Comparative Life Cycle Assessment of Tetra Pak® beverage carton with rPET and PEF bottles on the Dutch market

Final report

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commissioned by Tetra Pak

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Table of contents

Table of contents

Table of contents

64 # Abbreviations

ACE	Alliance for Beverage Cartons and the Environment
BE	Belgium
BR	Brazil
COD	Chemical oxygen demand
DE	Germany
EA	European Aluminium
EAA	European Environment Agency
EU27+2	European Union & Switzerland and Norway
EU27+3	European Union & Switzerland, Norway & Iceland
ES	Spain
FEFCO	Fédération Européenne des Fabricants de Carton Ondulé (Brussels)
FI	Finland
FSC	Forest Stewardship Council™
FU	Functional unit
FR	France
GWP	Global Warming Potential
HBEFA	Handbook Emission Factors for Road Transport
HDPE	High density polyethylene
IEA	International Energy Agency
ifeu	Institut für Energie- und Umweltforschung Heidelberg GmbH (Institute for Energy and Environmental Research)
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
IT	Italy
JNSD	Juice, Nectars and Still Drinks
LCA	Life cycle assessment
LCI	Life cycle inventory
LDPE	Low density polyethylene
LPB	Liquid packaging board
LU	Luxembourg

MIR	Maximum Incremental Reactivity
MSWI	Municipal solid waste incineration
NMIR	Nitrogen-Maximum Incremental Reactivity
NL	The Netherlands
NO_X	Nitrogen oxides
PA6	Polyamid 6
pc	packs
PET	Polyethylene terephthalate
PP	Polypropylene
rPET	recycled PET
SE	Sweden
SBM	Stretch blow moulding
TRS	Total reduced sulphur
UBA	Umweltbundesamt (German Federal Environmental Agency)
VOC	Volatile organic compounds
WMO	World Meteorological Organization

65

1 Goal and scope

1.1 Background and objectives

As one of the world's leading suppliers, Tetra Pak® provides complete processing and carton packaging systems and machines for beverages, dairy products and food. Currently, the range of packaging systems comprises eleven alternatives, e.g. Tetra Brik®, Tetra Rex®, Tetra Top® (Tetra Pak 2021). Tetra Pak® is part of the Tetra Laval Group, which was formed in January 1993. The three industry groups Tetra Pak, DeLaval and Sidel are currently included in the group.

An integral part of Tetra Pak's business strategy and activities is the systematic work on the efficient use of resources and energy. The 2020 environmental targets of Tetra Pak focus on the use of sustainable materials to continuously improve the entire value chain and the increase of recycling to further reduce the impact on the environment. All paperboard sourced by Tetra Pak comes from wood from Forest Stewardship Council™ (FSC™)-certified forests and other controlled sources. Tetra Pak supports the sustainable production of sugarcane by purchasing Bonsucro certified plant-based plastic. For more details please visit *www.bonsucro.com*.

Tetra Pak has recently finalised LCA studies for several packaging formats including plant-based polymers alternatives in several European markets. In this study one beverage packaging format of Tetra Pak, PET bottles with recycled content (rPET) and bottles made of plant-based polyethylene furanoate (PEF) are examined in the segment JNSD Family Pack (ambient) on the Dutch market. All relevant packaging formats analysed are selected by Tetra Pak.

The main objectives of this study are:

(1) to compare the environmental performance of Tetra Pak's beverage carton system with rPET bottles on the Dutch market.

(2) to compare the environmental performance of Tetra Pak's beverage carton system with PEF bottles on the Dutch market.

(3) to assess the impact of the deposit system and the associated higher collection rate on the compared packaging systems.

This assessment is done following the rules of life cycle assessment according to the international standards ISO 14040/14044.

The examined beverage carton system in the segment JNSD Family Pack (ambient) on the Dutch market is:

- Tetra Brik® Aseptic 1000 Edge LightWing™ 30 with plant-based polymers (1000 mL)

The examined competing beverage packaging systems the segment JNSD Family Pack (ambient) on the Dutch market are:

- 50% rPET bottle (1000 mL)
- 65% rPET bottle (1000 mL)
- PEF bottle (1000 mL)

Further information on the selection of competing packaging systems can be found in **section 2.1**.

Organisation of the study

This study was commissioned by Tetra Pak in 2025. It is being conducted by the Institute for Energy and Environmental Research Heidelberg gGmbH (ifeu).

The members of the project panel are:

- **Tetra Pak**: Maren Fuhrich, Magdalena Psuja
- **ifeu**: Samuel Mahami, Saskia Grünwasser, Frank Wellenreuther, Andrea Drescher

The modelling of the Life Cycle Assessment was done with the software Umberto 5.5.

Use of the study and target audience

The comparative results of this study are intended to be used by the commissioner (Tetra Pak) to support comparative assertions. Further, they shall serve for information purposes of Tetra Pak's customers, e.g. fillers and retail customers. The study and/or its results are therefore intended to be publicly disclosed.

This full LCA is consistent with the ISO standards on LCA (ISO 14040 2006; ISO 14044: 2006). Therefore, a critical review process is undertaken by an independent panel of three LCA experts.

The members of the independent panel are:

- Prof. Dr. Guido Sonnemann (chair), as freelancer, The Life Cycle Group CyVi, France
- Dr. Alex Hetherington, 3Keel Group Ltd., UK
- Meis Uijttewaal, CE Delft, the Netherlands

Additional to the critical review panel no other interested parties were involved in the study.

Functional unit

The function examined in this LCA study is the packaging of ambient beverages for retail. The functional unit (FU) for this study is the provision of 1000 L of product at the point of sale in the Netherlands. The packaging of the beverages is provided for the required shelf life of the product.

The shelf life of all packaging systems is longer than required for the usual consumption period. Therefore, the function regarding beverage safety stays the same for all examined packaging solutions.

The primary packages examined are technically equivalent regarding the mechanical protection of the packaged beverage during transport, the storage at the point-of-sale and the use phase as described in the following section.

The reference flow of the product system assessed here, refers to the actual filled volume of the containers and includes all packaging elements, e.g. beverage carton and the transport packaging (corrugated trays and shrink film, pallets), which are necessary for the packaging, filling and delivery of 1000 L beverage.

1.2 System boundaries

The study is designed as a ‘cradle-to-grave’ LCA without the use phase, in other words, it includes the extraction and production of raw materials, converting processes, all transports and the final disposal or recycling of the packaging system.

In general, the study covers the following steps:

- Production, converting, recycling and final disposal of the primary base materials used in the primary packaging elements from the studied systems including closures, straws (if existent) and labels.
- Production, converting, recycling and final disposal of primary packaging elements and related transports.
- Production, recycling, and final disposal of transport packaging (stretch film, pallets, cardboard trays).
- Production and disposal of process chemicals, as far as not excluded by the cut-off criteria (see end of this section).
- Transports of packaging material from producers to converters and fillers.
- Filling processes, which are fully assigned to the packaging system.
- Transport from fillers to potential central warehouses and final distribution to the point of sale.
- Material losses in all converting and recycling processes of packaging elements
- Material losses in raw material production as applied in aggregated datasets

Not included are:

- The production and disposal of the infrastructure (machines, transport media, roads, etc.) and their maintenance (spare parts, heating of production halls) as their impact is considered negligible. To determine if infrastructure can be excluded the authors apply two criteria: Capital goods should be included if the costs of maintenance and depreciation are a substantial part of the product (Heijungs 1992) and if environmental hot spots within the supply chain can be identified (Frischknecht et al. 2007). Both criteria are considered to assess relevant information on the supply chain from producers and retailers. An inclusion of capital goods might also lead to data asymmetries as data on infrastructure is not available for many production data sets.
- Production of beverage and transport to fillers as no relevant differences between the systems under examination are to be expected.
- Distribution of beverage from the filler to the point-of-sale (distribution of packages is included) as the same amount of beverage is transported for all regarded packaging systems (see transport allocation in **section 1.4.1**).
- Environmental effects from accidents like breakages during transportation as from a methodological point, accidents are not considered in this LCA.
- Losses of beverage at different points in the supply and consumption chain which might occur for instance in the filling process, during handling and storage, etc. as they are considered to be roughly the same for all examined packaging systems. Significant differences in the amount of lost beverage between the assessed packaging systems might be conceivable only if non-intended uses or product treatments are considered as for example in regard to different breakability of packages or potentially different amount of residues left in an emptied package due to the design of the package/closure. Further possible losses are directly related to the handling of the consumer in the use phase, which is not part of this study as handling behaviours are very different and difficult to assess. Some data about beverage losses in households is available, these losses though

cannot be allocated to the different beverage packaging systems. Further, no data is available for losses at the point of sale. Therefore, possible beverage loss differences are not quantifiable. In consequence, a sensitivity analysis regarding beverage losses would be highly speculative and is not part of this study. This is indeed not only true for the availability of reliable data, but also uncertainties in inventory modelling methodology of regular and accidental processes and the allocation of potential beverage waste treatment aspects.

- Activities at the points of sale, as no relevant differences between the systems under examination are to be expected.
- Transport of filled packages from the point of sale to the consumer as no relevant differences between the systems under examination are to be expected and the implementation would be highly speculative as no reliable data is available. Further beverages are mostly bought by consumers among other goods, an allocation of the transport to the beverage packaging would also be highly speculative.
- Use phase of packages at the consumers as no relevant differences between the systems under examination are to be expected (for example in regard to cleaning before disposal or chilling at home) and the implementation would be highly speculative as no reliable data is available.

The following simplified flow charts shall illustrate the system boundaries considered for the packaging systems beverage cartons (Figure 1), PET bottles (Figure 2) and PEF bottles (Figure 3). For more details regarding specifications of the packaging systems see **section 2.2.** In case recycled material is used as recycled content in a closed loop, the flow charts show a connection between the recycling process and the material supply phase. Specific percentages of end-of-life streams are shown in **section 2.3**. As there are no refillable packaging systems established on the Dutch market for the packaging of ambient beverage, only single use packaging systems are included in this study.

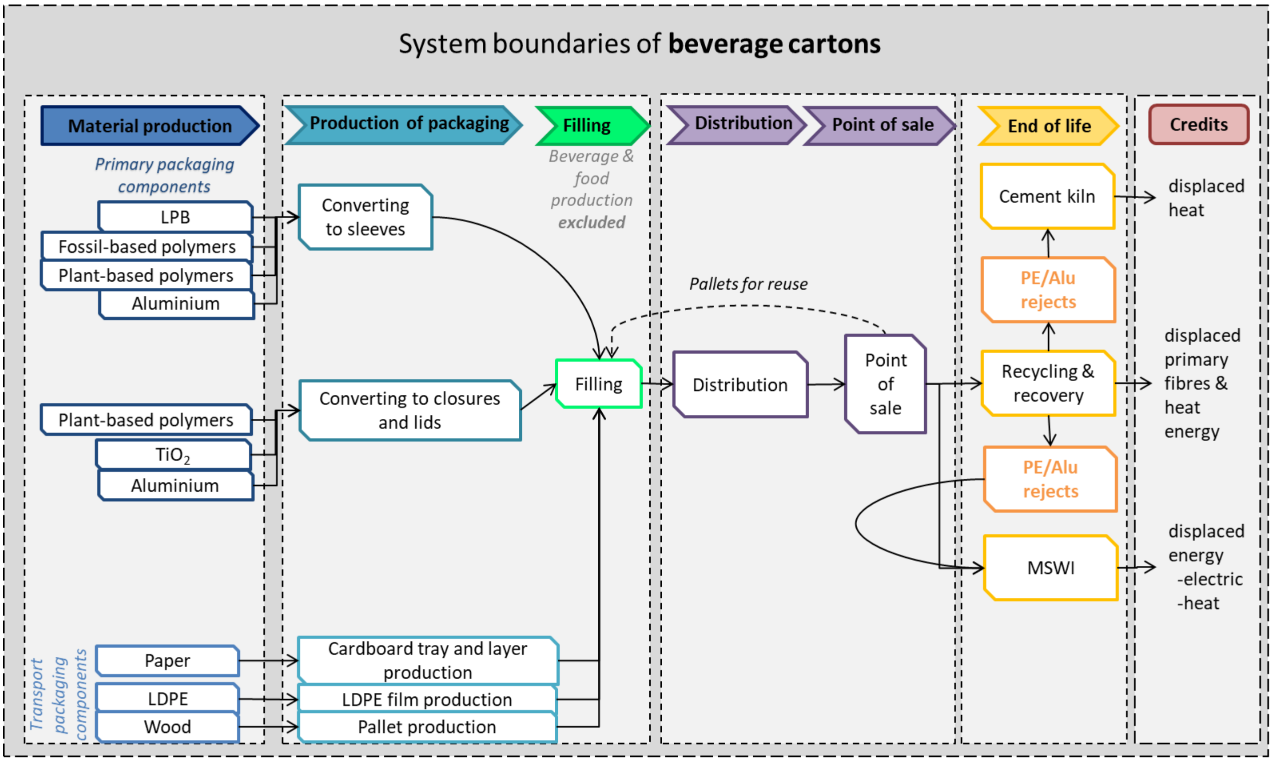
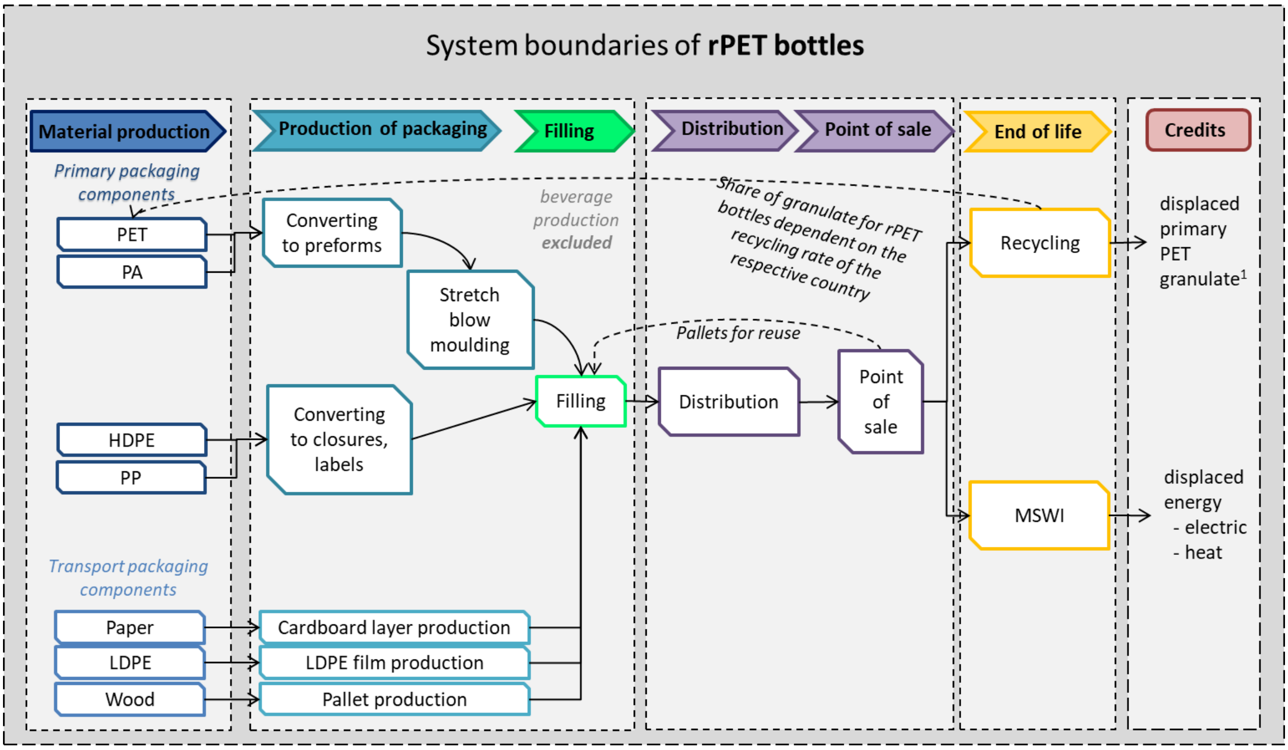
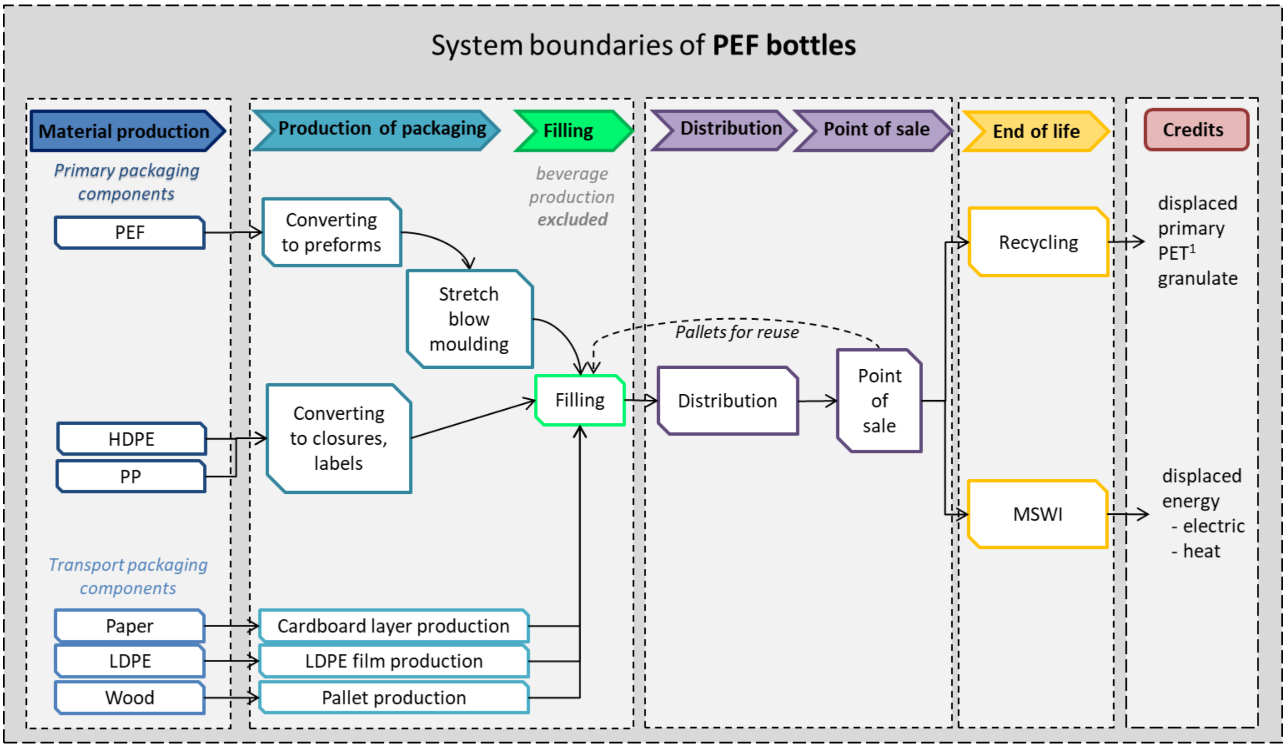


Figure 1: System boundaries of beverage cartons



[1]only if the share of recycled content is lower than the recycling rate of the respective country

Figure 2: System boundaries of rPET bottles



[1]PEF bottles in this study are treated as PET bottles in the end-of-life, see section 2.3 and 3.9

Figure 3: System boundaries of PEF bottles

For recycling and recovery routes the system boundary is set at the point where a secondary product (energy or recycled material) is obtained. The secondary products can replace primary energy generation processes and virgin materials, respectively. This effect is accounted for in the life cycle assessment by attributing credits for secondary products. These credits are calculated based on the environmental burdens of the corresponding primary energy generation process or material. The final disposal of those recycled materials undergoing another life cycle in a subsequent system is included in this study. Thus, all recycled materials finally end up in MSWI or landfills, depending on the municipal solid waste stream of the regarded country, which are the Netherlands in most cases regarded in this study (PET bottles, PEF bottles, transport packaging). As there is a landfill ban for municipal waste in the Netherlands (EEA 2025), no landfill shares are considered in the Netherlands. In case of beverage cartons from the Dutch market, these are exported for recycling to various countries (DE, FR, IT and ES). The final disposal of the recycled fibres is modelled depending on the municipal solid waste stream of the country in which the recycling takes place. .

Packaging systems which are not collected and recycled are sent to incineration plants (thermal recovery).

Cut-off criteria

In order to ensure the symmetry of the packaging systems to be examined and in order to maintain the study within a feasible scope, a limitation on the detail in system modelling is necessary. So-called cut-off criteria are used for that purpose. According to ISO standard (ISO 14044: 2006), cut-off criteria shall consider mass, energy or environmental significance. Regarding mass-related cut-off, prechains from preceding systems with an input material share of less than 1% of the total mass input of a considered process were excluded from the present study. However, total cut-off is not to surpass 5% of input materials as referred to the FU.

Based on the mass-related cut-off the amount of printing ink used for the surface of beverage cartons and labels of the bottles was excluded in this study. The mass of ink used per packaging never exceeds 1% of the total mass of the primary packaging for any beverage carton examined in this study. Due to the fact that the printed surface of the labels on the bottles is smaller than the surface of a beverage carton, the authors of the study assume, that the printing ink used for the labels will not exceed 1% of the total mass of the primary packaging as well. Environmental relevance of ink in beverage packaging systems is low. Ruttenborg (2017) included ink in a LCA of beverage cartons. The contribution of ink to Climate Change is less than 0.2%. According to Tetra Pak, inks are not in direct food contact. However, the requirements on inks are that they need to fulfil food safety requirements. This is also valid for all base materials included in the packages. From the toxicological point of view therefore no relevance is to be expected.

1.3 Data gathering and data quality

The datasets used in this study are described in **section 3**. The general requirements and characteristics regarding data gathering and data quality are summarised in the following paragraphs.

Geographic scope

The production of the beverage carton, rPET bottles and PEF bottles in this LCA study takes place in specific countries as stated in **Table 1**. The distribution and disposal of the packaging systems takes place in the specific regarded market of this LCA study, which are the Netherlands. Country-specific data for the market is generated by using European process data as a proxy combined with the local electricity mix of the Netherlands. A certain share of the raw material production for packaging systems takes place in specific countries. For these, country-specific data is used (liquid packaging board (LPB)). In cases in which only aggregated datasets are available European average[1] data are used. **Table 1** lists the geographic scopes of the applied data in the considered market.

Table 1: Geographic scope of applied process data and electricity prechains // packaging systems on the NL market

		beverage cartons	rPET bottles	PEF bottles
Raw material extraction / cultivation for	LPB	Northern Europe	-	-
	polymers	Global	Global	Global
	plant-based polymers	BR		Europe
	aluminium	Global	-	-
	corrugated cardbaord	n/a	n/a	n/a
Materials	LPB	SE, FI	-	-
	polymers	Europe[1]	Europe[1]	Europe[1]
	plant-based polymers	BR	-	Europe[2]
	aluminium	EU27+3[3]	-	-
	corrugated cardbaord	Europe[4]	Europe[3]	Europe[3]
Converting	bodies	DE[5]	LU[5]	BE[5]
	closures	EU27+3[5]	FR[5]	FR[5]
End of Life		NL, ES, FR, IT, DE	NL	NL

[1] based on several plants in Europe (EcoInvent 3.10).
[2] based on literature (see section 3.1.6)
[3] EU27+3 (Norway, Switzerland, Iceland), (EAA 2013), (EAA 2018). The applied dataset is only available as aggregated European dataset.
[4] based on several plants in Europe (FEFCO and Cepi Container Board 2024).
[5] European process data combined with electricity prechains of EU27+3, Germany, France, Luxembourg and Belgium.

[1] European data includes UK data before leaving the EU

Time scope

The packaging specifications listed in **section 2** as well as the market situation for the choice of beverage packaging systems refers to 2025. Therefore, the reference time for the study is 2025.

The applied data is referring to the period between 2005 and 2025 (see Table 13 in **section 3**). Exceptions are the data for PA6 (1999). In this and other cases in which old data is used no newer data was available. In these cases, the data has been checked for its representativeness (see for example the choice of dataset for PA6 described in **section 3.1.7**. If possible, always the most up to date pre-chains are used (for example electricity production for beverage carton converting). Particularly with regard to data on end-of-life processes of the packages examined, the most current available information is used to correctly represent the recent changes in this area. The datasets for transportation, energy generation and waste treatment processes are taken from ifeu's internal database in the most recent version (2023). The data for plastic production originates from the EcoInvent 3.10 database published on EcoInvent (2023) and refer to different years, depending on material and year of publication.

More detailed information on the applied life cycle inventory data sets can be found in **section 3**.

Technical reference

The process technology underlying the datasets used in the study reflects process configurations as well as technical and environmental levels which are typical for process operations in the reference period.

Completeness

In general, the data collection and data implementation for the ifeu internal database takes place in four phases: In phase one, to understand the processes like filling, converting or plastics production, they are analysed based on available literature, discussions with the respective stakeholders or the production sites are directly visited. In this phase, the relevant flows of following flow types are identified: reference product, co-products, intermediate inputs, raw inputs, (material, energy, and water), waste to treatment (solid and hazardous and liquid), emissions to air (GHGs, Criteria Air Pollutants, Toxics + Other and Water), emissions to water (Nutrients and Toxics + Other), and emissions to soil (Nutrients and Toxics + Other). In phase 2, the respective companies provide data on the identified inputs (e.g., amount of raw materials, energy, or water) and main output products (e.g. emissions to air and water). In phase 3, a completeness check regarding all possible used impact and inventory categories are carried out based on information from phase 1. Based on this, additional relevant data are collected, concerning emissions to air and water, amounts of waste, and transport information. In phase 4, an additional completeness check is carried out, where the LCIA results of the implemented data are cross checked with available LCIA results (e.g., previous data, data from other geographic regions, similar processes). Missing information on land-use, water use, and toxicity are discussed in **section 1.5** in the respective sections.

Consistency

All data intended to be used are considered to be consistent for the described goal and scope regarding: applied data, data accuracy, technology coverage, time-related coverage and geographical coverage (see **section 3** for further details).

