. This is the latest data that has been found and orginates from 2017. Two collection methods are currently in place for packaging plastics including small plastic bottles; source collection and in the municipal solid waste (MSW). Due to the different pathways with their own efficiency and environmental requirements, a distinction was made in the collection. According to *Figure 10*, 190 metric tons of packaging plastics were collected via source collection and 210 metric tons in MSW in the Netherlands. For the plastics ending up in the MSW, unfortunately, no distinction between the source of disposal (industry or consumer) was made. According to M. Brouwer et al. (2018 and 2019), approximately 22% of the packaging plastics in MSW was recovered in 2014 and 2017. Note, that this is not the efficiency of a MRF, but this percentage includes as well the small plastic bottles that are disposed in the MSW in source seperating municipalities that send the MSW directly to an incineration plant. This percentage is used to track which fraction of the 210 metric tons packaging plastics has been thrown away by consumers and is thus including plastic bottles. Based on this calculation, it is found that 41.8% of the packaging plastics is disposed in the MSW whereas 58.2% is collected through the separate collection system. A collection rate of 59% is reported for separate collection of plastic packaging waste for 2017 which is very close (Milieu Centraal, 2018). Although this number is including clear PET bottles > 0.5 L that are collected by the deposit system, the overestimation is small due to the relative small share of this fraction compared to the total packaging plastics (see *Figure 10*). So far, only the collection of plastic packages in general was discussed. As no collection data was specifically found for small plastic bottles, this distinction was also used for the collection of small plastic bottles. Therefore, this implies the assumption that small plastic bottles behave the same as packaging plastics in general during the collection. Combining the small plastic bottle fraction that is collected at the source and the fraction in MSW multiplied by the material recovery rate of 22%, the total collection rate of small bottles is calculated as 65% for the year 2017. This is almost equivalent with an estimation on the collection rate of small bottles by the Dutch system, done by Thoden van Velzen (66%), a Dutch packaging scientist (Verpakkingsmanagement, 2019). A note should be made that this is expected to be a relatively high estimation because both people (source separation) and NIR cameras (post-separation) detect small bottles efficiently compared to other plastics. This is not reflected based on our calculated collection rates.

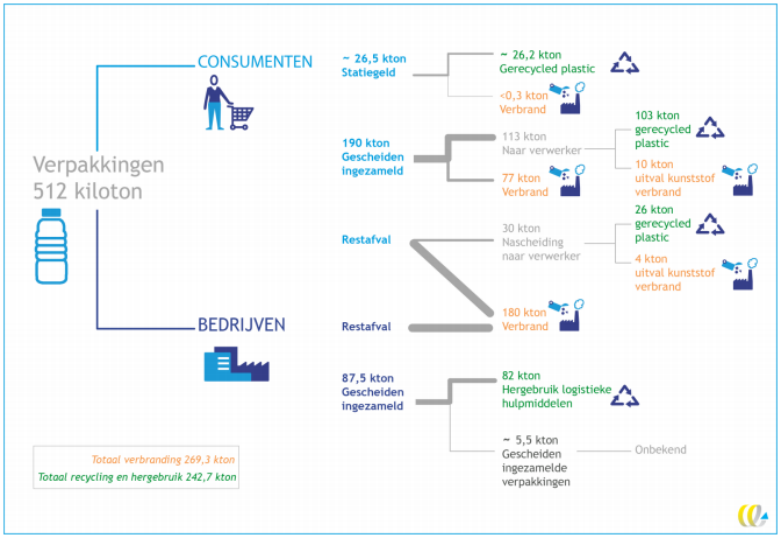

Figure 10. Overview of processing waste streams of packaging plastics in the Netherlands from 2017 (CE Delft, 2019a)

With the deposit system on clear PET bottles ≤ 0.5L having its introduction in 2021, responses in the Netherlands are estimated in different studies (CE Delft, 2017; T. Elliott et al., 2015). CE Delft (2011) estimates the collection percentage of clear PET bottles ≤ 0.5L between 73% based on Swedish results (at a deposit amount of €0.10), and 90% based on a prognosis on the Dutch case (at a deposit amount of 0.25€) (TNS-NIPO, 2011). Another study from Eunomia has investigated the relationship between the

collection rate and the height of the deposit amount based on results of different European countries. Based on a causal relationship, collection rates between 86% (at a deposit amount of €0.10) and 90% (at a deposit amount of €0.25) were found. The deposit amount in the Netherlands is set on €0.15 (Rijksoverheid, 2020). Based on these studies a collection rate of 85% will be assumed in the long-term for the clear PET bottles ≤ 0.5L. Although the collection via source separation has slightly expanded compared to post-separation the recent years (CE Delft, 2017), the influence on the results of the potential continuation of this trend is expected to be limited due to the domination of the the deposit system in the long-term collection. Moreover the purpose of the study is to assess the environmental impact of the different EoL-options rather than the different collection systems. Therefore, the remaining 15% is assumed to be collected in the same ratio as in the short-term being 58.2% and 41.8%.

The environmental impact of the collection stage is limited to the required energy needed in a MRF for the plastic recovery out of MSW. According to industial data obtained from Dutch MRF's by CE Delft (2011), the energy requirements for the recovery step of plastic are approximately four times higher as the sorting of unsorted plastics into fractions. However, not all plastics collected in the MSW are exposed to this recovery step since a fraction is directly sent to incineration in source seperating municipalities. Based on an estimation that 50% of the waste collected in MSW is subjected to post-separation, the recovery step is thus modelled as two times the requirements of sorting (thus with an efficiency of 22%). Ecoinvent provides data on the sorting of plastics. A description of the recovery process and related data is given in *Table 3*. The energy use for disposing or returning the small bottles to the collection point in the supermarket by the costumer is assumed to be negligible. The emissions released during the transport of the bottles to the sorting facility or the material recovery facility are mentioned under Section *3.2.2.7*.

Table 3. Details of the plastic bottle recovery step. For specifications of this step see Appendix E.1.

Process	Description process	Efficiency	Database used	Adjustments done in process
Recovery of small plastic bottles from MSW in a MRF (*Appendix E.1.)*	The recovery of 1kg plastics from 4.5kg plastics collected in MSW in a MRF that is afterwards processed further in the recycle chain. Assumed is that 50% of the plastics in MSW is never exposed to this recovery step.	22% (M. Brouwer et al., 2019)	Polyethylene terephthalate, for recycling, sorted {CH}| treatment of waste polyethylene terephthalate, for recycling, unsorted, sorting | APOS U (*Ecoinvent 3.4*)	The recovery step is modelled as two times* the impact of the sorting step. For more information on the sorting step, see the next *Section 3.2.2.5.*
* The motivation of this factor could be found in the text				

3.2.2.5. Sorting

Specific sorting efficiencies of small clear PET bottle ≤ 0.5 recycling in the Netherlands are found (M. Brouwer et al., 2018; M. Brouwer et al., 2019). Whereas the sorting efficiency of clear PET bottles ≤ 0.5 from M. Brouwer et al. (2018) is distinguished in 70% for source separated fractions and 62% for post separated fractions with a weighted average of 68%, M.T. Brouwer et al. (2019) mentions only the sorting efficiency of 76% of clear PET bottle ≤ 0.5. A sorting efficiency of 75% for specifically clear PET bottles ≤ 0.5 by the NIR sorting process is reported in another study which is in line with the latter (M. Jansen et al., 2015). An assumed sorting efficiency of 76% implies that this fraction of small bottles will end up in the desired PET fraction (DKR-328-1).The remaining small PET bottles ≤ 0.5 end up in the mixed plastic fraction (12%), the other mono fractions (6%) and in the sorting residue (6%) (M. Brouwer et al., 2019). These remaining 24% of the clear PET bottles ≤ 0.5 is assumed to be incinerated with energy recovery. PET ending up in the mixed plastic fraction (DKR-350) is undesired due to the quality degradation potential (TNO, 2017). The allowable containment of PET is therefore limited to a maximum of 4% (DerGrunePunkt, 2018). In addition, the mixed plastic fraction is sometimes just incinerated due to a lack of market demand

(K. Kaiser et al., 2017). Sorted fractions for one type of plastic normally end with high purities, suggesting that PET is further downstream sorted out the fraction when sorted wrongly and the sorted residue is usually incinerated (M. Brouwer et al., 2019; K. Kaiser et al., 2017). Because the deposit system is responsible for 85% of the bottle collection, this study does not focus on improved sorting technologies with higher efficiencies in the long-term scenarios as these will have minor impacts in the EoL-scenarios.

Different studies point out that the environmental impact at the sorting stage is insignificant (Nordic Council, 2015; U. Arena et al., 2003; A. Detzel et al., 2004). Based on this L. Shen et al. (2010) assumed that the environmental impact associated with sorting, baling and compacting is negligible. However, in this study the sorting requirements will be considered to cover the full picture. Moreover, the confirmation of this assumption would serve as an additional justification of the reliability of the results. Ecoinvent data was used representing the treatment of unsorted PET waste yielding 1kg of sorted PET for recycling into sorted PET bales (T. Kägi et al., 2017). The Dutch electricity and heat source is added to this data. Also the lost fraction that is incinerated, is removed from the dataset as this is considered manually in the waste treatments by the found sorting efficiencies. Moreover, PE incineration originating from the bottle caps and labels was covered, which is not considered in this study. There is hardly no difference in energy requirements of sorting separate collected plastics or recovered plastics (CE Delft, 2011). Based on interviews with Dutch sorters, CE Delft reported energy requirements for the sorting of post seperated plastics at 165 MJ per ton of input and for the source seperated plastics at 160 MJ/ton (CE Delft, 2011). This is also in range with the energy requirements of sorting used by Plastics Europe that reported a need of 50 kWh (=180 MJ) of electricity per ton input (Plastics Europe, 2014). The values are close to the foreground energy in the Ecoinvent sorting process which adds up to 181 MJ per tonne output almost exclusively consisting of electricity. A description of the process and related data is given in *Table 4*. The specifications of the sorting process can be found in *Appendix E.1*.

Table 4. Details of the sorting step of plastic bottles. For specifications of this step see Appendix E.1.

Process	Description process	Efficiency	Database used	Adjustments done
Sorting of post seperated plastics / Sorting of source seperated plastics (*Appendix E.1.)*	Treatment of 1.31kg unsorted PET waste yielding 1kg of sorted PET in bales for further recycling.	76% (M. Brouwer et al., 2019)	Polyethylene terephthalate, for recycling, sorted {CH}| treatment of waste polyethylene terephthalate, for recycling, unsorted, sorting | APOS U (*Ecoinvent 3.4*)	Dutch electricity production mix and heat source is used. Treatment of losses is removed from this process, however later taken into account in waste treatments.

3.2.2.6. Treatment (EoL-options)

In this section the mechanical and chemical recycling treatment of small PET bottles is mapped. But first the quality factor is introduced in order to account for quality degradation to enable a fair comparison between the waste treatments and EoL-scenarios. The most important reason to use a quality factor here is to account for the differences in quality for rPET obtained from mechanical recycling and chemical recycling (glycolysis). During chemical recycling PET is decomposed to molecules and rebuild into long chains again, that requires from a thermodynamic point of view inherently more energy in the form of temperature and pressure (R. Geyer et al., 2017). On the other hand, the quality obtained during chemical recycling is close to virgin PET (L. Shen et al., 2010; R. Geyer et al., 2017), whereas mechanical recycling cause degradation in the polymer structures which limits the number of times it can be effectively recycled as the polymer become degraded. Also, mechanical recycling is unable to separate the additives and the non-intentionally added substances that are present in plastic waste; this explains why contaminated plastic often cannot be turned into food-grade applications (Zero Waste Europe, 2019). Chemically

recycled fibres can theoretically be applied in a wider range than mechanically recycled fibres for example (L. Shen et al., 2010).

Many studies have simply applied a one-to-one substitution for the mechanical recycling of PET (U. Arena et al., 2003; F. Perugini et al., 2005; RDC Environment & Pira International, 2003; L. Shen et al., 2010; WRAP, 2006; D. Turner et al., 2015). Some of these studies worked with a sensitivity analysis on the substitution factor. A one-to-one substitution ratio means that recycled materials replace the same amount of virgin materials with the same quality. As this is often not the case in practice for mechanical recycling of PET, some professionals in the field have considered the issue of quality deterioration by applying the concept of a substitution factor within the LCA framework (R. Noda et al., 2001). As a result, several studies worked with a substitution factor lower than one (P. Ferrão et al., 2014; L. Rigamonti et al., 2009; L. Rigamonti et al., 2013; L. Rigamonti et al., 2014; G. Valentino et al., 2016). However, a fixed method to define the substitution factor is not established yet (J. Nakatani et al., 2011). For example, L. Rigamonti et al. (2009) approached the quality degradation as the relative difference in the price of virgin PET and recycled PET. This is, however, not considered as the most reliable method as prices of plastics strongly fluctuate over time due to the relation to the oil price (TNO, 2012; A. Gala et al., 2015). Moreover, a strong demand for rPET from bottle manufacturers in 2018 resulted in higher prices than virgin PET and therefore even decoupled from price fluctuations (EUNOMIA, 2018). Ideally, this correction factor represents to what extent the inherent properties of the material are lost, using the limiting factor as quality parameter (European Comission, 2013). The intrinsic viscosity (IV) of PET is considered as a good indicator, because it is often used as a parameter in quality control studies (D. Ulrich & K. Thiele, 2007; J. Nakatani et al., 2011). The IV is a general indicator of the degree of polymerization that in turn relates to the melting point, crystallinity and tensile strength (J. Nakatani et al., 2011; EUNOMIA, 2018) and eventually to the applicability of rPET. Although, r-PET pellets are typically processed by solid-state polycondensation (SSP) to obtain a recycled resin with an IV close to that of virgin PET (RDC Environnement , 2011), the contaminants impact the maximum achievable IV (F. Chacon et al., 2019).

A. Elamri et al. (2015) studied the mechanical losses (i.e. IV), with respect to virgin material, and G. Valentino et al. (2016) calculated based on the relative differences in IV the associated quality factor. A. Elamri et al. (2015) measured the IV from rPET originating from three different PET feedstock. Without going into detail, the study distinguishes rPET originating from clear and light blue post-consumer bottles, rPET coming from heterogeneous deposits of various coloured bottles. The IV's measured of the rPET resin are respectively 0.67, 0.64 and 0.75 for the virgin PET, resulting in quality factors of 0.90 for the homogenous blue bottle fraction and 0.85 for the more heterogeneous bottle fraction. Bottles originating from the Dutch deposit refund system are generally in line with the EPBP design guidelines (E. Thoden van Velzen et al., 2016) and therefore equivalent with the clear and light blue bottle fraction. The quality factor of 0.90 is therefore used on rPET resulting from the mono collected bottles in the Netherlands. The quality factor based on the heterogeneous bottle fraction (0.85) is applied on rPET originating from the sorted fractions. According to the specification of DKR 328-1 a minimum of 90% must contain of beverage bottles (DerGrunePunkt, 2018) representing considerably the used heterogeneous fraction. The IV for SSP treatment of Dutch secondary PET is measured to be in the order of 0.65 (E. Thoden van Velzen et al., 2016), which validates the range of the factors. These quality factors enable quality degradation caused by different collection methods as well, which is of large influence of the quality of rPET according to a study in the Netherlands. The authors concluded that the contamination present in rPET were mainly caused by the origins of the collected bottles instead of the inaccuracy of the sorting and purification

activities (E. Thoden van Velzen et al., 2016). Nevertheless, the uncertainty of the quality factors used remain. In any case, a sensitivity analysis should be done on the quality correction factor (D. Schrijvers et al., 2016).

Mechanical recycling

According to *Figure 9*, in the Netherlands 12.6 metric tons of the DKR-328-1 fraction resulting from source collection was converted in 11.1 metric tons rPET. The fraction DKR-328-1 resulting from post-separation, amounting to 1.5 metric tons was converted into 1.3 metric tons rPET. These conversion steps imply processing efficiencies of 88 and 87%, with a combined weighted conversion efficiency of 88% (see *Figure 9*). These rates are similar to the conversion rates shown in *Figure 10*. Moreover, the efficiency is equal to the technical yield reported in Denmark for the advanced mechanical recovery system, most similar to the Dutch recycle infrastructure (G. Faraca et al., 2019). Due to the higher purity, the conversion efficiency for deposit bottles is even higher. CE Delft (2019) reported a conversion efficiency of 98.9% (see *Figure 10*), however the input and output stages are not well defined. Therefore, the conversion efficiency of PET bottle to pellet in the long-term scenario is estimated at 95% based on L. Shen et al. (2010).

In the Netherlands PET bottles collected by the deposit refund system, separate collection and the mechanical recovery system is all used to generate new bottles, trays and fibre fill (E. Thoden van Velzen et al., 2016). Although, the purity of rPET from the sorted fractions is quite good at 99%, it is currently partly used in circular applications (M. Brouwer et al. ,2019). The major hurdle for closed loop recycling (bottle-to-bottle) of the sorted PET fraction, is the large content of PET non-food flasks that do not satisfy the bottle design guidelines. These design guidelines were introduced by the EPBP to encourage packaging designers, converters and users to integrate certain criteria in a plastic bottle in order to facilitate PET recycling (EPBP, 2020). From a study to the quality of rPET in the Netherlands, it appeared that rPET contaminants present in the PET packaging products itself is the major factor affecting the suitability of post-consumer PET flakes for closed loop recycling, rather than the sorting performances (E. Thoden van Velzen et al., 2016). There is hardly any impact of more precise sorting on the quality of rPET. Also from a regulation point of view, it is difficult to turn sorted PET fractions into food-grade material. In sorted PET fractions, the share of non-food products amounts to 17-24%, whereas 5% is the legal limit set by EFSA (European Food Safety Authority) for food-grade recycling. According to an interview with Louis Jetten, an expert on PET recycling (published in *Appendix C*), this is being controlled actively in the Netherlands by taking random samples of the incoming bales at the processor site (Jetten, 2020). Therefore, it is assumed that the PET bottles ending up in the sorted PET fraction are replacing amorphous PET. Amorphous PET is suitable for fibre and film applications (Plastics Europe, 2019). PET bottles from the deposit refund system are currently already being used in food-grade applications due to guaranteed homogeneity of this stream as only beverage containing bottles are collected (that largely comply with the EPBP design guidelines). According to Louis Jetten, PET originating from deposit refund systems is mostly used in second generation bottles up to a certain percentage (Jetten, 2020), although the resulting flakes first have to be exposed to SSP (E. Thoden van Velzen et al., 2016; Jetten, 2020). As a fraction of the small bottles are made from HDPE and thus will be co-collected with the PET bottles, a sorting step might be needed in the future. However the GWP-emissions for sorting and losses are expected to be negligible and therefore not considered.

Ecoinvent contained data on requirements for the production of bottle-grade rPET granulate and amorphous rPET granulate. The system boundaries of the production of 1kg of rPET granulate range from the unwiring of the sorted PET bales to produced rPET granulate. All purification steps are included in the

data. For the production of bottle-grade rPET the SSP step to increase the IV is included as well. However, while using the APOS allocation method, the amorphous rPET granulate production produces a higher GWP than the production of bottle-grade rPET granulate production, which makes the Ecoinvent data counterintuitive. Therefore, the production data of bottle-grade rPET granulate was directly used for the recycling of bottles from the deposit sytem into secondary material. The data on the production of amorphous PET granulate was derived by subtracting the requirements for SSP from the production process of bottle-grade rPET granulate. The energy requirements for SSP were found to be 33% of the total energy requirements given on the polymerization process which could be divided into 1) esterification and melt polymerisation 2) and SSP (Plastics Europe, 2017). The GWP of SSP calculated by this method differs only 10% from the GWP of the confidential data on the SSP process from IV 0.6 (amorphous) to 0.82 (bottle-grade) obtained from Avantium. The GW-impact differs only 20% of the emission factor mentioned in L. Shen et al. (2011) validating the impact for SSP. As the recycling of PET is taking place in the Netherlands the electricity and heat needs are adjusted to the Dutch energy mixes in the above standing processes. Moreover the standardly added plastic waste is removed from the data as bottle accessories are not part of the functional unit. With help of the applied efficiencies, the PET losses are taken into account. A description of the recycling processess and related data is given in *Table 5*. The specifications of the sorting process can be found in *Appendix E.2, E.3 and E.4*.

The avoided virgin bottle-grade PET granulate production was based on data from Plastics Europe (called Industry Data 2.0 in SimaPro) that represents average data of the real industry instead of literature data that is used in Ecoinvent. Although the data are collected at great expense, it is claimed by Avantium that they include more modern installations than older ones, so that the results are not real average values and are therefore flattering towards the fossil based polymers. This explains why the Plastics Europe data on virgin granulate production is approximately differing with plus minus 50% compared to the Ecoinvent data on virgin PET granulate production averaged in Europe. As the research boundaries are set on the Netherlands, this data does fit well as the modern virgin PET production facilities are most likely located in Western Europe. Another frequent criticism of this data is that the data is not made transparent. It was therefore not possible to replace the process' electricity source with the electricity production mix as of 2030. The method to approach this issue is described in *Appendix B*. The avoided GWP by virgin amorphous PET granulate production could also not directly be obtained as Plastics Europe has not stand alone production data of virgin amorphous PET granulate (Plastics Europe, 2020). In order to obtain the production requirements of virgin amorphous PET granulate the production requirements of virgin bottle-grade granulate was subtracted with the requirements for SSP mentioned before. L. Shen (2011) suffered the same challenge and solved this with the same approach to calculate the GWP of the production of virgin amorphous PET granulate.

Table 5. Details of the mechanical treatment of plastic bottles. For specifications of this step see Appendix E.2., E.3., and E.4.

Process	Description process	Efficiency	Database used	Adjustments done on database
Processing of baled PET bottles into bottle-grade PET granulate at factory gate (*Appendix E.2.*)	Treatment of 1.05kg baled PET bottles into 1kg of rPET (bottle-grade) granulate	95% (L. Shen et al., 2011)	Polyethylene terephthalate, granulate, bottle-grade, recycled {CH}| polyethylene terephthalate production, granulate, bottle-grade, recycled | APOS, U (*Ecoinvent 3.4*)	Dutch electricity production mix and heat source is used. Treatment of losses is removed from this process, however later taken into account in waste treatments.
Processing of baled PET bottles into amorphous PET granulate at factory gate (*Appendix E.3.*)	Treatment of 1.14kg baled PET bottles into 1kg of rPET (amorphous) granulate	88% (M. Brouwer et al., 2019)	Polyethylene terephthalate, granulate, bottle-grade, recycled {CH}| polyethylene terephthalate production, granulate, bottle-grade, recycled | APOS, U (*Ecoinvent 3.4*)	This process is derived as the production of bottle-grade rPET granulate subtracted with SSP. Dutch electricity production mix and heat source is used. Treatment of losses is removed from this process, however later taken into account in waste treatments.
Solid State Poly-condensation (SSP) (*Appendix E.4.*)	Treatment of 1kg of amorphous PET quality (IV≈0.6) into bottle- grade PET quality (IV≈0.82)	100% (assumed)	No database used. Process created based on literature data.	This process is derived by dividing the polymerisation process into two sub-processes for a) esterification and melt polymerisation and b) SSP. Energy requirements for both processes have the shares: a) 67 % and b) 33 % (Plastics Europe, 2017)
Virgin PET bottle-grade granulate production	Production of 1kg of bottle-grade PET granulate	-	PET, bottle-grade, at plant/RER (*Industrial Data 2.0*)	-
Virgin PET amorphous granulate production	Production of 1kg of amorphous PET granulate	-	PET, bottle-grade, at plant/RER (*Industrial Data 2.0*)	This process is derived as the production of virgin bottle-grade PET granulate subtracted with SSP.

Glycolysis

Glycolysis is the chemical degradation of a polyester by glycol molecules in the presence of a catalyst into BHET monomers and/or oligomers. During glycolysis ester linkages are broken and replaced with hydroxyl terminals. The reaction products of glycolysis depend on the glycol used, catalysts and reaction conditions (T. Vuorinen & H. Joki, 2017). Although chemical recycling adds most value on dirty PET fractions (Zero Waste Europe, 2019), the PET bottles from the deposit refund system are objected to glycolysis in the long-term waste treatment. It has two reasons that this fraction is chosen to be exposed to glycolysis. The first reason is that the input of glycolysis needs to be at relatively good quality as the technique itself is not able to remove dyes, colours and copolymers (S. Park & S. Kim, 2014). K. Ragaert et al. (2017) even mentions that glycolysis is absolutely not able to the remove low levels of copolymers, colorants or dyes and that PET scrap lost during the virgin production chain are best suited due to the homogeneity. Although additional purification steps enable removing these contaminants from the fluid mixture (J. Aguado & D. Serrano, 1999; M. Gouthier, 1995). A second reason is that the regulations on the guaranteed 95% origins from food packaging also apply for chemically recycled material (KIDV & CE Delft, 2018).

Since glycolysis is relatively new, barely any data on efficiency, energy requirements and material requirements are publically available in literature to the author's knowledge, especially not at an industrial scale. The found NREU and GWP of a glycolysis and repolymerization process of PET on pilot plant scale by Far Eastern New Century (FENC) based in Taiwan did allow to make an estimation the GWP of this process (L. Shen et al., 2010). As the system boundaries of the data, as illustrated in *Figure 11,* suit not perfectly the relevant process, it was necessary to make some adjustments on the data. The data on the NREU and the GWP contains the depolymerization of PET flakes from PET bottles into oligomers that are purified by a fine filtration step. The purified BHET oligomers are than repolymerised again into PET pellets that are eventually converted into fibers. At first, the amount of electricity and heat needed for spinning

and finishing according to Taiwanese energy mixes, given in the article, was deducted to obtain the NREU for the production of PET pellets with a fibre-grade IV of around 0.6. To obtain the GWP for the production of bottle-grade PET pellets via glycolysis, the requirements for SSP to bottle-grade are added. The geographic boundaries for this study are Western Europe and Taiwan. Although it is uncertain if this adjusted process fully fits in a realistic production process towards bottle-grade PET granulate, it should be able to give an impression on the GWP-impact of chemical recycling via glycolysis. Note that pilot plant data is used here. Optimization of chemical recycling processes could lead to significant scale advantages and thus greenhouse gas reductions (Zero Waste Europe, 2019; KIDV & CE Delft, 2018). The energy used during the glycolysis, fine filtration and repolymerization was assumed to come fully from natural gas. As the NREU was given as primary energy use, a gas-to-heat efficiency of 85% was used in order to calculate the required heat from natural gas. According to *Figure 11*, the efficiency of the glycolysis and repolymerization process is 98%. Catalyst use is typically not included in a LCA in homogenous reactions like this as these could be recovered and reused. A. Raheem (2019) reported several glycolysis catalysts that can be re-covered, treated and reused with excellence performance. Moreover, the MEG that is used as input for the glycolysis is almost the same amount of MEG that is released during the repolymerization. According to L. Shen et al. (2010) the MEG is typically recovered due to its economic value and therefore not impacting the LCA result. A description of the recycling processess and related data is given in *Table 6*. The specifications of the sorting process can be found in *Appendix E.5*.

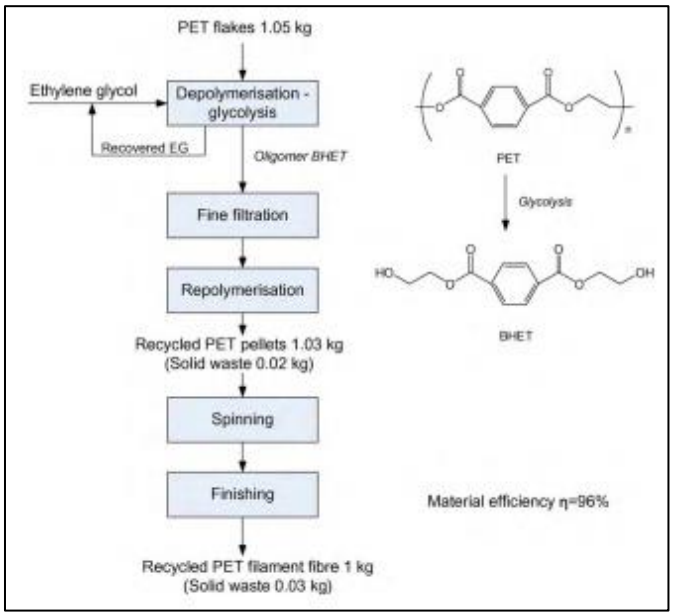

Figure 11. The schematic diagram of the glycolysis process where data is acquired from (L. Shen et al., 2010)

Table 6. Details of the chemical treatment of plastic bottles. For specifications of this step see Appendix E.5.

Process	Description process	Efficiency	Database used	Adjustments done on database
Processing of baled PET bottles into bottle-grade PET granulate at factory gate via glycolysis and repolymerization (*Appendix E.5.)*	Treatment of 1.05kg baled PET bottles into 1.03 kg of rPET (bottle-grade) granulate	98 % (L. Shen et al., 2010)	No database used. Process created based on literature data.	NREU use of glycolysis and repolymerization process was taken from L. Shen et al. (2010). Energy requirements for fiber spinning and finishing (TW) was subtracted and SSP was added. The remaining NREU use was fully allocated to heat from gas with an assumed efficiency of 85%.

3.2.2.7. Transport

All transport within the different processing facilities in the recycle chain is taken into account and presented in *Table 7*. The route distances are identified by CE Delft (CE Delft, 2011). For the collection transport distances the standardized transport distances were used from MER-LAP taking into account that distances are smaller when more locations are present in the Netherlands. The remaining transport distances were based on average distances within the Netherlands. Emissions of the transport of losses during the recycle chain to the incineration facility are considered in the incineration waste treatment.

Table 7. Details on transport distances within the EoL-scenarios.

Route	Distance (km)	Mean of transport	Database used	Details
Municipal waste to mechanical recovery facility	35	Collection vehicle	Municipal waste collection service by 21 metric ton lorry {CH}| market for municipal waste collection service by 21 metric ton lorry | APOS, U (*Ecoinvent 3.4*)	Average distance calculated on multiple municipalities – transhipment station distances (Rijkswaterstaat, 2002)
Source separated packaging plastics to transhipment station	35	Collection vehicle	Municipal waste collection service by 21 metric ton lorry {CH}| market for municipal waste collection service by 21 metric ton lorry | APOS, U (*Ecoinvent 3.4*)	Average distance calculated on 19 transhipment stations from SITA and 6 other remaining collection companies (Rijkswaterstaat, 2002)
Deposit packaging via a distribution center to the PET processer	75	Truck	Transport, freight, lorry 16-32 metric ton, EURO5 {GLO}| market for | APOS, U (*Ecoinvent 3.4*)	Based on distance to 3 to 4 deposit PET processors within the Netherlands (Rijkswaterstaat, 2002)
Deposit packaging to chemical recycling plant	225	Truck	Transport, freight, lorry 16-32 metric ton, EURO5 {GLO}| market for | APOS, U (*Ecoinvent 3.4*)	Based on average distances from the middle of the Netherlands (Amersfoort) to the locations of the current pilot plants by Ioniqua (Geleen) and CURE (Emmen) (Own calculation)
Material from facility to AEC	40	Truck	Transport, freight, lorry 16-32 metric ton, EURO5 {GLO}| market for | APOS, U (*Ecoinvent 3.4*)	Based on (M. Corsten et al., 2010)
Source separated packaging plastics to the sorting facility	170	Truck	Transport, freight, lorry 16-32 metric ton, EURO5 {GLO}| market for | APOS, U (*Ecoinvent 3.4*)	Weighted average distance in the Netherlands. Weighting done based on material amounts (CE Delft, 2011)
Post separated packaging plastics to the sorting facility	230	Truck	Transport, freight, lorry 16-32 metric ton, EURO5 {GLO}| market for | APOS, U (*Ecoinvent 3.4*)	Average distance from MRF to processors (CE Delft, 2011)
Sorted plastics to the processor and producer	200	Truck	Transport, freight, lorry 16-32 metric ton, EURO5 {GLO}| market for | APOS, U (*Ecoinvent 3.4*)	Average distance of source separated and post separated plastics back to the Netherlands. It is assumed here that the recycled plastic are processed and used in the Netherlands (CE Delft, 2011)

3.2.2.8. Energy Recovery

Losses during the recycle chain are incinerated with energy recovery. Ecoinvent provides data on the environmental outputs of the incineration of waste PET. This process is called '*Waste polyethylene terephthalate {CH}| treatment of, municipal incineration with fly ash extraction | APOS, U*', which is used. As mentioned in *Section 3.2.2.7*, the transport of waste to the incineration facility is included to this process rather than modelling this step separately. Moreover the recovered energy in the form of electricity and heat is added. Waste incineration facilities in the Netherlands recover on average 20% electricity and 23% district heating in relation to the calorific value of the waste (RvO, 2020). The lower heating value of PET is 22 MJ/kg (TU Delft, 2015; TNO, 2020). The specifications of the avoided energy sources could be found in *Appendix D*. In the long-term scenarios the energy credits for electricity recovery are accounted for the new electricity mix used. The incineration process is both used as complementary in the different waste treatments to account for the losses as well as the reference waste treatments in which all bottles will be send to incineration.

Table 8. Details of the incineration of plastic bottles. For specifications of this step see Appendix I.

Process	Description process	Efficiency	Database used	Adjustments done
Incineration of 1kg of waste PET bottles without energy recovery (*Appendix I*)	This process represents the activity of waste disposal of waste polyethylene terephtalate in a municipal solid waste incinerator	-	Waste polyethylene terephtalate {CH}| treatment of, municipal incineration with fly ash extraction - ER/transport | APOS, U (*Ecoinvent 3.4*)	Transport of waste bottles to incineration facility is added.
Incineration of 1kg of waste PET bottles with energy recovery (*Appendix I*)	This process represents the activity of waste disposal of waste polyethylene terephtalate in a municipal solid waste incinerator	23% heat and 20% electricity recovery (RvO, 2020)	Waste polyethylene terephtalate {CH}| treatment of, municipal incineration with fly ash extraction - ER/transport | APOS, U (*Ecoinvent 3.4*)	Transport of waste bottles to incineration facility is added. Moreover, the recovered heat and electricity is added as an substituted product.

3.2.2.9. Production of the bottles

The results on the life cycle of the small bottles contains the sum of the GWP-impact during the EoL-phase and the GWP-impact of the production. Therefore the production impact of bottles is required. The production process of bottles could be distinguished in two processes (Plastics Europe, 2020). The first process includes the production of the virgin polymer granulate. The database used for virgin PET granulate production is already described in *Table 5*. For the production of the bottles from the polymer granulate a stretch-blow moulding step is required (Plastics Europe, 2020). For this process the Ecoinvent process called '*Stretch-blow moulding {RER}\| production \| APOS, U'* is used. The long-term production process is accounted for the new electricity production mix as described in Appendix B.

3.3. Summary waste treatments and EoL-scenarios

3.3.1. Waste treatments

From the inventory analyses, different waste treatments for small bottles could be distinguished during the short and long-term EoL in the Netherlands. The waste treatments vary on collection method, recycling technology and could also differ in the included short or long-term electricity production mix. In *Appendix F, G and H* the waste treatments of small bottles including the chain efficiencies are visualized within the different scenarios. The characteristics of the waste treatments are summarized in *Table 9*. The reference waste treatments are added which contain the incineration of the full functional unit with and without energy recovery. Results for incineration have been presented with and without energy recovery. The results without energy recovery are calculated by excluding the energy substitution.

- Collection by MSW and mechanically recycled (MSW)
- Collection by MSW and mechanically recycled long-term (MSW+)
- Collection separately at the source and mechanically recycled (SS)
- Collection separately at the source and mechanically recycled long-term (SS+)
- Collection by deposit system and mechanically recycled long-term (DS-MR+)
- Collection by deposit system and chemically recycled long-term (DS-CR+)
- Incineration with energy recovery (In with ER)
- Incineration with energy recovery long-term (In with ER+)
- Incineration without energy recovery (In without ER)

To assess the environmental performance, all waste treatments have a common functional unit being 1kg of collected small plastic bottles. In *Appendix I,* the specifications of the waste treatments are explained where all involved processes and efficiencies are normalized against the functional unit. Due to the fact that sorting and processing efficiencies are assumed the same in the long-term waste treatments, these specifications are applicable for both the short-term and long-term waste treatments. Obviously, the relevant processes in the long-term waste treatments, that are marked in *Appendix I* as well, were accounted for the new electricity production mix.

Table 9. A summarized overview of the waste treatments

	MSW & MSW+	**SS & SS+**	**DS-MR+**	**DS-CR+**	**In with ER, In with ER+ & In without ER**
Collection	1kg of bottles is collected	1kg of bottles is collected	1kg of bottles is collected	1kg of bottles is collected	1kg of bottles is collected
Sorting (from unsorted plastics to sorted bales)	* **22%** of small bottles are recovered * **76%** of bottles are sorted in the PET fraction (DKR 328-1) (M. Brouwer et al., 2019)	* **76%** of bottles are sorted in the PET fraction (DKR 328-1) (M. Brouwer et al., 2019)	* Deposit fraction does not require sorting step **(100%)**	* Deposit fraction does not require sorting step **(100%)**	Not needed
Processing (sorted bales to recycled granulate)	Sorted fraction is converted with efficiency of **88%** (M. Brouwer et al., 2019)	Sorted fraction is converted with efficiency of **88%** (M. Brouwer et al., 2019)	Mechanical recycling of deposit bottles occurs at **95%** (L. Shen et al., 2011)	Chemical recycling of deposit bottles occurs at **98%** (L. Shen et al., 2010)	Not needed
	Sorted fraction substitutes **amorphous** granulate -> Substitution **0.85**	Sorted fraction substitutes **amorphous** granulate -> Substitution **0.85**	Deposit fraction substitutes **bottle-grade** PET granulate -> Substitution **0.90**	Deposit fraction substitutes **bottle-grade** granulate -> Substitution **1.0**	Not needed
Recycling rate	**14.7%** of bottles will be recycled replacing **12.5%** rPET granulate	**66.9%** of bottles will eventually be recycled replacing **56.8%** rPET granulate	**95.0%** of bottles will eventually be recycled replacing **85.5%** rPET granulate	**98.0%** of bottles will eventually be recycled replacing **98%** rPET granulate	Not needed
Losses	Rest is incinerated with energy recovery (20% electricity, 23% heat)	Rest is incinerated with energy recovery (20% electricity, 23% heat)	Rest is incinerated with energy recovery (20% electricity, 23% heat)	Rest is incinerated with energy recovery (20% electricity, 23% heat)	All bottles **(100%)** are incinerated with(out) energy recovery (20% electricity, 23% heat)

3.3.2. EoL-scenarios

The waste treatments are in the scenarios combined to representative EoL-scenarios for the Netherlands. By accounting the waste treatments with the collection rates given in *Section 3.2.4*, the waste treatments could be combined in one short-term scenario and two long-term scenarios. In this section an overview is given of the scenarios including the eventual recycling rates of small PET bottles in the Netherlands. The flow diagrams of the scenarios are visualized in *Appendix F, G and H*. The EoL-scenarios are summarized in *Table 10*.

Table 10. A summarized overview of the short-term and the two long-term EoL-scenarios

	Short-term Scenario	Long-term Scenario (MR)	Long-term Scenario (CR)
Collection	All bottles are collected	All bottles are collected	All bottles are collected
	Separately collected (**58.2%**) & in MSW (**41.8%**)	Separately collected (**8.7%**), in MSW (**6.3%**) & deposit fraction (**85%**)	Separately collected (**8.7%**), in MSW (**6.3%**) & deposit fraction (**85%**)
Sorting (from unsorted plastics to sorted bales)	* **76%** of bottles are sorted in the PET fraction (DKR 328-1) (M. Brouwer et al., 2019)	* **76%** of bottles are sorted in the PET fraction (DKR 328-1) (M. Brouwer et al. 2019) * Deposit fraction does not require sorting step **(100%)**	* **76%** of bottles are sorted in the PET fraction (DKR 328-1) (M. Brouwer et al., 2019) * Deposit fraction does not require sorting step **(100%)**
Processing (sorted bales to recycled granulate)	* Sorted fraction is converted with efficiency of **88%** (M. Brouwer et al., 2019)	* Sorted fraction is converted with efficiency of **88%** (M. Brouwer et al., 2019) * Mechanical recycling of deposit bottles occurs at **95%** (L. Shen et al., 2011)	* Sorted fraction is converted with efficiency of **88%** (M. Brouwer et al., 2019) * Chemical recycling of deposit bottles occurs at **98%** (L. Shen et al., 2010)
	* Sorted fraction substitutes **amorphous** granulate -> Substitution **0.85**	* Sorted fraction substitutes **amorphous** granulate -> Substitution **0.85** * Deposit fraction substitutes **bottle-grade** PET granulate -> Substitution **0.90**	* Sorted fraction substitutes **amorphous** granulate -> Substitution **0.85** * Deposit fraction substitutes **bottle-grade** granulate -> Substitution **1.0**
Recycling rate	**45%** of bottles will eventually be recycled	**85%** of bottles will eventually be recycled	**85%** of bottles will eventually be recycled
Losses	Rest (**55%**) incinerated with energy recovery (20% electricity, 23% heat)	Rest (**15%**) incinerated with energy recovery (20% electricity, 23% heat)	Rest (**15%**) incinerated with energy recovery (20% electricity, 23% heat)

3.4. Differences PEF compared to PET

In terms of environmental input there are no differences assumed in the collection and sorting in the PEF waste treatments. Although the molecular structure of PET and PEF slightly differ, their IR spectrum is significantly different which make them separately recognizable by the near infrared cameras. Only updating the software of these camera would enable them to distinguish the plastic types according to Avantium. Currently, tests are being planned to see how PEF sorting behaves in real practice and if for example the lower weight of PEF could inhibit the sorting accuracy.