Sources of data

Process data for base material production and converting were either collected in cooperation with the industry or taken from literature and the ifeu database. Ifeu's internal database includes data either collected in cooperation with industry or is based on literature. The database is continuously updated. Background processes such as energy generation, transportation, MSWI and landfill were taken from the most recent version of it. All data sources are summarised in Table 13 and described in **Section 3**.

Summary of data quality

The quality of the data applied is summarized with data quality indicators as described in (Weidema et al. 2013). **Table 2** describes the indicators with their potential scores. **Table 3** summarizes the data quality by scoring the data for the most relevant processes in the study.

Table 2: Pedigree matrix used to assess the quality of data (Weidema et al. 2013)

Indicator score	1	2	3	4	5
reliability	Verified[1] data based on measurements[2]	Verified data partly based on assumptions or non-verified data based on measurement	Non-verified data partly based on qualified estimates	Qualified estimate (e.g. by industrial expert)	Non-qualified estimate
completeness	Representative data from all sites relevant for the market considered, over an adequate period to even out normal fluctuations	Representative data from >50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations	Representative data from only some sites (<<50%) relevant for the market considered or >50% of sites but from shorter periods	Representative data from only one site relevant for the market considered or some sites but from shorter period	Representativeness unknown or data from a small number of sites and from shorter periods
temporal correlation	Less than 3 years of difference to the time period of the dataset	Less than 6 years of difference to the time period of the dataset	Less than 10 years of difference to the time period of the dataset	Less than 15 years of difference to the time period of the dataset	Age of data unknown or more than 15 years of difference to the time period of the dataset
geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from area with similar production conditions	Data from area with slightly similar production condition	Data from unknown or distinctly different area (North America in-stead of Middle East, OECD-Europe instead of Russia)
further technological correlation	Data from enterprises, processes and materials under study	Data from processes and materials under study (i.e. identical technology) but from different enterprises	Data from processes and materials under study but from different technology	Data on related processes or materials	Data on related processes on laboratory scale or from different technology

[1] Verification may take place in several ways, e.g. by on-site checking, by recalculation, through mass balances or cross-checks with other sources

[2] ncludes calculated data (e.g. emissions calculated from inputs to an activity), when the basis for calculation is measurements (e.g. measured inputs). If the calculation is based partly on assumptions, the score would be 2 or 3

Table 3: Summary of data quality with data quality indicators

		reliability	completeness	temporal correlation	geographical correlation	Further technological correlation
Raw material extraction / cultivation and material production	LPB	1	1	3	2	1
	fossil polymers	1	1	4/1[1, 2]	2	1
	plant-based PE	1	1	4	1	1
	plant-based PEF	2	3	4	2	2
	aluminium foil	1	1	2	2	1
	corrugated cardbaord	1	1	2	2	1
Converting	PET bodies	2	2	3	2	2
	PEF bodies	2	2	3	2	4
	beverage carton sleeves	1	1	1	1	1
Filling	plastic bottles	2	2	3	2	2
	beverage cartons	1	1	1	1	1
End of Life	PET bottle recycling	1	2	5	2	1
	PEF bottle recycling	1	2	5	2	4
	Beverage carton recycling	1	3	5	2	1
	MSWI	1	1	3	1	1
Back-groud data	electricity	1	1	2	1	1
	transports	1	1	3	1	1

[1] score 4 refers to final polymerization process, score 1 for raw material extraction

[2] except PA 6, see section 3.1.7

Precision and uncertainty

For studies to be used in comparative assertions and intended to be disclosed to the public, ISO 14044 asks for an analysis of results for sensitivity and uncertainty. Uncertainties of datasets and chosen parameters are often difficult to determine by mathematically sound statistical methods. Hence, for the calculation of probability distributions of LCA results, statistical methods are usually not applicable or of limited validity. To define the significance of differences of results, an estimated significance threshold of 10 % is chosen as pragmatic approach. This is recommended by practitioners of LCA studies comparing different product systems (Detzel et al. 2016; Kupfer et al. 2017). This means differences ≤ 10 % are considered as insignificant.

1.4 Methodological aspects

1.4.1 Allocation

Allocation refers to “partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems” (ISO 14044: 2006 definition 3.17). This definition comprises the partitioning of flows regarding re-use and recycling, particularly open loop recycling.

In the present study, a distinction is made between process-related and system-related allocation, the former referring to allocation procedures in the context of multi-input and multi-output processes and the latter referring to allocation procedures in the context of open loop recycling.

Both approaches are further explained in the subsequent sections.

Process-related allocation

For *process-related allocations,* a distinction is made between multi-input and multi-output processes.

Multi-input processes

Multi-input processes occur especially in the area of waste treatment. Relevant processes are modelled in such a way that the partial material and energy flows due to waste treatment of the used packaging materials can be apportioned in a causal way. The modelling of packaging materials that have become waste after use and are disposed in a waste incineration plant is a typical example of multi-input allocation. The allocation for e.g. emissions arising from such multi-input processes has been carried out according to physical and/or chemical cause-relationships (e.g. mass, heating value (for example in MSWI), stoichiometry, etc.).

Multi-output processes

For data sets prepared by the authors of this study, the allocation of the outputs from coupled processes is generally carried out via the mass as this is usual practice. Physical causality is also the preferred method after system expansion according to (ISO 14040 2006; ISO 14044 2006). If different allocation criteria are used, they are documented in the description of the data in case they are of special importance for the individual data sets. For literature data, different allocation criteria are also documented in the description of the data or reference is made to the data source.

Transport processes

An allocation between the packaging and contents was carried out for the transportation of the filled packages to the point-of-sale. Only the share in environmental burdens related to transport, which is assigned to the package, has been accounted for in this study. That means the burdens related directly to the beverage is excluded. The allocation between package and filling goods is based on mass criterion. This allocation is applied as the FU of the study defines a fixed amount of beverage through all scenarios. Impacts related to transporting the beverage itself would be the same in all scenarios. Thus, they don’t need to be included in this comparative study of beverage packaging systems.

System-related allocation

System-related allocation is applied in this study regarding open loop recycling and recovery processes. Recycling refers to material recycling, whereas recovery refers to thermal recovery for example in MSWI with energy recovery or cement kilns. System-related allocation is applied to both recycling, and recovery in the end of life of the assessed system and processes regarding the use of recycled materials by the assessed system. System-related allocation is not applied regarding disposal processes like landfills with minor energy recovery possibilities. **Figure 4** illustrates the general allocation approach used for uncoupled systems and systems which are coupled through recycling. In **Figure 4** (upper diagram) in both, 'system A' and 'system B', a virgin material (e.g., polymer) is produced, converted into a product which is used and finally disposed. A virgin material in this case is to be understood as a material without recycled content. A different situation is shown in the lower diagram of **Figure 4**. Here product A is recovered after use and supplied as a raw material to 'system B' avoiding thus the environmental burdens related to the production ('MP-B') of the virgin materials, e.g., polymer and the disposal of product A ('Dis-A'). In order to do the allocation consistently, besides the virgin material production ('MP-A') already mentioned above and the disposal of product B ('Dis-B'), also the recovery process 'Rec' has to be taken into consideration.

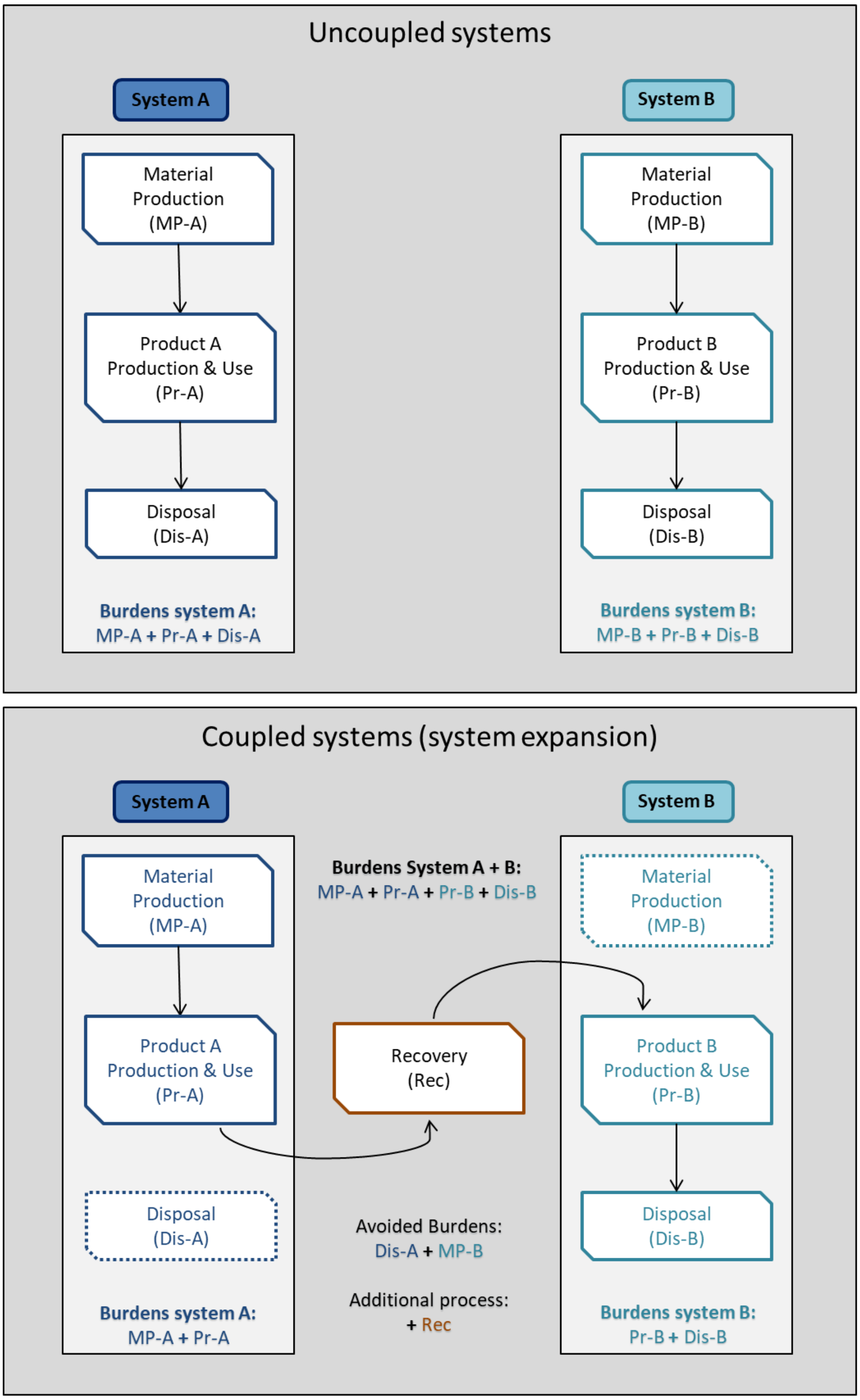


Figure 4: Additional system benefit/burden through recycling (schematic flow chart)[1]

If the system boundaries of the LCA are such that only one product system is examined it is necessary to decide how the possible environmental benefits and burdens of the material recovery and recycling and the benefits and burdens of the use of recycled materials shall be allocated (i.e. accounted) to the assessed system. In LCA practice,

[1] boxes with dashed lines are avoided processes

several allocation methods are found. There is one important premise to be complied with by any allocation method chosen: the mass balance of all inputs and outputs of 'system A' and 'system B' after allocation must be the same as the inputs and outputs calculated for the sum of 'systems A and B' before allocation is performed.

System allocation approaches used in this study

The approach chosen for system-related allocation is illustrated in **Figure 5** and **Figure 6**. Both diagrams show two example product systems, referred to as product 'system A' and 'product system B'. 'System A' shall represent systems under study in this LCA in the case if material is provided for recycling or recovery. 'System B' shall represent systems under study in this LCA in the case recycled materials are used.

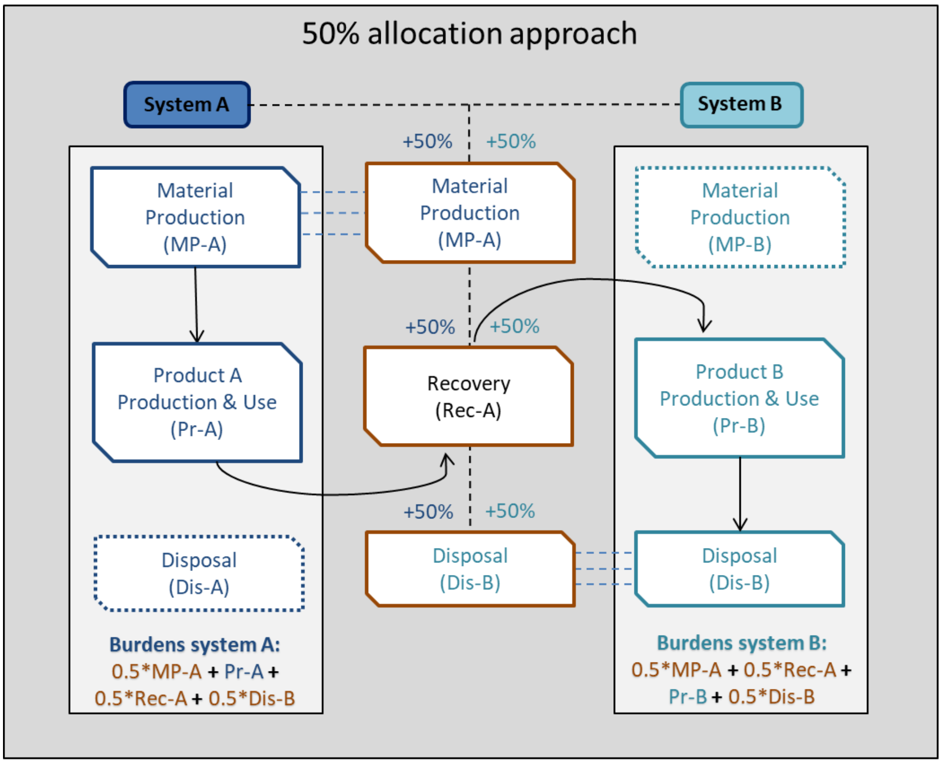


Figure 5: Principles of 50% allocation (schematic flow chart)[1]

Allocation with the 50% method (Figure 5)

In this method, benefits and burdens of 'MP-A', 'Rec-A' and 'Dis-B' are equally shared between 'system A' and 'system B' (50:50 method). Thus, 'system A', from its viewpoint, receives a 50% credit for avoided primary material production and is assigned with 50% of the burden or benefit from waste treatment (Dis-B). If recycled material is used in the assessed system, the perspective of 'system B' applies. Also in this case benefits and burdens of 'MP-A', 'Rec-A' and 'Dis-B' are equally shared between 'system A' and 'system B'. The benefits and burdens of 'MP-B' and 'Dis-A' are avoided in this method and thus neither charged to 'system A' nor to 'system B'. The allocation treatment described for material recovery is also valid for energy recovery.

Example 1 ('system A'), virgin beverage carton, which is recycled or thermally recovered after its use: All burdens from recycling and recovery processes are shared between the regarded beverage carton system and the following system (use of secondary material or energy production). Also the benefits from replacing virgin materials or grid

[1] boxes with dashed lines are avoided processes

energy are shared between the regarded system and the following systems. For energy recovery, electricity or heat energy of the target market are credited.

Example 2 ('system B'), PET bottle containing recycled PET (rPET): All burdens from recycling of the used rPET are shared between the regarded rPET bottle system and the preceding system. Also the benefits from replacing virgin materials are shared between the regarded system and the preceding system.

The 50% method has often been discussed in the context of open loop recycling, see (Fava et al. 1991; Frischknecht 1998; Kim et al. 1997; Klöpffer 1996). According to (Klöpffer 2007), this rule is furthermore commonly accepted as a "fair" split between two coupled systems.

The approach of sharing the burdens and benefit from both, providing material for recycling and recovery, as well as using recycled material, follows the goal of encouraging the increase in recyclability as well as the use of recycled material. These goals are also in line with those of several packaging waste directives and laws as for the EU Single Use Plastic Directive (Directive (EU) 2019/904 EC), which specific targets includes incorporating 25% of recycled plastic in PET beverage bottles from 2025, and 30% in all plastic beverage bottles from 2030, the European Packaging and Packaging Waste Directive (EU 2018) or the German packaging law (Verpackungsgesetz - VerpackG 2021) Extended, according to the EU 'Proposal for a regulation on packaging waste', from 2040, single use plastic beverage bottles shall contain a minimum of 65 % recycled content (European Commission 2022).

The 50:50 method has been used in numerous LCAs carried out by ifeu and is also an often recommended standard approach, for example by the German and French environmental agencies (ADEME 2022; UBA 2000, 2016).

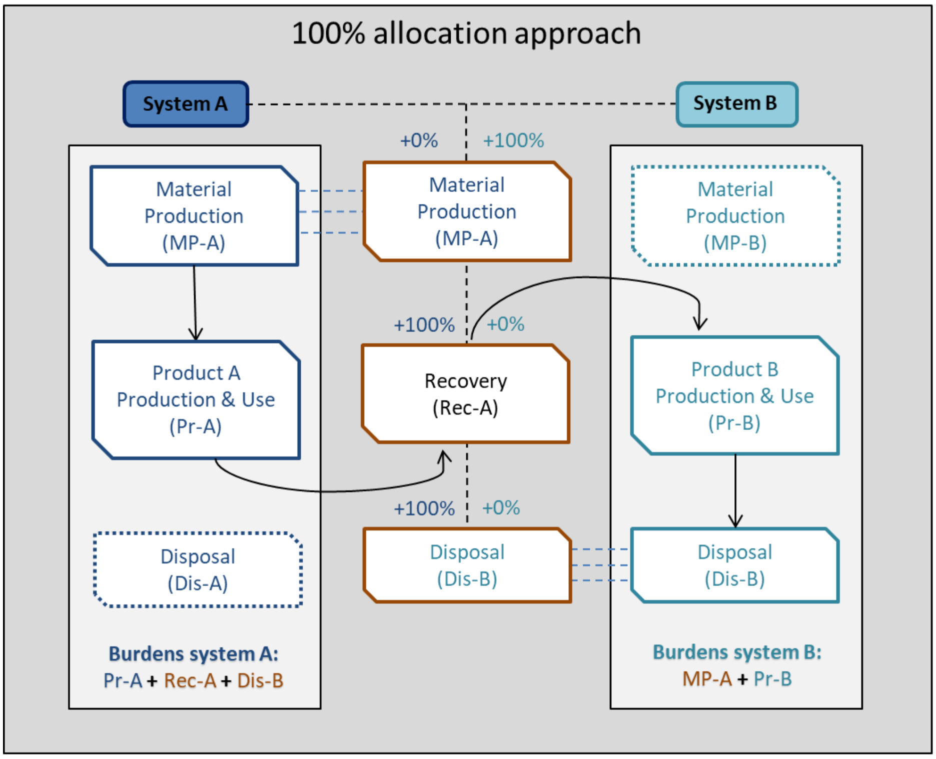


Figure 6: Principles of 100% allocation (schematic flow chart) [1]

[1] boxes with dashed lines are avoided processes

Allocation with the 100% method (Figure 6)

In this method, the principal rule is applied that 'system A' gets all benefits for displacing the virgin material and the involved production process 'MP-B'. At the same time, all burdens for producing the secondary raw material via 'Rec-A' are assigned to 'system A'. The same is valid for thermal recovery. All benefits and burdens for displacing energy production are allocated to 'system A'. In addition, also the burdens that are generated by waste treatment of 'product B' in 'Dis-B' is charged to 'system A', whereas the waste treatment of 'product A' is avoided and thus charged neither to 'system A' nor to 'system B'.

If recycled material is used in the assessed system, the perspective of 'system B' applies. The burdens associated with the production process 'MP-A' are then allocated to 'System B' (otherwise the mass balance rule would be violated). However, 'system B' is not charged with burdens related to 'Rec' as the burdens are already accounted for in 'system A'. At the same time, 'Dis-B' is not charged to 'system B' (again a requirement of the mass balance rule), as it is already assigned to 'system A'.

Example 1 ('system A'), virgin beverage carton which is recycled or thermally recovered after its use: All burdens from recycling and recovery processes are allocated to the regarded beverage carton system. Also the benefits from replacing virgin materials or grid energy are fully allocated to the regarded system.

Example 2 ('system B'), PET bottle containing recycled PET (rPET): All burdens from recycling of the used rPET are allocated to the preceding system. Also the benefits from replacing virgin materials are allocated to the preceding system.

The application of the allocation 100% is considered as a conservative approach from the view of the beverage carton. It means that a comparatively unfavourable case for the beverage cartons is chosen. For example, the PET and PEF bottles benefit more from accounting of 100% material credits due to the much higher burdens of their avoided primary material production, compared to the production of LPB. The allocation factor of 100% is expected to lead to higher benefits for PET and PEF bottles.

This approach is also in line with earlier LCA studies done for Tetra Pak.

Following the ISO standard's recommendation on subjective choices, the 50% and 100% allocation methods are applied equally in this study. Conclusions in terms of comparing results between packaging systems are only drawn if they apply to both allocation methods.

General notes regarding Figure 4 to Figure 6

The diagrams are intended to support a general understanding of the allocation process and for that reason they are strongly simplified. The diagrams serve

- to illustrate the difference between the 50% allocation method and the 100% allocation method
- to show which processes are allocated:
  - primary material production
  - recycling and recovery processes
  - waste treatment of final residues

However, within the study the actual situation is modelled based on certain key parameters, for example the actual recycling flow and the actual recycling efficiency (**Table 12**) as well as the actual substituted material including different substitution factors.

The allocation of final waste treatment is consistent with UBA LCA methodology established in studies (UBA 2000, 2016) and additionally this approach – beyond the UBA methodology – is also in accordance with (ISO 14044: 2006).

For simplification some aspects are not explicitly documented in the mentioned diagrams, among them the following:

- Material losses occur in both 'systems A and B' but are not shown in the diagrams. These losses are of course taken into account in the calculations; their disposal is included within the respective systems.
- Hence, not all material flows from 'system A' are passed on to 'system B', as the simplified material flow diagrams may imply. Consequently, only the effectively recycled and recovered material's life cycle steps are allocated between 'systems A and B'.
- The diagrams do not show the individual process steps relevant for the waste material flow out of 'packaging system A', which is sorted as residual waste, including the respective final waste treatment.
- For simplification, a substitution factor of 1 underlies the diagrams. However, in the real calculations smaller values are used where appropriate. For example, if a material's properties after recycling are different from those of the primary material it replaces, this translates to a loss in material quality. A substitution factor < 1 accounts for such effects. For further details regarding substitution factors please see the following section.

Application of allocation rules

The allocation factors have been applied on a mass basis (i.e. the environmental burdens of the recycling process are charged with the total burdens multiplied by the allocation factor) and where appropriate have been combined with substitution factors. The substitution factor indicates what amount of the secondary material substitutes for a certain amount of primary material. For example, a substitution factor of 0.9 means that 1 kg of recycled (secondary) material replaces 0.9 kg of primary material and receives a corresponding credit. With this, a substitution factor < 1 also accounts for so-called 'down-cycling' effects, which describe a recycling process in which waste materials are converted into new materials of lesser quality.

The substitution factors used in the current LCA study to calculate the credits for recycled materials provided for consecutive (down-stream) uses are based on a report by the European Commission (Nessi et al. 2021). The substitution factor for PET from bottles is 1.0 as recycling from bottle to bottle is possible. Recycled granulate from PET bottles containing PA as barrier material has a lower quality than granulate from PET bottles without PA. Therefore, the substitution factor for recycled PET from PET bottles containing PA is reduced from 1.0 to 0.9 (corresponding to the substitution factor for non-SSP recycling stated in (Nessi et al. 2021). The substitution factors apply to the secondary materials after the recycling processes with their production losses (see **section 3.9**).

- Paper fibres
  - from LPB (carton-based primary packaging): 1.0
  - in cardboard trays (secondary packaging): 1.0
- LDPE film: 0.75
- PEF in bottles (bottle-to-bottle recycling): 1.0
- PET in bottles containing PA (bottle-to-bottle recycling): 0.9
- HDPE: 0.9

1.4.2 Biogenic carbon

Renewable materials like paper fibres originate from renewable biomass that absorbs carbon from the air. The growth of biomass reduces the amount of CO_2 in the atmosphere. In this study, the fixation of CO_2 by the plants is referred as CO_2 uptake and the (re-)emission of CO_2 at the material's end of life is referred as biogenic CO_2.

Application and allocation

At the impact assessment level, it must be decided how to model and calculate the uptake and emissions of biogenic CO_2. In the present study, the non-fossil CO_2 has been included at two points in the model, its uptake during the plant growth phase attributed with negative GWP values and the corresponding re-emissions at end of life with positive ones. In this study biogenic CO_2 is treated in the same way as other resources and emissions and is therefore subject to the same allocation rules as other resources and emissions. According to packaging waste directives and laws as for example the European Packaging and Packaging Waste Directive (EU 2018), the German packaging law (Verpackungsgesetz - VerpackG 2021) or the 'Proposal for a regulation on packaging waste' (European Commission 2022), the following practices in packaging production shall be promoted:

- Use of recycled content in packaging systems
- Recyclability of packaging systems
- Use of renewable resources in packaging systems

In the view of the authors, it is important that the environmental benefits of all of these practices are made visible in the results of LCA.

The first two practices are considered by the choice of the allocation factor 50% for system-related allocation as one of the two allocation approaches equally applied in this study. As described in **section 1.4.1** the application of the allocation 50% shows benefits for the use of recycled content in packaging systems as well as their recycling. In order to not restrain the recyclability of packaging systems and in order to also promote the use of renewable resources a convention in this study is made, that implies that the CO_2 uptake is not considered in credited materials or energy.

The application of the CO_2 uptake in credits would reduce the CO_2 uptake of assessed packaging systems containing biogenic materials by the amount of CO_2 which has been absorbed from the atmosphere by the substituted processes. The selection of substituted processes is based on the current market situation within the addressed geographic scope. Regarding energy credits from the incineration of biogenic materials, the substituted processes are the production of electrical and thermal energy. These to a high extent fossil-based processes do absorb negligibly small amounts of biogenic CO_2. Therefore, almost no CO_2 uptake would be attributed to the substituted processes. The benefit of the CO_2 uptake of the assessed packaging systems containing biogenic materials would not be reduced.