PEF is largely compatible with existing recycling equipment according to Avantium. Although PEF could be mechanically recycled with the same performances, two steps are different in terms of environmental requirements, according to Avantium's internal knowledge. The differences are both related to the lower melting point of PEF. At first the SSP of PEF needs to be performed at a lower temperature. Although the process temperature requires less energy, the SSP needs to be done for a longer time to compensate the traction. Moreover, the evaporation of the contaminants from PEF requires more time because of the higher gas barrier characteristics. This has a footnote as well, because on the other hand the contaminants are less penetrated as they are obstructed by the same barrier characteristics. The overall estimated energy requirements for SSP of PEF are minimally the same and maximally 50% higher compared to the SSP of PET. Because the overall impact of SSP is relatively small, the maximum is used in the waste treatments of PEF. The second difference in the mechanical recycling process of PEF compared to PET takes place at the extrusion. Due to the lower melting point, the extrusion of PEF should be done on a temperature of 250 °C instead of 270 °C. Because the data used on extrusion covers the whole process ranging from baled PET bottles processed into PET granulate, the data did not allow to adjust this easily.

Due to the small relative temperature difference in the extrusion phase, and it was found that the heat requirements in the extrusion phase are small (<3%) compared to the heat requirements for washing and drying (RDC Environnement , 2011), this difference was not taken into account.

No differences in chemical recycling have been identified. As data on PET glycolysis and repolymerization was already limited available, data on PEF was not publically available at all. It was also not possible to forecast how PEF would behave in a glycolysis and repolymerization process according to Avantium's internal knowledge. For now, the same requirements are assumed for the glycolysis of PEF. However a range is added to assess the dependency on this assumption. According to Avantium's internal knowledge, a range of 80-120% would cover the extreme differences. This range is incorporated in the results of the PEF waste treatments.

Other differences in the waste treatment that does not relate to the recycling chain itself, are inventoried. One important difference for the PEF waste treatments is the GWP of the PEF granulate production that is substituted due to recycling. In 2017, nova-Institute has investigated the GWP-impact on the PEF granulate production for both the short and long-term which are consistent with the time frames used in this study (nova-Institute GmbH, 2017). The long-term assessment is including the European electricity mix of 2030 and the production at an industrial scale. In their methodology, it was assumed that PEF was made from starch produced from wheat which is yielded in the North-West of Europe. An economic allocation was originally used and it appeared that the use of mass allocation barely impacts the results. Furthermore, the GWP-impact was calculated according to the GWP100a method from IPCC. It was assumed that the byproducts humins are incinerated with energy recovery. Nova-Institute, however, has not taken ILUC-emissions into account. In conclusion, the methodology of nova-Institute on the PET granulate production and the methodology from PlasticsEurope on PET granulate production are quite consistent, making the results suitable for the comparable assessment. The methodology and the results of PET and PEF granulate production are illustrated in *Table 11*. Note that at the time of writing of this report their calculations and assumptions are being reviewed making the results not definitive yet. In the short-term the production of PEF requires more GWP-impact. In the long-term the GWP on PEF granulate production is lower than the GWP related to the PET granulate long-term production due to the influence of economies of scale and production process improvements. Although the impact of modern electricity mix of 2030 and the increased efficiency of the feedstock farming is contributing as well, these influences are minor compared to the influence of economies of scale. The absorbed carbon by the biomass is directly subtracted from the GHG-impact of during PEF granulate production as it is part of the short-term carbon cycle. As a disclaimer, note that the GWP should only be compared on an application basis rather than on a weight basis to account for different polymer functionalities.

Table 11. Methodology and results on GWP on PEF granulate production (nova-Institute GmbH, 2017) and PET granulate production (Plastics Europe, 2017)

	GWP of granulate production in $kgCO_2$ eq. / kg polymer			
	Starch-based PEF		**Fossil-based PET**	
Methodology				
Functional unit	Production of 1kg PEF resin		Production of 1kg PET resin	
Made of	Starch from wheat		Crude oil	
System boundaries	Cradle-to-grave		Cradle-to-grave	
Allocation	Economic / physical allocation		Economic / physical allocation	
Temporal scope	Current and 2030		Current and 2030*	
Geographical scope	West of Europe		North-West Europe	
Technical scope	Current France electricity mix and European electricity use as of 2030		Current European electricity miz and European electricity mix as of 2030	
Assessment method	GWP100a from IPCC		GWP100a from IPCC	
Transport	As far as possible excluded		Only in foreground processes	
Results	Short-term	Long-term	Short-term	Long-term
C (as CO_2) uptake from biomass	-1.93	-1.93	0	0
Polymer production, cradle-to-gate	5.26	3.39	2.19	1.98
Total	**3.33**	**1.46**	**2.19**	**1.98**

***** The long-term PET polymer production is derived in this study by taking into account electricity mix of 2030 as described in *Appendix B*

Furthermore, the carbon content of PEF is lower compared to the carbon content of PET which decreases the incineration emissions. The carbon content from PET is found as 62.5% (TNO, 2020; Y. Yuliusman et al., 2017), whereas the carbon content from PEF is determined at 52.5% based on simple calculations on the molecule structure. Therefore, the resulting GWP-impact from incineration of PEF is calculated as the multiplication of the GWP-impact from incineration of PET and the relative difference in carbon content between the polymers. On the other hand, the substituted energy credits are also less for PEF due to the lower caloric value. For PET the caloric value was found as 22 MJ/kg (TU Delft, 2015; TNO, 2020), whereas the caloric value of PEF was found as 17 MJ/kg based on A. Muralidhara (2019). An overview is given of the differences of PEF waste treatments compared to PET waste treatments that were taken into account in this study in *Table 12.*

Table 12. Overview of the differences of PEF waste treatments compared to PET waste treatments taken into account in this study.

	Collection	**Sorting**	**Mechanical recycling**	**Chemical recycling**	**Others**
PET	-	-			- Substitutes virgin PET granulate production - Carbon content is 62.5% - Caloric value is 22 MJ
PEF	-	-	SSP requires 50% more energy	No differences are identified for the glycolysis and repolymerization process due to lack of data. Therefore a range of 80-120% is used	- Substitutes virgin PEF granulate production - Carbon content is 52.5% - Caloric value is 17 MJ

4. Results

4.1. Life Cycle Assessment 1: Waste treatments

4.1.1. PET Waste treatments

The GWP-impacts of the waste treatments for PET including the normalized contribution of the involved processes are presented in *Figure 12* and *Table 13*. It can be concluded from *Figure 12*, that recycling of PET makes sense as all waste treatments are performing better than the incineration with energy recovery in the related period. It can also be observed that the impact of transport is small in the waste treatments. Moreover, the sorting requirements are small in the SS and SS+ waste treatments, which is also in line with literature. In the MSW and MSW+ waste treatments, the sorting impact becomes more significant because of the additional required recovery step that has a low efficiency. The ranking among the waste treatments that rely on mechanical recycling strongly depend on the recycling rate that in turn is dependent on the collection method. This is the reason that the DS-MR+ waste treatment, which has a recycling rate of 85.5%, is excelling compared to other PET waste treatments. In the MSW and MSW+ waste treatments eventually 85% is incinerated causing few benefits compared the full reference waste treatment. Despite the large recycling rate and the one-to-one substitution, the environmental impact of DS-CR+ is only close to GWP-neutrality due to the intensive glycolysis and repolymerization requirements. The GWP-advantage for chemical recycling could probably be more significant when industrial data is used rather than pilot plant data. However based on the data used, it can be concluded that mechanical recycling is the preferred EoL-option for PET recycling.

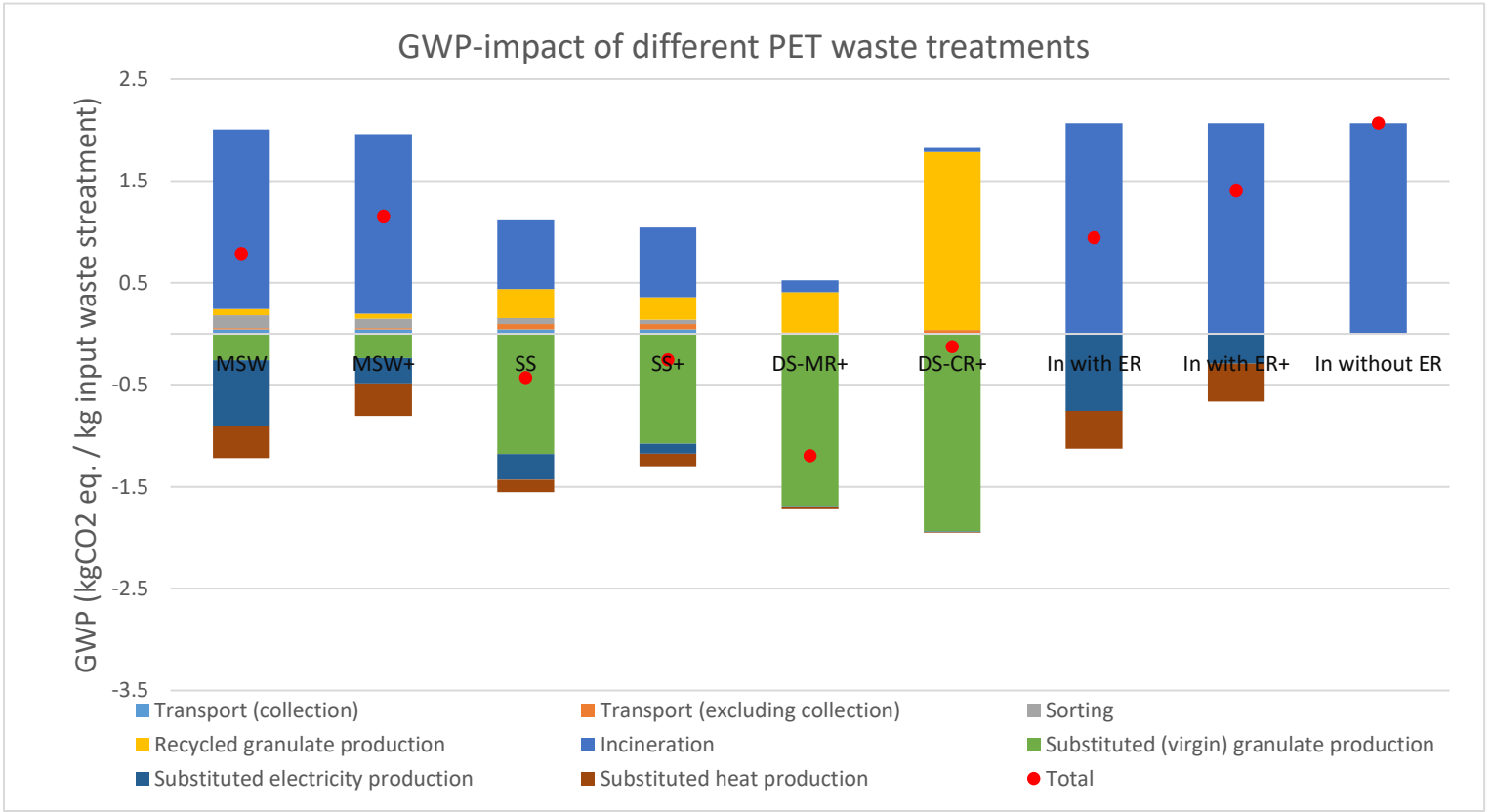

Figure 12. Global warming potential impact of the identified waste treatments of PET in the Netherlands

Striking is more that the total GWP-impact in the long-term waste treatments is slightly worse compared to short-term waste treatments due to the inclusion of the electricity production mix of 2030. Although the cleaner sorting and recycling process of MSW+ leads to approximately 26% GWP-benefits compared to MSW whereas the SS+ saves 23% on this compared to the SS, the long-term waste treatments do not benefit in the end. Apparently, the GWP-win due to cleaner sorting and recycling process weights less than the GWP-loss due to cleaner avoided virgin granulate and electricity production. This difference is especially large in the comparison of 'In with ER' and 'In with ER+' as this waste treatment does not have any benefits.

The findings on the PET waste treatments in this study are compared with other studies to validate robustness. The short-term reference incineration waste treatment is quite well in line with a study to the GWP-impact of current waste treatments of PET trays in the Netherlands (CE Delft, 2019c). The GWP-impact of the incineration of 1kg of PET is more or less the same validating the PET incineration data. However, the substituted energy credits are slightly lower in the study of CE Delft. This can be explained by the different assumed energy recovery rates, which are tending towards a higher relative heat recovery rather than electricity recovery. Although the functional unit used by CE Delft is defined at the gate of the recycling facility rather than at the collection stage used in this study, their results of PET mechanical recycling and chemical recycling are comparable with the DS-MR+ and DS-CR+ waste treatments of this study. No losses have been assumed in the collection and sorting in the waste treatment that rely on the deposit system, making the system boundaries of the functional units comparable. However, the results regarding mechanical and chemical recycling of PET differ significantly with the results of DS-MR+ and DS-CR+. Although the methodology and the background of the data was not well defined, it can be concluded that the study assumed lower environmental impacts and larger environmental benefits related to recycling compared to this study, making their results more desirable. The larger recycling benefits can not only be explained by the one-to-one substitution factor that was assumed, which gives the impression that the avoided virgin PET production has larger GWP-impacts. Unfortunately, the data that was used for virgin PET production could not have been derived. Other results from the European Commission (2018) on the GWP-impact related to the recycling of small PET bottles in Europe assumed that 60% goes to recycling combined with a substitution factor of 0.81. The remainder is being incinerated with energy recovery (20%) and landfilled (20%). In the SS waste treatment a recycling rate of 66.9% with a substitution factor of 0.85 was assumed, making the GWP-impact of the recycling process itself and the substituted PET production quite comparable. The other contributing processes are depending on underlying assumptions which are expected to not represent the Netherlands like energy recovery rates and type of incineration plant. It appears that the GWP-impact as a consequence of sorting and recycling comes out close. Nevertheless, the substituted PET granulate production contains an apprimately 20% larger impact in their study despite of the lower recycling rate and substitution factor that was used. This could be related to the data they used on average European production data in stead of Plastics Europe data that was used in this study. It is therefore decided to apply an sensitivity analyses on the GWP-impact of PET granulate production to test the sensitivity on the use of PlasticsEurope data.

Table 13. GWP-impact of the PET and PEF waste treatments and the difference.

Total costs / benefits ($kgCO_2eq./kg$) per waste treatments			
Waste treatment of 1kg of …	PET	PEF	Difference
MSW	0.79	0.59	0.20
MSW+	1.15	1.07	0.08
SS	-0.43	-1.07	0.64
SS+	-0.26	0.01	-0.26
DS-MR+	-1.21	-0.73	-0.48
DS-CR+	-0.13	0.42	-0.55
In with ER	0.94	0.87	0.07
In with ER+	1.40	1.22	0.18
In without ER	2.07	1.74	0.33

4.1.2. PEF Waste treatments

Based on the adjustments for PEF in the waste treatments described in *Section 3.4,* the results are presented in *Figure 13* and *Table 14*. The biogenic emissions are not added up in the totals as these were also taken up by the wheat growth and therefore part of the short-term carbon cycle. In the DS-CR+ waste treatment the uncertainty range was included. As the sorting and collection are considered the same for PEF, the transport and sorting requirements have still a low impact. It was also found that the larger SSP requirements for PEF needed in the DS-MR+ and DS-CR+ waste treatments still have a small impact on the results. The GWP-impact becomes only 10% higher in the mechanical recycling process and 3% higher in the chemical recycling process. However, other significant differences exist compared to PET waste treatments. Mechanical recycling still performs better than chemical recycling, making it the preferable EoL-option for PEF as well. However, the SS waste treatment appears to have the highest environmental benefits rather than the DS-MR+ waste treatment despite the substantial lower recycling rate. This is due to the avoided short-term PEF granulate production that has relatively high GWP-impacts that compensated the larger recycling rate in the long-term. Due to the same reason, PEF recycling in the short-term is more beneficial in terms of GWP compared to the recycling of PET, as illustrated in *Table 14*. In the long-term, PEF recycling becomes less beneficial in the SS+, DS-MR+ and DS-CR+ waste treatments compared to PET. Although the greener electricity mix is contributing, this can mainly be explained by the GWP of optimized PEF granulate production being lower than the GWP of PET granulate production leading to lower recycling credits for PEF recycling. This turns even the negative emissions achieved in the SS+ and DS-CR+ waste treatments for PET into positive emissions for the same waste treatments for PEF. Only the long-term PEF waste treatment MSW+ remains beneficial compared to its PET variant. This is explained by the low recycling rate resulting in a low dependency on the type of substituted polymer. Moreover, the incineration of PEF is more advantageous in terms of GWP. Apparently, the lower carbon content is of larger influence than the lower caloric value and thus the consequential lower substituted energy credits favouring PEF. Due to the reduced electricity credits in the long-term, PEF incineration becomes even more beneficial compared to PET incineration. The gap is thus increasing between PEF incineration and PET incineration over time in terms of absolute and relative values. In general, it can be concluded that the performance of the waste treatments are highly dependent on the substituted GWP of granulate production, which is largely dependent on the type of polymer, and in the case of PEF if the short or long-term granulate production is avoided.

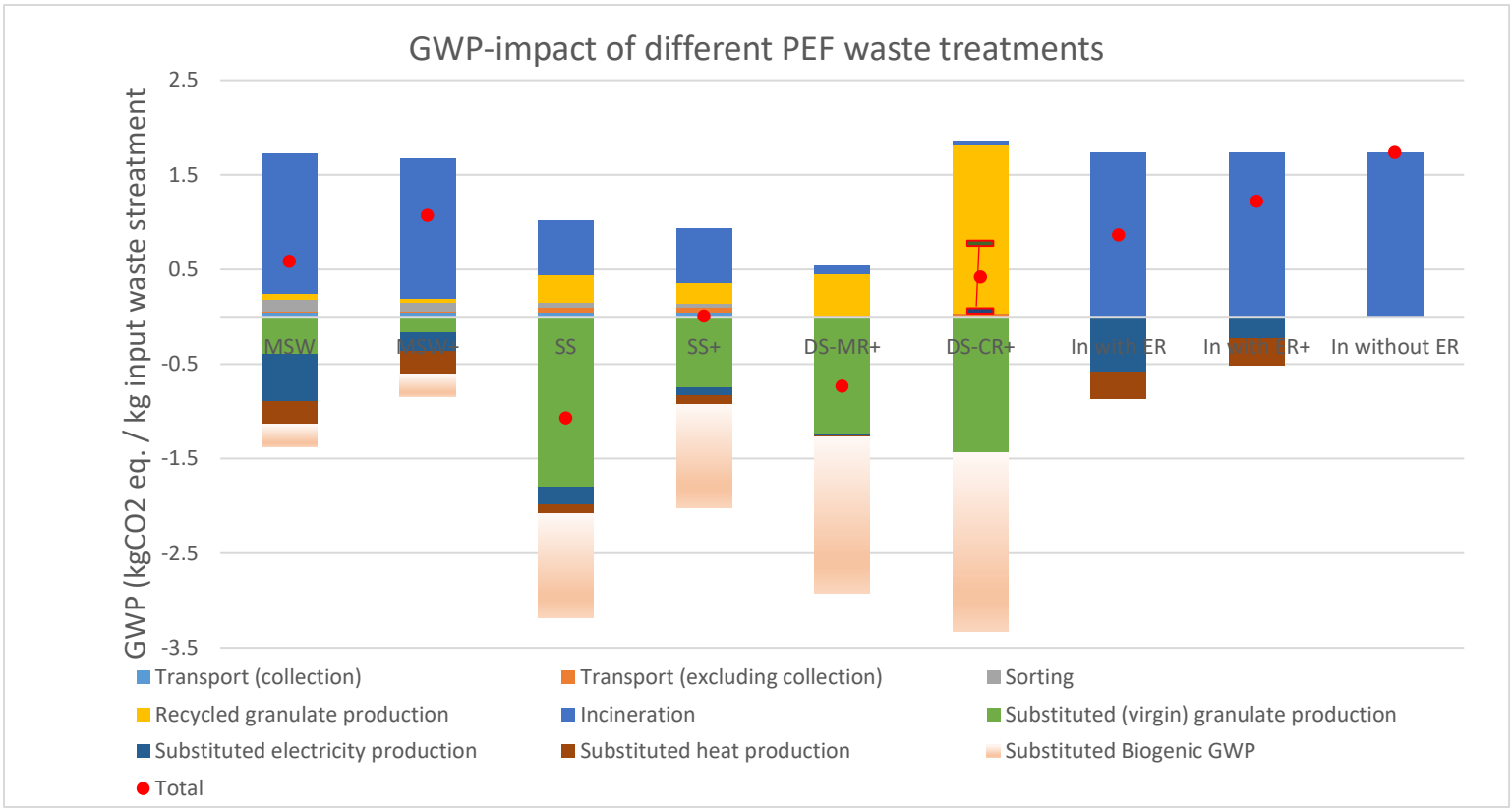

Figure 13. Global warming potential impact of the identified waste treatments of PEF in the Netherlands. An uncertainty bar was included in the DS-CR+ waste treatment as no data has been found on the glycolysis and repolymerization of PEF.