On the other hand, if packaging systems containing biogenic materials are materially recycled, and if the substituted processes for the material credits are the production of other primary biogenic materials, the absorption of CO_2 from the atmosphere would be substituted. Therefore, the benefits of the CO_2 uptake of assessed packaging systems would be reduced by the CO_2 uptake of the substituted processes.

Using the example of mainly biogenic materials like liquid packaging board, the application of the CO_2 uptake in credits would deter from recycling efforts of packaging containing biogenic materials as incineration instead of recycling would lead to lower LCA results for 'Climate Change'.

The authors of this study acknowledge that with the application of this convention only the producers of products containing primary biogenic materials benefit. This is considered appropriate as these producers are responsible for sourcing renewable materials in the first place. Producers of products which merely contain biogenic materials sourced from recycling processes would not be benefited. As no primary packaging which contain recycled biogenic materials are analysed in this study, this approach of not considering CO_2 uptake in credits is seen suitable within this study. Incineration plants that burn used packaging for energy recovery also do not get a benefit for incinerating plant-based materials. This is considered appropriate, because in contrast to the producer of the packaging, the operator running an incineration plant does not deliberately choose plant-based materials for incineration. This convention does also comply with ISO 14040/14044 as the mass balance of all inputs and outputs regarding biogenic CO_2 of 'system A' and 'system B' together stays the same.

As described in **section 1.4.1** system-related allocation is applied in this study for thermal recovery processes like MSWI with energy recovery and incineration in cement kilns. Therefore system-related allocation applies for the emissions of biogenic CO_2 from thermal recovery of biogenic materials. In case of allocation 50%, half of the biogenic CO_2 emissions are attributed to the examined system and half of the biogenic CO_2 emissions are attributed to the following system, for example the MSWI plants with thermal recovery.

Together with the full CO_2 uptake for the assessed system and the non-consideration of the CO_2 uptake in credits the mass balance of all biogenic carbon is the same after and before allocation following ISO 14040 and 14044. Regarding the LCA results for 'Climate Change', packaging systems containing biogenic materials benefit if the system-related allocation 50% is applied for recovery processes. When applying the allocation 50% approach the benefit regarding the LCA results for 'Climate Change' of packaging systems containing biogenic materials can promote the increase of use of biogenic materials in packaging system.

In case of applying allocation 100% for recovery processes all of the biogenic CO_2 emissions are attributed to the assessed system. Therefore, in this case, the additional benefit for 'Climate Change' results—typically granted to packaging systems with primary biogenic materials by allocating only 50% of the biogenic CO_2 emissions—is no longer applied.

As these decisions and conventions applied in this study are partly based on political reasons, it is especially important to consider the results of the 100% allocation approach equally alongside those of the 50% allocation approach. All conclusions in this study will always be based on the outcomes of both assessments, the 50% allocation and 100% allocation approach.

If renewable materials end up in landfills (depending on the landfill-incineration split of the specific country), they are not completely biodegraded. This effect leads to undegraded paper-board material remaining in landfills. A small fraction of biogenic carbon remains undegraded known as carbon storage, resulting in an imbalance between the biogenic carbon inputs and outputs of the system. This difference can affect the outcome of LCAs. However, the effective storage of substances in landfill represents an assumption of real-world conditions and is therefore a feature of the LCA model.

1.5 Life Cycle Impact Assessment

The environmental impact assessment is intended to increase the understanding of the potential environmental impacts for a product system throughout the whole life cycle (ISO 14040 2006; ISO 14044: 2006).

To assess the environmental performance of the examined packaging systems, a set of environmental impact categories is used. Related information as well as references of applied models is provided below. In this study, midpoint categories are applied. Midpoint indicators represent potential primary environmental impacts and are located between emission and potential harmful effect. This means that the potential damage caused by the substances is not taken into account.

The selection of the impact categories is based on the current practice in LCA. Also important is the applicability of a characterisation model with the least possible uncertainties and the completeness and availability of the inventory data. This choice is similar to that of the UBA approach (UBA 2016), which is fully consistent with the requirements of (ISO 14040 2006; ISO 14044: 2006). However, it is nearly impossible to carry out an assessment in such a high level of detail, that all environmental issues are covered. A broad examination of as many environmental issues as possible is highly dependent on the quality of the available inventory datasets and of the scientific acceptance of the certain assessment methods. ISO 14044: 2006 recommends that: “the impact categories, category indicators and characterisation models should be internationally accepted, i.e., based on an international agreement or approved by a competent international body”. As there are almost no truly international (i.e. global) agreements or bodies beyond ISO or IPCC that endorse specific environmental impact categories in LCA practice, categories, indicators and characterisation models which are widely used are considered to fulfil this recommendation. All the impact categories, category indicators and characterisation models used in this study are widely used internationally and are endorsed by internationally accepted bodies like EPA, IPCC, UBA, WMO or CARB (California Air Resources Board).

The LCA framework in this study addresses potential environmental impacts calculated based on generic spatial independent inventory data with global supply chains. Therefore, the characterisation models and associated factors are intended to support Life Cycle Impact Assessment on a global level for each impact category.

The description of the different impact categories and their indicators is based on the terminology by (ISO 14044: 2006). It must be noted; that the LCIA results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins or risks. All the applied methodologies for impact assessment can be considered to be internationally accepted.

The selected impact categories and additional inventory categories to be assessed and presented in this study are listed and briefly addressed below.

Additionally, the chapter is further describing categories are excluded and the reasoning for exclusion.

1.5.1 Impact categories

This section provides a description of the impact categories, applied as a mixed methodology.

Climate change

Climate Change addresses the impact of anthropogenic emissions on the radiative forcing of the atmosphere. Greenhouse gas emissions enhance the radiative forcing, resulting in an increase of the earth’s temperature. The characterisation factors applied here are based on the category indicator Global Warming Potential (GWP) for a 100-year time horizon (IPCC 2021).

Land use change is not considered in this study as no land use change can be identified regarding the LPB production, and no robust data on land use change is available for the two other plant-based materials (see sections 3.1.4, 3.1.6 and 3.2).

In reference to the functional unit (FU), the category indicator results, GWP results, are expressed as kg CO_2-eq/FU.

The applied method is (IPCC 2021).

Acidification

Acidification affects aquatic and terrestrial ecosystems by changing the acid-basic-equilibrium through the input of acidifying substances. The acidification potential expressed as SO_2-equivalents according to (Heijungs 1992) is applied here as category indicator.

The characterisation model by (Heijungs 1992) is chosen as the LCA framework addresses potential environmental impacts calculated based on generic spatial independent global inventory data. The method is based on the potential capacity of the pollutant to form hydrogen ions. The results of this indicator, therefore, represent the maximum acidification potential per substance without an undervaluation of potential impacts.

The method by (Heijungs 1992) is, in contrast to methods using European dispersion models, applicable for emissions outside Europe. Even though this study focusses on the European market on the product level, many processes especially the sourcing of resources (f.e. oil and coal) take place outside Europe and therefore need a global scope. The authors of the method using accumulated exceedance note that “the current situation does not allow one to use these advanced characterisation methods, such as the AE method, outside of Europe due to a lack of suitable atmospheric dispersion models and/or measures of ecosystem sensitivity” (Posch et al. 2008).

The unit for Acidification is kg SO_2-eq/FU.

The applied method is (Heijungs 1992).

Photochemical-Oxidant Formation

Photochemical-Oxidant Formation is the photochemical creation of reactive substances (mainly ozone), which affect human health and ecosystems. This ground-level ozone is formed in the atmosphere by nitrogen oxides and volatile organic compounds in the presence of sunlight.

In this study, ‘Maximum Incremental Reactivity‘ (MIR) developed in the US by William P. L. Carter is applied as category indicator for the impact category photochemical oxidant formation. MIRs expressed as [kg O_3-eq/emission i] are used in several reactivity-based VOC (Volatile Organic Compounds) regulations by the California Air Resources Board (Air Resources Board 2000). The approach of William P. L. Carter includes characterisation factors for individual VOC, unspecified VOC and Nitrogen oxides (NOx). The ‘Nitrogen-Maximum Incremental Reactivity‘ (NMIR) for NOx is introduced for the first time in 2008 (Carter 2008). The MIRs and NMIRs are calculated based on scenarios where ozone formation has maximum sensitivities either to VOC or NOx inputs. The factors applied in this study were published by Carter (2010). According to Carter (2008), “MIR values may also be appropriate to quantify relative ozone impacts of VOCs for life cycle assessment analyses as well, particularly if the objective is to assess the maximum adverse impacts of the emissions of the compounds involved.” The results reflect the potential where VOC or NOx reductions are the most effective for reducing ozone.

The MIR concept seems to be the most appropriate characterisation model for LCIA based on generic spatial independent global inventory data and combines following needs:

- Provision of characterisation factors for more than 1100 individual VOC, VOC mixtures, nitrogen oxides and nitrogen dioxides
- Consistent modelling of potential impacts for VOC and NOx
- Considering of the maximum formation potential by inclusion of most supporting background concentrations of the gas mixture and climatic conditions. This is in accordance with the precautionary principle.

Characterisation factors proposed by (Guinée 2002) and (Goedkoop et al. 2013) are based on European conditions regarding background concentrations and climate conditions. The usage of this characterisation factors could lead to an underestimation of the photo-oxidant formation potential in regions with e.g. a high solar radiation.

The unit for photochemical oxidant formation is kg O_3-eq/FU.

The applied method is (Carter, 2010)

Ozone depletion

This impact category addresses the anthropogenic impact on the earth’s atmosphere, which leads to the decomposition of naturally present ozone molecules, thus disturbing the molecular equilibrium in the stratosphere. The underlying chemical reactions are very slow processes and the actual impact, often referred to in a simplified way as the ‘ozone hole’, takes place only with considerable delay of several years after emission. The consequence of this disequilibrium is that an increased amount of UV-B radiation reaches the earth’s surface, where it can cause damage to certain natural resources or human health. In this study, the Ozone Depletion compiled by the World Meteorological Organisation (WMO 2011, 2019) is used as category indicator.

While the exact impact of nitrous oxide (N_2O) on Ozone depletion is less precisely known than that of halogenated substances, its ability to deplete stratospheric ozone has been recognized since 1970. Consequently, reducing N_2O emissions would also reduce climate forcing. However, other methodological approaches, such as CML (2016) and EF 3.1 (2022) do not account N_2O in their LCIA methods. In contrast, this study includes N_2O emissions into its analysis, utilizing the category indicator of 0.017 (Ravishankara et al. 2009; WMO 2011), which is also consistent within the range specified in WMO (2022).In reference to the functional unit, the unit for Ozone depletion is kg R-11-eq/FU.

The applied method is (WMO 2011, 2019)

Eutrophication

Eutrophication means the excessive supply of nutrients and can apply to both surface waters and soils. As these two different media are affected in very different ways, a distinction is made between water-eutrophication and soil-eutrophication:

1. ***Terrestrial Eutrophication*** (i.e., eutrophication of soils by atmospheric emissions)
2. ***Aquatic Eutrophication*** (i.e., eutrophication of water bodies by effluent releases)

Nitrogen- and phosphorus-containing compounds are among the most eutrophying elements. The eutrophication of surface waters also causes oxygen-depletion. A measure of the possible perturbation of the oxygen levels is given by the Chemical Oxygen Demand (COD). In order to quantify the magnitude of this undesired supply of nutrients and oxygen depletion substances and to cover their overall potential of secondary effects, the eutrophication potential according to (Guinée 2002; Heijungs 1992), covering COD, was chosen as an impact indicator.

The environmental impacts regarding eutrophication and oxygen depletion are therefore addressed by the following impact categories:

Terrestrial Eutrophication (including eutrophication of oligotrophic systems)
Category indicator: Terrestrial eutrophication
Characterisation factors: EP_i (kg PO_4^{3-}-e/kg $emission_i$) based on (Guinée 2002; Heijungs 1992)
Emissions to compartment: Emissions to air

Aquatic Eutrophication
Category indicator: Aquatic eutrophication
Characterisation factors: EP_i (kg PO_{43-}-e/kg $emission_i$) based on (Guinée 2002; Heijungs 1992)
Emissions to compartment: Emissions to water

The unit for both types of eutrophication is kg PO_4-eq/FU.

The applied method is (Guinée 2002; Heijungs 1992)

Particulate Matter

The category covers effects of fine particulates with an aerodynamic diameter of less than 2.5 µm (PM 2.5) emitted directly (primary particles) or formed from precursors as NOx and SO_2 (secondary particles). Epidemiological studies have shown a correlation between the exposure to particulate matter and the mortality from respiratory diseases as well as a weakening of the immune system. Following an approach of (de Leeuw 2002), the category indicator aerosol formation potential (AFP) is applied. Within the characterisation model, secondary fine particulates are quantified and aggregated with primary fine particulates as PM2.5 equivalents. This approach addresses the potential impacts on human health and nature independent of the population density.

The characterisation models suggested by Goedkoop et al. (2013) and (JRC 2011) calculate intake fractions based on population densities. This means that emissions transported to rural areas are weighted lower than transported to urban areas. These approaches contradict the idea that all humans independent of their residence should be protected against potential impacts. Therefore, not the intake potential, but the formation potential is applied for the impact category particulate matter.

In reference to the functional unit, the unit for particulate matter is kg PM 2.5-eq/FU.

The applied method is (de Leeuw 2002)

The following **Table 4:** summarises some examples of elementary flows and their classification to the impact categories included in the study and described before.

Table 4: Examples of elementary flows and their classification to emission related impact categories

Impact category	Elementary flows								Unit
Climate change	CO_2*	CH_4**	N_2O	$C_2F_2H_4$	CF_4	CCl_4	C_2F_6	R22	kg CO_2-eq
Ozone depletion	CFC-11	N_2O	HBFC-123	HCFC-22	Halon-1211	Methyl Bromide	Methyl Chloride	CCl_4	kg CFC-11-eq
Photochemical oxidant formation	CH_4	NMVOC	Benzene	Formal-dehyde	Ethyl acetate	VOC	TOC	NOx	kg O3-eq
Acidification	NO_x	NH_3	SO_2	TRS***	HCl	H_2S	HF		kg SO2-eq
Terrestrial eutrophication	NO_x	NH_3	SO_x						kg PO4-eq
Aquatic eutrophication	COD	N	NH^{4+}	NO^{3-}	NO^{2-}	P			kg PO4-eq
Particulate matter	PM 2.5	SO_2	NO_X	NH_3	NMVOC				kg PM 2.5-eq

* included: CO_2 fossil and biogenic
** included: CH_4 fossil and biogenic
*** Total reduced sulphur

1.5.2 Additional categories at the inventory level

This section provides a description of the inventory categories. Inventory level categories differ from impact categories to the extent that no characterisation step using characterisation factors is used for assessment.

Primary energy

The Total Primary Energy and the Non-renewable Primary Energy serve primarily as a source of information regarding the energy intensity of a system.

Total primary energy (Cumulative Energy Demand, total)

The Total Primary Energy is a parameter to quantify the primary energy consumption of a system. It is calculated by adding the energy content of all used fossil fuels, nuclear and renewable energy (including biomass). This category is described in (VDI 1997) and has not been changed considerably since then. It is a measure for the overall energy efficiency of a system, regardless the type of energy resource which is used.

The unit for Total Primary Energy is MJ/FU.

Non-renewable primary energy (Cumulative Energy Demand, non-renewable)

The category Non-renewable Primary Energy considers the primary energy consumption based on non-renewable, i.e. fossil and nuclear energy sources.

The unit for Non-renewable Primary Energy is MJ/FU.

Table 5: Examples of elementary flows and their classification to inventory level categories

Categories at inventory level		Elementary flow examples					Unit
Total Primary Energy	Non-renewable primary energy	hard coal	brown coal	crude oil	natural gas	uranium ore	MJ
	Renewable primary energy	hydro energy	solar energy	biomass	wind energy		

1.5.3 Categories not considered

Human and Eco Toxicity (excl. Particulate Matter)

There are various models for the life cycle assessment of human and eco toxicity. However, LCA results on toxicity are often unreliable, mainly due to incomplete inventories, and also due to incomplete impact assessment methods and uncertainties in the characterisation factors. None of the available models is clearly better than the others, although there is a slight preference for the model USEtox. USEtox is a consensus-based model developed under the United Nations Environment Program (UNEP) and the Society for Environmental Toxicology and Chemistry's (SETAC) Life Cycle Initiative. It provides midpoint and endpoint characterization factors for human toxicological and freshwater ecotoxicological impacts of chemical emissions in life cycle assessment. The REACH database, a EU regulatory framework for Registration, Evaluation, Authorisation and Restriction of Chemicals, contains substance properties and is used to generate input data and to calculate final substance characterisation factors with the USEtox® 2.1 model (Saouter et al. 2020).
Even though the development of the USEtox model is ongoing, with continuous efforts to enhance its accuracy, applicability, and scientific foundation (Andreasi Bassi et al. 2023), the robustness of the impact category has not yet reached a satisfactory level. Therefore, no assessment of human and eco toxicity is included in this study.

Use of nature

Land use could have large impacts on the natural environment, such as decrease in biodiversity due to direct loss of natural area or indirect impacts like area fragmentation and impacts on the life support function of the biosphere, such as raw materials providing or climate regulation. It can be especially relevant when examining products based on agriculture or forestry compared to products with other base and/or main materials.

The available data does not state information regarding the specific ecoregions and forest management types. Therefore, it is not possible to produce robust results that allow comparative assessments by applying an assessment methodology. Therefore, no assessment of the use of nature is included in this study.

Water scarcity

Due to the growing water demand, increased water scarcity in many areas and degradation of water quality, water as a scarce natural resource has become increasingly central to the global debate on sustainable development.

Due to the lack of mandatory information, for example regarding the region of water use in the applied data sets, water scarcity footprint cannot be examined on an LCIA level within this study. Some of the qualitative aspects are considered in this report in the impact category "Aquatic Eutrophication".

Abiotic resources

ADP is one possible assessment method for the abiotic resources' category. As described above, water and land use cannot be included in the study. In the author's opinion, abiotic resources should not be included for the following two reasons:

(1) Without analysing the categories use of nature and water scarcity, it is not possible to show an overall picture of the resources.

(2) With the abiotic resources category, exactly the resource category whose results look unfavourable for the competing packaging systems would be examined.

2 Packaging systems and scenarios

In general terms, packaging systems can be defined based on the primary, secondary and tertiary packaging elements they are made up of. The composition of each of these individual packaging elements and their components' masses depend strongly on the function they are designed to fulfil, i.e. on requirements of the filler and retailer as well as the distribution of the packaged product to the point-of-sale. The main function of the examined primary packaging is the packaging and protection of beverage. The packaging protects the filled products' freshness, flavours, and nutritional qualities during transportation, whilst on sale and at home. All examined packaging systems are considered to achieve this.

All packaging systems examined in this study are presented in the following **sections** (**2.1** & **2.2**), including the applied end-of-life options (**section 2.3**). **Section 2.4** provides information on all assessed scenarios.

2.1 Names of beverage cartons, selection and comparison overview of packaging systems

The focus of this study are the beverage cartons produced by Tetra Pak for which this study aims to provide knowledge of their strengths and weaknesses regarding environmental aspects. The beverage cartons are compared with corresponding competing packaging systems.

2.1.1 Names of beverage cartons

Table 6 presents the complete names of the beverage carton used in the main text of the report and the corresponding abbreviated names applied in tables and figures.

Table 6: List of names of beverage carton used in this study

Complete name used in the report (in the main text)	Abbreviated name used in the report (in tables and figures)
Tetra Brik® Aseptic 1000 Edge LightWing™ 30 with plant-based polymers	TBA 1000 E LW30 plant-based PE

2.1.2 Reason for selection

The choice of beverage cartons has been made by Tetra Pak based on market relevance. The carton selected is the main competitor to the regarded rPET and PEF bottles for JNSD on the Dutch market. The local marketing team of Tetra Pak has very detailed knowledge of the regarded market based on communication with their customers and Dutch retailers and on statistical market data purchased from data providers like NielsenIQ, GfK and Euromonitor. Main criterion for choosing a specific packaging was the market share within the respective segment. Usually, the products of the brands with the highest market share were chosen. As the importance of the packaging for Tetra Pak's existing or targeted customers was also a selection criterion, in some cases not the packaging with the highest market share, but another packaging with a very high market share of one of these customers was selected. Therefore, the chosen alternative packaging system is typical on the Dutch market but do not represent the entire market in the sense that every available alternative option is examined. This means that this study does not support claims for the best option to pack a certain product in the specific market but aims to present comparative LCA environmental impact results for Tetra Pak's beverage cartons and their main competitors. Details regarding the chosen packaging systems and their reason for selection are shown in **Table 7**

Table 7: Selection and reason of competing packaging systems in segment **JNSD, Family Pack (ambient)**

Segment	Geographic scope	Competing packaging system	Reason for selection
JNSD Family Pack (ambient)	NL	50% rPET bottle 1000 mL	The PET bottle is the main competitor in the JNSD ambient segment in the Netherlands. The rPET share is typically 50%. In order to consider also the target for recycled content of the European regulation[1], the same bottle is also considered with 65% rPET.
		65% rPET bottle 1000 mL	
		PEF bottle 1000 mL	Retailers on the Dutch market are introducing PEF bottles. The PEF bottle considered is being introduced in the 1000 mL JNSD segment.

2.1.3 Comparison overview of packaging systems

The following **Table 8** shows which beverage cartons are compared with the selected competing systems. The number of packages required for the functional unit is also listed. Similar volume sizes will be compared.

Table 8: List of Tetra Pak beverage cartons in segment **JNSD, Family Pack (ambient)** and corresponding competing packaging systems in the Netherlands

Carton based packaging systems	ambient	Reference flow (systems / 1000 L)	Geographic scope	Competing packaging systems	ambient	Reference flow (systems / 1000 L)	Geographic scope
TBA 1000E LW30 plant-based PE 1000 mL	✓	1000	NL	50% rPET bottle 1000 mL	✓	1000	NL
				65% rPET bottle 1000 mL	✓	1000	NL
				PEF bottle 1000 mL	✓	1000	NL

[1] (*Regulation (EU) 2025/40 of the European Parliament and of the Council of 19 December 2024 on packaging and packaging waste, amending Regulation (EU) 2019/1020 and Directive (EU) 2019/904, and repealing Directive 94/62/EC* 2024)

2.2 Packaging specifications

Specifications of beverage carton packaging systems are listed in

Table 9 were provided by Tetra Pak. In Tetra Pak's internal database typical specifications of all primary packages sold are registered. The specifications of individual packages of one single carton system may vary to a small degree over different production batches or production sites. To get the final specifications per beverage carton type the exact specifications of different batches were averaged taking into consideration the production volumes of each production batch. For confidentially, in case of the polymers used in the beverage carton systems, no differentiations to specific polymers are shown in the tables. The calculations are calculated with the specific shares of each polymer used. These are disclosed to the critical review panel.

In case of primary packaging of beverage cartons, no materials with recycled content are used. Although aluminium is a widely recycled material, aluminium foil with the very low thickness required for beverage cartons is currently not available with a recycled content.

Data on secondary and tertiary packaging for beverage cartons was also provided by Tetra Pak from its internal packaging system model. The data is periodically updated, and the most recent data of 2020-2025 is used in this LCA.

Specifications of the competing packaging types that have been identified as relevant in the examined segments are listed in **Table 10**. They were provided by the customer of Tetra Pak. In case of the primary packaging of PET bottle the specifications of primary packaging were additionally determined by ifeu in 2025 based on three samples collected by Tetra Pak on the Dutch market. As no significant differences were observed, this can be considered a representative sample. The samples were assessed by ifeu regarding the type of materials and their quantified weights. Specifications were determined by weighing the separate parts of the packaging systems. Materials were classified by the declaration on the packaging parts. As the PEF bottle is not yet on the market no samples were able to be analysed. Specifications of the PEF bottle were provided by the customer of Tetra Pak. Specifications of secondary and tertiary packaging systems were provided by the customer of Tetra Pak and checked and supplemented with standard ifeu internal data in case of stretch film per pallet and cardboard layers.

Based on the specifications provided by the customer of Tetra Pak, the PET bottle has currently a recycled PET content of 50%. Additionally a PET bottle with the same specifications but a recycled content of 65% is calculated in order to represent the goal of recycled in content for single-use plastic bottles in 2040 based on the European regulation (*Regulation (EU) 2025/40 of the European Parliament and of the Council of 19 December 2024 on packaging and packaging waste, amending Regulation (EU) 2019/1020 and Directive (EU) 2019/904, and repealing Directive 94/62/EC* 2024)

These specifications are used to calculate the base scenarios for all packaging systems.

2.2.1 Specifications of beverage carton systems

Table 9: Packaging specifications for assessed carton systems for the packaging of **JNSD, Family Pack (ambient)**

Specification	Unit	Packaging system
		TBA 1000 E LW30 plant-based PE
volume	mL	1000
geographic Scope	-	NL
ambient		
primary packaging (sum)[1]	**g**	**32.02**
primary packaging (per FU)	**g/FU**	**32020**
composite material (sleeve)	g	29.3
- liquid packaging board	g	22.2
- fossil-based polymer	g	4.1
- plant-based polymer	g	1.6
- virgin aluminium	g	1.4
closure[2]	g	2.72
- plant-based polymer	g	2.7
- fossil-based polymer	g	-
- alu lid	g	0.02
secondary packaging (sum)[3]	**g**	**176**
secondary packaging (per FU)	**g/FU**	**17600**
- corr. cardboard tray	g	176
- stretch film per tray	g	-
tertiary packaging (sum)[4]	**g**	**32250**
tertiary packaging (per FU)	**g/FU**	**31618**
- pallet	g	30000.0
number of use cycles	-	25
- cardboard layer (per pallet)	g	1750.0
- number of cardboard layers	-	5
- stretch film (per pallet) (LDPE)	g	500.0
pallet configuration		
Prim. packaging per sec. packaging	pc	12
sec. packaging per layer	pc	17
layers per pallet	pc	5
prim. packaging per pallet	pc	1020

[1] per primary packaging unit
[2] Note: a small proportion of the closures contains titanium dioxide
[3] per secondary packaging unit
[4] per tertiary packaging unit (pallet)

2.2.2 Specifications of alternative packaging systems

Table 10: Packaging specifications for assessed alternative systems in the segment **JNSD, Family Pack (ambient)**

JNSD Family Pack (ambient)

Specification	Unit	Packaging system		
		50% rPET bottle	65% rPET bottle	PEF bottle
volume	mL	1000	1000	1000
geographic Scope	-	NL	NL	**NL**
clear / opaque	-	clear	clear	clear
ambient				
primary packaging (sum)[1]	**g**	**33.40**	**33.40**	**27.40**
primary packaging (per FU)	**g/FU**	**34400**	**34400**	**27400**
bottle	g	29.79	29.79	23.80
- PET	g	28.30	28.30	-
- PEF	g			23.80
- PA6	g	1.49	1.49	-
rPET	g	14.15	18.40	-
rPET	%	50	65	-
label	g	**0.84**	**0.84**	**0.84**
- PP	g	0.84	0.84	0.84
closure[2]	g	2.77	2.77	2.77
- HDPE	g	2.77	2.77	2.77
secondary packaging (sum)[3]	**g**	**10.56**	**10.56**	**10.56**
secondary packaging (per FU)	**g/FU**	**1760**	**1760**	**1760**
- stretch film per tray	g	10.56	10.56	10.56
tertiary packaging (sum)[4]	**g**	**30250.0**	**30250.0**	**30250.0**
tertiary packaging (per FU)	**g/FU**	**33611**	**33611**	**33611**
- pallet	g	28000.0	28000.0	28000.0
number of use cycles	-	25	25	25
- cardboard layer (per pallet)	g	1750.0	1750.0	1750.0
- number of cardboard layers	-	5	5	5
- stretch film (per pallet) (LDPE)	g	500.0	500.0	500.0

[1] per primary packaging unit
[2] Note: a small proportion of the closures contains titanium dioxide
[3] per secondary packaging unit
[4] per tertiary packaging unit (pallet)

pallet configuration				
prim. packaging per sec. packaging	pc	6	6	6
sec. packaging per layer	pc	30	30	30
layers per pallet	pc	5	5	5
prim. packaging per pallet	pc	900	900	900

2.3 End-of-life

For each packaging system assessed in the study, scenarios are modelled and calculated using country-specific recycling rates for post-consumer packaging. Additionally, a distinction is made between domestic recycling and recycling abroad (export for recycling). The applied recycling quotas and recycling locations are derived from published data. Material recycling quotas represent the actual amount of recycled material leaving a material recycling process. The recycling rate therefore includes losses in sorting and recycling processes. The remaining post-consumer packaging waste is modelled and calculated based on the country-specific split between landfilling and incineration (MSWI) in the Netherlands.

Due to the similar structure of PEF and PET, up to 5% of PEF can be incorporated into the PET recycling streams (PETplanet 2024; SpecialChem 2021). Therefore PEF bottles in this study are treated as PET bottles in the end-of-life.

Recycling locations of beverage cartons

Beverage cartons on the Dutch market are exported to Germany, France, Italy and Spain for recycling.

Recycling locations of PET / PEF bottles

The PET bottles on the Dutch market are assumed to be recycled domestically (ICIS 2024).

Table 11 presents the country-specific disposal split for the Netherlands, indicating the shares of waste managed via the Municipal Solid Waste Incineration (MSWI) rate and the landfill rate. **Table 12** lists various packaging types and provides the respective material recycling or recovery rates for each type. To determine the specific disposal routes (MSWI share and landfill share) for each packaging type, the following methodological approach is applied:

For each packaging type, the share that is not recycled is calculated by subtracting the recycling rate (C) from 100%.

$$Non-recycled\ share = 100\% - C$$

The remaining share is then split between MSWI and landfill according to the proportions specified in Table 16. The MSWI share is calculated by multiplying the non-recycled share by the MSWI rate (A) and dividing by 100:

$$MSWI\ share = \frac{(100\% - C) \times A}{100}$$

Similarly, the landfill share is calculated using the landfill rate (B):

$$landfill\ share = \frac{(100\% - C) \times B}{100}$$

The sum of the recycling rate, MSWI share, and landfill share for each packaging type equals 100%.

Example calculation: PET / PEF bottles

To illustrate the calculation, the example of the PET bottle is used:

- Recycling rate (C): 60%
- Non-recycled share: 100% - 60% = 40%
- MSWI rate (A, from **Table 11**): 100%
- Landfill rate (B, from **Table 11**): 0%

Calculation of the MSWIl share of PET bottles:

$$MSWI\ share = \frac{(100\% - 60\%) \times 100}{100} = 40\%$$

The landfill share can be calculated analogously using the corresponding rate.

Table 11: Applied end of life disposal split in the Netherlands and countries for final treatment of recycled beverage cartons

market	MSWI rate (A)	landfill rate (B)
the Netherlands	100%	0%
	(EEA 2025)	
	2025	
mix (France, Germany, Italy, Spain)	57%	43%
	(eurostat 2025)	
	2021	

Table 12: Applied end of life quotas for beverage cartons and competing packaging systems in the Netherlands

Packaging system	Material recycling/recovery & reference & ref. year (C)	MSWI share Calculation → ((100-C) x A)/100	Landfill share Calculation → ((100-C) x B)/100
Beverage carton	46%[1] (verpact 2025a), 2024	54%	0%
PET / PEF bottle (base scenario)	60%[2] (verpact 2025a), 2024	40%	0%
PET / PEF bottle (sensitivity scenario)	65%[3] (verpact 2025a), 2024	35%	0%

The following flow charts illustrate the applied end-of-life models of beverage cartons, PET and PEF bottles for the Dutch market. The applied percentages are based on the end-of-life quotas in **Table 12**. For the sorting process typical efficiencies from the internal ifeu database are applied (90% for beverage cartons and non-deposit PET/PEF bottle collection) and 99% for deposit PET/PEF bottle collection)

[1] Recycling rate refers to the output of recycled material. 46% includes also shares of PolyAl recycling. In this study only the fibre content is recycled. (see section 3.9). Therefore, the output recycling rate applied in the study refers only to the fibres and is with 41% (verpact 2025b) slightly lower than the published recycling rate of 46%.

[2] Recycling rate refers to the output of recycled material. It is based on the collection rate of 77% published by (verpact 2025). The recycling rate of 60% includes losses in sorting and recycling processes.

[3] Recycling rate refers to the output of recycled material. It is based on the collection rate of 83% published by (verpact 2025). The recycling rate of 65% includes losses in sorting and recycling processes.

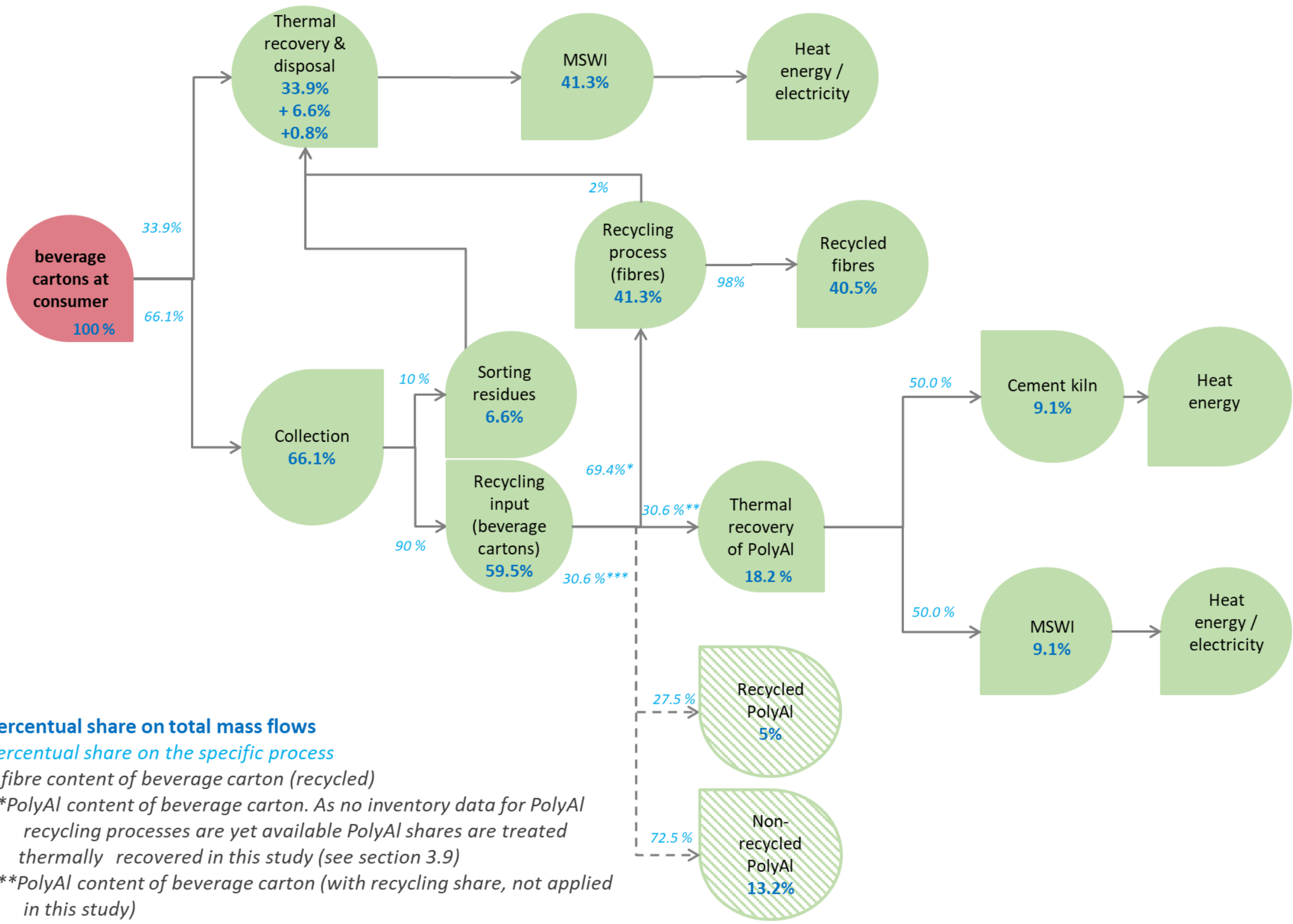


Figure 7: Applied end-of-life quotas for beverage cartons in the Netherlands

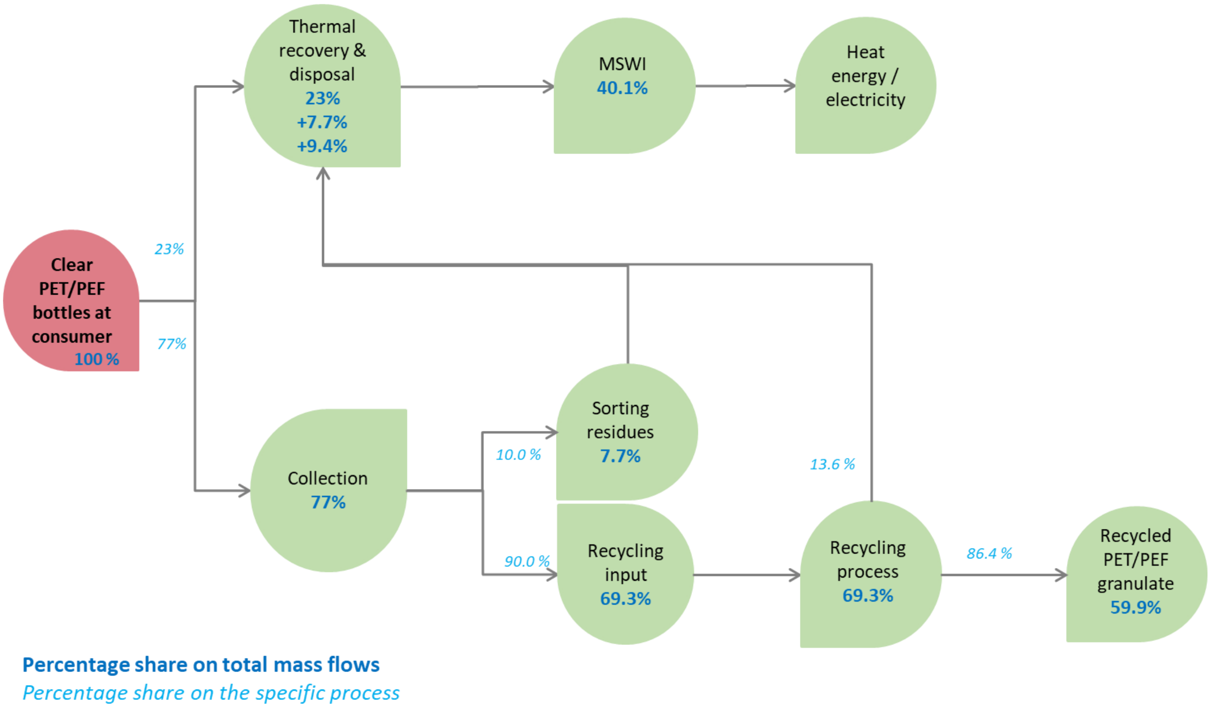


Figure 8: Applied end-of-life quotas for PET/PEF bottles in the Netherlands (base scenario)

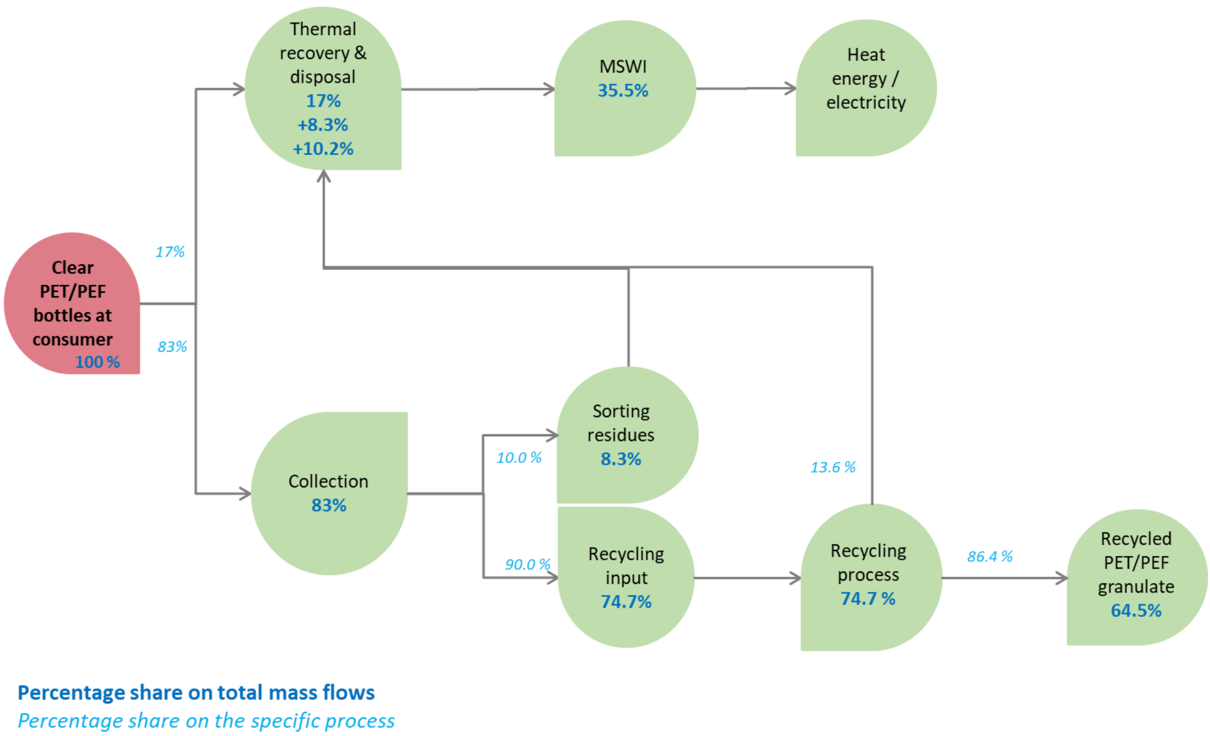


Figure 9: Applied end-of-life quotas for PET/PEF bottles in the Netherlands (sensitivity scenario)

2.4 Scenarios

2.4.1 Base scenarios

For each of the studied packaging systems a scenario for the Dutch market is defined, which is intended to reflect the most realistic situation under the described scope. Following the ISO standard's recommendation, a variation of the allocation procedure shall be conducted. Therefore, two scenarios to be considered equally regarding the open-loop allocation are calculated for each packaging system:

- with a system allocation factor of 50 %
- with a system allocation factor of 100 %

2.4.2 Sensitivity scenarios

Additional sensitivity scenarios are calculated regarding:

- the recycled PET content of the rPET bottles. Besides the considered recycled PET contents of 50% and 65% a sensitivity analysis is calculated for the rPET bottle with a recycled PET content of 100%. On a technical basis this is possible and 100% rPET bottles exist. In the perspective of LCA, 100% rPET bottles are seen critically as not all material can be sourced from closed loop bottle to bottle material (due to recycling rates lower than 100% and losses in the recycling process). The additional sourced rPET open loop material can therefore not be used in other applications with recycled PET contents, leading to no real environmental benefit considering the whole circularity of PET.
- the collection rate of PET and PEF bottles. In the base scenarios the PET and PEF bottles are modelled with a non-deposit collection. A collection rate of 77% is applied (verpact 2025). This refers to the current collection status of plastic beverage bottles in the Netherlands being a mix of collection through a deposit system and through a collection of mixed packaging waste without deposit, as currently only a portion of JNSD packaging is part of the deposit refund system (verpact 2025). As no PET bottle specific collection rate with no share of deposit collection is available the applied collection rate of 77% in the base scenarios is a conservative approach in the perspective of the beverage cartons. As a sensitivity the collection rate of 83% representing plastic beverage bottles collected exclusively with the deposit refund system (verpact 2025) is added for all rPET and PEF bottles.

3 Life cycle inventory

Data on processes for packaging material production and converting were either collected in cooperation with the industry or taken from literature and the ifeu database. Concerning background processes (energy generation, transportation as well as waste treatment and recycling), the most recent version of ifeu's internal, continuously updated database was used. Table 13 gives an overview of important datasets applied in the current study. Primary data collected in 2025 for example for filling processes are not extrapolated for the end of the year as the data are based on machine consumption. All data used meet the general requirements and characteristics regarding data gathering and data quality as summarised in **section 1.3.**

Table 13: Overview on inventory/process datasets used in the current study

Material / process	Source	Reference year/ period	Collected data
Intermediate goods			
Fossil PP	EcoInvent 3.10, (11/2024)	2011-2024	secondary
Fossil LDPE	EcoInvent 3.10, (11/2024)	2011-2024	secondary
Fossil HDPE	EcoInvent 3.10, (11/2024)	2011-2024	secondary
Plant-based PE	Braskem 2018	2015	secondary
Fossil PET	EcoInvent 3.10, (11/2024)	2015-2024	secondary
Plant-based PEF	Eerhart et al. 2012, EcoInvent 3.10, (11/2024)	2012-2024	secondary
Fossil PA	PlasticsEurope 2005	1999	secondary
Aluminium (primary)	European Aluminium 2025	2023	secondary
Aluminium foil	European Aluminium 2025	2022	secondary
Corrugated cardboard	FEFCO and Cepi Container Board 2024	2022	secondary
Liquid packaging board	ifeu data, obtained from ACE (ACE and ifeu 2020)	2018	secondary
Production			
Beverage carton converting	Tetra Pak 2025	2023	primary
PET preform production	Ifeu database	2019	primary
Filling			
Filling of beverage cartons	Data provided by Tetra Pak	2025	primary
Filling plastic bottles	Ifeu database, SBM is included in data for PET bottles	2019	primary
Recovery			
Beverage carton recycling	ifeu database, based on data from various European recycling plants	2004	primary

Material / process	Source	Reference year/ period	Collected data
PET bottle	ifeu database, data collected from different recyclers in Germany and Europe	2009	primary
Background data			
Electricity production	ifeu database, based on statistics and power plant models	2021	secondary
Municipal waste incineration	ifeu database, based on statistics and incineration plant models	2016-2021	secondary
Thermal recovery in cement kilns	ifeu database, German cement industry association (VDZ)	2006	primary
Truck transport	ifeu database, based on statistics and transport models, emission factors based on HBEFA 4.1 (INFRAS 2017).	2017	secondary
Rail transport	EcoTransIT World 2016	2016	secondary
Sea ship transport	EcoTransIT World 2016	2016	secondary

3.1 Plastics

The following plastics are used within the packaging systems under study:

- Polypropylene (PP)
- Low density polyethylene (LDPE)
- High density polyethylene (HDPE)
- Plant-based polyethylene (LDPE and HDPE)
- Polyethylene terephthalate (PET)
- Plant-based polyethylene furanoate (PEF)
- Polyamide 6 (PA6)

3.1.1 Polypropylene (PP)

Polypropylene (PP) is produced by catalytic polymerisation of propylene into long-chained polypropylene. The two important processing methods are low pressure precipitation polymerisation and gas phase polymerisation. In a subsequent processing stage the polymer powder is converted to granulate using an extruder.
The present LCA study utilises data published by EcoInvent (2023). The dataset covers the production of PP from cradle to the polymer factory gate. The polymerisation data refer to the 2011 time period and were acquired from a total of 35 polymerisation plants producing. The total PP production in Europe (EU27+2) in 2011/2012 was 8,500,000 tonnes. The EcoInvent data set hence represented 77% of PP production in Europe.

3.1.2 Low density polyethylene (LDPE)

Low density polyethylene (LDPE) is manufactured in a high-pressure process and contains a high number of long side chains. The present LCA study uses the data published by EcoInvent (2023).
The data set covers the production of LDPE granulates from the extraction of the raw materials from the natural environment, including processes associated with this. The data refer to the 2011 time period. Data were acquired from a total of 22 participating polymerisation units. The data set represent 72% of LDPE production in Europe (EU27+2).

3.1.3 High Density Polyethylene (HDPE)

High density polyethylene (HDPE) is produced by a variety of low pressure methods and has fewer side-chains than LDPE. The present LCA study uses the data published by EcoInvent (2023).

The data set covers the production of HDPE-granulate from the extraction of the raw materials from the natural environment, including processes associated with this. The data refer to the 2011 time period and were acquired from a total of 21 participating polymerisation units. The data set represented 68% of HDPE production in Europe (EU27+2).

3.1.4 Plant-based polyethylene

All packaging systems analysed in this study, which contain plant-based polyethylene (PE) are beverage carton systems. The plant-based PE used by Tetra Pak in the assessed beverage carton systems is supplied by Braskem in Brazil. The PE is produced from ethanol derived from sugar cane. The plant-based PE has the same characteristics as fossil-based PE. Therefore, the same end of life applies to plant-based PE and fossil-based PE. The plant-based PE in this study shall not be mistaken with biodegradable plastics. This study uses two LCA datasets provided by Braskem, one for plant-based HDPE and one for plant-based LDPE (Braskem 2018). In order to address co-products for produced bioelectricity in the plant-based PE production, the Braskem LCA datasets used in this study use the approach of economical allocation instead of substitution of energy production. The allocation approach complies with previous studies regarding plant-based and fossil HDPE (Murphy 2013). Credits for land use change have been excluded from the datasets as underlying assumptions and models are not known.

3.1.5 Polyethylene terephthalate (PET)

Polyethylene terephthalate (PET) is produced by direct esterification and melt polycondensation of purified terephthalic acid (PTA) and ethylene glycol. The model underlying this LCA study uses data published by EcoInvent (2023) with a reference year of 2015, that represents the production in European PET plants. Data for foreground processes of PTA production are taken from the PTA eco-profile (CPME 2016) which is based on primary data from five European PTA producers covering 79% of the PTA production in Europe. The foreground process of ethylene glycol production is taken from the Eco-profile of steam cracker products (PlasticsEurope 2012). For PET production data from 12 production lines at 10 production sites in Belgium, Germany, Lithuania (2 lines), the Netherlands, Portugal, Spain (4 lines) and United Kingdom (2 lines) supplied data with an overall PTA volume of 2.9 million tonnes – this represents 85% of the European production volume (3.4 million tonnes).

3.1.6 Plant-based polyethylene furanoate (PEF)

Plant-based polyethylene furanoate (PEF) is produced by the polymerization of plant-based monoethylene glycol (MEG) and plant-based 2,5-Furandicarboxylic acid (FDCA). The model underlying this LCA study is based on Eerhart et al. (2012). Process data in terms of input/ouput data not stated in Eerhart et al. (2012) originate from confidential data from previous LCA projects. This European model based on corn does not include land use change. The only available corn dataset that includes impacts from land use change is only available for Hungary. As the land use change in that dataset is very low, the authors prefer a European average dataset over a dataset for a specific country. Prechain data for the processes were taken from Ecoinvent 3.10.

3.1.7 Polyamide 6 (PA6)

Polyamide 6 is manufactured from the precursors benzene and hydroxylamine. The present LCA study uses the ecoprofile published on the website of Plastics Europe (data last calculated March 2005) and referring to the year 1999 (PlasticsEurope 2005). A more recent dataset is available provided by PlasticsEurope. However in this dataset ammonium sulphate is seen as a by-product of the PA6 production process of the PA6 pre-product caprolactam. The dataset uses a substitution approach to account for ammonium sulphate. As basically all ammonium sulphate on the market is derived from the PA6 production, in the view of the authors it is not valid to substitute a separate ammonium sulphate production process. Even within the PlasticsEurope methodology this approach is only allowed, "…if there is a dominant, identifiable production path for the displaced product" (PlasticsEurope 2019). Unfortunately, no dataset applying another approach apart from the substitution approach is available. The applied dataset in this study shows very high N_2O emissions. Based on a more recent confidential PA dataset, N_2O emissions in present PA6 production are significantly lower. Since the N_2O emissions of the PA6 dataset are the main driver in the impact category 'Ozone depletion', results for 'Ozone depletion' involving packaging systems containing PA6 should be treated with caution.

3.2 Production of liquid packaging board (LPB)

The production of liquid packaging board (LPB) was modelled using data gathered from all board producers in Sweden and Finland. It covers data from four different production sites where more than 95% of European LPB is produced. The reference year of these data is 2018. It is the most recent available and also published in the EcoInvent 3.10 database.