4.2. Life Cycle Assessment 2: Single bottle

In this section the GWP-impact of the life cycle of a single small bottle made of PET and PEF with an equal shelf life is assessed. The different weights of the bottle are thus included in this LCA. In *Figure 14*, the impact of the GWP-impacts over the full life cycle including different EoL-scenarios of a small PET bottle (weighting 26 grams) is given. The GWP-impact is distinguished in PET granulate production, the stretch-blow moulding process and the EoL. The bottle production is added as well which could be seen as a theoretical reference of the GWP-impact of the full life cycle in which no EoL is assumed simulating the permanent storage of the used bottles. The impact of the stretch-blow moulding process is significant compared to the granulate production. In the short-term this process accounts for 36% to the bottle production whereas the contribution decreases in the long-term until 26% due to the cleaner electricity use. The production impact of a PET bottle decreases from 88 g CO_2 eq./bottle in the short-term to 70 g CO_2 eq./bottle in the long-term. This is a reduction of 21%, which could all be owed to the greening electricity production mix. The EoL highly contributes to the life cycle impact of a PET bottle as can be observed from *Figure 14*. Although, in the short-term the EoL based on mechanical recycling adds 2% of the GWP-impact compared to the production, the EoL saves 20% GWP-impact compared to incineration with energy recovery. In the long-term the EoL-scenario based on mechanical recycling reduces the PET bottle life cycle with 37% compared to the bottle production and 58% compared to incineration. Although the same recycling technology is used the benefits are higher in the long-term mainly due to the higher recycle rate. The EoL-scenario based on chemical recycling causes GWP-impact reductions of 2% and 36% over the life cycle compared to respectively the bottle production and incineration with energy recovery.

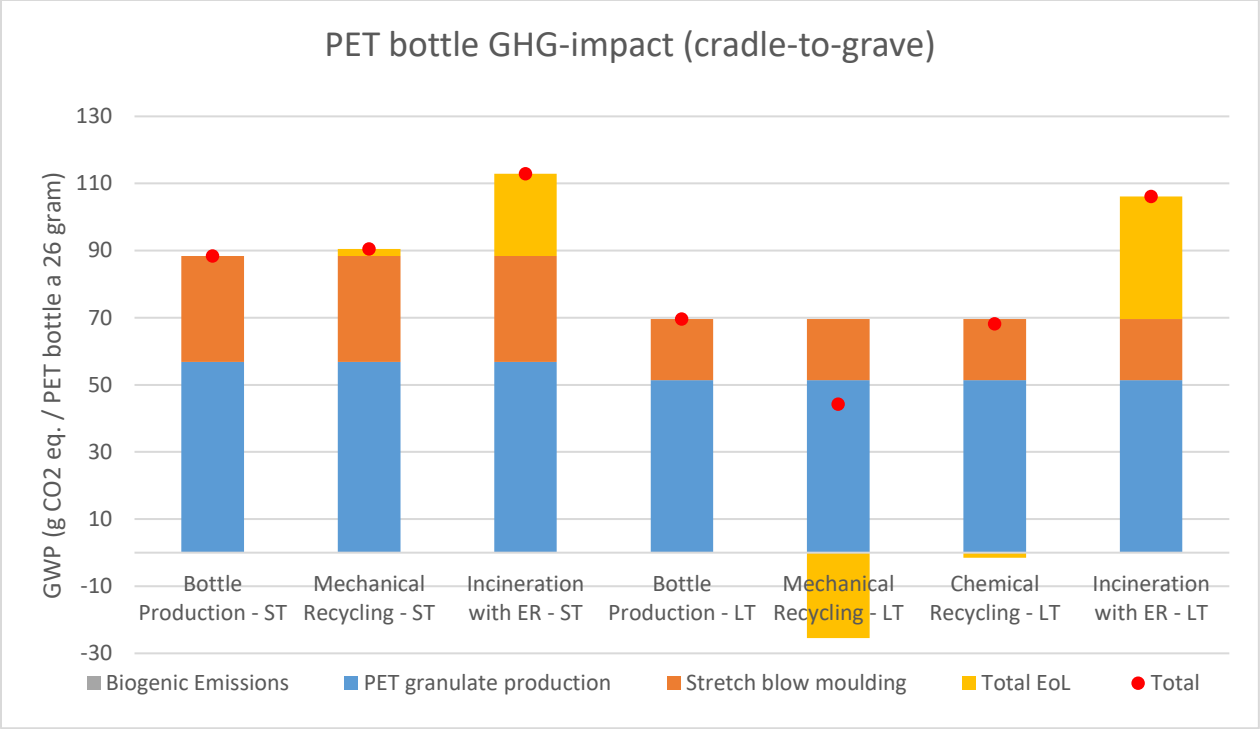

Figure 14. The GWP-impact of the life cycle of one PET bottle containing 250 ml of beverage and providing a shelf life of 12 weeks produced in Europe and disposed in the Netherlands weighting 26 grams. ST = short-term and LT= long-term.

In *Figure 15*, the same results are shown for the small PEF bottle (weighting 10 gram). In the case of the small PEF bottle, the avoided biogenic emissions are shown as well, but again not included in the totals as these are assumed to be avoided. The range from the uncertainty of chemical recycling of PEF is included as well. In contradiction to the PET bottle, the stretch-blow moulding process contributes in the short-term less (27%) than in the long-term (33%). Although the greener electricity production mix is decreasing the GWP-impact of stretch-blow moulding, the granulate production GWP-impact reductions play an even larger role. The overall production GWP-impact of one PEF bottle is decreasing from 45 CO_2 eq./bottle to 21 CO_2 eq./bottle, which is equivalent with a reduction of 52%. This is explained by the more renewable electricity mix, but most importantly due to the optimization of PEF granulate production in the long-term. Again, it could be observed that EoL-choices for PEF could significantly influence the GWP-impact of the life cycle. The short-term EoL-scenario reduces the life cycle impact of PEF by 8% compared to the production impact and 23% compared to incineration with energy recovery. In the long-term, mechanical recycling of PEF leads to 26% and 53% reductions in the life cycle of one PEF bottle compared to respectively bottle production and incineration. The long-term EoL-scenario based on chemical recycling leads to an increase of 20% compared to the production and a decrease of 24% compared to incineration with energy recovery. Given the uncertainty range on the EoL-impact based on chemical recycling, it could not reach reductions in the life cycle of the PEF bottle compared to the production. According to the relative EoL-impacts on the life cycle of PEF compared to PET, PEF recycling generated higher GWP-impact reductions on the life cycle in the short-term, whereas PET does in the long-term. This is in line with the results from the waste treatments. Note, that the life cycle results of a PEF bottle could change if Nova-Institute releases updated results on the PEF granulate production.

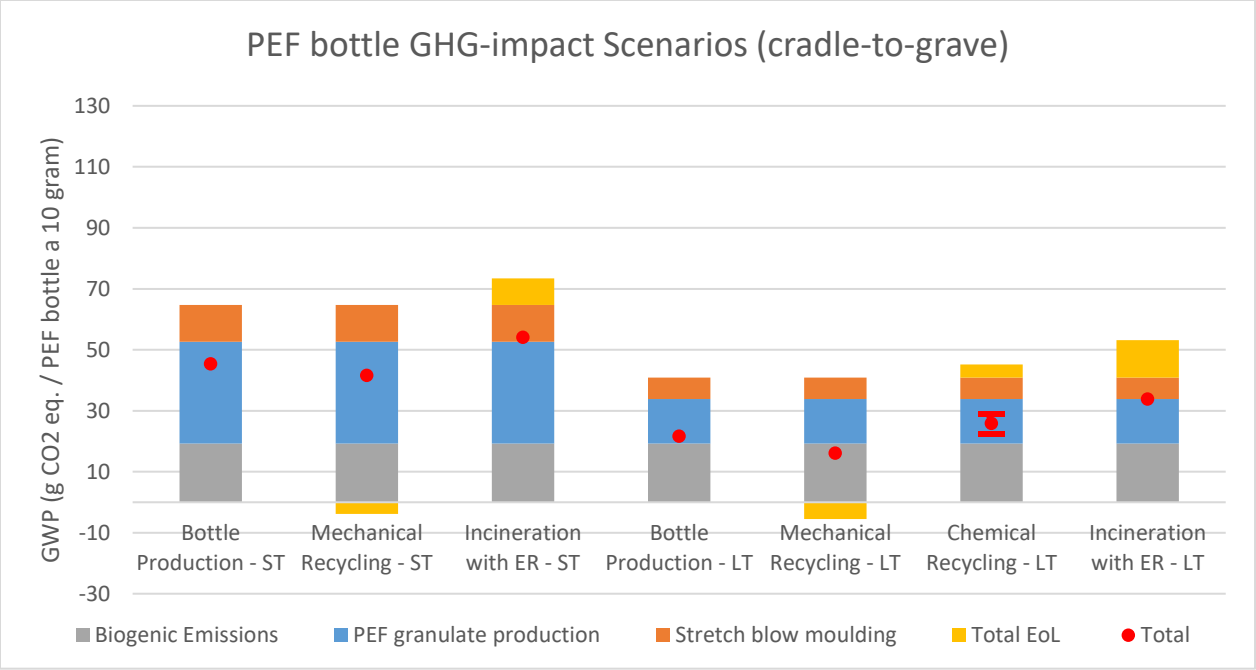

Figure 15. The GWP-impact of the life cycle of one PEF bottle containing 250 ml of beverage and providing a shelf life of 12 weeks produced in Europe and disposed in the Netherlands weighting 10 grams. ST = short-term and LT= long-term.

The total GWP-impacts from cradle-to-grave including different EoL-choices for one PET and PEF bottle is shown in *Figure 16*. In *Table 14,* the total GWP-impact results for both bottle types are presented next to each other including the absolute and relative differences. It could be observed that the life cycle GWP-impact of a PEF bottle is significantly lower than a PET bottle, regardless of the EoL-scenario. Even if the carbon absorbed by the biomass is not assumed to be avoided, it could be seen that the life cycle of a PEF bottle consistently performs better.

When comparing the life cycle of a PET and a PEF bottle, the impact of EoL has some minor influences in the relative cradle-to-grave differences. As can be derived from *Table 14*, the relative advantage over the life cycle of using PEF in the long-term is larger compared to the short-term, despite that PEF recycling appeared to be less beneficial in the long-term compared to PET recycling. This could be explained by the even larger dependency on the polymer granulate production during the production phase, which weights out the substitution impact of the polymer's granulate production during the EoL. The disadvantageous PEF recycling credits compared to PET recycling in the long-term, will be compensated by the higher advantages resulting from the PEF granulate production required during the bottle production. In other words, as long as the recycling rate is not 100%, the influence of the granulate production on the whole life cycle GWP-impact will always be larger than the counteracting GWP-impact of the EoL. This explains why the relative advantage of using PEF is especially emphasized in the long-term when no EoL (only bottle production) is considered. When recycling is included, the relative advantage of the PEF bottle is counteracted, confirmed by *Table 14*. Due to the same reason, the relative advantage for PEF is least in the short-term PEF bottle production (without EoL). In the short-term applies that including recycling would increase the relative advantage of PEF as PEF recycling bears higher environmental credits compared to PET recycling in the short-term. *Table 14* confirms also that the relative advantage of PEF incineration becomes larger in the long-term in terms of relative and absolute GWP-impacts compared to PET incineration. This is due to the lower dependency from PEF on the obtained energy credits.

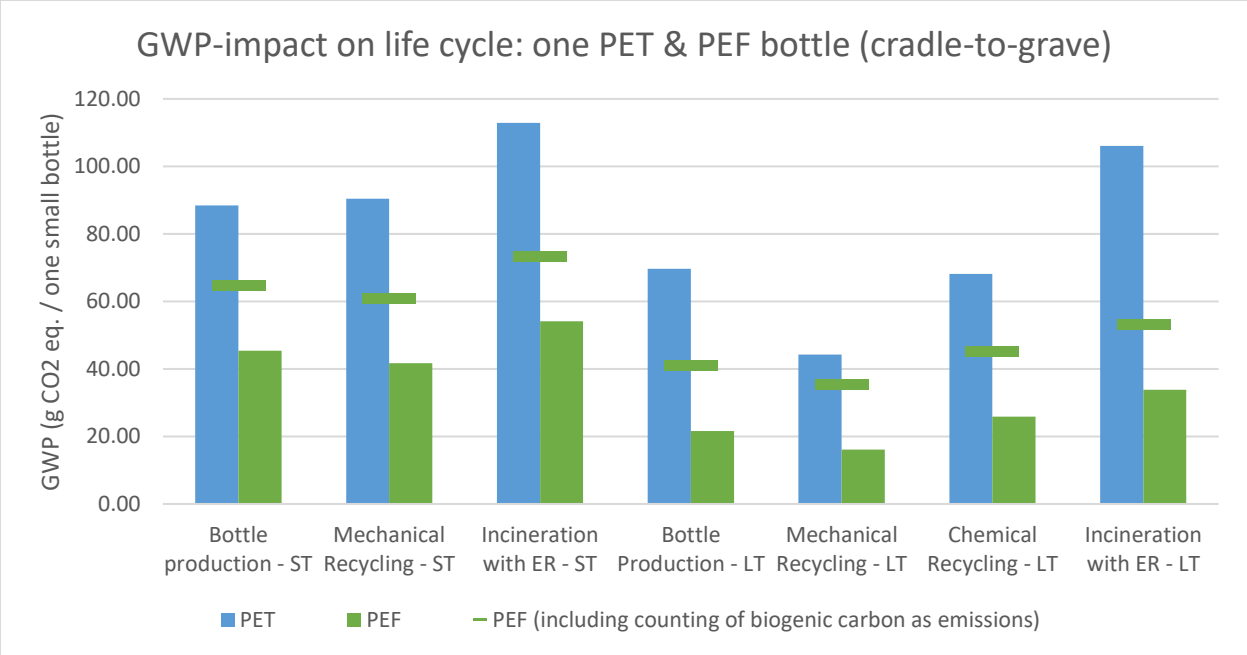

Figure 16. A comparative assessment on the GWP-impact over the full life cycle of a single small (250 ml) beverage bottle with a shelf life of 12 weeks, made from PET or PEF disposed in the Netherlands. ST = short-term and LT= long-term.

Table 14. GWP-impact of the PET and PEF bottles. Green is in favour of PEF bottles.

Total life cycle impacts in gCO_2 eq. per bottle providing shelf life of 12 weeks				
Life cycle of one bottle	PET	PEF	Absolute Difference	Relative Difference
Bottle Production - ST	88.4	45.4	43.0	48.6%
Mechanical Recycling - ST	90.5	41.7	48.8	53.9%
Incineration with ER - ST	112.9	54.1	58.8	52.1%
Bottle Production - LT	69.7	21.6	48.0	68.9%
Mechanical Recycling - LT	44.2	16.1	28.1	63.6%
Chemical Recycling - LT	68.1	25.9	42.3	62.0%
Incineration with ER - LT	106.1	33.9	72.2	68.1%

In *Figure 17* the GWP-impact of the full life cycle of 1 kilogram of small PET bottles and 1kg of small PEF bottles is shown which serves as a clarification on previous results. Because 1kg of PEF is containing 2.6 times as much small bottles as 1kg of PET, the function is not equal, making the results not one-to-one comparable. When the life cycle of 1kg of PET and PEF small bottles are compared here, the results do show that the impacts are much more converging than when taking into account the different weights as done in the bottle-to-bottle comparison. This indicates that the light weighting of bottles could play a major role in decreasing the GWP-impact over the life cycle. From *Figure 17*, it could also be observed that the GWP-impact of granulate production has a higher cost than it serves as a benefit during the EoL. This is represented in the short-term by the higher GWP-impact of 1kg PEF bottles over the life cycle compared to 1kg of PET bottles. Vice versa this is valid for 1kg of PET bottles in the short-term that bears higher impacts if 1kg of bottles are considered.

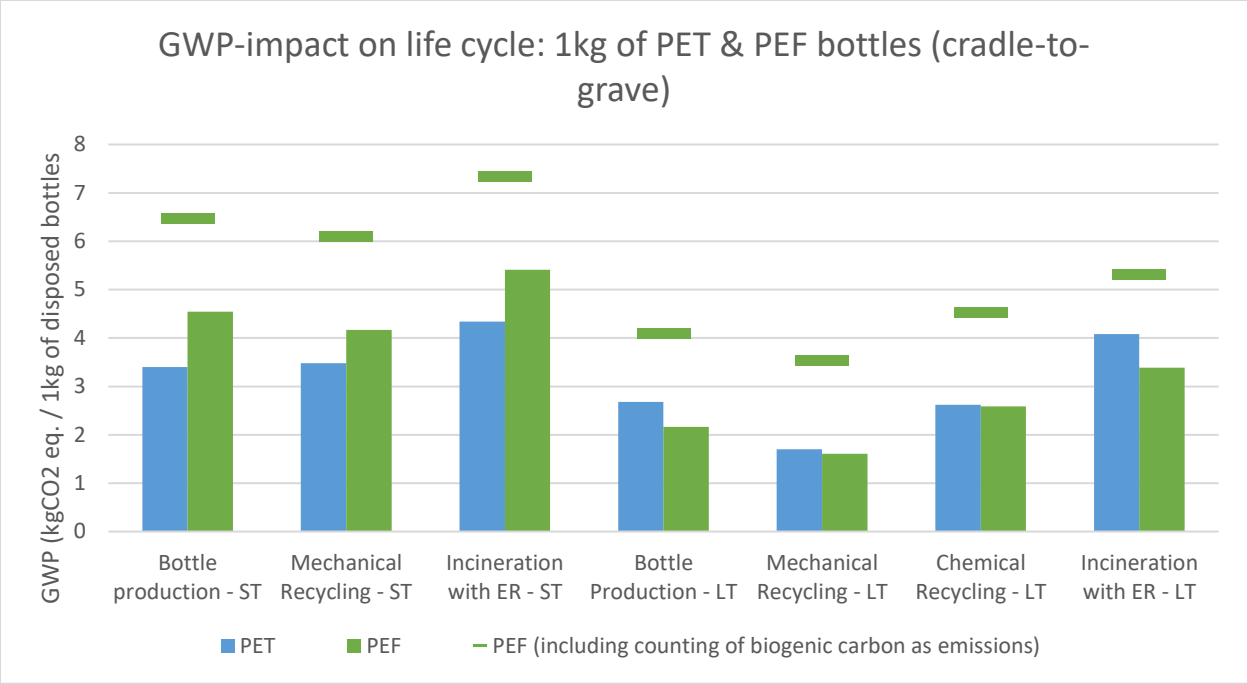

Figure 17. A comparative assessment on the GWP-impact over the full life cycle of 1k of small bottles, made from PET or PEF disposed in the Netherlands. ST = short-term and LT= long-term.

5. Discussion

5.1. Sensitivity analyses

In this study two major uncertainties are identified. In the uncertainty analyses their impact on the results of both the waste treatments and the life cycle of the bottles is assessed.