The four datasets based on similar productions volumes were combined to one average. They cover all process steps including pulping, bleaching and board manufacture. They were combined with data sets for the process chemicals used from ifeu´s database and Ecoinvent 3.6 including a forestry model to calculate inventories for this sub-system. Energy required is supplied by electricity as well as by renewable on-site energy production by incineration of wood and bark. The specific energy sources were taken into account.

For the forestry area listed in this dataset no land use change has to be considered as greenhouse gas emissions or removals from land use change from forest to forest do not apply. Further no data are available to prove that land use change from non-forest to forest plantations has taken place in the last rotation periods, no greenhouse gas removals associated with land use change are ac-counted for the production of LPB.

3.3 Production of primary material for aluminium bars and foils

The data set for primary aluminium covers the manufacture of aluminium ingots starting from bauxite extraction, via aluminium oxide manufacture and on to the manufacture of the final aluminium bars. This includes the manufacture of the anodes and the electrolysis. The data set is based on information acquired by the European Aluminium (EA) covering the year 2021. The data are covering primary aluminium used in Europe consisting of 52% European aluminium data and 48% IAI data developed by the International Aluminium Institute (IAI) for imported aluminium. After data was collected for 2021 due to the global energy crisis some plants decreased their production or were idled. Also the electricity mix for the aluminium production changed. (European Aluminium 2025).
Therefore a dataset was compiled by (European Aluminium 2025) which was adjusted to reflect the electricity mix used by the plants still operating in 2023. This dataset is used in this study.

The data set for aluminium foil (5-200 µm) is based on data acquired by the European Aluminium together with European Aluminium Foil Association (EAFA) covering the year 2022. For aluminium foils, this represents more than 80% of the total production in Europe including Turkey. Aluminium foil for the packages examined in this study is assumed to be sourced in Europe. According to EA (EAA 2013), the foil production is modelled with 70% of the production done through hot rolling and 30% through continuous casting.

3.4 Manufacture of cardboard trays

For the manufacture of corrugated cardboard packaging the data sets published by FEFCO (FEFCO and Cepi Container Board 2024) were used. More specifically, the data sets for the manufacture of 'Kraftliners' (predominantly based on primary fibres), 'Testliners' and 'Wellenstoff' (both based on recycled fibres) as well as for corrugated cardboard packaging were used. The data sets represent weighted average values from European locations recorded in the FEFCO data set. They refer to the year 2022. All corrugated cardboard trays are assumed to be sourced from European production.

In order to ensure stability, a fraction of fresh fibres is often used for the corrugated cardboard trays. According to (FEFCO and Cepi Container Board 2024) this fraction on average is 12% in Europe. Due to a lack of more specific information this split was also used for this study.

3.5 Converting

3.5.1 Converting of beverage cartons

The manufacture of composite board was modelled using European average converting data from Tetra Pak that refer to the year 2023. The converting process covers the lamination of LPB with LDPE and aluminium including, cutting, and packing of the composite material. The examined Tetra Pak beverage cartons are produced in Europe. The packaging materials used for shipping of carton sleeves to fillers are included in the model as well as the transportation of the package material.

Process data provided by Tetra Pak were then coupled with required prechains, such as process heat, electricity, and inventory data for transport packaging used for shipping the coated composite board to the filler.

3.5.2 PET and PEF preform and bottle production

The production of PET bottles is usually split into two different processes: the production of preforms from PET granulate, including drying of granulate, and the stretch-blow-moulding (SBM) of the actual bottles. While energy consumption of the preform production strongly correlates with preform weight one of the major factors influencing energy consumption of SBM is the volume of the produced bottles. Data for the SBM and preform production were provided by Tetra Pak and crosschecked with the internal ifeu database. The process data is coupled with the required prechain of the Dutch electricity mix in order to adjust the process data to the production in the Netherlands.

For PEF bottles the same data is applied as for PET bottles.

3.6 Filling

Filling processes are similar for beverage cartons and alternative packaging systems regarding material and energy flows. The respective data for beverage cartons were provided by Tetra Pak in 2025 (ref. year 2025) distinguishing between the consumption of electric and thermal energy as well as of water and air demand. Those were cross-checked by ifeu with data collected for earlier studies.

The data for the filling of plastic bottles was provided by Tetra Pak and crosschecked with the internal ifeu database. For PEF bottles the same data is applied as for PET bottles.

3.7 Transport settings

Table 14 provides an overview of the transport settings (distances and modes) applied for packaging materials. Data were obtained from Tetra Pak and several producers of raw materials. Where no such data were available, expert judgements were made, e.g. through exchanges with representatives of the logistic sector and suppliers. The converting locations of the converted carton rolls are in various European countries.

Table 14: Transport distances and means of transports

Packaging element	Distance of material producer to converter		Distance of converter to filler (km)	
Fossil PE competitors	500 km[a]	[truck]		
Fossil PE beverage cartons	1100 km[b]	[truck]		
Plant-based PE beverage cartons	10800 km[b]	[ship]		
	520 km[b]	[truck]		
	120 km[b]	[train]		
PET	500 km[a]	[truck]		
PA	500 km[a]	[truck]		
Aluminium	500 km[a]	[truck]		
Aluminium foil	920 km[b]	[truck]		
	1510 km[b]	[ship]		
Paperboard for composite board	130 km[b]	[truck]		
	300 km[b]	[ship]		
	1480 km[b]	[train]		
Paper for corrugated cardboard for trays and layers	320 km[c]	[ship]		
	614 km[c]	[train]		
	553 km[c]	[truck]		
Wood for pallets	500 km[a]	[truck]		
LDPE stretch film	500 km (material production site = converter)[a]			[truck]
Trays			500 km[a]	[truck]
Pallets			100 km[a]	[truck]
Converted carton rolls			300 km[b]	[truck]
PET bottles			375 km[d]	[truck]
PEF bottles			175 km[e]	[truck]

[a] ifeu assumption (500km for raw material transport within Europe)
[b] Tetra Pak data based on supplier data
[c](FEFCO and Cepi Container Board 2024)
[d] distance converting in Luxembourg to filling in Bodegraven, NL
[e] distance converting in Belgium to filling in Bodegraven, NL

3.8 Distribution of filled packs from filler to point of sale

Table 15 shows the applied distribution distances in this study. They are based on information from Dutch JNSD producers. Distribution centres are the places where the products are temporarily stored and then distributed to the different point of sales (i.e. supermarkets). The same distribution model is applied for all packages.
It is assumed, that not the full return distance is driven with an empty load, as lorries and trains load other goods (outside the system boundaries of this study) for at least part of their journey. As these other goods usually cannot be loaded at the final point of the beverage packaging delivery it is assumed that a certain part of the return trip is made without any load and so has to be allocated to the distribution system. No primary data is available on average empty return distances. It was assumed that lorries have an empty return trip with 30 % of the distance of the fully loaded trip. The estimation is based on expert judgement from ifeu's department for mobility and transport.

Table 15: Distribution distances in km for the Netherlands

	Distribution distance			
	Distribution Step 1		Distribution step 2	
market	Filler → distribution centre (delivery)	Distribution centre → filler (return trip)	Distribution centre → POS (delivery)	POS → distribution centre (return trip)
Netherlands	125 km	37.5 km	75 km	22.5 km

3.9 Recovery and recycling

Beverage cartons

Beverage cartons which are collected and sorted are subsequently sent to a paper recycling facility for fibre recovery. Paper is separated from plastic and aluminium layers with an efficiency of 98%. The secondary fibre material is used e.g. as a raw material for cardboard. As the LPB fibres consist of 87% pulp, only this share is substituting virgin pulp production. A substitution factor 1.0 is applied.

On the Dutch market, beverage cartons are exported for recycling to Germany, France, Italy and Spain. The process data is coupled with the required prechain of the electricity mixes of Germany, France, Italy and Spain with equal shares.

After this recycling process, an aluminium/polyethylene (PolyAl) compound is left over. The individual materials of this PolyAl compound are difficult to separate thus they have been used mainly in cement kilns as substitute fuel. In recent years, technologies to recycle these PolyAl compounds have been further developed and applied in a small scale in different recycling plants. The actual share of these compounds undergoing a material recycling is not disclosed. Also, no inventory data for these recycling processes are yet available. However, as the creation of an inventory dataset is currently ongoing, there might be more details for modelling those processes in the future. For these reasons, in the current study it is still assumed, that a share of 50% of the remaining rejects furthermore undergoes a thermal treatment in cement kilns and 50% undergoes the country-specific landfill-incineration split and will therefore not obtain material credits. This can be seen as a conservative approach from the perspective of the beverage cartons.

Plastic bottles

Plastic bottles which are collected and sorted are usually followed by a regranulation process. Ultimately the different plastics are separated by density (PET, PE, PP). They are shredded to flakes, other plastic components are separated and the flakes are washed before further use as a raw material. The data used in the current study is based on ifeu's internal database based on data from various recycling plants. Based on experimental results of (Welle et al. 2012) PA mixed into the PET recycling stream does not negatively affect the bottle-to-bottle recycling with analysed PA shares up to 0.1% in the PET recycling stream. On the Dutch market most PET bottles are filled with water or carbonated drinks whose bottles don't contain PA. Therefore the PA from PET bottles filled with juice is not expected to exceed 0.1% in the total PET recycling stream. Therefore PET bottles containing PA are considered as being bottle-to-bottle recycled in this study which is a conservative approach in the perspective of the beverage cartons. As the regarded PET bottles contain rPET, the share of rPET is modelled as closed loop recycling as much as the recycled material can provide. Additionally recycled material is modelled as open loop recycling.

Due to the similar structure of PEF and PET, up to 5% of PEF can be incorporated into the PET recycling streams (PETplanet 2024; SpecialChem 2021). Therefore, PEF bottles in this study are treated as PET bottles in the end-of-life. Until now the regarded PEF bottle is not yet on the Dutch market, therefore a share of PEF higher of 5% in the PET recycling stream is not expected in the near future. It is important to understand, however, that, if more used PEF bottles enter the waste stream (thus reaching more than 5%), they will have to be sorted out from the PET recycling route. This will lead to a 0% recycling rate for PEF bottles until a separate PEF recycling route can be installed. The regarded PEF bottle does not contain recycled content, therefore all recycled material is modelled as open loop recycling.

3.10 Background data

3.10.1 Transport processes

Truck transport

The dataset used is based on standard emission data that were collated, validated, extrapolated and evaluated for the Austrian, German, French, Norwegian, Swedish and Swiss Environment Agencies in the 'Handbook Emission Factors for Road Transport' (HBEFA) (Notter et al. 2019). The 'Handbook' is a database application giving, as a result, the transport distance related fuel consumption and the emissions differentiated into truck size classes and road categories**.** Data are based on average fleet compositions within several truck size classes. The weighted average of HBEFA data was computed from EURO norms 0 to VI. Data in this study refer to lorries with a loading capacity of 23 tonnes. The emission factors used in this study refer to the year 2017.

Based on the above-mentioned parameters – truck size class and road category – the fuel consumption and emissions as a function of the transport load and distance were determined (tonne km). Wherever cooling during transport is required, additional fuel consumption is modelled accordingly based on data from ifeu's internal database. This estimation is based on expert judgement from ifeu's department for mobility and transport. The average capacity utilization of 50% combines load factors and empty trip factors based on (EcoTransIT World 2016) and communication with the logistics sector.

Ship transport

The data used for the present study represent freight transport with an overseas container ship (10.5 t/TEU[1]) and an utilisation capacity of 70% (EcoTransIT World 2016). Energy use is based on an average fleet composition of this ship category with data taken from (EcoTransIT World 2016). The Ecological Transport Information Tool (EcoTransIT) calculates environmental impacts of any freight transport. Emission factors and fuel consumption have been applied for direct emissions (tank-to-wheel) based on (EcoTransIT World 2016). For the consideration of well-to-tank emissions data were taken from ifeu's internal database.

Rail transport

The data used for rail transport for the present study also is based on data from (EcoTransIT World 2016). Emission factors and fuel consumption have been applied for direct emissions based on (EcoTransIT World 2016). The needed electricity is modelled with the electricity mix of the country the train is operating in (see also **section 3.10.2**).

3.10.2 Electricity generation

Modelling of electricity generation is particularly relevant for the production of base materials as well as for converting, filling processes and recycling processes. Electric power supply is modelled using country specific grid electricity mixes, since the environmental burdens of power production varies strongly depending on the electricity generation technology. The country-specific electricity mixes are obtained from a master network for grid power modelling maintained and annually updated at ifeu as described in (Fehrenbach et al. 2016). It is based on national electricity mix data by the International Energy Agency (IEA)[2]. The market specific electricity mix (IT), reference year 2021 is applied as a prechain for most processes (see Table 1 and **section 3**). This the most up to date data available at the time the study is conducted. The applied shares of energy sources to the related market are given

[1] Twenty-foot Equivalent Unit
[2] http://www.iea.org/statistics/

in Table 16. Data for future electricity mixes are only available as expert estimation. As this attributional LCA is aiming to provide robust results for comparison of products to customers of Tetra Pak, no scenarios with future electricity mixes are included.

Table 16: Share of energy source to specific energy mix, reference year 2021.

Energy source	Geographic scope							
	EU 27+3	**NL**	**BE**	**FR**	**DE**	**IT**	**LU**	**ES**
Hard coal	5.6%	11.4%	0.0%	0.9%	9.4%	4.7%	0.0%	1.7%
Brown coal	6.6%	0.0%	0.0%	0.0%	18.9%	0.0%	0.0%	0.0%
Fuel oil	1.2%	0.0%	0.0%	1.0%	0.8%	2.1%	0.0%	3.5%
Natural gas	21.0%	50.1%	25.1%	6.5%	16.1%	51.5%	14.1%	27.0%
Nuclear energy	23.2%	3.1%	50.3%	68.2%	12.1%	0.0%	0.0%	20.5%
Hydropower, wind, solar & geothermal	35.6%	25.3%	18.8%	21.2%	33.2%	34.6%	50.4%	44.5%
Hydropower	44.9%	0.3%	2.3%	52.8%	10.5%	46.8%	17.3%	11.2%
Wind power	39.4%	60.9%	66.4%	33.0%	62.1%	21.7%	52.6%	23.2%
Solar energy	14.7%	38.9%	31.3%	14.1%	27.2%	25.7%	30.1%	10.1%
Geothermal energy	0.4%	0.0%	0.0%	0.1%	0.1%	5.8%	0.0%	0.0%
Biomass energy	5.0%	6.8%	3.6%	1.3%	7.7%	5.5%	26.7%	2.1%
Waste	1.5%	3.3%	2.1%	0.8%	1.7%	1.6%	8.7%	0.6%

3.10.3 Municipal waste incineration

The electrical and thermal efficiencies of the municipal solid waste incineration plants (MSWI) are shown in **Table 17**.

Table 17: Electrical and thermal efficiencies of the incineration plants for the Netherlands and countries for final treatment of recycled beverage cartons.

Market	Electrical efficiency	Thermal efficiency	Reference period	Source
Netherlands	18%	31%	2016	(Stichting Nationale Milieudatabase 2022)
mix (France, Germany, Italy, Spain)	16%	17%	2019-2021	(Equanimator Ltd 2023)

The efficiencies are used as parameters for the incineration model, which assumes a technical standard (especially regarding flue gas cleaning) that complies with the requirements given by the EU incineration directive (EU 2018).

It is assumed that the electrical energy generated in MSWI plants substitute the market specific grid electricity and that the thermal energy recovered in MSWI plants serves as process heat. The exported heat is assumed to substitute heat from natural gas and oil. The applied shares are 72% natural gas and 28% oil (CE Delft and Prognos 2021).

3.10.4 Thermal recovery in cement kilns

The process data for thermal recovery in cement kilns refer to the year 2006 and are taken from ifeu's database. The respective dataset is based on information provided by the German Cement Works Association (VDZ) and is considered to be representative for the thermal recovery in cement kilns in any country. The applied process data cover emissions from the treatment in the clinker burning process. Parameters are restricted to those which change compared to the use of primary fuels. The output cement clinker is a function of the energy potential of the fuel and considers the demand of base material. According to VDZ (2021), cement plants have thermal efficiencies of 70%-80%.The primarily substitution of hard coal in cement kilns was confirmed by the economic, technical and scientific association for the German cement industry (VDZ e.V.) (VDZ 2019). However, in this study it is assumed that the cement kiln is only a suitable substitute for high-efficiency thermal recovery, and therefore heat energy is credited.

4 Base results

In this section, the results of the examined packaging systems for the Dutch market are presented separately for the different categories in graphic form.

Numerical values and figures

The following individual life cycle elements are shown in sectoral (stacked) bar charts. Life cycle steps that only include the production of primary packaging are referred to as **cradle to gate**. The remaining life cycle steps, which also include transport packaging, filling, distribution, and the end of life as well as the associated credits and the CO_2 uptake are referred to as **gate to grave**. Net results are referred to as **cradle to grave**.

<u>Cradle to gate:</u>

- Production and transport of liquid packaging board (**LPB**)
- Production and transport of plastics and additives for Tetra Pak beverage cartons (**plastics for sleeve**)
- Production and transport of aluminium & converting to foil for beverage cartons (**aluminium foil**)
- Production and transport of PET and PEF (including additives, e.g., PA,) for bodies of PET and PEF (**PEF / PET for bottle**)
- Converting processes of cartons, PET bottles and PEF bottles (**converting**)
- Production, converting and transport of closures & labels and their base materials (**closure & label**)

<u>Gate to grave:</u>

- Production of secondary and tertiary packaging: wooden pallets, LDPE shrink film and corrugated cardboard trays **(transport packaging)**
- Filling process including packaging handling **(filling)**
- Retail of the packages from filler to the point-of-sale **(distribution)**
- Collection, sorting, recovery and disposal processes **(recovery & disposal)**
- Biogenic CO_2 emissions from incineration and landfilling of plant-based and renewable materials **(biogenic CO_2 (recovery & disposal))**

Secondary products (recycled materials and recovered energy) are obtained through recovery processes of used packaging materials, e.g., recycled fibres from cartons may replace primary fibres. It is assumed, that those secondary materials are used by a subsequent system. In order to consider this effect in the LCA, the environmental impacts of the packaging system under investigation are reduced by means of credits based on the environmental burdens of the substituted material. Following the ISO standard's recommendation on subjective choices, the 50% and 100% allocation factor methods are used for the recycling and recovery as well as crediting procedure to verify the influence of the allocation method on the final results. (see **section 1.4**). For each segment the results are shown for the allocation factor 50% and allocation factor 100%.

The negative impacts are shown in form of separate bars in the LCA results graphs. They are broken down into:

- Credits for energy recovery (replacing e.g., grid electricity, hard coal) **(credits energy)**
- Credits for material recycling **(credits material)**
- Uptake of atmospheric CO_2 during the plant growth phase **(CO_2 uptake)**

The LCA results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins or risks. Therefore, **the category indicator results represent potential environmental impacts per functional unit.**

Each impact category graph includes three bars per packaging system under investigation, which illustrate (from left to right):

- Sectoral results of the packaging system itself (first stacked bar with positive values)
- Credits given for secondary products leaving the system and CO_2 uptake (second stacked bar with negative values)

Cradle to grave:

- Net results as results of the subtraction of credits from overall environmental burdens (grey bar, **net results**)

All category results refer to the primary and transport packaging material flows required for the delivery of 1000 L beverage to the point of sale including the end-of-life of the packaging systems.

A note on significance: For studies intended to be used in comparative assertions intended to be disclosed to the public ISO 14044 asks for an analysis of results for sensitivity and uncertainty. It's often not possible to determine uncertainties of datasets and chosen parameters by mathematically sound statistical methods. Hence, for the calculation of probability distributions of LCA results, statistical methods are usually not applicable or of limited validity. To define the significance of differences of results an estimated significance threshold of 10% is chosen. This can be considered a common practice for LCA studies comparing different product systems. This means differences ≤ 10% are considered as insignificant.

4.1 JNSD Family Pack (ambient)

In this section, the results of the examined packaging systems for the Dutch market in the segment JNSD Family Pack (ambient) are presented.

4.1.1 Allocation factor 50% of JNSD Family Pack (ambient)

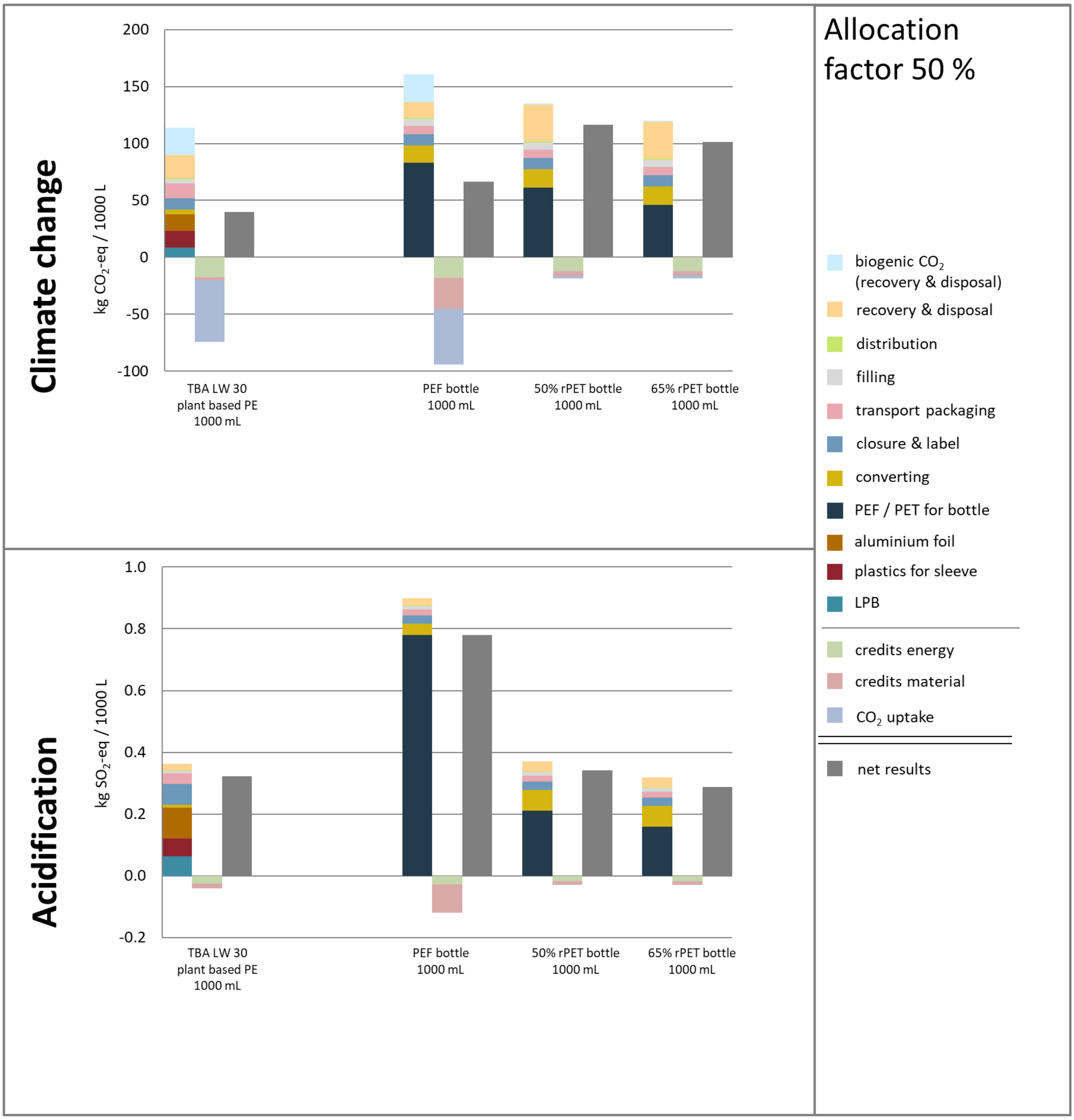
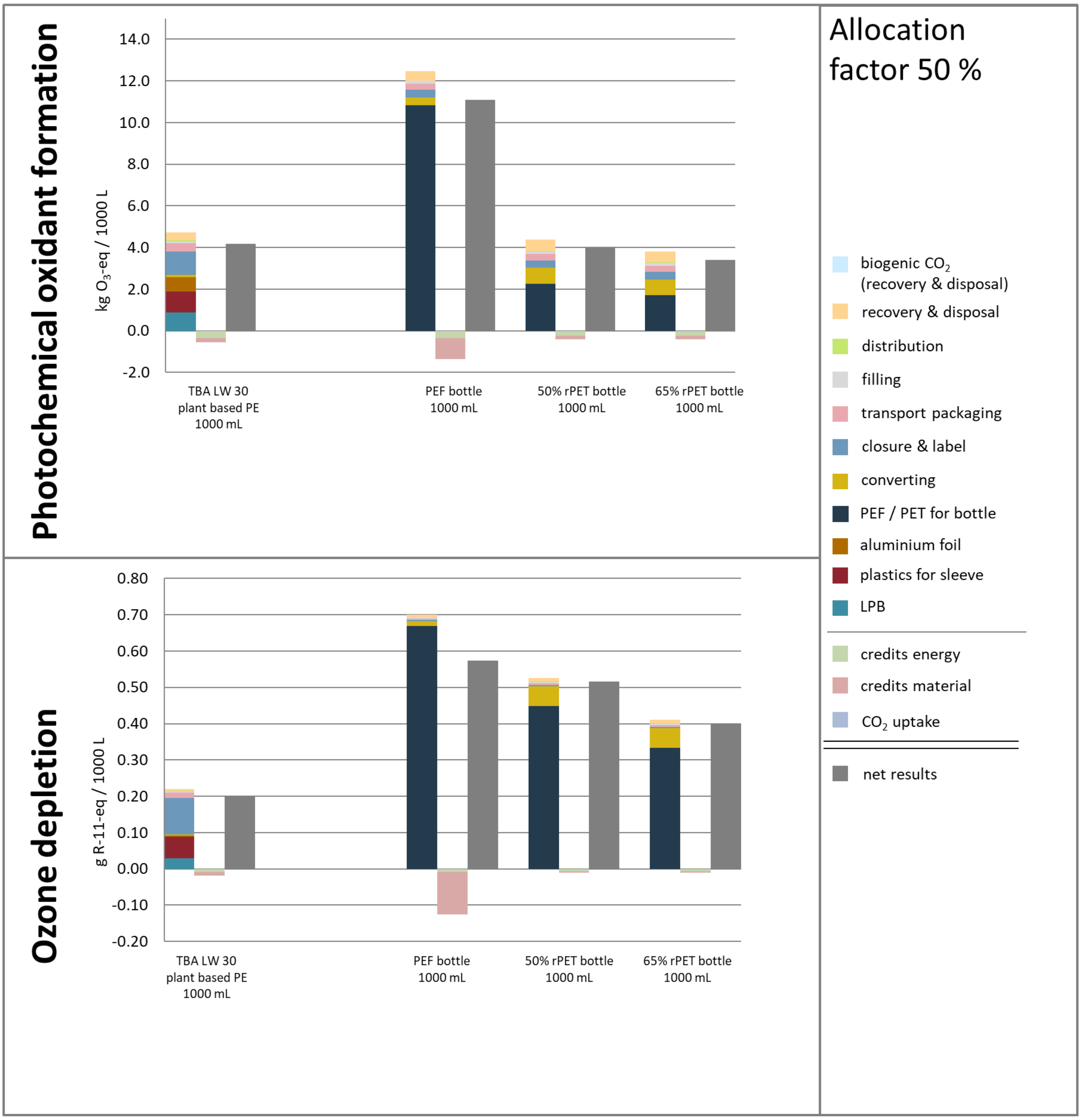