- At first, the substitution factor is taken into account. The uncertainty range of the substitution factor for both PET and PEF is based on the findings of G. Faraca et al. (2019). The authors reviewed fifteen articles that used substitution factors for mechanically recycled PET. The substitution factors for rPET used among the different articles lay between 0.81 and 1.0. Therefore, in the lower case the uncertainty of 0.81 is used in this study for all mechanically recycled PET and PEF, regardless of the collection method. However, the chemically recycled plastics are stuck to the one-to-one substitution in the lower case. In the upper case, the substitution factor of 1.0 is applied on all waste stream, regardless of the recycling technology and collection method, implying that all recycled plastic is replacing virgin material. In the sensitivity analyses on the waste streams the relative change in the variable is just calculated as the relative difference between the original and the extreme substitution factor. This approach was not suitable in the case of the sensitivity analyses on the life cycle of bottles, because the included EoL contains multiple waste streams with different substitution factors at the same time. Therefore, the relative change in the variable is calculated based on the relative difference of the totally assumed substituted plastic production in the EoL-scenarios between the normal situation and the extreme situation.
- Secondly, the GWP-impact of the granulate production is taken into account to perform a sensitivity analyses. For both PET and PEF granulate production, the data used contains uncertainties. In the case of PEF granulate production, the related GWP-impact used was based on the results of nova-Institute, which were updating their results at the time of this writing this report. The used PEF granulate production data are from 2017 and were for example not including ILUC-emissions (nova-Institute GmbH, 2017). Regarding PET granulate production, the related data on GWP-impact differ extensively between the existing databases. In this study, the database of Plastics Europe is used on virgin PET granulate production, which are criticized for including data of more modern installations than older ones resulting in lower GWP-impacts compared to Ecoinvent data. As a result the Ecoinvent data on PET granulate production contains a 51% higher GWP-impact compared to Plastics Europe data. Although, the geographical scope of this study is more likely to represent the Plastics Europe data, an uncertainty analyses is performed on the GWP-impact on the PET granulate production. Therefore, the PET production impact of the Ecoinvent data base is used as an upper limit for both PEF and PET granulate production. A lower limit of 80% is used.

In *Section 5.1.1* the influence of the uncertainty of both variables on the results of the waste treatments are presented. In *Section 5.1.2* the influence on the results of the bottle life cycle is shown.

5.1.1. Sensitivity analyses on waste treatments

Figures 18 and 19 are including the sensitivity analyses of the waste treatments of respectively PET and PEF including both uncertainty factors being the substitution factor and the GWP-impact related to granulate production. The range of the substitution factor is given by the uninterrupted lines (SF) and the range of the GWP-impact of the granulate production is given by the dashed lines (GP). For the DS-CR+ waste treatment, no extreme substitution factors are assumed, which is reflected by the single dot. It can be observed from *Figure 18 and 19* that the uncertainty ranges per waste treatment are overlapping each other. This can be explained by the fact that both uncertainties relate to the GWP-emissions saved by the substituted virgin granulate production. However, due to the relative larger uncertainty range in the GHG-intensity of granulate production, this line is longer and therefore forms a larger absolute uncertainty. As a consequence of the relationship to the substituted virgin granulate production, the slope of the uncertainties depend on the recycle rate, resulting in an unequal sensitivity per waste treatment. Whereas the MSW and MSW+ waste treatments are relatively little sensitive to the uncertainties, the DS-MR+ and DS-CR+ waste treatments are more impacted. For PET this is also valid in absolute terms with DS-CR+ having the largest absolute uncertainty differing between 0.26 $kgCO_2eq$ and -1.22 $kgCO_2$ due to the highest recycle rate. For PEF the SS waste treatment has the highest absolute uncertainty amounting from -0.71$kgCO_2eq$ until -1.99 $kgCO_2eq$. This because the absolute uncertainty is a function of the GWP-impact related to the granulate production which is much higher in the short-term than in the long-term. Generally, waste treatments benefit from a higher GWP-impact of granulate production due to the higher attributed recycling credits, as could be observed from *Table 15*.

Table 15. The extreme GWP-impacts ($kgCO_2$ eq. / kg input waste treatment) of the PET and PEF waste treatments as a result of the uncertainty in granulate production.

	PET ($kgCO_2$ eq. / kg)			**PEF ($kgCO_2$ eq. / kg)**		
	Min	Max	Difference	Min	Max	Difference
MSW	0.84	0.65	0.18	0.67	0.39	0.28
MSW+	1.20	1.03	0.17	1.10	0.99	0.12
SS	-0.19	-1.03	0.84	-0.71	-1.99	1.27
SS+	-0.04	-0.81	0.77	0.16	-0.38	0.54
DS-MR+	-0.87	-2.07	1.20	-0.48	-1.37	0.88
DS-CR+	0.26	-1.12	1.38	0.71	-0.31	1.01

In general, the rankings of the waste treatments are robust and does hold almost completely while subjected to given uncertainty ranges. Only the position of the DS-CR+ waste treatment shifts compared to the other waste treatments in case of extreme GWP-impacts related to granulate production. In case of high GWP-impacts of granulate production for PET, the DS-CR+ waste treatment is performing better due to the high recycle rate, than the SS and SS+ waste treatments, despite of the intense glycolysis requirements. In case of low GWP-impacts of granulate production for PEF, the position of the DS-CR+ waste treatment is overtaken by the MSW treatment despite of the much higher recycle rate. Note here that, the short-term and the long-term waste treatments for PEF are compared which differ already largely in the granulate production intensity.

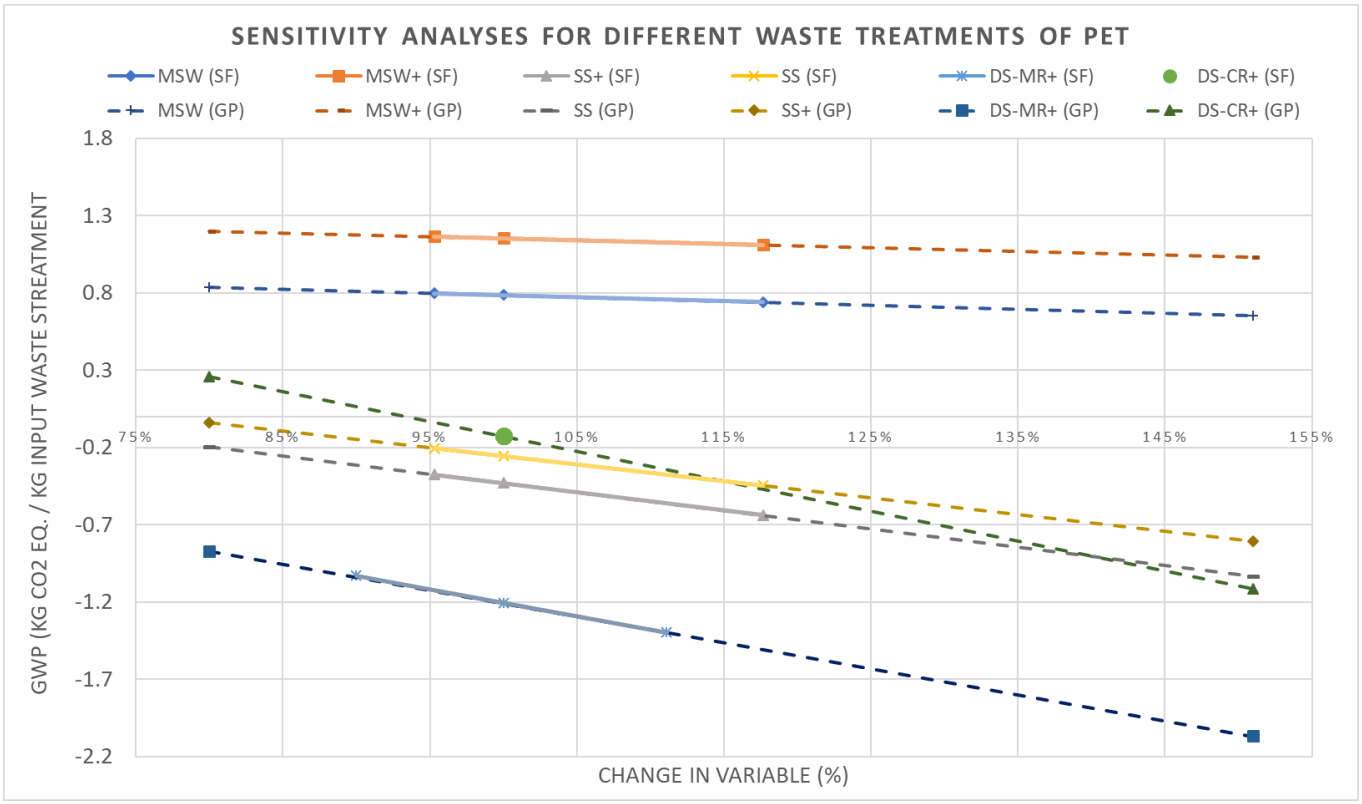

Figure 18. The sensitivity analyses on the GWP-results of the PET waste treatments including both variables. The uninterrupted lines are representing the uncertainty range of the substitution factor (SF) and the dashed lines are representing the uncertainty range of the PET granulate production (GP).

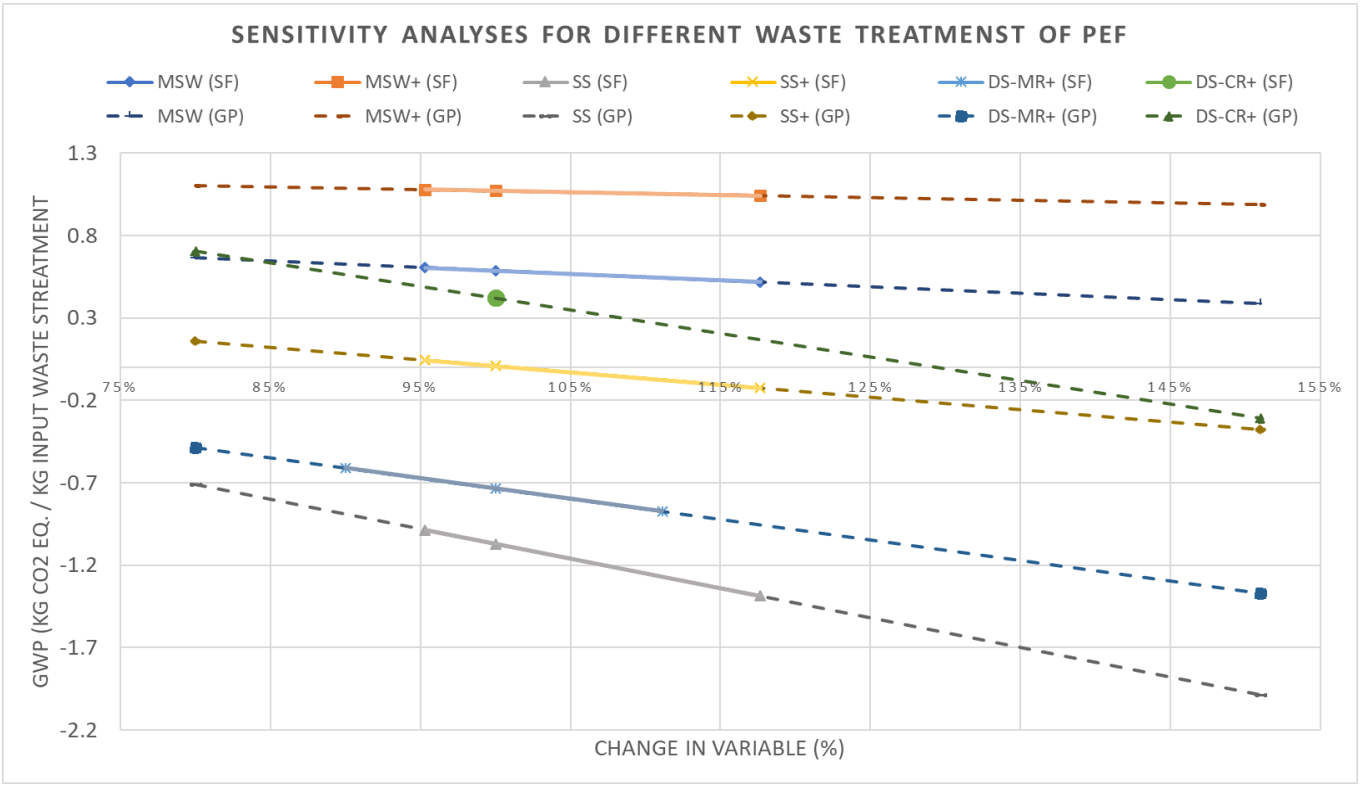

Figure 19. The sensitivity analyses on the GWP-results of the PEF waste treatments including both variables. The uninterrupted lines are representing the uncertainty range of the substitution factor (SF) and the dashed lines are representing the uncertainty range of the PEF granulate production (GP).

5.1.2. Sensitivity analyses on life cycle of single bottle

In *Figure 20 and 21* the sensitivity analyses on the GWP-impact of the life cycle is presented for respectively the PET bottle and the PEF bottle including the different EoL-scenarios. Again, the range of the substitution factor is given by the uninterrupted lines (SF) and the range of the GWP-impact of the granulate production is given by the dashed lines (GP). The life cycle impacts on the production of bottles without EoL and with incineration including energy recovery are presented as well with their related uncertainty. As no virgin granulate is substituted in these reference life cycles, these results are not sensitive for the substitution factor reflected by the single dots. On the other hand these reference scenarios have the steepest slope caused by the uncertainty on the granulate production GWP-impact, indicating that they are most sensitive for the uncertain GWP-impact related to the granulate production, as can be seen from *Figure 20 and 21*. As these reference life cycles do not substitute granulate production in the EoL, only the influence of the GWP-impact of the granulate production during the bottle production is forcing the results. In case virgin granulate is substituted during the EoL, the avoided granulate production counteracts the uncertainty involved in the production phase and thus tends towards equilibrium. This equilibrium could theoretically be achieved if the recycle rate is 100% combined with an optimal substitution. As can be seen from *Figure 20 and 21*, the slopes of the life cycles including the long-term recycling EoL-scenarios, which have the highest, recycle rates, are almost linear. However, the influence of the granulate production during the production phase is still dominant, resulting in a higher GWP-impact from a life cycle perspective when having higher granulate production requirements. Moreover, it could be observed from *Figure 20 and 21* that the order of the life cycles of PET and PEF bottles including an EoL-scenario is not changing given the used uncertainty ranges. The extreme ranges of the life cycle impacts from a small PET bottle and a small PEF bottle as a consequence of the uncertainty in the granulate production are presented in *Table 16*. The results of the life cycle including the short-term EoL-scenario of a PET bottle range from 83 gCO_2 eq. / bottle to 109 gCO_2 eq. / bottle. The long-term life cycle impact of a PET bottle treat by mechanical recycling and chemical recycling obtains respectively ranges of 42 gCO_2 eq. / bottle to 50 gCO_2 eq. / bottle and 67 gCO_2 eq. / bottle to 71 gCO_2 eq. / bottle. For PEF these ranges are 36 gCO_2 eq. / bottle to 57 gCO_2 eq. / bottle in the short-term, 14 gCO_2 eq. / bottle to 22 gCO_2 eq. / bottle in long-term mechanical recycling and 23 gCO_2 eq. / bottle to 33 gCO_2 eq. / bottle in long-term chemical recycling. These results show that the uncertainty as a result of the granulate production impact reduces if the recycling rate becomes higher. Although not presented, this is the same for the substitution factor; the larger the substitution factor assumed, the lower the uncertainty is of the GWP-impact of the life cycle.

Table 16. The extreme GWP-impacts (gCO_2 eq. / bottle) of the PET and PEF life cycles as a result of the uncertainty in granulate production.

	PET (g CO_2 eq. / bottle)			**PEF (g CO_2 eq. / bottle)**		
	Min	Max	Difference	Min	Max	Difference
Bottle production - ST	77	117	-40	39	62	-24
Mechanical Recycling - ST	83	109	-26	36	57	-21
Incineration with ER - ST	102	142	-40	47	71	-24
Bottle Production - LT	59	96	-36	19	29	-10
Mechanical Recycling - LT	42	50	-8	14	22	-8
Chemical Recycling - LT	67	71	-4	23	33	-10
Incineration with ER - LT	96	132	-36	31	41	-10

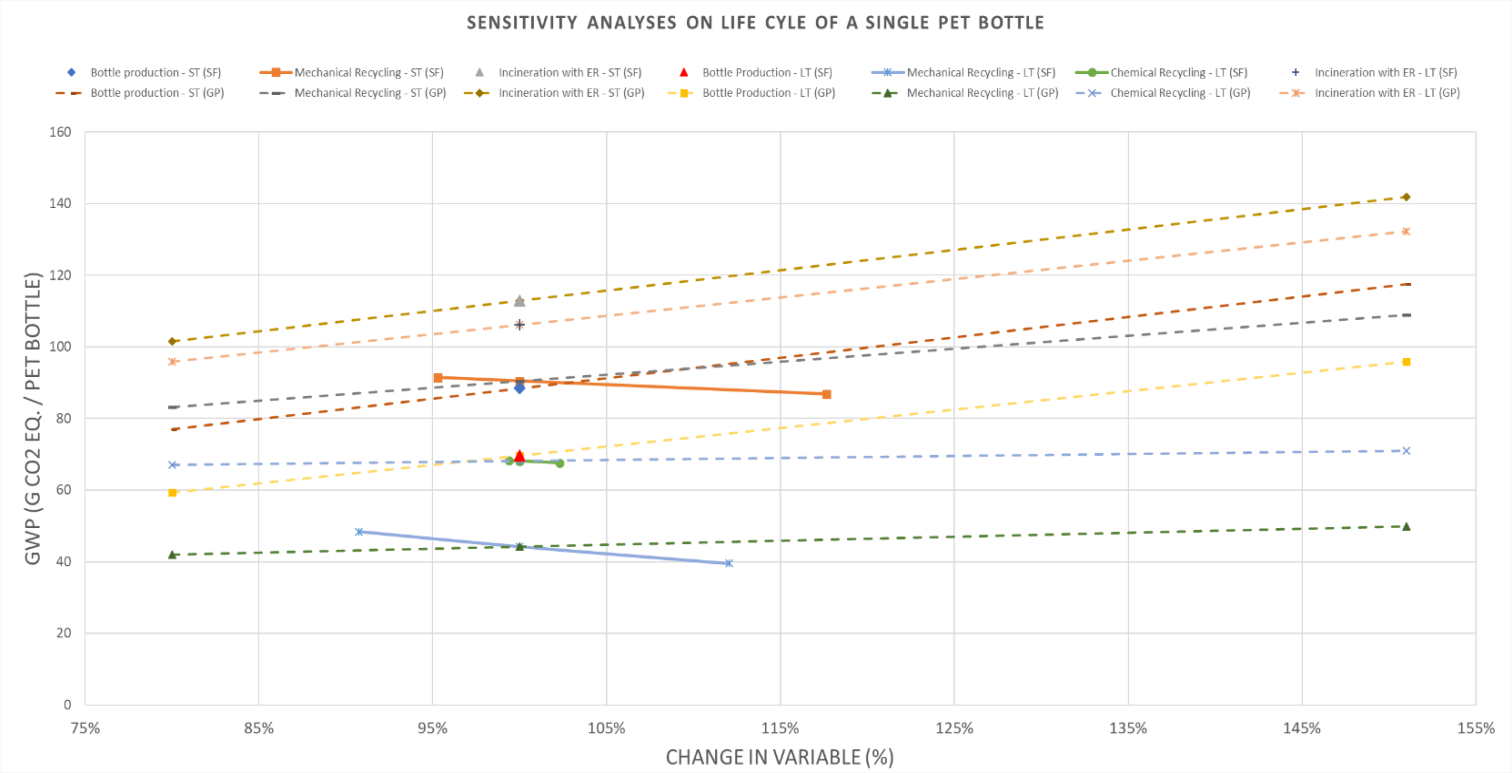

Figure 20. The sensitivity analyses on the GWP-results of PET bottle life cycle including both variables. The uninterrupted lines are representing the uncertainty range of the substitution factor (SF) and the dashed lines are representing the uncertainty range of the PET granulate production (GP).