Figure 10: Indicator results of **segment JNSD Family Pack (ambient)**, allocation factor 50% (Part 1/5)



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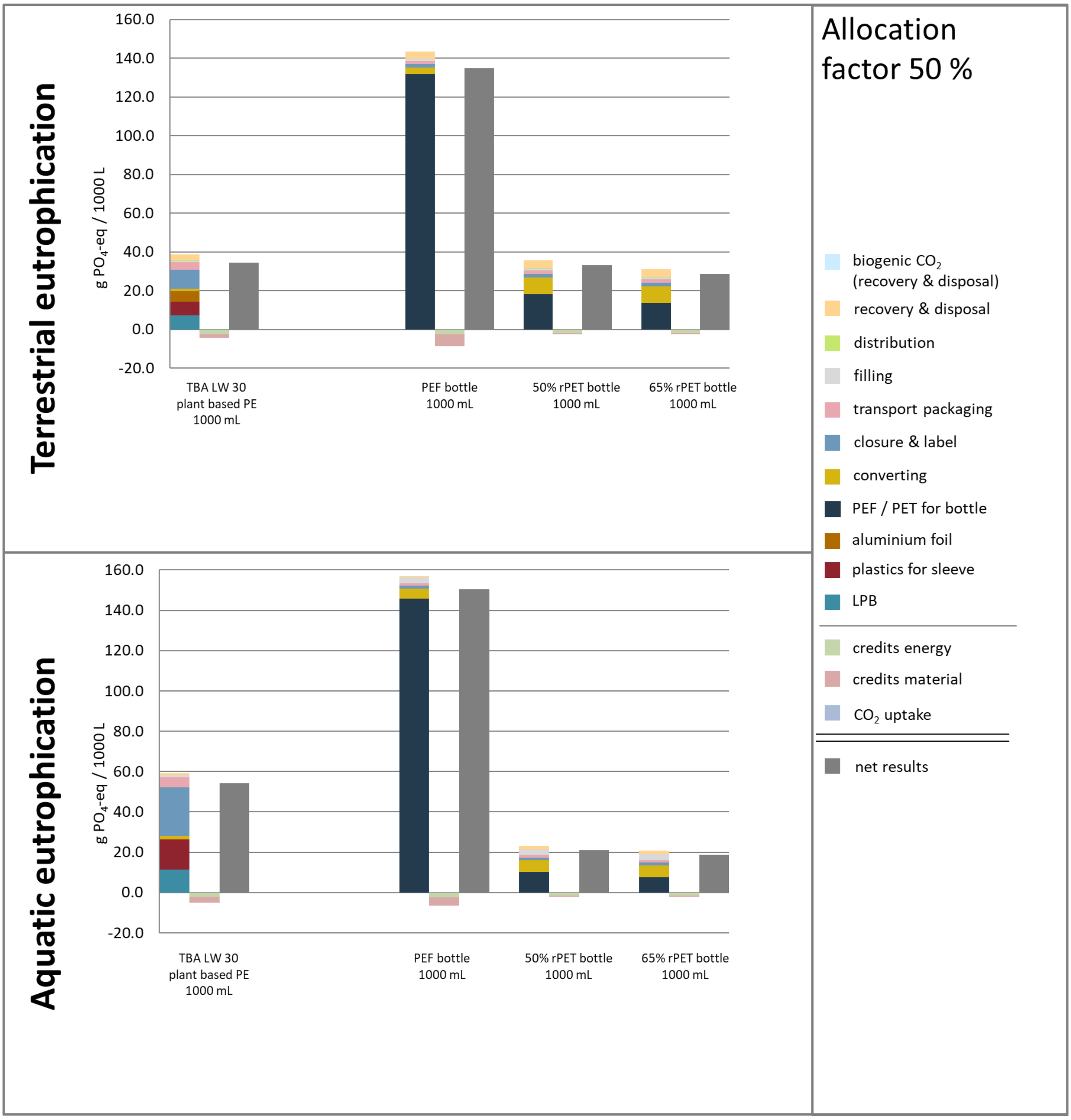
1322 **Figure 11:** Indicator results of **segment JNSD Family Pack (ambient)**, allocation factor 50% (Part 2/5)



1323

1324 **Figure 12:** Indicator results of **segment JNSD Family Pack (ambient)**, allocation factor 50% (Part 3/5)

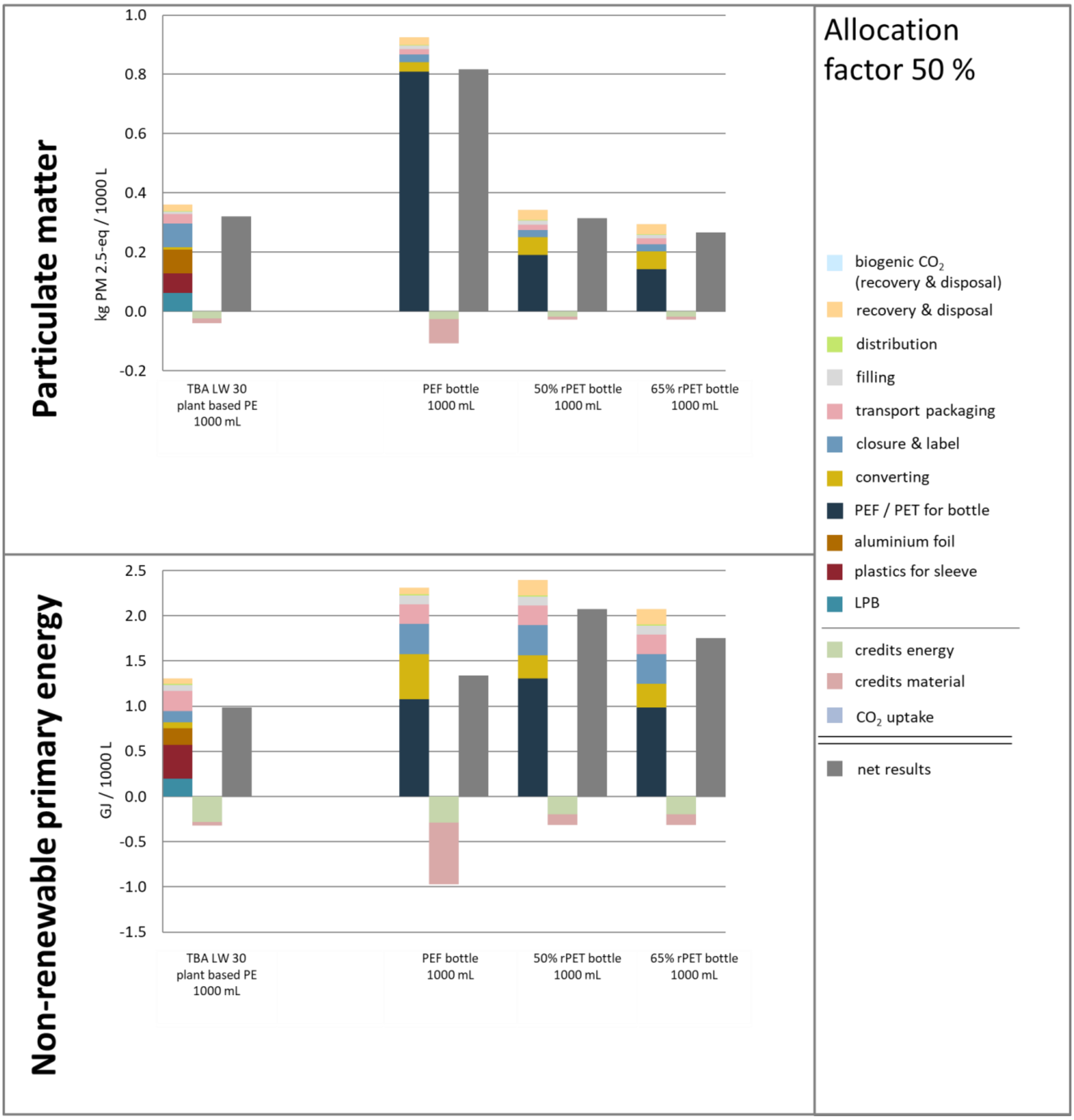
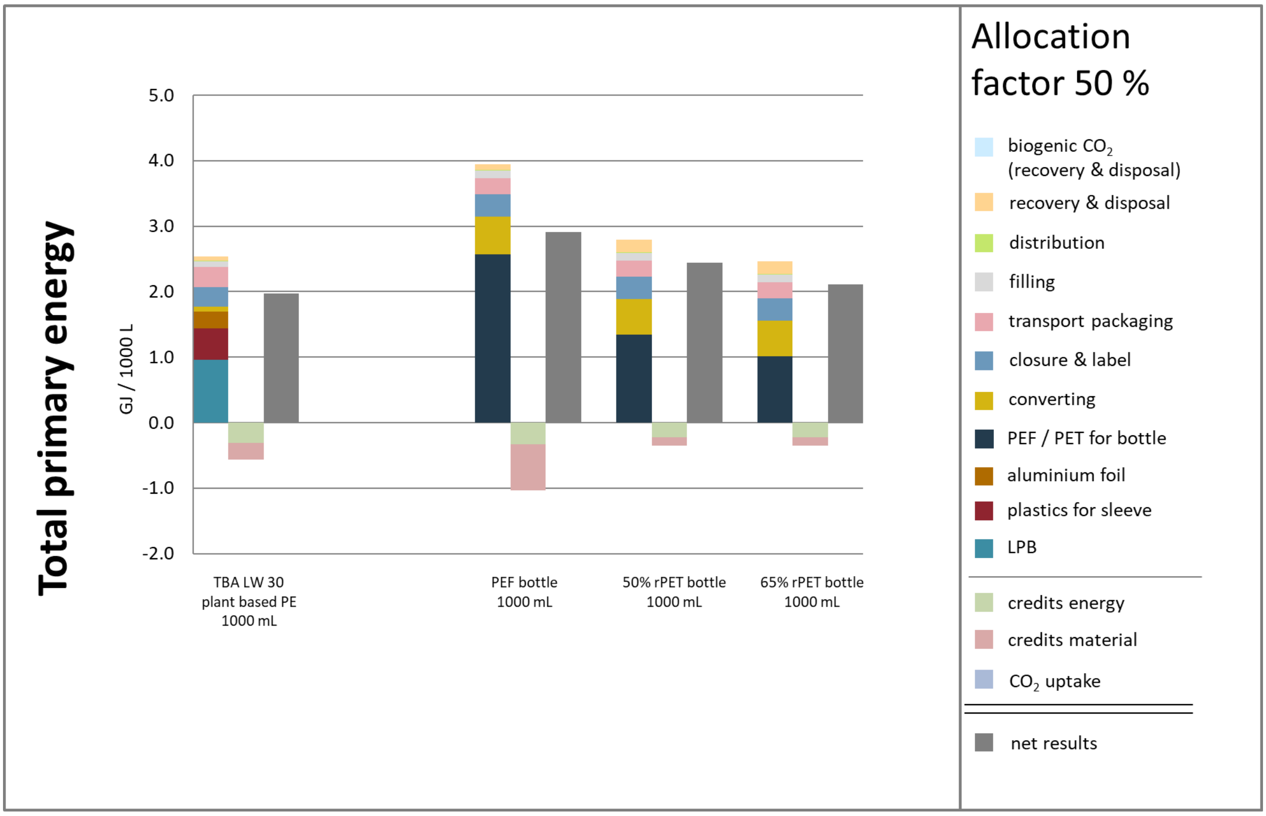


Figure 13: Indicator results of **segment JNSD Family Pack (ambient)**, allocation factor 50% (Part 4/5)



1327

1328 **Figure 14:** Indicator results of **segment JNSD Family Pack (ambient)**, allocation factor 50% (Part 5/5)

Table 18: Category indicator results of **segment JNSD Family Pack (ambient)** - burdens, credits and net results per FU of 1000 L, allocation factor 50% (All figures are rounded to two decimal places.)

NL allocation factor 50 %		TBA LW 30 plant based PE 1000 mL	PEF bottle 1000 mL	50% rPET bottle 1000 mL	65% rPET bottle 1000 mL
Climate change [kg CO_2-eq / 1000 L]	burdens	89.84	136.20	134.13	118.97
	biogenic CO_2	23.98	24.58	1.29	1.29
	credits	-20.02	-45.15	-16.25	-16.24
	CO_2 uptake	-54.24	-49.15	-2.58	-2.58
	net results (∑)	**39.56**	**66.47**	**116.59**	**101.44**
Acidification [g SO_2-eq / 1000 L]	burdens	0.36	0.90	0.37	0.32
	credits	-0.04	-0.12	-0.03	-0.03
	net results (∑)	**0.32**	**0.78**	**0.34**	**0.29**
Photochemical oxidant formation [g O_3-eq / 1000 L]	burdens	4.74	12.46	4.37	3.80
	credits	-0.56	-1.37	-0.40	-0.40
	net results (∑)	**4.18**	**11.09**	**3.97**	**3.41**
Ozone depletion [g R-11-eq / 1000 L]	burdens	0.22	0.70	0.53	0.41
	credits	-0.02	-0.13	-0.01	-0.01
	net results (∑)	**0.20**	**0.57**	**0.52**	**0.40**
Terrestrial eutrophication [g PO_4-eq / 1000 L]	burdens	38.86	143.54	35.82	31.23
	credits	-4.26	-8.63	-2.50	-2.50
	net results (∑)	**34.60**	**134.90**	**33.32**	**28.73**
Aquatic eutrophication [g PO_4-eq / 1000 L]	burdens	59.25	157.03	23.26	20.72
	credits	-5.11	-6.49	-2.11	-2.11
	net results (∑)	**54.14**	**150.53**	**21.15**	**18.60**
Particulate matter [g PM 2.5- eq / 1000 L]	burdens	0.36	0.93	0.34	0.29
	credits	-0.04	-0.11	-0.03	-0.03
	net results (∑)	**0.32**	**0.82**	**0.31**	**0.27**
Non-renewable primary energy [GJ / 1000 L]	burdens	1.30	2.31	2.39	2.07
	credits	-0.32	-0.97	-0.32	-0.32
	net results (∑)	**0.98**	**1.34**	**2.07**	**1.75**
Total primary energy [GJ / 1000 L]	burdens	2.54	3.95	2.79	2.46
	credits	-0.57	-1.03	-0.35	-0.35
	net results (∑)	**1.97**	**2.91**	**2.45**	**2.12**

4.1.2 Allocation factor 100% of JNSD Family Pack (ambient)

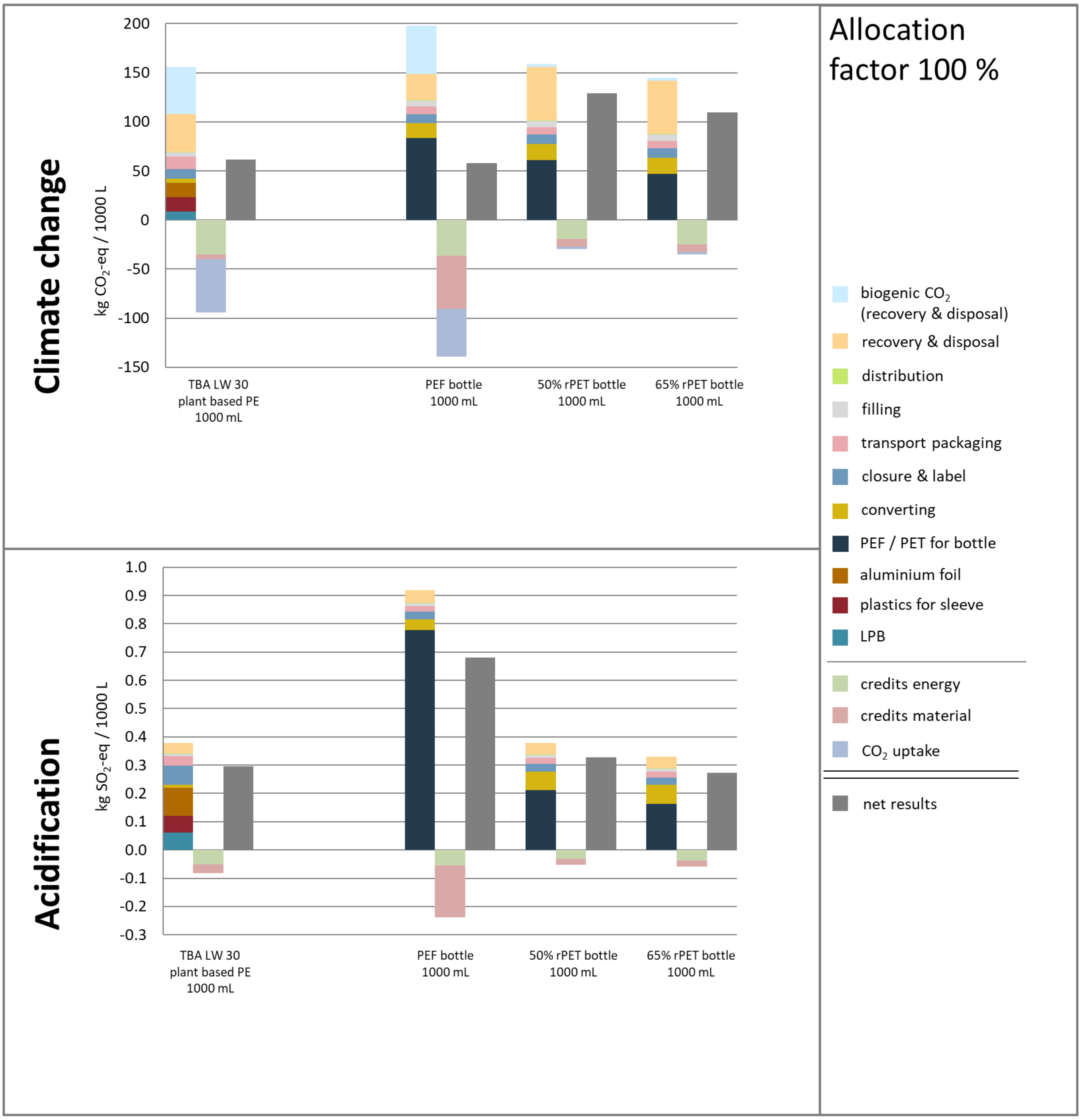
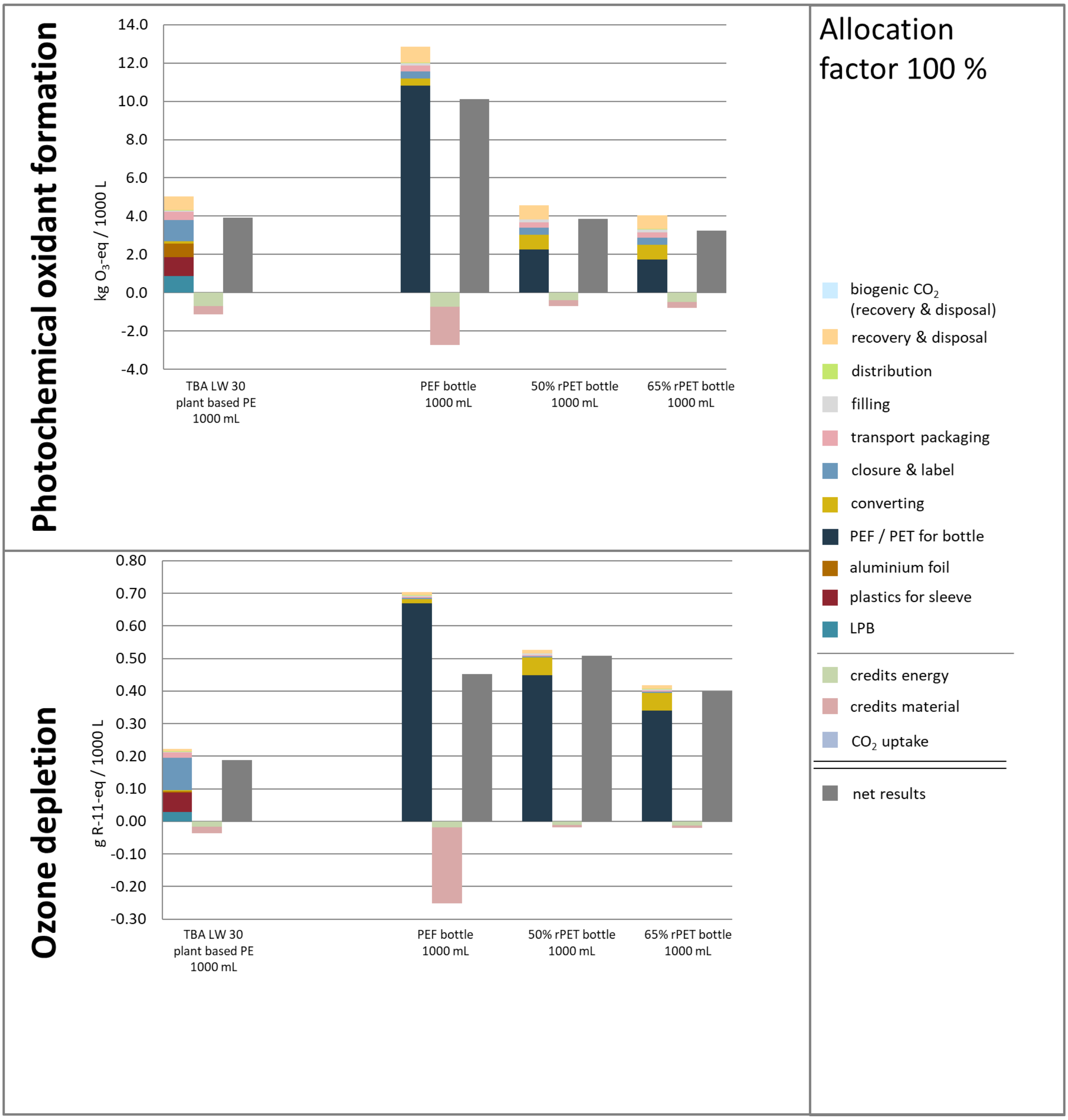


Figure 15: Indicator results of **segment JNSD Family Pack (ambient)**, allocation factor 100% (Part 1/5)



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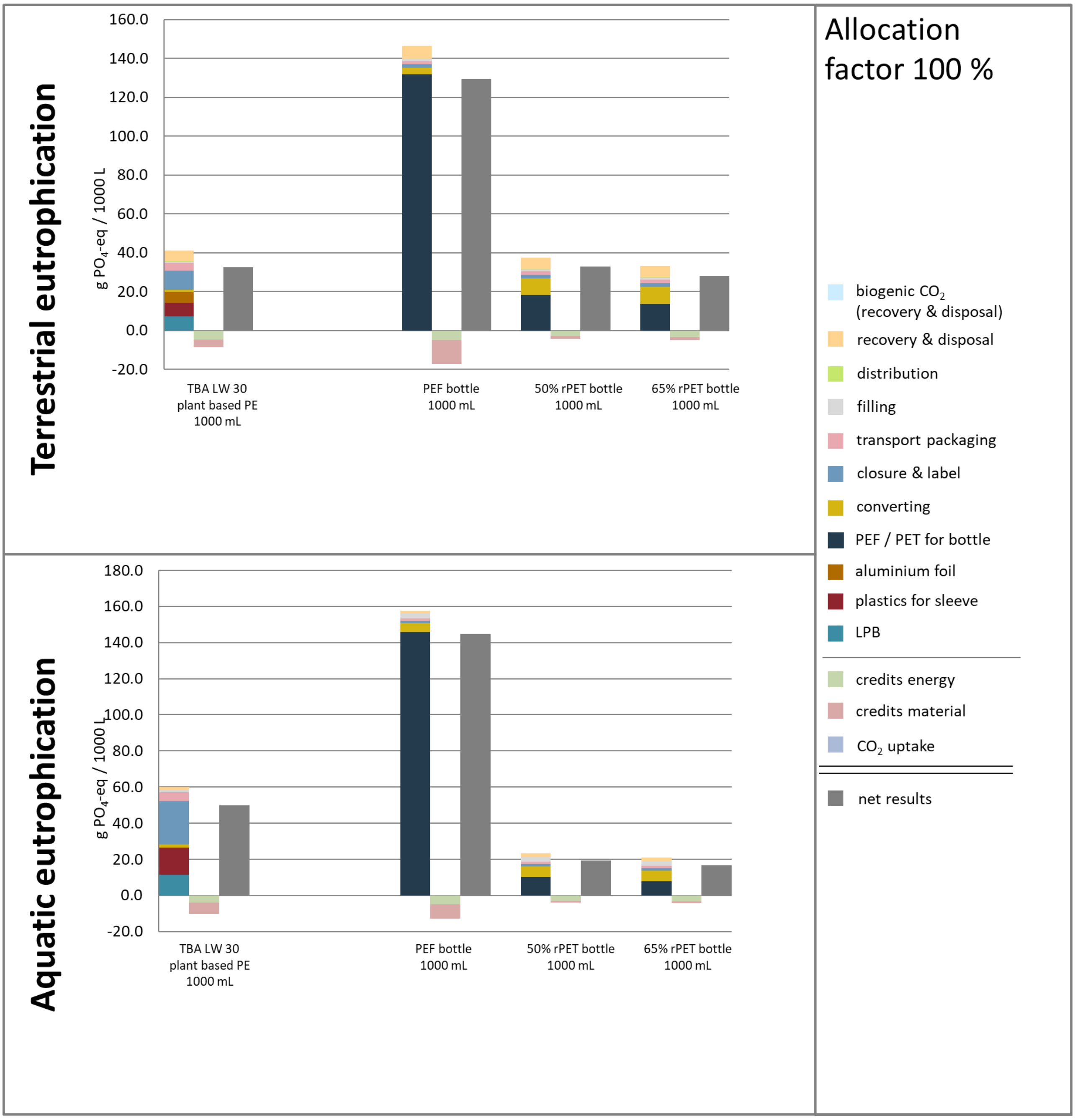
1338 **Figure 16:** Indicator results of **segment JNSD Family Pack (ambient)**, allocation factor 100% (Part 2/5)