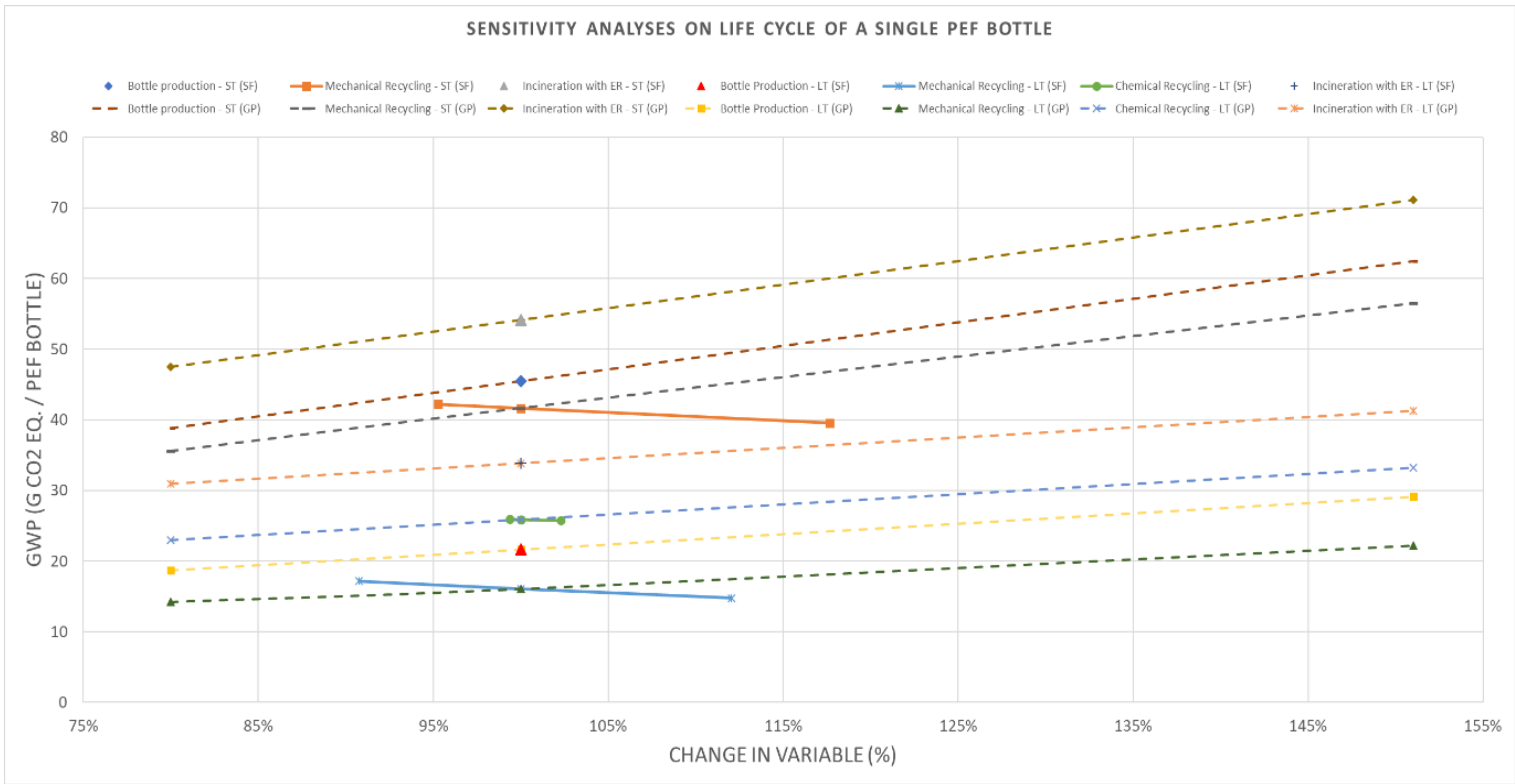

Figure 21. The sensitivity analyses on the GWP-results of PEF bottle life cycle including both variables. The uninterrupted lines are representing the uncertainty range of the substitution factor (SF) and the dashed lines are representing the uncertainty range of the PEF granulate production (GP).

5.2. Indirect land use change emissions

As the GWP-impact on the PEF granulate production was not including the ILUC-emissions (nova-Institute GmbH, 2017), these are not considered yet in this study. ILUC-emissions could take place when bio-feedstock is produced on existing agricultural land and consequently somewhere else the food and feed have to be produced in order to meet the constant demand. This can result into land use change, which could result in CO_2 emissions by for example deforestation (European Commission, 2012). Here, the ILUC-contribution is calculated for the PEF bottle in order to get an impression of the importance. The European Commission used a standardized method to account for ILUC-emissions in their assessment (European Commission (Draft), 2020). The ILUC-contribution due to GHG-emissions derived from land clearing should be quantified by applying the ILUC-factors proposed in the EU 2015/1513 Directive (European Commission, 2015). These ILUC-factors were reported per type of crop required (differing between starch-rich, sugar-rich, and oil-rich) as gram CO_2-eq / MJ. By multiplying this factor with the typical yield per strain adapted from H. Valin et al. (2015) another ILUC-factor expressed in $kgCO_2$-eq / $ha^{-/}$ a could be obtained. The results of this are presented in Table *17*. If this factor is multiplied by the land demand given in ha / functional unit, the ILUC-contribution per PEF bottle could be obtained. A. Eerhart et al. (2012) reported a land requirement of 0.23 ha of corn starch for the required FDCA production for one tonne of PEF. Note that this production route is based on starch, which is assumed as well by nova-Institute (although from wheat starch). Based on this and the weight of one PEF bottle (e.d. 10 gram) it could be derived that the ILUC-contribution for the production of one bottle is approximately 1.4 gCO_2-eq, which is roughly 4% and 10% compared to respectively the short and long-term PEF granulate production GWP-impacts. It is important to note that the research into ILUC-factors is still under development (A. Eerhart et al., 2012).

Table 17. GHG contribution as a consequence of ILUC recalculated on the basis of the figures in EU 2015/1513 (European Commission, 2015)

	Unit	Starch-rich	Sugar-rich	Oil-rich
ILUC-factor	gCO_2-eq. MJ^{-1}	12	13	55
Yield	MJ ha^{-1} a^{-1}	51000	135000	37000
ILUC-factor	$kgCO_2$-eq. ha^{-1} a^{-1}	612	1755	2035
Amortization time	a	20	20	20
ILUC-factor	$kgCO_2$-eq. ha^{-1}	12240	35100	40700

5.3. Limitations and other uncertainties

In the short-term PEF is assumed to be co-recycled with PET into bottle-grade material. This assumption is at least applicable until a market penetration of 2% compared to PET packaging plastics in Europe is reached which equalizes the allowable production of 50-70 metric tons (EPBP, 2017). Although Avantium claims that higher percentages until 10% of co-recycling does not affect the quality of the recycled mix, this needs to be verified. In this study the long-term horizon is determined based on the moment in which PEF has appropriated an own sorting stream. This occurs when the share of PEF has achieved a fraction of 2-10% in the total collected plastic packaging volume. From this point PEF could be recycled individually avoiding the potential disadvantages of quality reduction due to co-recycling. In the timeframe between the moment where co-recycling of PEF starts to become contaminating the stream and when the share is not high enough yet to be viable sorting it out separately, the results on PEF recycling might not apply. As PEF could behave as a contamination in the existing PET stream, PEF will most likely end up in the mixed plastics fraction, which is typically incinerated or recycled into low-value applications. Moreover, local accumulations of PEF in the waste system could lead to insufficient qualities for recycling the stream.

Further tests need to be done on the co-recycling of PEF in PET to see at what point the PEF recycling chain must be adjusted properly to avoid contaminating the existing PET recycling streams. As the deposit system on small bottles will be introduced already from 2021 and until that moment the penetration of PEF in the sorted waste has certainly not achieved the allowable share of 2%, most bottles will be collected by the deposit system and accordingly recycled into high value applications. The impact of the potential loss of recycled bottles shall be therefore limited in the Netherlands.

In addition, the assumption that sorting data from small clear PET bottle ≤ 0.5 L was used for the considered small PEF bottles, carries some uncertainty. The small PEF bottles are smaller as well as made with thinner walls making the weight considerably lower. Whereas there is no reason to assume that collection and treatment efficiencies are sensitive to the size and weight of the bottles, the sorting rates are. Sorting installations separate plastics by blowing the plastic package at the end of the roller conveyer into certain fractions after recognition by the NIR camera. Although the NIR camera is able to distinguish PEF from PET and other plastics, the accuracy of the blowing out of PEF could be impacted by the lighter material weight. And indeed, at the time of finalizing this paper a confirmation is received from Morssinkhof: light weighting of plastic containers lead to a lower sorting efficiency as containers can be blown out in the wind sifting step along with flexibles. Therefore, the sorting efficiency of PEF bottles could be overestimated leading to less beneficial results for the PEF waste treatments.

Another issue faced during the execution of this study was the data availability on glycolysis. The glycolysis of PET is a relatively new technology, which is at least not used on an industrial scale yet in Europe (Zero Waste Europe, 2019). Due to the maturity of the technology, the data of chemical recycling via glycolysis was limited, especially at an industrial scale. Eventually pilot plant data from a certain glycolysis process has been found which is used. By using industrial data on glycolysis and the repoymerization, the chemical recycling could optimize its environmental performance. Another way, how chemical recycling could become more attractive compared to mechanical recycling is due to the increasing demand towards higher quality of recycled plastic. Currently the recycled plastics have to contain 95% of used food packaging plastics in Europe, which does not stimulates improving the quality of rPET if this prerequisite could not be guaranteed. This is a limitation Dutch recyclers have to comply with. However, this seems to be a precautionary condition, rather than evidence based (F. Welle, 2013). When this regulation will be relaxed which possibly will in the future (E. Thoden van Velzen et al., 2016), the market for qualitative recycled plastic could evolve causing higher demands. Besides the fact that chemical recycling becomes more interesting, mechanical recycling needs to intensify the recycling chain to keep up the desired quality, leading to higher environmental requirements.

In this study, only one recycling cycle has been taken into account. By increasing several recycling trips the environmental credits to the first generation's bottle could be increased even more as the virgin material could substitute material in multiple generations. L. Shen et al. (2011) did an analyses to the impact on the first generation product system by the inclusion of multiple recycling trips. According to the study, the benefits of PET recycling into PET fibres and PET bottles on NREU and GWP are respectively 20% and 18% after one recycling trip and could maximally increase to 26% and 23% compared to the reference system. The maximum benefits are already achieved at the third recycling trip indicating that the recycling credits are largely obtained during the first recycling trip. The study considered as well the recycling of PET solely into PET bottles. Although PET bottles could be recycled for several trips in contrast to PET fibres which are mostly incinerated after first use, the beneficial impact of recycling stops after four recycling trips. This might also be an important finding to consider the impact of the higher

biodegradability of PEF compared to PET. As a result of the absent environmental benefits after three recycling trips, the higher biodegradability of PEF would hardly impact the environmental performance of the recycling of PEF bottles from a multiple recycling perspective.

5.4. Additions and suggestions

In this study only two bottle systems are considered. The bottle fully made of PET is considered as a reference. In practice, also the multilayer PET bottles exists on the market (e.g. plastic wine and beer bottles) which is excluded from this study due to the limited existence in the Netherlands (E. Thoden van Velzen et al., 2016). As the multilayer PET bottles contain PET on both the inside and the outside of the bottle, they barely be recognized by the near infrared cameras and will therefore partly end up in the sorted PET fraction (DKR 328-1) (E. Thoden van Velzen et al., 2016; Marle, 2020). Most common multilayers are produced with a layer of nylon in between, which belong to the polyamides. These substances behave as a contamination (E. Thoden van Velzen et al., 2016) and are therefore prefereably rejected before the recycle stream is turned into rPET. Although barrier layers after delamination are partly seperated further downstream the recycling process, the presence of some barrier layers remain leading to quality deterioration (Jetten, 2020; E. Thoden van Velzen et al., 2016). Moreover the incineration of the polyamides generates higher GWP-impact as nitrous oxide emissions are generated due to the high nitrogen content in polyamides (K. Svoboda et al., 2005). Due to the lower recyclability and the larger incineration impacts, the environmental advantage of PEF is even more expressed when it replaces multilayers bottles. Moreover, Avantium is considering the launch of PEF as an barrier layer applied in PET bottles, which reduces the weight of the PET bottle and hence the material requirements, while increasing barrier properties. The environmental performance of the PET multilayer and PEF/PET bottle could be a avenue for further investigation and eventually strengthen decision-making on market entrance strategy.

Another foreseen application for PEF is in the flexible packaging market as a replacement for multilayer film, which are typically doomed for incineration as a result of bad recyclability. Besides the lower material requirements, the use of monolayer PEF could deliver benefits for recycling because of the mono composition. However, an interview with the KIDV pointed out that these potential recycle benefits are hard to realize in the current Dutch recycling system. Films are currently separated from rigids in the early sorting processes (K. Kaiser et al., 2017; TU Eindhoven, 2015; M. Jansen et al., 2015). The downstream sorting chain for films is installed in such a way to separate the polyolefins, which represent the majority of the plastic films (see *Figure 22*). Depending on the composition and purity of the material, the films are eventually recycled into low value applications as roadside posts and park benches. As the sorting chain is based on the polyolefins, the remaining film materials are destined for incineration. According to Martijn van Nierle from the KIDV, this could happen to PEF as well as long as it does not contain a significant fraction in the film waste (Marle, 2020). From the perspective of the CBE, the application of PEF in packaging films is therefore not desirable in the Netherlands.

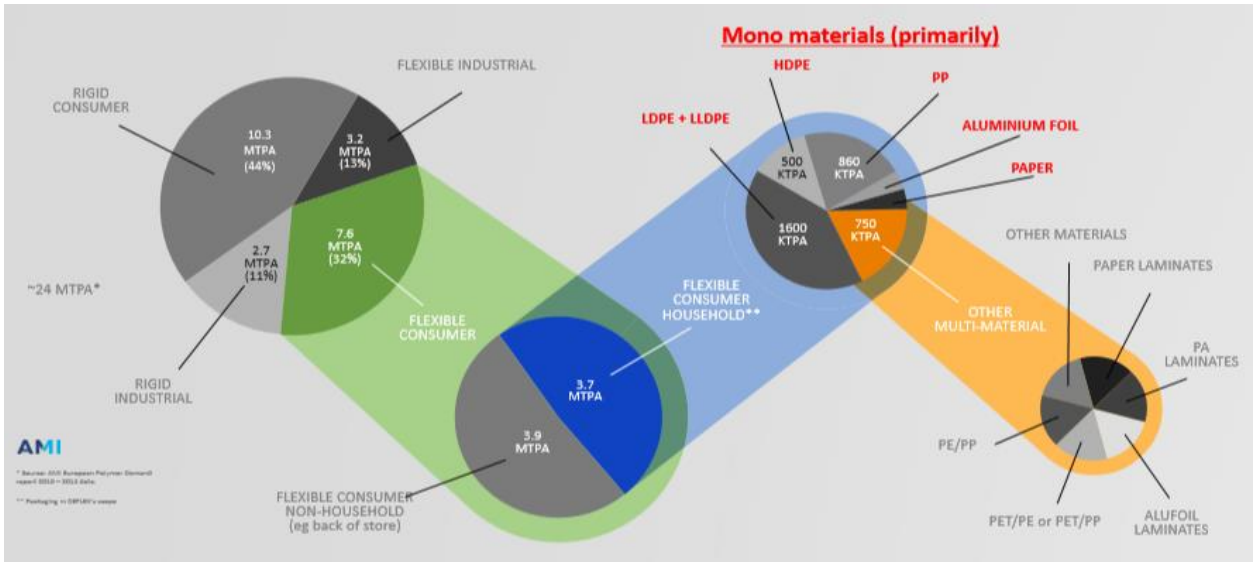

Figure 22. The compositions of films in Europe and its recycle fractions (AMI, 2015)

6. Conclusion

PEF is an innovative bio-plastic with superior food packaging characteristics compared to PET that could lead to light weighting combined with an enhanced shelf life. Moreover, the contaminating influence on existing recycling streams is limited allowing co-recycling with PET until at least up to 2%, which could accelerate the market introduction. A promising production process has been developed by Avantium and is technically ready for implementation. However, the environmental advantage compared to existing fossil-based plastics has been discussed heavily when it comes to using biomass as a feedstock. Limited scientific research is dedicated to the environmental performance of specifically PEF and especially to the EoL. This study has investigated the environmental performance in terms of GWP-impact of different EoL-options for PEF that contribute to a circular bio-economy with a higher resolution compared to existing studies. The EoL of small PEF bottles has been compared to that of small PET bottles as this is specifically one of the applications where the technical characteristics of PEF are emphasized. While using the LCA methodology, the EoL-options have been assessed in the short (2020) and the long-term (2030-2035). The Netherlands was used as the reference region for waste management. The long-term includes the extension of the deposit system on small bottles which is introduced from 2021 in the Netherlands.

In the first assessment circular EoL-options for PET and PEF were identified and integrated into Dutch waste treatments that differ in collection method. The potential prioritized EoL-options that follow the principles of the circular economy that have been qualified were limited in the short-term to mechanical recycling and in the longer term mechanical and chemical recycling. The waste treatments were corrected by appropriate substitution factors to account for the different obtained qualities and applicability of the recycled material depending on the collection system and recycling technology. The obtained results thus provided insight in the GWP-impact of EoL-options as well as different collection systems. The GWP-impact per collection method appeared to be largely proportional to the related recycling rate resulting in an excelling performance for the deposit system. Especially the lower chain losses are responsible rather than the unnecessary sorting requirements. The waste treatments based on recycling perform all better than the incineration with energy recovery, confirming the benefit of recycling. Among the EoL-options, mechanical recycling achieves the largest environmental benefits, although the results for chemical recycling might be reduced if industrial data rather than pilot plant data is used. When waste treatments of PET and PEF are mutually compared, no large differences are identified in the mechanical and chemical recycling process itself. Mechanical recycling of PEF is largely compatible with PET recycling and potential differences in chemical recycling could not have been identified due to the lack of knowledge and process details available. The difference in performance of the waste treatments is rather dependent on the avoided virgin granulate production whose GWP-impact differs substantially for PET and PEF. In the short-term, the PEF production is not benefitting from economies-of-scale and process optimization, resulting in a higher GWP-impact compared to PET granulate production. In the long-term, when PEF is produced at industrial scale, the production impact end up eventually lower than PET, because of the bio-based origins. As a result, recycling of PEF has found to be more beneficial in the short-term, whereas in the long-term PET recycling is more beneficial in terms of GWP. In case of incineration with energy recovery, PEF is more beneficial than PET as the influence of the lower carbon content appeared to weigh higher than the fewer energy credits achieved due to of the lower caloric value. This gap is increasing absolutely and relatively in the long-term due to the greener electricity mix.

In the second assessment, a cradle-to-grave LCA was done on a single bottle containing 250 ml providing a shelf life of 12 weeks, which thus takes into account the different bottle weights of PET and PEF. The

different waste treatments of PET and PEF were combined into representative EoL-scenarios for small PET and PEF bottles during the EoL in the Netherlands and have been added to the production phase to simulate the full life cycle. Three EoL-scenarios were distinguished; 1) EoL relying on short-term mechanical recycling, 2) EoL relying on long-term mechanical recycling 3) and the EoL relying on long-term chemical recycling. The resulting cradle-to-grave impact in terms of GWP of one PET bottle has been found in the short-term at 91 gCO_2 eq./bottle and in the long-term 44 gCO_2 eq./bottle (MR) and 68.1 gCO_2 eq./bottle (CR). At the time of writing this report, the PEF granulate production GWP-impacts are being reviewed by nova-Institute meaning that the exactness of the results should be considered with reservation. For the PEF bottle the GWP-impact is determined at 41.7 gCO_2 eq./bottle for the short-term and in the long-term 16.1 gCO_2 eq./bottle (MR) and 25.9 gCO_2 eq./bottle (CR). Compared to a single PET bottle, this is a relative GWP-advantage of 53.9% (short-term), 63.6% (long-term based on MR) and 62.0% (long-term based on CR) per functional unit. Also when the carbon stocks taken up during the biomass growth are not considered as avoided, the PEF bottle still performs much better in terms of GWP. The largest relative advantage for PEF is expressed the most in the long-term life cycle without an EoL as the impact of PEF granulate production then bears only advantages compared to PET granulate production. The inclusion of EoL leads to small reductions in the relative advantage for PEF as PEF recycling is less beneficial compared to PET recycling. This falls in line with the findings on the waste treatments; PEF recycling is more advantageous in the short-term whereas PET recycling is more advantageous in the long-term. The advantages in favour of PEF were largely explained by the different bottle weights. Therefore, decarbonizing packaging solutions (making them lighter) is a major driver for achieving GWP reductions.

It appeared that an EoL-scenario could have a strong contribution on the life cycle GWP-impact. For the life cycle performance of a single small PEF bottle, it was found that the short-term EoL-scenario could reduce the life cycle impact of PEF by 8% compared to the production impact. In the long-term, mechanical recycling of PEF the EoL-scenarios lead to 26% and 53% reductions in the life cycle of one PEF bottle compared to having no EoL. As a reference, the life cycle of a bottle destined for incineration with energy recovery has been included as well. Compared to the life cycle including incineration, PEF recycling delivers in the short-term an advantage of 23% and in the long an advantage of 53% (MR) and 24% (CR).