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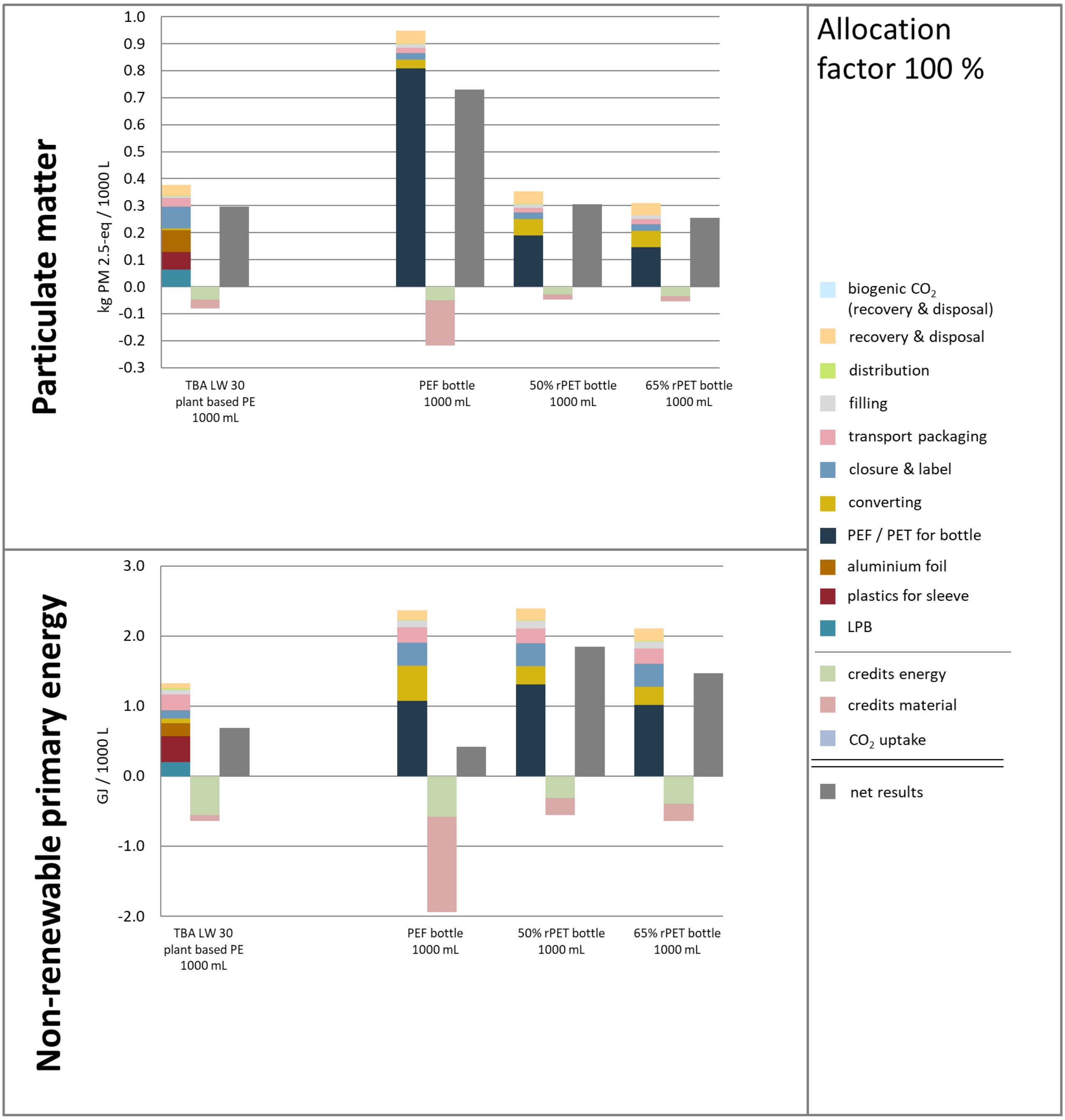
1340 **Figure 17:** Indicator results of **segment JNSD Family Pack (ambient)**, allocation factor 100% (Part 3/5)



1341

1342 **Figure 18:** Indicator results of **segment JNSD Family Pack (ambient)**, allocation factor 100% (Part 4/5)

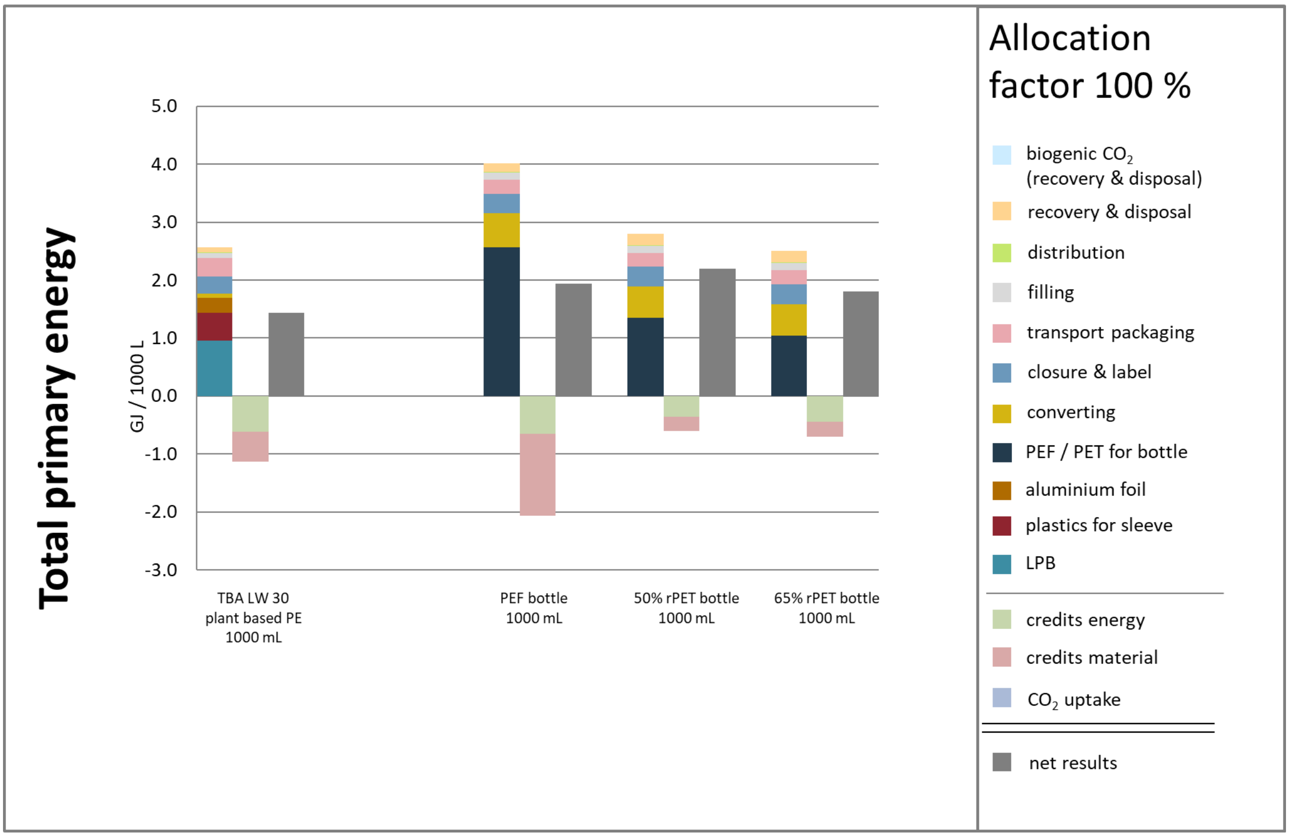


Figure 19: Indicator results of **segment JNSD Family Pack (ambient)**, allocation factor 100% (Part 5/5)

Table 19: Category indicator results of **segment JNSD Family Pack (ambient)** burdens, credits and net results per FU of 1000 L, allocation factor 100% (All figures are rounded to two decimal places.)

NL allocation factor 100 %		**TBA LW 30 plant based PE 1000 mL**	**PEF bottle 1000 mL**	**50% rPET bottle 1000 mL**	**65% rPET bottle 1000 mL**
Climate change [kg CO_2-eq / 1000 L]	burdens	107.71	148.52	156.09	142.06
	biogenic CO_2	47.96	49.15	2.58	2.58
	credits	-40.06	-90.36	-32.56	-32.55
	CO_2 uptake	-54.24	-49.15	-2.58	-2.58
	net results (∑)	**61.37**	**58.15**	**123.54**	**109.52**
Acidification [g SO_2-eq / 1000 L]	burdens	0.38	0.92	0.38	0.33
	credits	-0.08	-0.24	-0.06	-0.06
	net results (∑)	**0.30**	**0.68**	**0.32**	**0.27**
Photochemical oxidant formation [g O_3-eq / 1000 L]	burdens	5.03	12.84	4.56	4.04
	credits	-1.11	-2.74	-0.80	-0.80
	net results (∑)	**3.91**	**10.10**	**3.76**	**3.25**
Ozone depletion [g R-11-eq / 1000 L]	burdens	0.22	0.70	0.53	0.42
	credits	-0.04	-0.25	-0.02	-0.02
	net results (∑)	**0.19**	**0.45**	**0.51**	**0.40**
Terrestrial eutrophication [g PO_4-eq / 1000 L]	burdens	41.25	146.60	37.45	33.13
	credits	-8.53	-17.27	-5.01	-5.01
	net results (∑)	**32.72**	**129.32**	**32.44**	**28.11**
Aquatic eutrophication [g PO_4-eq / 1000 L]	burdens	59.96	157.67	23.31	20.93
	credits	-10.23	-12.99	-4.23	-4.23
	net results (∑)	**49.74**	**144.68**	**19.08**	**16.70**
Particulate matter [g PM 2.5- eq / 1000 L]	burdens	0.38	0.95	0.35	0.31
	credits	-0.08	-0.22	-0.05	-0.05
	net results (∑)	**0.30**	**0.73**	**0.30**	**0.25**
Non-renewable primary energy [GJ / 1000 L]	burdens	1.33	2.36	2.40	2.10
	credits	-0.64	-1.94	-0.64	-0.64
	net results (∑)	**0.69**	**0.42**	**1.76**	**1.47**
Total primary energy [GJ / 1000 L]	burdens	2.57	4.01	2.80	2.50
	credits	-1.13	-2.07	-0.70	-0.70
	net results (∑)	**1.43**	**1.94**	**2.10**	**1.80**

4.1.3 Description and interpretation

The following three subsections describe the results of the life cycle steps for beverage cartons and rPET and PEF bottles.

4.1.3.1 Beverage cartons (specifications see section 2.2.1)

The **LPB** shows considerable contributions in the results of 'Acidification', 'Photochemical oxidant formation', 'Terrestrial eutrophication', 'Aquatic eutrophication', 'Particulate matter', 'Non-renewable primary energy' and 'Total primary energy'.

The production of the paper-based materials generates emissions that cause contributions to both 'Aquatic eutrophication' and 'Terrestrial eutrophication', the latter to a lesser extent. Approximately half of the aquatic eutrophication potential is caused by the high Chemical Oxygen Demand (COD). As the production of LPB causes high contributions of organic compounds into the surface water an overabundance of oxygen-consuming reactions takes place which therefore may lead to oxygen shortage in the water. In the terrestrial eutrophication potential nitrogen oxides are determined as main contributor. For the separation of the cellulose needed for paper production from the ligneous wood fibres, the so called 'Kraft process' is applied, in which sodium hydroxide and sodium sulphide are used. This leads to additional emissions of SO_2, thus contributing significantly to the acidifying potential. The required energy for paper production mainly originates from recovered process internal residues (hemicellulose and lignin dissolved in black liquor). Therefore, the required process energy is mainly generated from renewable sources. This and the additional electricity reflect the results for the categories 'Total primary energy' and 'Non-renewable primary energy'.

The production of **plastics for sleeve** as well as of **closure & label** show burdens in all categories. Large shares of environmental burdens are shown in the categories 'Ozone depletion', 'Acidification', 'Photochemical oxidant formation', 'Terrestrial eutrophication', 'Aquatic eutrophication' and 'Particulate matter' deriving from agricultural and bagasse combustion processes in the plant-based PE production.

The production of **aluminium foil** for the sleeves of the ambient beverage cartons with aluminium foil barrier shows burdens in most impact categories. High shares of burdens are shown in the impact categories 'Acidification', 'Terrestrial eutrophication' and 'Particulate matter'. These result from SO_2 and NOx emissions from the aluminium production.

Thermal energy and electricity are the main inputs for the life cycle steps **converting** and **filling.** The contributions for the examined beverage cartons are small in all categories.

The **transport packaging** contributes to all examined categories. The results are dominated by the production of corrugated cardboard boxes. The paper production plays a major role in most impact and inventory categories. The pallet and the stretch film production play a minor role.

The life cycle step **distribution** shows small burdens in all impact categories for all carton systems.

The end-of-life phase **recovery & disposal** is clearly most relevant in the impact category 'Climate change', however the emissions also visibly contribute to 'Acidification', 'Photochemical oxidant formation', 'Terrestrial eutrophication', and 'Particulate matter'. A share of the greenhouse gases is related to energy generation required in the respective processes. Material recycling processes are commonly run on electricity; thus, this end-of-life treatment contributes directly to the result values for the impact on 'Climate change'. When the packaging materials are used as fuel in cement kilns or incinerated in MSWI facilities, this also leads to GHG emissions. Due to the final disposal of the fibres recycled in countries with landfill shares a significant share of 'Climate change' impacts derive from the degradation process of fibres on landfills, where the contained carbon is partially emitted as methane. These impacts from methane play a larger role than the benefits from carbon storage due to non-degraded biogenic material. The contributions to the impact categories ‘Acidification’ and ‘Terrestrial eutrophication’ are mainly caused by NO_2 emissions from incineration plants.

Biogenic CO_2 (recovery & disposal) describes separately all regenerative CO_2 emissions from recovery and disposal processes. In case of beverage cartons, these derive mainly from the incineration of paper as well as from landfills. Together with the fossil-based CO_2 emissions of the life cycle step ‘recycling & disposal’ they represent the total CO_2 emissions from the packaging’s end-of-life. Due to the energy recovery at incineration plants system-related allocation is applied.

The **energy credits** arise from substituted grid electricity and heat produced in incineration plants, where energy recovery takes place and from substituted heat from the use of polymer/aluminium rejects from beverage cartons as fuel in cement kilns.

Material credits are only given for material that is effectively recycled. The majority is received by the recycling of paper. The paper production causes high waterborne emissions, especially due to the transformation of raw wood to paper fibres. Therefore, the post-consumer recycling of paper fibres from LPB avoids this determining process step (as secondary paper fibres substitute for primary fibres), which leads to material credits.

The **uptake of CO_2** by the trees harvested for the production of paperboard plays a significant role in the impact category ‘Climate change’. The carbon uptake refers to the conversion process of carbon dioxide to organic compounds by trees. The assimilated carbon is then used to produce energy and to build body structures. However, the carbon uptake in this context describes only the amount of carbon which is stored in the product under study.

Burdens from recycling and recovery including biogenic CO_2 as well as credits are affected by the choice of allocation factor 50% or 100%. In case of allocation factor 100%, these are fully allocated to the beverage carton, in case of allocation factor 50%, only 50% of these burdens are allocated to the beverage carton. As the CO_2 uptake (mainly from LPB production) is not included in the credits, ‘Climate change’ results are lower with allocation factor 50% (see **section 1.4.2.**)

4.1.3.2 PET bottles (specifications see section 2.2.2)

In the examined PET bottle, the biggest part of the environmental burdens are caused by the production of base materials of the bottle (**PET for body** and **closure & label**). These base materials originate from fossil resources (crude oil). Furthermore, the production processes are associated with a high energy demand, with fossil fuels being the main energy source for these processes. Therefore, the results of the plastic bottles show an increased consumption of ‘Non-renewable primary energy’ and ‘Total primary energy’ as well as high burdens in ‘Particulate matter’, ‘Acidification’, ‘Photochemical oxidant formation’ and ‘Terrestrial eutrophication’. Main contributor to the ‘Aquatic eutrophication’ is the extraction of crude oil. Half of the emissions are caused by the COD and phosphate emissions. Additionally, for PET bottles, the PET production causes very high contributions to the ‘Ozone depletion’. The high share originates from methyl bromide, which inevitably occurs during the production of pure terephthalic acid (PTA). Even higher contributions to the ‘Ozone depletion’ are caused by the production of PA6, deriving from the production of the intermediate product caprolactam, which is not necessary for the production of other polymers see (**section 3.1.7**). The examined PET bottle includes PA6 as additive.

Thermal energy and electricity are the main inputs for the life cycle steps **converting**. The contributions for the examined PET bottles are high in all categories.

Thermal energy and electricity are the main inputs for the life cycle steps **filling**. Depending on the country-specific energy mix of the filling country (NL) the contributions for the examined PET bottles are minor in all categories except ‘Aquatic eutrophication’ with high shares.

The **transport packaging** contributes to almost all examined categories. The results are dominated by the production of LDPE film.

The life cycle step **distribution** shows small burdens in all categories.

The impact of the PET bottle’s **‘recycling & disposal’** life cycle step is most noticeable regarding ‘Climate Change’. The incineration of plastic bottles in MSWIs causes high shares of greenhouse gas emissions. Additionally, smaller shares of environmental burdens are caused by the electricity used for sorting and recycling processes.

Energy credits of PET bottles originate from substituted grid electricity and heat produced in MSWI plants, where energy recovery takes place.

The **material credits** originate mainly from the substitution of virgin PET. Therefore, the credits show small avoided burdens of the virgin PET production in all categories. As the regarded PET bottles contain 50% and 65% rPET, most of the recycled material resulting from 60% PET recycling rate is recycled in a closed loop. Material credits are only shown for the remaining open loop material. The usage of closed loop material is considered in the life cycle step PET for body.

Small amounts of **CO_2 uptake** and corresponding **Biogenic CO_2 (recovery & disposal)** emissions are caused by the biogenic material in secondary and tertiary packaging.

Burdens from open-loop recycling and recovery including biogenic CO_2 as well as credits are affected by the choice of allocation factor 50% or 100%. In case of allocation factor 100%, these are fully allocated to the PET bottle, in case of allocation factor 50%, only 50% of these burdens are allocated to the PET bottle.

4.1.3.3 PEF bottles (specifications see section 2.2.2)

In the examined PEF bottle, the biggest part of the environmental burdens are caused by the production of base materials of the bottle (**PEF for body**). PEF originates from plant-based resources (corn). In most of the regarded categories PEF production dominates the results in all impact categories resulting from burdens from agriculture activities as well as from production processes.

Thermal energy and electricity are the main inputs for the life cycle steps **converting**. The contributions for the examined PEF bottles are small in all impacts categories. In case of ‘Non-renewable primary energy’ and ‘Total primary energy’ higher shares can be seen.

Thermal energy and electricity are the main inputs for the life cycle steps **filling**. The contributions for the examined PEF bottles are small in all categories.

The **transport packaging** contributes to small shares in all examined categories. The results are dominated by the production of LDPE film.

The life cycle step **distribution** shows small burdens in all categories.

The impact of the PEF bottle’s **‘recycling & disposal’** life cycle step is most noticeable regarding ‘Climate Change’. The incineration of plastic bottles in MSWIs causes high shares of greenhouse gas emissions. Additionally, , smaller shares of environmental burdens are caused by the electricity used for sorting and recycling processes.

Biogenic CO_2 (recovery & disposal) describes separately all regenerative CO_2 emissions from recovery and disposal processes. In case of the PEF bottle, these derive mainly from the incineration of PEF. Together with the fossil-based CO_2 emissions of the life cycle step 'recycling & disposal' they represent the total CO_2 emissions from the packaging's end-of-life. Due to the energy recovery at incineration plants system-related allocation is applied.

Energy credits of PEF bottles originate from substituted grid electricity and heat produced in MSWI plants, where energy recovery takes place.

The **material credits** originate mainly from the substitution of virgin PET as up to 5% of PEF can be incorporated into the PET recycling streams due to the similar structure of PEF and PET (PETplanet 2024; SpecialChem 2021). Therefore, the credits show the considerable avoided burdens of the virgin PET production in all categories. As the regarded PEF bottles contains no recycled PET, all of the recycled material resulting from 60% recycling rate is recycled in an open loop resulting in material credits.

The **uptake of CO_2** by the corn plants harvested for the production of corn plays a significant role in the impact category 'Climate change'. The carbon uptake refers to the conversion process of carbon dioxide to organic compounds by corn plants. The assimilated carbon is then used to produce energy and to build body structures. However, the carbon uptake in this context describes only the amount of carbon which is stored in the product under study.

Burdens from open-loop recycling and recovery including biogenic CO_2 as well as credits are affected by the choice of allocation factor 50% or 100%. In case of allocation factor 100%, these are fully allocated to the PEF bottle, in case of allocation factor 50%, only 50% of these burdens are allocated to the PEF bottle. As the CO_2 uptake (mainly from PEF production) is not included in the credits, 'Climate change' results are lower with allocation factor 50% (see **section 1.4.2.**)

4.1.4 Comparison between systems

The net result comparison of the beverage cartons and alternative packaging solutions is illustrated by figures that include the comparison between two packaging systems. The percentage is based on the net results of each compared packaging system. Both scenarios, scenario AF 50% and scenario AF 100%, are equally used for the comparison between the systems.

The following figures show the difference between two compared packaging systems. The colors green and blue illustrate the distinction between lower (green) and higher (blue) net results in the respective categories. The packaging system in the upper part of the figure is the 'reference', which is being compared with the packaging system in the lower part of the figure. Blue bar charts mean that the packaging system in the upper part of the figure has higher impacts, green bar charts mean that the packaging system in the upper part of the figure has lower impacts.
Percentages lower than 10% are considered as insignificant differences and therefore marked in a grey box. This can be considered a common practice for LCA studies comparing different product systems (Kupfer et al. 2017). The classification of the differences into lower/higher or insignificant is based on the significance which is described in **section 1.3.**

The scale is capped at 100% due to graphical limitations in representing higher values. A 100% difference indicates a substantial disparity. However, it should not be interpreted as an absolute threshold. The actual difference may exceed this displayed maximum.

Please note: As described in **section 3.1.7**, this study utilizes an older dataset for PA6, with very high N_2O emissions. According to a more recent confidential PA dataset, N_2O emissions in present PA6 production are significantly lower. Since the N_2O emissions in the PA6 dataset are the main driver in the impact category ‘Ozone depletion’, comparative results for ‘Ozone depletion’ involving packaging systems containing PA6 are not considered reliable. In this section, the rPET bottles contain PA6. Therefore, results for ‘Ozone depletion’ are excluded from comparisons involving the rPET bottles.