Two uncertainty factors were taken into account being the granulate production impact and the substitution factor. The influence of the uncertainty on the substitution factor seemed to have a low impact on the life cycle results due to the small relative range. The uncertainty on the GWP-impact of the granulate production is relatively large as a wide range was token based on divergent available PET granulate production data. The uncertainty on the GWP-impact of the granulate production affects both the bottle production and the recycling in an opposite way. A higher recycling rate means a higher counter effect of recycling, making the life cycles based on different EoL-scenarios unequally sensitive. By taking into account this uncertainty, the results of the life cycle including the short-term EoL-scenario of a PET bottle range from 36 gCO_2 eq./bottle to 57 gCO_2 eq./bottle. The long-term life cycle impact complemented by mechanical recycling and chemical recycling obtains respectively ranges of 14 gCO_2 eq./bottle to 22 gCO_2 eq./bottle and 23 gCO_2 eq./bottle to 33 gCO_2 eq./bottle. Although the uncertainty on the granulate production could significantly impact the life cycle results, it does not lead to different rankings in EoL-scenario preferences. These results show that the uncertainty as a result of the granulate production impact reduces if the recycling rate becomes higher. The same is true for the uncertainty of the substitution factor.

In 2017 a total amount of 3.4 megatons of PET bottles were placed on the European market (EUNOMIA, 2018). The saved GWP-impact is calculated here if all PET bottles are replaced by PEF to see the potential significance for Europe in reducing emissions. Although this will be an overestimation as the advantage for PEF is lower when the bottle size grows, it is expected that this will at least give a range to think of. The short-term production advantage is 43 gCO2 eq./ PET bottle and in the long-term 48 gCO_2 eq./bottle as could be calculated from *Table 14.* Based on the PET bottle production volume from 2017 and the weight of a small PET bottle, it could be calculated that the theoretical savings are 5.2 giga tons of gCO2 equivalent per year in the short-term and 5.8 giga tons gCO2 equivalent per year in the long-term. As the market of PET bottles is growing (EUNOMIA, 2018) these potential savings could be higher in the future. In particular PET for the use in bottles is expected to grow in the longer term (EUNOMIA, 2018).

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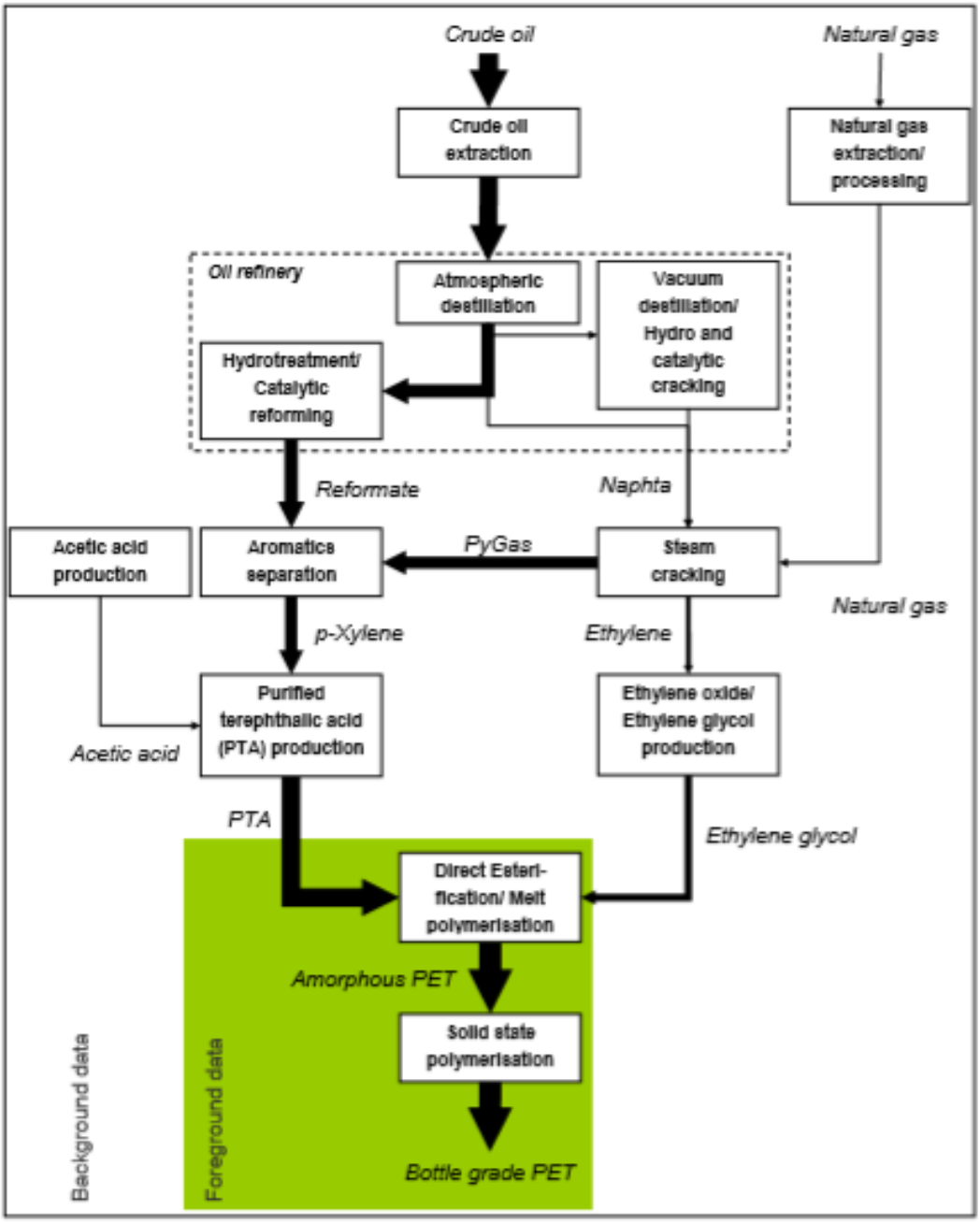
Appendix

Appendix A: System boundaries PET and PEF granulate production

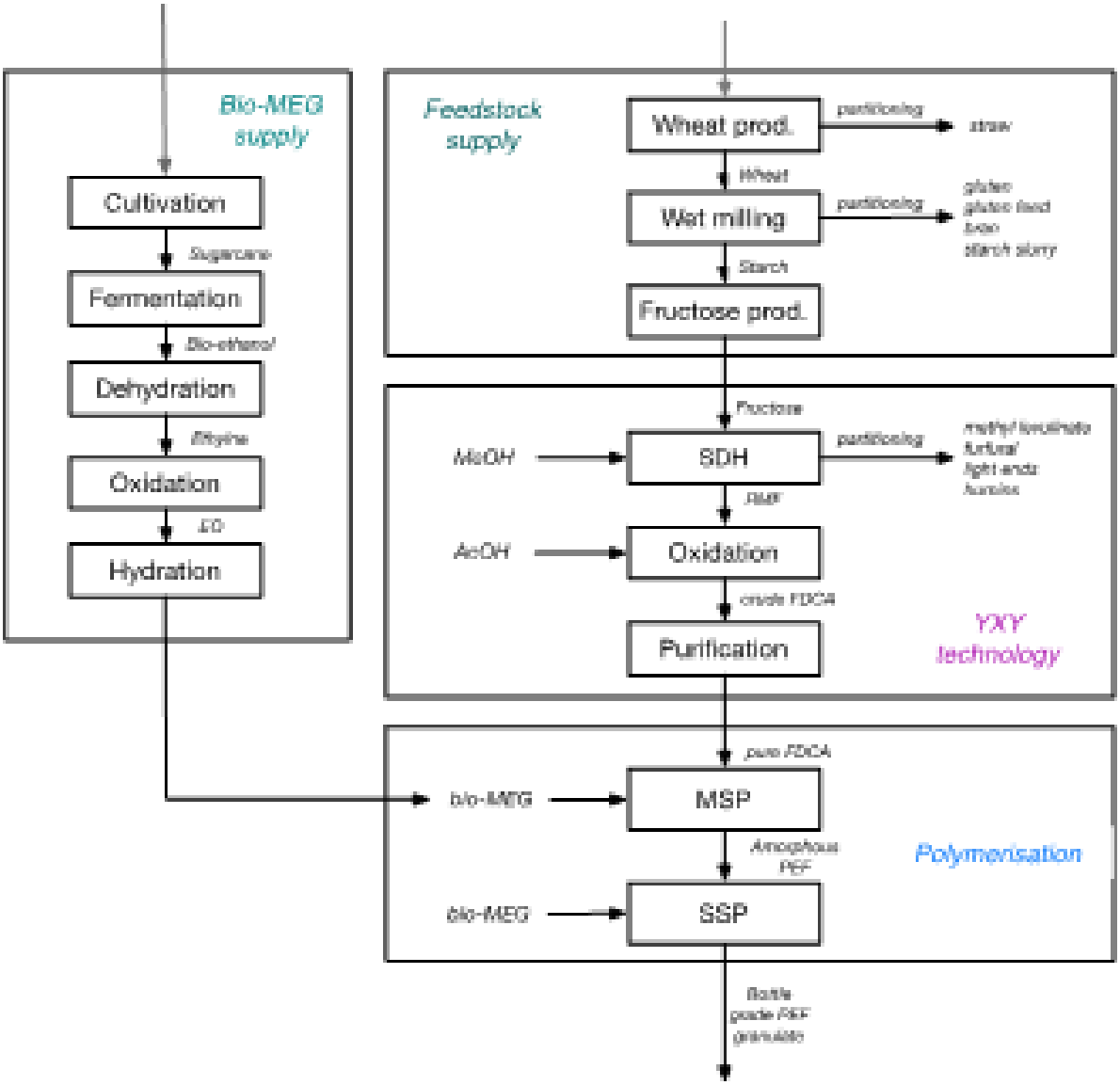
System boundaries for PET granulate production according to Plastics Europe

PTA and MEG are both formed from fossil-based feedstock. The production of PET granulate starts with the esterification of PTA and MEG to BHET. As a next step, the molecules are sent to melt poly-condensation under vacuum conditions and high temperature to crystallize PET resulting in higher molecular weights. Finally the obtained PET is exposed to SSP in order to extent the molecular chains so it can be used as bottle-grade PET.



System boundaries for PEF bottle-grade granulate production according to nova-Institute

PEF granulate is produced from starch that is obtained from wheat yielded in France, Belgium and the Netherlands. The starch is converted into fructose which is again turned into FDCA with the YXY-technology. Then the purified FDCA is reacted with bio-MEG to polymerize the obtained PEF. Finally the PEF is treated with SSP.



Appendix B. Approach to account for electricity mix in virgin PET granulate production

As an alternative approach, it was derived how much GWP was caused by the electricity use in the PET bottle-grade granulate production, and the different feedstock production processes upstream based on reports from Plastics Europe. Besides the foreground process of PET bottle-grade granulate production (13.2%), the feedstock production processes that impact the GWP are, PTA (24.4%) which in turn needs p-xylene, p-xylene (36%) and MEG (25%) covering 98.7% in total of the GWP in the full PET bottle-grade granulate production (Plastics Europe, 2017). These upstream production are also described in reports of Plastics Europe that include the GWP impact of electricity in the foreground production process (Plastics Europe, 2016; Plastics Europe, 2012; Plastics Europe, 2013). Due to fact that the upstream feedstock are directly produced from fossils the influence of electricity on the GWP becomes smaller especially compared to the impact on the GWP of the PET bottle-grade granulate production. It was calculated that 15.8% of the GWP of the PET bottle-grade granulate production was caused by the electricity use including given upstream feedstock production processes. By multiplying this percentage with the GWP ratio between the electricity mixes of 2030 and now, it could be calculated how much GWP was saved in the PET bottle-grade granulate production due to the new electricity mix. As the feedstock production process are also taking place at a global scale, this calculation implies that the GWP of the global electricity mix is greening proportional to the European electricity mix. As the GWP ratio of the electricity mixes is calculated as 39% based on the high voltage electricity mix, this means that the total GWP savings on the granulate production is (15.8%*(100%-39%)) = 9.6 %. Therefore the functional unit in the Plastics Europe data on virgin PET granulate production is accordingly changed (100%/(100%-9.6%)) = 1.106659 kg to account for the GWP win due to the modern electricity production mix. In case of the GWP of the production of amorphous PET granulate due to the modern electricity production, the benefit is a slightly smaller here. This is because of the fact that little less electricity is needed due to the redundant SSP process. The electricity needed for the SSP, defined as 33% of the electricity of the PET bottle-grade production process, is thus subtracted here, which slightly reduces the benefit of greening (Plastics Europe, 2017).

Appendix C: Interview Louis Jetten

With permission of Louis Jetten, the interview in the form of an email conversation is published. This conversation is in Dutch.

Beste Louis Jetten,

Naar aanleiding van een gesprek met Niels van Marle van het KIDV (toegevoegd in CC) waarin een aantal van mijn vragen onbeantwoord zijn gebleven, ben ik gerefereerd naar u. Ik hoop dat u in staat en bereid bent om deze vragen te beantwoorden en mij zo te helpen met mijn afstudeeronderzoek.

Even kort iets over mezelf en de context van deze vragen. Ik doe momenteel een onderzoek bij Avantium (als stagair) naar het broeikasgas voordeel van PEF applicaties, ten opzichte van conventionele PET applicaties met behulp van een LCA toegepast in Nederland. Hiervoor wil ik allereerst de kunstofstromen van verpakkingsplastics in Nederland in kaart zetten, om te analyseren welke weg de PET (en mogelijke PEF applicaties) bewandelen gedurende de End-of-Life fase. De applicatie waar ik mij voornamelijk op ga richten is de small beverage bottle (transperant) ≤ 0.5.

Beste Ties,

Hierbij een aantal antwoorden op je vragen. Zie toevoegingen in de tekst hieronder.

Recycling PET flesjes

1. Zit er een groot verschil in de toepasbaarheid van rPET uit statiegeld fracties en gesorteerde PET fracties (DKR-328-1)?
   In principe niet. Punt is dat de hoge maat van vervuiling van 328-1 hogere eisen stelt aan het recycling proces, meer scheidings- en zuiveringsstappen in het proces.

   Wordt statiegeld rPET momenteel in grote mate gebruikt voor food-grade recycling?
   Ja, weliswaar als pellet dus na upgrading van de rPET flakes door extrusie en SSP.

   Kan rPET afkomstig van DKR-328-1 worden ingezet voor food-grade toepassingen?

   Ja. Kritisch aspect is nog dat aangetoond moet worden dat 95 % van de input afkomstig is van food-grade verpakkingen. In praktijk gaat dit materiaal niet terug in flessen omdat het niet op kleur is gesorteerd. Het gaat wel in trays.

Multilayer PET flesjes

2. In het rapport 'Technical quality of rPET' geschreven door WUR (waarin u een van de industrial board members en de industrial reviewer bent) in 2016 staat dat het aandeel multilayer flesjes in statiegeld 0 - 0.6% is in Nederland. In bron- en nagescheiden afval is dit aandeel 1-2%. Is het aandeel van multilayer flesjes nog steeds zo klein in Nederland?
   Deze informatie heb ik niet. Heeft te maken met marktaandeel van sappen versus frisdranken en waters. Ook met keuze voor glas, drankkarton, kunststof, blik.

   Is de verwachting dat dit aandeel groter of juist kleiner wordt in de toekomst?
   ?? Zal in beweging blijven en regelgeving van overheid kan een rol spelen. Kosten zijn voor groot deel bepalend.
3. Worden de barrierelagen op dit moment verwijderd uit het recyclaat? Bijvoorbeeld door de verwerker gedurende de vermaling van de flessen naar vlokken?
   Deel van de binnenlagen van bij MXD6 (nylon) komt vrij door delaminatie van de flakes en wordt in zigzag zifter verwijderd.

   Kan je iets zeggen over de vermindering in toepasbaarheid van het rPET door de aanwezigheid van de multilayer PET flesjes?
   Er zijn testen uitgevoerd. Daar komt een maximaal toelaatbaar percentage uit. Erg hard zijn dergelijke getallen niet omdat het mede afhangt van de apparatuur van de flessenproducent. Voor een overzicht van testen zie deze link

PEF integratie in huidige afval infrastructuur

4. Hoe kijkt u aan tegen de integratie van PEF in de PET stroom in de bestaande recycling infrastructuur? Wat zijn de uitdagingen hiervan? Liggen er misschien ook kansen?
   Is moeilijk om op voorhand in te schatten welk percentage PEF toelaatbaar is zonder dat er problemen ontstaan in de verwerking.

5. Wat zijn de beste platformen om integratie van PEF bij de juiste instanties met beslissingsbevoegdheden te krijgen?

Zie EPBP. Testen kun je het beste laten uitvoeren door PFE in US. Ik heb daar goede ervaringen mee. Dit is 1 van de 2 door EPBP geaccrediteerde labs. Alternatieven ingang via Petcore of PRE. Beiden lid van EPBP.

Appendix D. Database: Energy sources (electricity and heat)

Electricity

Outputs	Amount
Electricity, high voltage {NL}| production mix | APOS, U	1 kWh
Inputs	
Electricity, high voltage {NL}| electricity production, hard coal | APOS, U	0.279 kWh
Electricity, high voltage {NL}| electricity production, hydro, run-of-river | APOS, U	0.001 kWh
Electricity, high voltage {NL}| electricity production, natural gas, combined cycle power plant | APOS, U	0.171 kWh
Electricity, high voltage {NL}| electricity production, natural gas, conventional power plant | APOS, U	0.086 kWh
Electricity, high voltage {NL}| electricity production, nuclear, pressure water reactor | APOS, U	0.051 kWh
Electricity, high voltage {NL}| electricity production, wind, <1MW turbine, onshore | APOS, U	0.017 kWh
Electricity, high voltage {NL}| electricity production, wind, >3MW turbine, onshore | APOS, U	0.010 kWh
Electricity, high voltage {NL}| electricity production, wind, 1-3MW turbine, offshore | APOS, U	0.005 kWh
Electricity, high voltage {NL}| electricity production, wind, 1-3MW turbine, onshore | APOS, U	0.031 kWh
Electricity, high voltage {NL}| heat and power co-generation, biogas, gas engine | APOS, U	0.001 kWh
Electricity, high voltage {NL}| heat and power co-generation, hard coal | APOS, U	0.095 kWh
Electricity, high voltage {NL}| heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical | APOS, U	0.120 kWh
Electricity, high voltage {NL}| heat and power co-generation, natural gas, conventional power plant, 100MW electrical | APOS, U	0.099 kWh
Electricity, high voltage {NL}| heat and power co-generation, oil | APOS, U	0.011 kWh
Electricity, high voltage {NL}| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | APOS, U	0.021 kWh

*Accounted for new electricity mix in long-term processes

Heat

Outputs	
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace low-NOx >100kW - NL | APOS, U	1 MJ
Inputs	
Electricity, low voltage {Europe without Switzerland}| market group for | APOS, U	0.005 kWh
Industrial furnace, natural gas {GLO}| market for | APOS, U	3.11 p
pressure Natural gas, high {NL}| market for | APOS, U	0.028

*Accounted for new electricity mix in long-term processes

Appendix E. Database: Environmental inputs processes involved in waste treatments

1. Sorting

Outputs	
Polyethylene terephthalate, for recycling, sorted {CH}| treatment of waste polyethylene terephthalate, for recycling, unsorted, sorting | APOS, U (Carbotech, no waste) NL	1000 kg
Inputs	
Diesel, burned in building machine {GLO}| market for | APOS, U	106.8 MJ
Electricity, low voltage {NL}| market for | APOS, U*	43.58 kWh
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace low-NOx >100kW - NL | APOS, U	24.22 MJ
Steel, low-alloyed {GLO}| market for | APOS, U	5.596 kg
Waste preparation facility {GLO}| market for waste preparation facility | APOS, U	1.861E-6 p
Wire drawing, steel {GLO}| market for | APOS, U	5.596 kg

*Accounted for new electricity mix in long-term processes

2. Production of bottle-grade rPET granulate via mechanical recycling

Outputs	
2. Polyethylene terephthalate, granulate, bottle-grade, recycled {CH}| polyethylene terephthalate production, granulate, bottle-grade, recycled | APOS, U - NL Elec - no waste	1kg
Known inputs from nature	
Water, cooling, unspecified natural origin, CH	0.006 m3
Water, unspecified natural origin, CH	0.0003 m3
Inputs	
Chemical, organic {GLO}| market for | APOS, U	0.0003 kg
Electricity, low voltage {NL}| market for | APOS, U*	0.338 kWh
Extrusion, plastic film {GLO}| market for | APOS, U	1.846E-5 kg
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace low-NOx >100kW - NL | APOS, U	2.541 MJ
Polypropylene, granulate {GLO}| market for | APOS, U	1.846E-5 kg
Soap {GLO}| market for | APOS, U	8.883E-5 kg
Sodium hydroxide, without water, in 50% solution state {GLO}| market for | APOS, U	0.030 kg
Steel, low-alloyed {GLO}| market for | APOS, U	9.476E-7 kg
Sulfuric acid {GLO}| market for | APOS, U	0.018 kg
Waste polyethylene terephthalate, for recycling, sorted {CH}| market for waste polyethylene terephthalate, for recycling, sorted | APOS, U	1.200 kg
Waste preparation facility {GLO}| market for waste preparation facility | APOS, U	1.974E-9 p
Wire drawing, steel {GLO}| market for | APOS, U	9.476E-7 kg
Treated waste	
Wastewater, average {CH}| market for wastewater, average | APOS, U	0.0062 m3

*Accounted for new electricity mix in long-term processes

3. Production of amorphous rPET granulate via mechanical recycling

Outputs	
1. Polyethylene terephthalate, granulate, amorphous (bottle-grade-SSP), recycled {CH}| polyethylene terephthalate production, granulate, recycled | APOS, U - NL Elec - no waste	1kg
Saved products / processess	
SSP (0.6 -> bottle-grade) (ecoprofiles)	1kg
Known inputs from nature	
Water, cooling, unspecified natural origin, CH	0.006 m3
Water, unspecified natural origin, CH	0.0003 m3
Inputs	
Chemical, organic {GLO}| market for | APOS, U	0.0003 kg
Electricity, low voltage {NL}| market for | APOS, U*	0.338 kWh
Extrusion, plastic film {GLO}| market for | APOS, U	1.846E-5 kg
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace low-NOx >100kW - NL | APOS, U	2.541 MJ
Polypropylene, granulate {GLO}| market for | APOS, U	1.846E-5 kg
Soap {GLO}| market for | APOS, U	8.883E-5 kg
Sodium hydroxide, without water, in 50% solution state {GLO}| market for | APOS, U	0.030 kg
Steel, low-alloyed {GLO}| market for | APOS, U	9.476E-7 kg
Sulfuric acid {GLO}| market for | APOS, U	0.018 kg
Waste polyethylene terephthalate, for recycling, sorted {CH}| market for waste polyethylene terephthalate, for recycling, sorted | APOS, U	1.200 kg
Waste preparation facility {GLO}| market for waste preparation facility | APOS, U	1.974E-9 p
Wire drawing, steel {GLO}| market for | APOS, U	9.476E-7 kg
Treated waste	
Wastewater, average {CH}| market for wastewater, average | APOS, U	0.0062 m3

*Accounted for new electricity mix in long-term processes

4. SSP

Outputs	
SSP (0.6 -> bottle-grade) (ecoprofiles)	1000 kg
Inputs	
Electricity, medium voltage {NL}| market for | APOS, U*	0.0667 kWh
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace low-NOx >100kW - NL | APOS, U	0.76 MJ
Heat, from steam, in chemical industry {RER}| market for heat, from steam, in chemical industry | APOS, U	0.1433 MJ

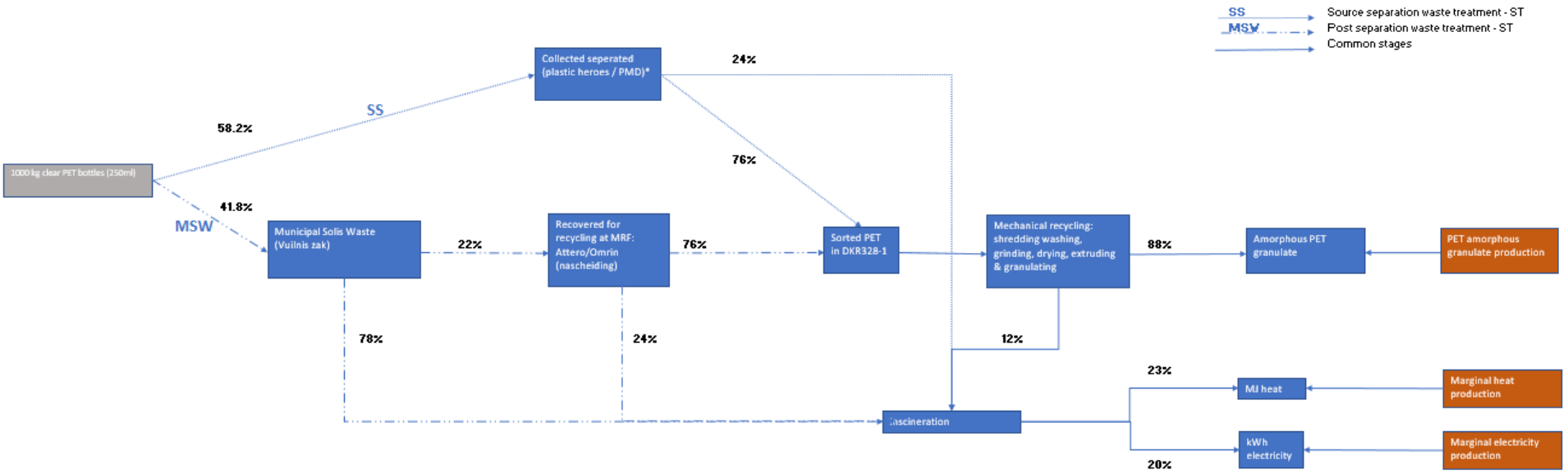
*Accounted for new electricity mix in long-term processes

5. Production of bottle-grade rPET granulate via glycolysis

Outputs	
Glycolysis and repolymerization of PET bottles into bottles-grade rPET granulate	1.03 kg
Saved products / processess	
Heat, district or industrial, natural gas {GLO}| market group for | APOS, U	5 MJ
Electricity, high voltage {TW}| production mix | APOS, U	0.64 kWh
Inputs	
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace low-NOx >100kW - NL | APOS, U	33.15 MJ
SSP (0.6 -> bottle-grade) (ecoprofiles)*	1.03 kg

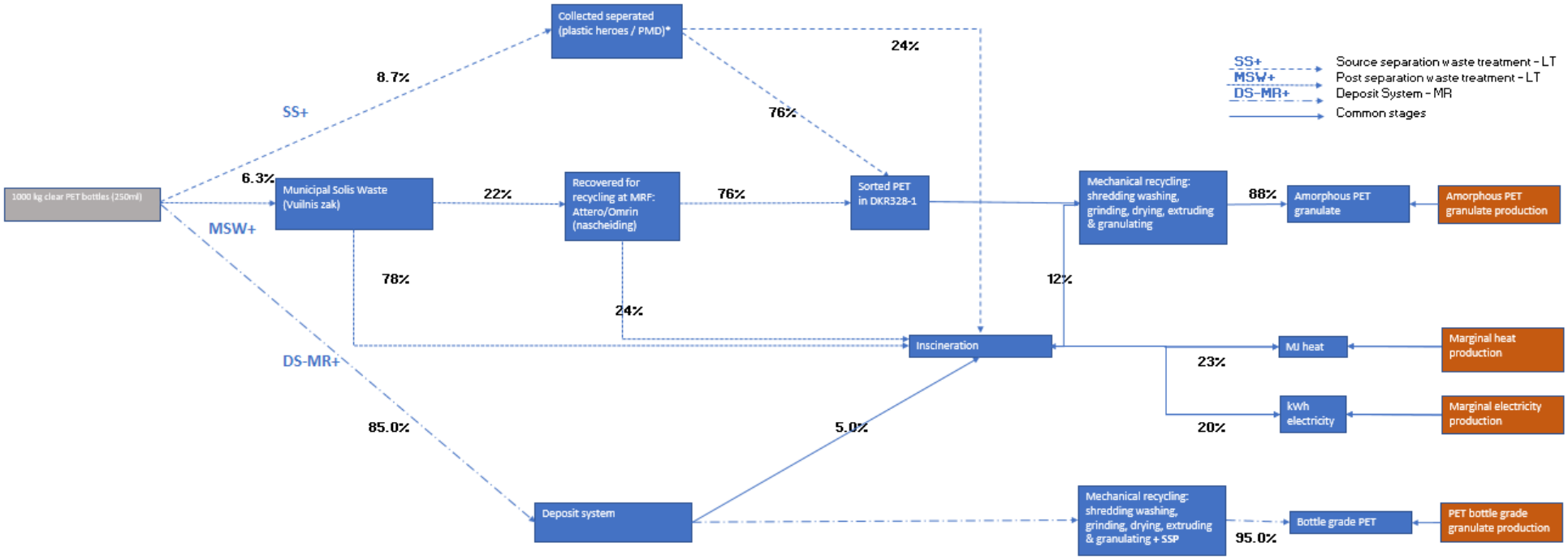
*Accounted for new electricity mix in long-term processes

Appendix F. Flow diagram short-term scenario



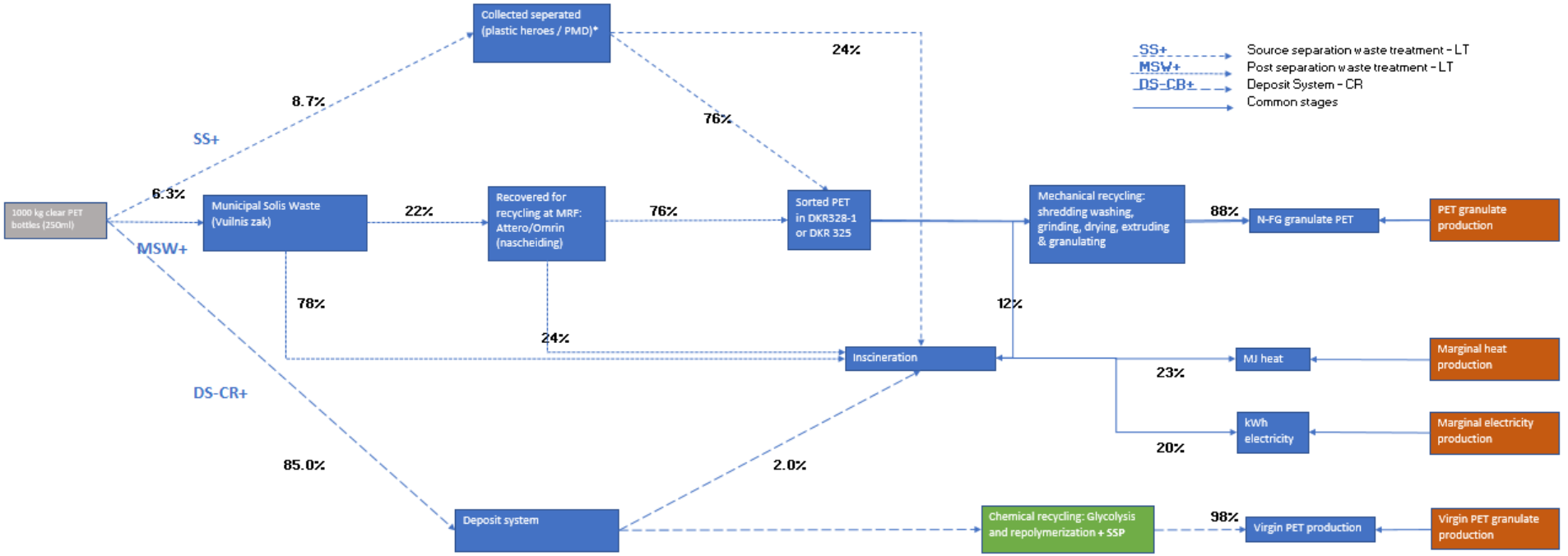
Collection	Sorting	Processing	Scenario characteristics
All small PET bottles are collected *(assumption)*	76% of small clear PET bottles are sorted in the PET fraction (DKR 328-1) *(M. Brouwers et al. 2019)*	The sorted PET fraction is not used in food-grade applications -> substituting amorphous PET granulate	**45%** of small PET bottles will eventually be recycled. Losses during chain are all incinerated with energy recovery
Separately collected & in MSW			Substitution factor sorted PET fraction is 0.85

Appendix G. Long-term scenario based on mechanical recycling



Collection	Sorting	Processing	Scenario characteristics
All small PET bottles are collected *(assumption)*	76% of small clear PET bottles are sorted in the PET fraction (DKR 328-1) *(M. Brouwers et al. 2019)*	The sorted PET fraction is not used in food-grade applications -> substituting amorphous PET granulate	**85%** of small PET bottles will eventually be recycled. Losses during chain are all incinerated with energy recovery
Separately collected, in MSW **& deposit system**	**The sorting losses and requirements for the deposit fraction are negligible**	**The deposit fraction is substituting bottle-grade PET granulate (SSP needed)**	Substitution factor sorted fraction is 0.85 **Substitution factor deposit fraction is 0.9**
85% will be collected by deposit system			

Appendix H. Long-term scenario based on chemical recycling



Collection	Sorting	Processing	Scenario characteristics
All small PET bottles are collected *(assumption)*	76% of small clear PET bottles are sorted in the PET fraction (DKR 328-1) *(M. Brouwers et al. 2019)*	The sorted PET fraction is not used in food-grade applications -> substituting amorphous PET granulate	**85%** of small PET bottles will eventually be recycled. Losses during chain are all incinerated with energy recovery
Separately collected, in MSW & deposit system	**The sorting losses and requirements for the deposit fraction are negligible**	The deposit fraction **is chemically recycled** and substituting bottle-grade PET granulate **(SSP still needed)**	Substitution factor sorted fraction is 0.85 **Substitution factor deposit fraction is 1.0**
85% will be collected by deposit system			

Appendix I. Database: Environmental inputs of waste treatments

Collection by MSW and mechanically recycled

Outputs	Unit	Description
PET bottles from Post-separation (waste treatment) NL - recycling - Input	1kg	Functional unit
Saved products / processes		
PET, amorphous, at plant/RER (bottle-grade - SSP)*	0.125 kg	1kgCOllected * 0.22 (recovery factor from MSW) * 0.76 (sorting efficiency) * 0.88 (processing efficiency) * 0.85 (substitution factor)
Inputs (materials, fuels)		
Municipal waste collection service by 21 metric ton lorry {CH}| market for municipal waste collection service by 21 metric ton lorry | APOS, U	0.0350 tkm	1kgCOllected * 35 km (collection to MRF)
Transport, freight, lorry 16-32 metric ton, EURO5 {GLO}| market for | APOS, U	0.0506 tkm	1kgCOllected * 0.22 (recovery factor from MSW) * 230 km (distance MRF to sorting facility)
Transport, freight, lorry 16-32 metric ton, EURO5 {GLO}| market for | APOS, U	0.0334 tkm	1kgCOllected * 0.22 (recovery factor from MSW) * 0.76 (sorting efficiency) * 200 km (distance sorting facility to processing facility)
Inputs (electricity, heat)		
Polyethylene terephthalate, for recycling, sorted {CH}| treatment of waste polyethylene terephthalate, for recycling, unsorted, sorting | APOS, U (Carbotech, no waste) NL*	2 kg	1kgCOllected * 4 (requirements recovery/requirements sorting) * 0.5 (fraction exposed to post-separation)
Polyethylene terephthalate, for recycling, sorted {CH}| treatment of waste polyethylene terephthalate, for recycling, unsorted, sorting | APOS, U (Carbotech, no waste) NL*	0.2200 kg	1kgCOllected * 0.22 (recovery factor from MSW)
Polyethylene terephthalate, granulate, amorphous (bottle-grade-SSP), recycled {CH}| polyethylene terephthalate production, granulate, recycled | APOS, U - NL Elec - no waste*	0.1471kg	1kgCOllected * 0.22 (recovery factor from MSW) * 0.76 (sorting efficiency) * 0.88 (processing efficiency)

*Accounted for new electricity mix in long-term waste treatments

Collection at the source and mechanically recycled

Outputs	Unit	Description
PET bottles from Source Seperation (waste treatment) NL - recycling - Input	1kg	Functional unit
Saved products / processes		
PET, amorphous, at plant/RER (bottle-grade - SSP)*	0.0568 kg	1kgCOllected * 0.76 (sorting efficiency) * 0.88 (processing efficiency) * 0.85 (substitution factor)
Inputs (materials, fuels)		
Municipal waste collection service by 21 metric ton lorry {CH}| market for municipal waste collection service by 21 metric ton lorry | APOS, U	0.0350 tkm	1kgCOllected * 35 km (collection to transshipment station)
Transport, freight, lorry 16-32 metric ton, EURO5 {GLO}| market for | APOS, U	0.170 tkm	1kgCOllected * 170 km (distance transshipment station-sorting facility)
Transport, freight, lorry 16-32 metric ton, EURO5 {GLO}| market for | APOS, U	0.1520 tkm	1kgCOllected * 0.76 (sorting efficiency) * 200 km (distance sorting facility to processing facility)
Inputs (electricity, heat)		
Polyethylene terephthalate, for recycling, sorted {CH}| treatment of waste polyethylene terephthalate, for recycling, unsorted, sorting | APOS, U (Carbotech, no waste) NL*	1kg	1kgCOllected

Polyethylene terephthalate, granulate, amorphous (bottle-grade-SSP), recycled {CH}| polyethylene terephthalate production, granulate, recycled | APOS, U - NL Elec - no waste*	0.6688 kg	1kgCOllected * 0.22 (recovery factor from MSW) * 0.76 (sorting efficiency) * 0.88 (processing efficiency)

*Accounted for new electricity mix in long-term waste treatments

Collection by deposit system and mechanically recycled

Outputs	Unit	Description
PET Bottles from Deposit System (recycling waste treatment) NL - recycling - Input	1kg	Functional unit
Saved products / processes		
PET, bottle-grade, at plant/RER*	0.855 kg	1kgCOllected * 0.95 (processing efficiency) * 0.9 (substitution factor)
Inputs (materials, fuels)		
Transport, freight, lorry 16-32 metric ton, EURO5 {GLO}| market for | APOS, U	0.075 tkm	1kgCOllected * 75 km (distance collection point to processing facility)
Inputs (electricity, heat)		
Polyethylene terephthalate, granulate, bottle-grade, recycled {CH}| polyethylene terephthalate production, granulate, bottle-grade, recycled | APOS, U - NL Elec - no waste*	0.95 kg	1kgCOllected * 0.95 (processing efficiency)

*Accounted for new electricity mix in long-term waste treatments

Collection by deposit system and chemically recycled

Outputs	Unit	Description
PET Bottles from Deposit System (glycolysis waste treatment) NL - recycling - 100% gas - Primary Energy - Input	1.05 kg	Functional unit based on process from which NREU is acquired
Saved products / processes		
Heat, district or industrial, natural gas {GLO}| market group for | APOS, U	5 MJ	Subtracting the energy use for spinning and finishing of 1kg fibers. Taiwanese electricity is used are used.
Electricity, high voltage {TW}| production mix | APOS, U	0.64 kWh	
PET, bottle-grade, at plant/RER*	1.03 kg	1.05 kgCOllected * 0.98 (processing efficiency) * 1.0 (substitution factor)
Inputs (materials, fuels)		
Transport, freight, lorry 16-32 metric ton, EURO5 {GLO}| market for | APOS, U	0.236 tkm	1.05 kgCOllected * 225 km (distance collection point to processing facility)
Inputs (electricity, heat)		
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace low-NOx >100kW - NL | APOS, U	33.15 MJ	39 MJ (NREU) * 0.85 (gas-to-heat efficiency)
SSP (0.6 -> bottle-grade) (ecoprofiles)*	1.03 kg	Upgrading granulate until bottle-grade quality

*Accounted for new electricity mix in long-term waste treatments

Incineration without energy recovery

Outputs		
Waste polyethylene terephtalate {CH}| treatment of, municipal incineration with fly ash extraction - ER/transport | APOS, U	1kg	
Inputs		
Waste polyethylene terephtalate {CH}| treatment of, municipal incineration with fly ash extraction | APOS, U	0.005 kWh	
Transport, freight, lorry 16-32 metric ton, EURO5 {GLO}| market for | APOS, U	0.04 tkm	

Incineration with energy recovery

Outputs		
Waste polyethylene terephtalate {CH}| treatment of, municipal incineration with fly ash extraction - ER/transport | APOS, U	1kg	
Saved products / processes		
Electricity, high voltage {NL}| production mix | APOS, U*	1.222 kWh	20% of 22 MJ (caloric value)
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace low-NOx >100kW - NL | APOS, U	5.06 MJ	23% of 22 MJ (caloric value)
Inputs		
Waste polyethylene terephtalate {CH}| treatment of, municipal incineration with fly ash extraction | APOS, U	0.005 kWh	
Transport, freight, lorry 16-32 metric ton, EURO5 {GLO}| market for | APOS, U	0.04 tkm	

*Accounted for new electricity mix in long-term waste treatments