The percentages in Figure 20 to Figure 22 show the difference of net results of the beverage carton and the competing packaging systems in the JNSD Family Pack (ambient) segment:

- Tetra Brik® Aseptic 1000 Edge LightWing™ 30 with plant-based polymers with PEF bottle (1000 mL)

- Tetra Brik® Aseptic 1000 Edge LightWing™ 30 with plant-based polymers with 50% rPET bottle (1000 mL)

- Tetra Brik® Aseptic 1000 Edge LightWing™ 30 with plant-based polymers with 65% rPET bottle (1000 mL)

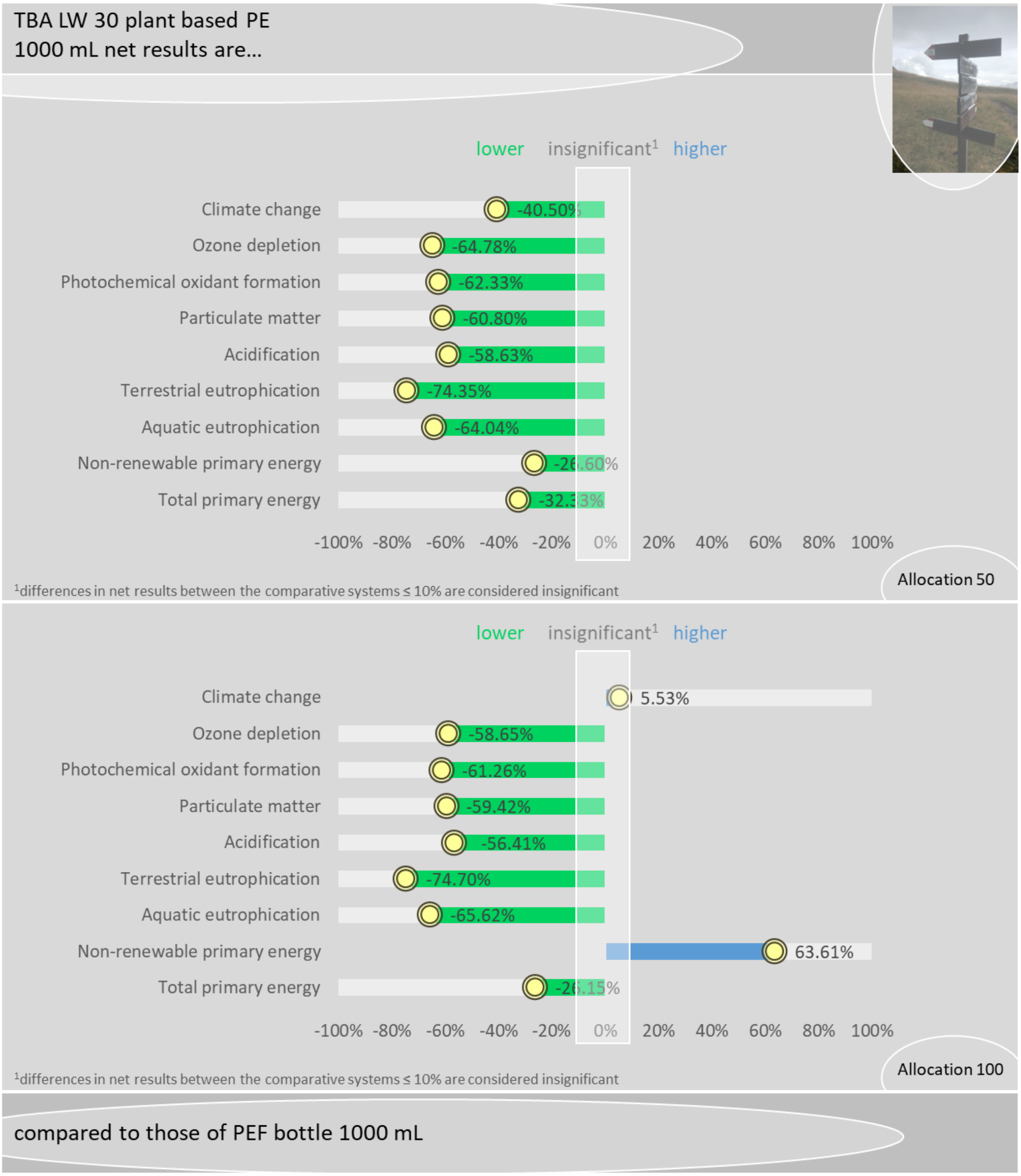


Figure 20: Comparison of net results **Tetra Brik® Aseptic 1000 Edge LightWing™ 30 with plant-based polymers with PEF bottle (1000 mL)**; allocation factor 50% and 100%

In both scenarios (allocation factor 50% and 100%), the ***Tetra Brik® Aseptic 1000 Edge LightWing™ 30 with plant-based polymers*** shows lower net results than ***PEF bottle 1000 ml*** in the impact categories 'Ozone depletion', 'Photochemical oxidant formation', 'Particulate matter', 'Acidification', 'Terrestrial eutrophication', 'Aquatic eutrophication' and in the inventory category 'Total primary energy'.

In the scenario allocation factor 50% the ***Tetra Brik® Aseptic 1000 Edge LightWing™ 30 with plant-based polymers*** shows lower net results than ***PEF bottle 1000 ml*** in the impact category 'Climate change' and in the inventory category 'Non-renewable primary energy'.

<u>In the scenario allocation factor 100%</u> the ***Tetra Brik® Aseptic 1000 Edge LightWing™ 30 with plant-based polymers*** shows higher net results than ***PEF bottle 1000 ml*** in the inventory category 'Non-renewable primary energy'.

<u>In the scenario allocation factor 100%</u> no significant differences are measured in the inventory category 'Non-renewable primary energy'.

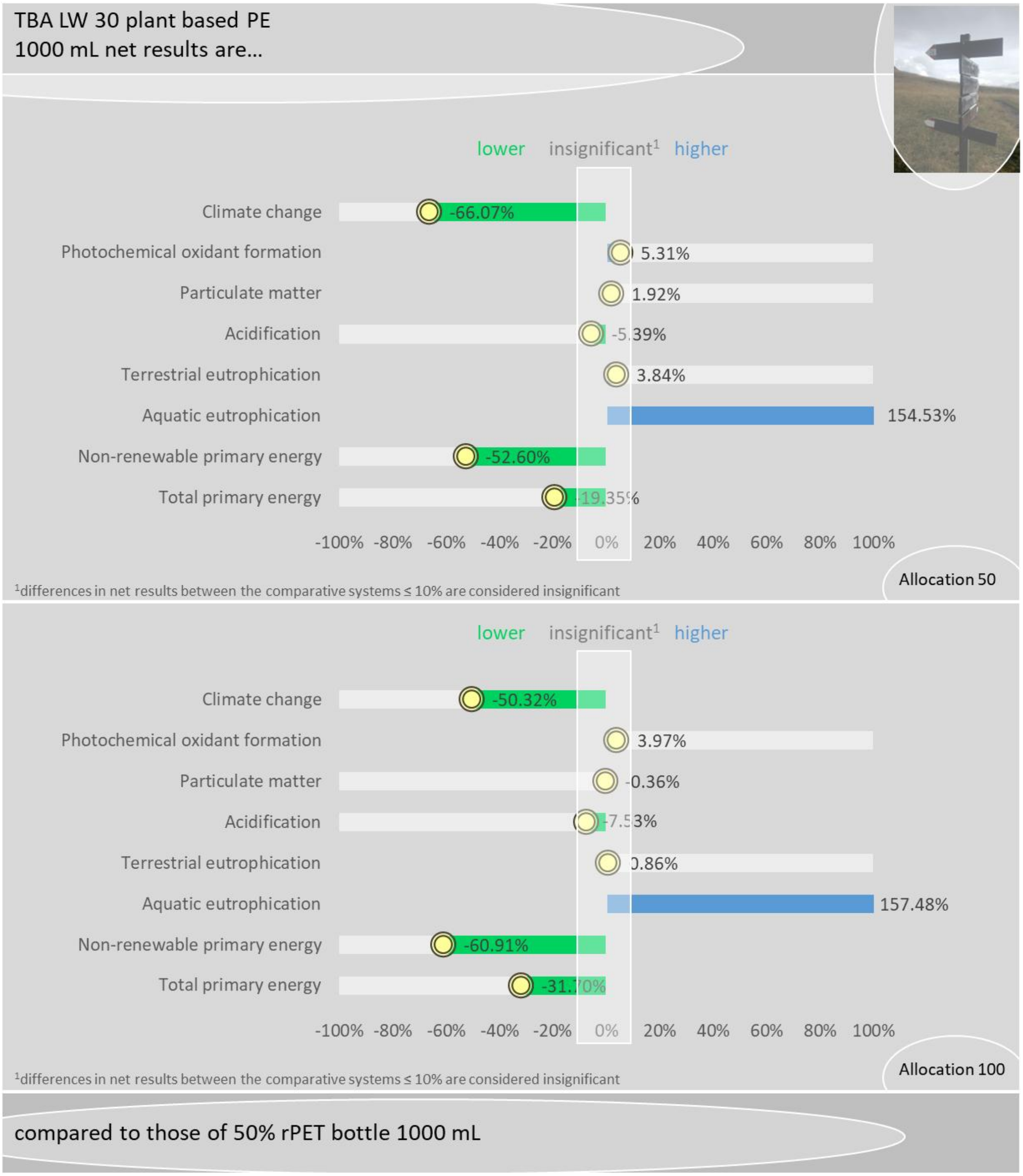


Figure 21: Comparison of net results **Tetra Brik® Aseptic 1000 Edge LightWing™ 30 with plant-based polymers with 50% rPET bottle (1000 mL)**; allocation factor 50% and 100%

<u>In both scenarios (allocation factor 50% and 100%)</u>, the ***Tetra Brik® Aseptic 1000 Edge LightWing™ 30 with plant-based polymers*** shows lower net results than **50% r*PET bottle 1000 ml*** in the category 'Climate change' and in the inventory categories 'Total primary energy' and 'Non-renewable primary energy'.

<u>In both scenarios (allocation factor 50% and 100%)</u>, the ***Tetra Brik® Aseptic 1000 Edge LightWing™ 30 with plant-based polymers*** measures higher net results than **50% r*PET bottle 1000 ml*** in the category 'Aquatic eutrophication'.

<u>In both scenarios (allocation factor 50% and 100%)</u> no significant differences are measured in the impact categories 'Photochemical oxidant formation', 'Particulate matter', 'Acidification', 'Terrestrial eutrophication'.

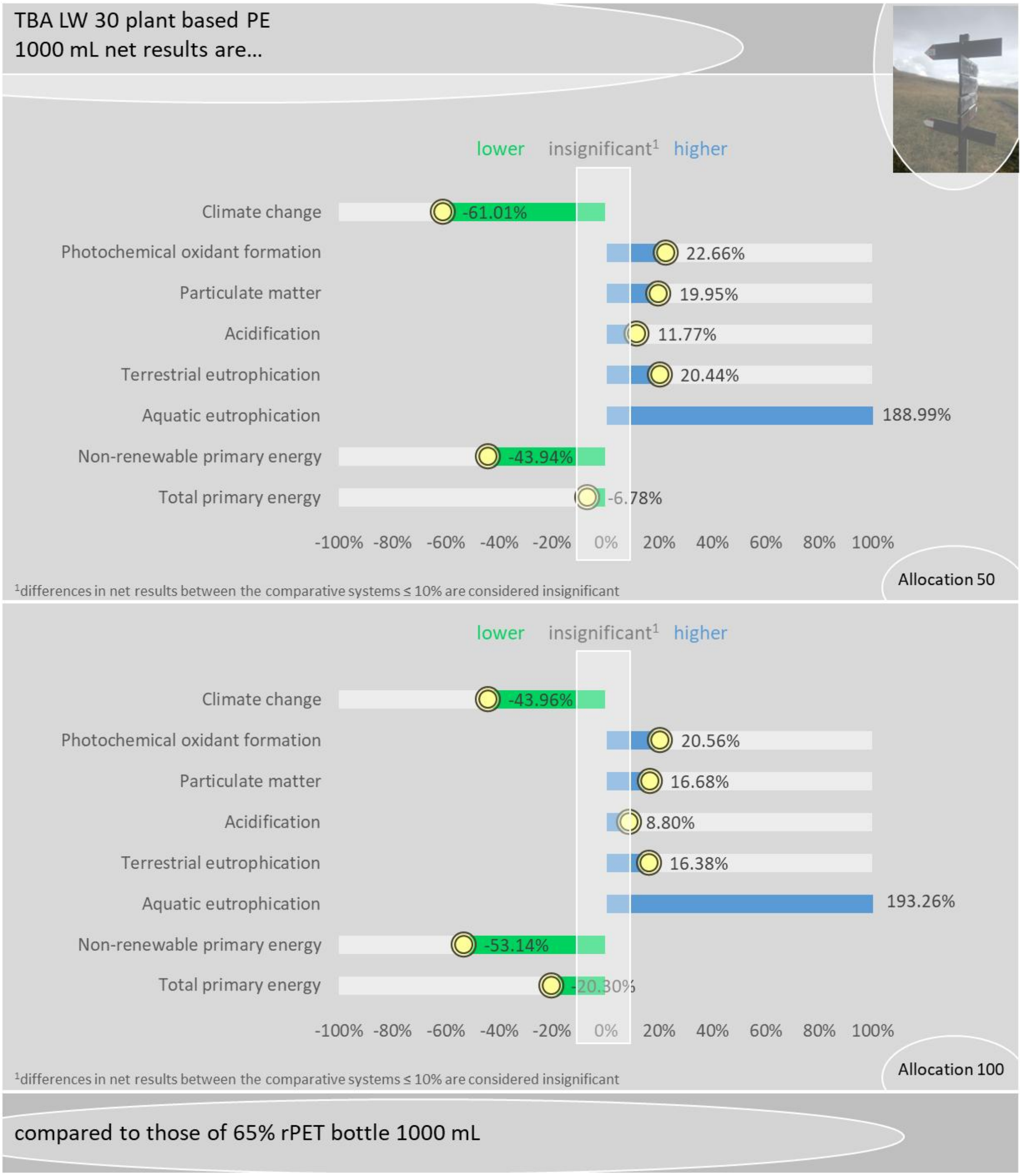


Figure 22: Comparison of net results **Tetra Brik® Aseptic 1000 Edge LightWing™ 30 with plant-based polymers with 65% rPET bottle (1000 mL)**; allocation factor 50% and 100%

In both scenarios (allocation factor 50% and 100%), the ***Tetra Brik® Aseptic 1000 Edge LightWing™ 30 with plant-based polymers*** shows lower net results than **65% r*PET bottle 1000 ml*** in the category ‘Climate change’ and in the inventory category ‘Non-renewable primary energy’.

In both scenarios (allocation factor 50% and 100%), the ***Tetra Brik® Aseptic 1000 Edge LightWing™ 30 with plant-based polymers*** measures higher net results than **65% r*PET bottle 1000 ml*** in the categories ‘Photochemical oxidant formation’, ‘Particulate matter’, ‘Terrestrial eutrophication’, and ‘Aquatic eutrophication’.

In the scenario allocation factor 50% the ***Tetra Brik® Aseptic 1000 Edge LightWing™ 30 with plant-based polymers*** shows higher net results than ***PEF bottle 1000 ml*** in the impact category ‘Acidification’.

In the scenario allocation factor 100% the ***Tetra Brik® Aseptic 1000 Edge LightWing™ 30 with plant-based polymers*** shows lower net results than ***PEF bottle 1000 ml*** in the inventory category ‘Total primary energy’.

In the scenario allocation factor 50% no significant differences are measured in the inventory category Total primary energy’.

In the scenario allocation factor 100% no significant differences are measured in the impact category ‘Acidification’.

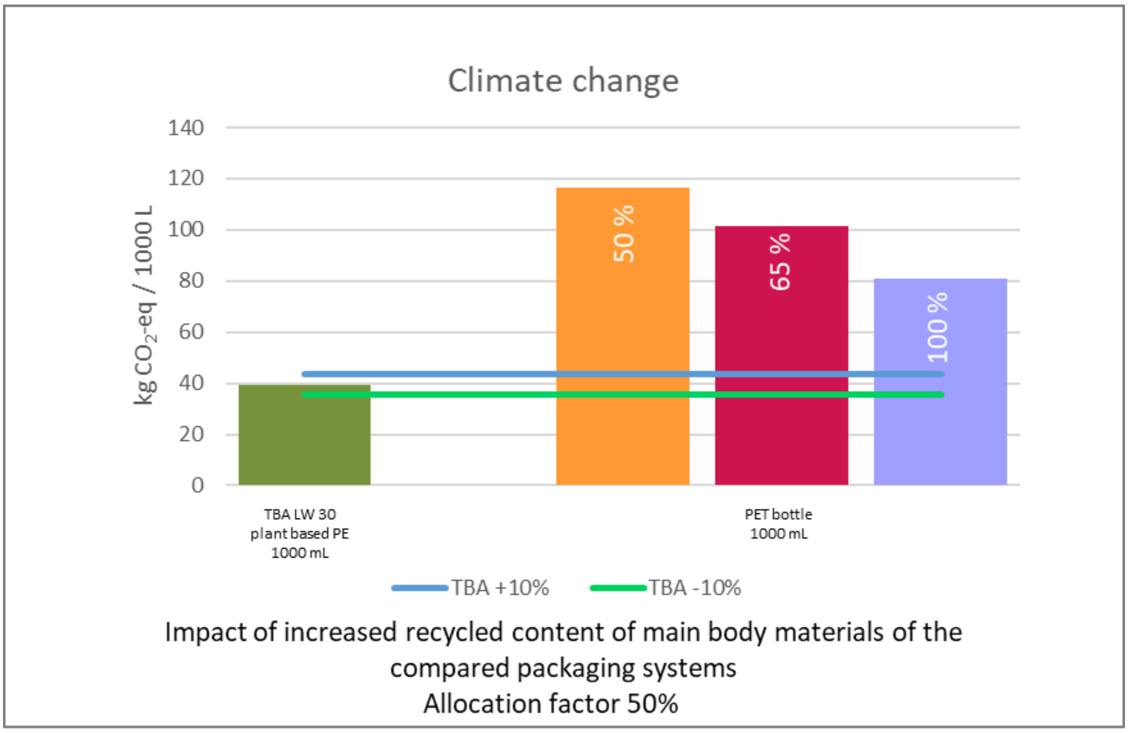
5 Results of the sensitivity analysis of recycled content

In this section the results of the examined beverage cartons and alternative packaging solutions are presented separately for the different categories in graphic form. In Figure 23 to Figure 30 the results for the recycled content sensitivity scenarios are shown for all impact categories. PET bottles in the base scenarios are modelled with 50% and 65% recycled PET content. As PET bottles can be produced with up to 100% recycled content, sensitivity scenarios are calculated with additional 100% recycled PET content. In these analyses, the allocation factor applied for open-loop-recycling is 50% and 100%. The net results of the scenario variants are presented in the following bar charts and shortly described. Additionally, in **Table 20** and **Table 21** the numerical results of the sensitivity scenarios are presented.

The constant lines in the figures indicate the significance thresholds of the alternative packaging systems in comparison to the beverage carton (+10% in blue and −10% in green), making it immediately visible from the graph whether significant differences to the beverage carton exist or not. Percentages lower than 10% are considered as insignificant differences. This can be considered a common practice for LCA studies comparing different product systems (Kupfer et al. 2017). The classification of the differences into lower/higher or insignificant is based on the significance which is described in **section 1.3**.

Please note: As described in **section 3.1.7**, this study utilizes an older dataset for PA6, with very high N_2O emissions. According to a more recent confidential PA dataset, N_2O emissions in present PA6 production are significantly lower. Since the N_2O emissions in the PA6 dataset are the main driver in the impact category ‘Ozone depletion’, comparative results for ‘Ozone depletion’ involving packaging systems containing PA6 are not considered reliable. In this section, the rPET bottles contain PA6. Therefore, results for ‘Ozone depletion’ are excluded from comparisons involving the rPET bottles.

5.1 Sensitivity scenarios recycled content – bar charts and description



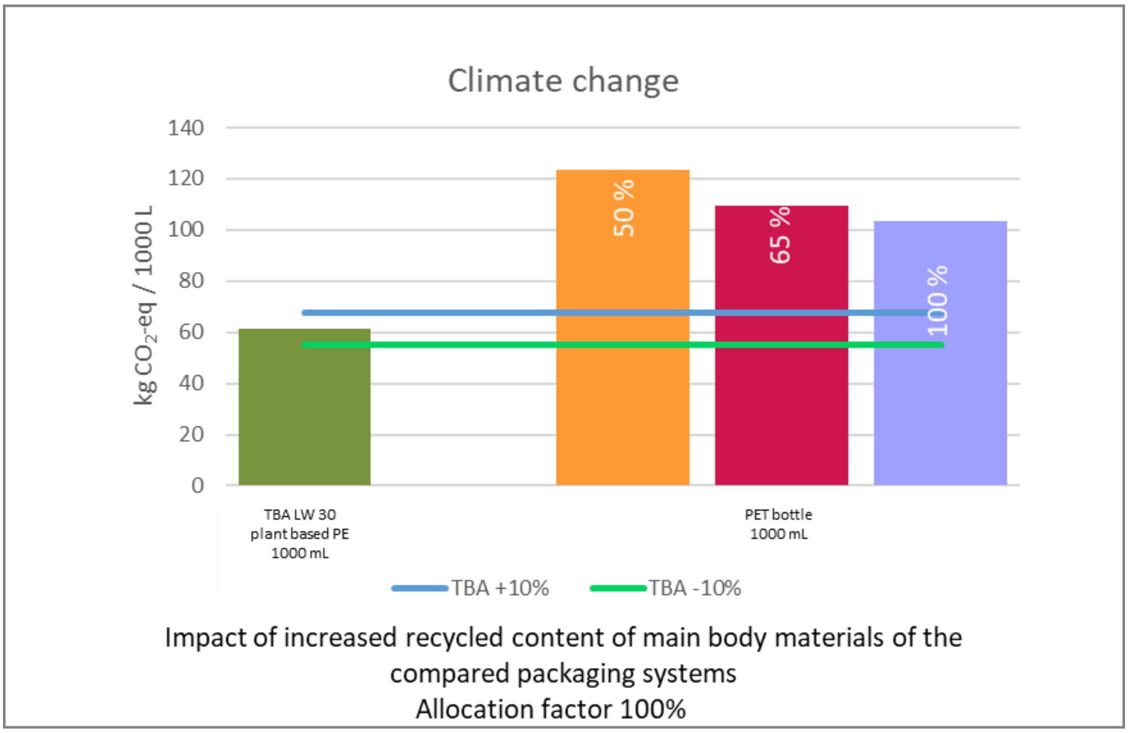
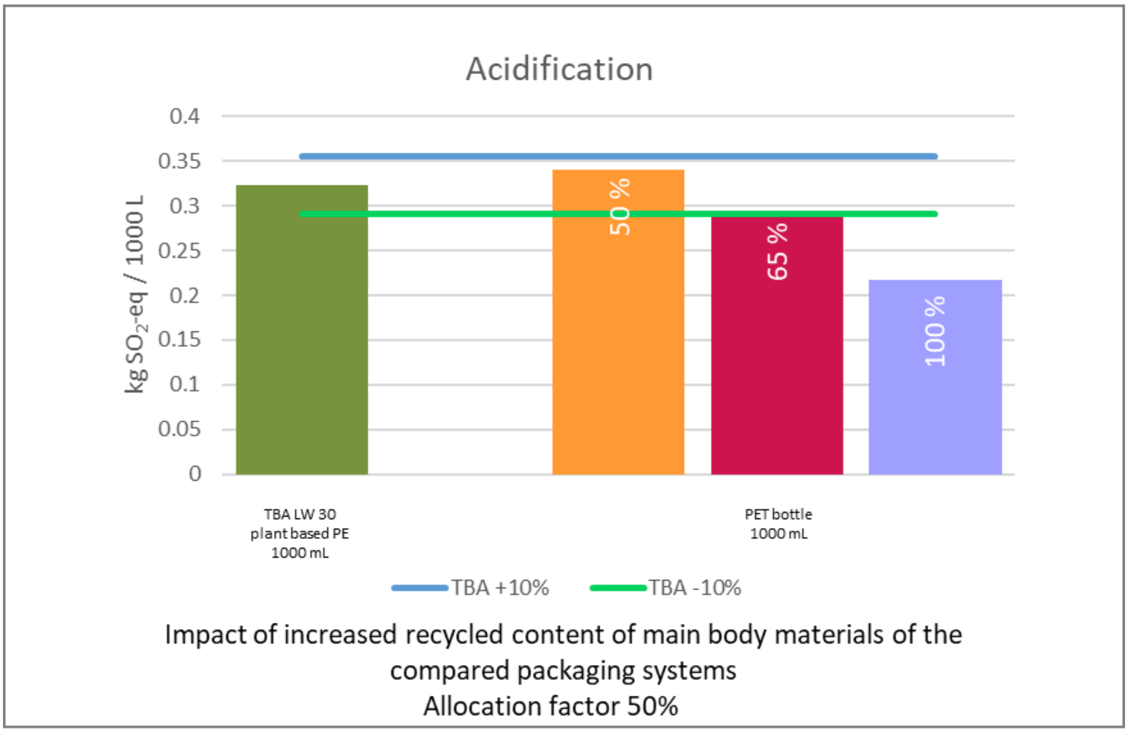


Figure 23: Tetra Brik® Aseptic 1000 Edge LightWing™ 30 with plant-based polymers: Climate change results for rPET sensitivity scenario, allocation factor 50% an 100%

In both scenarios (allocation factor 50% and 100%), the qualitative comparative results for 'Climate change' between the beverage carton and the *PET bottle* stay the same with increased recycled content from 50% rPET to 100% rPET and from 65% rPET to 100% rPET.



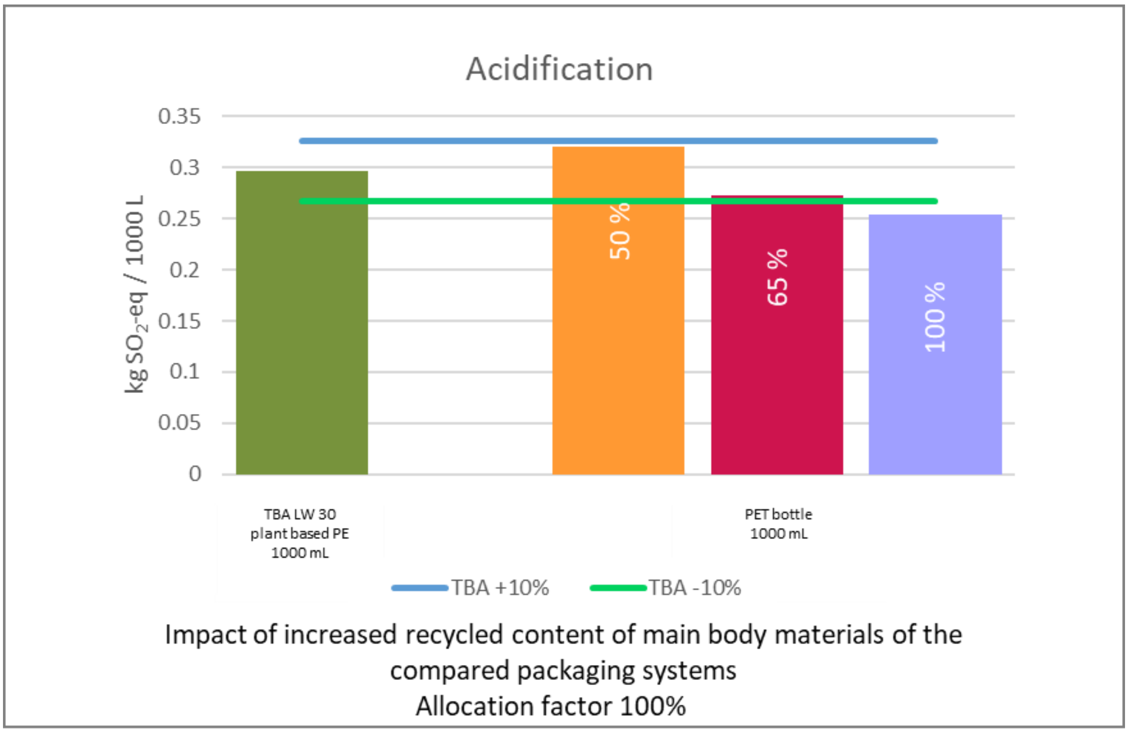
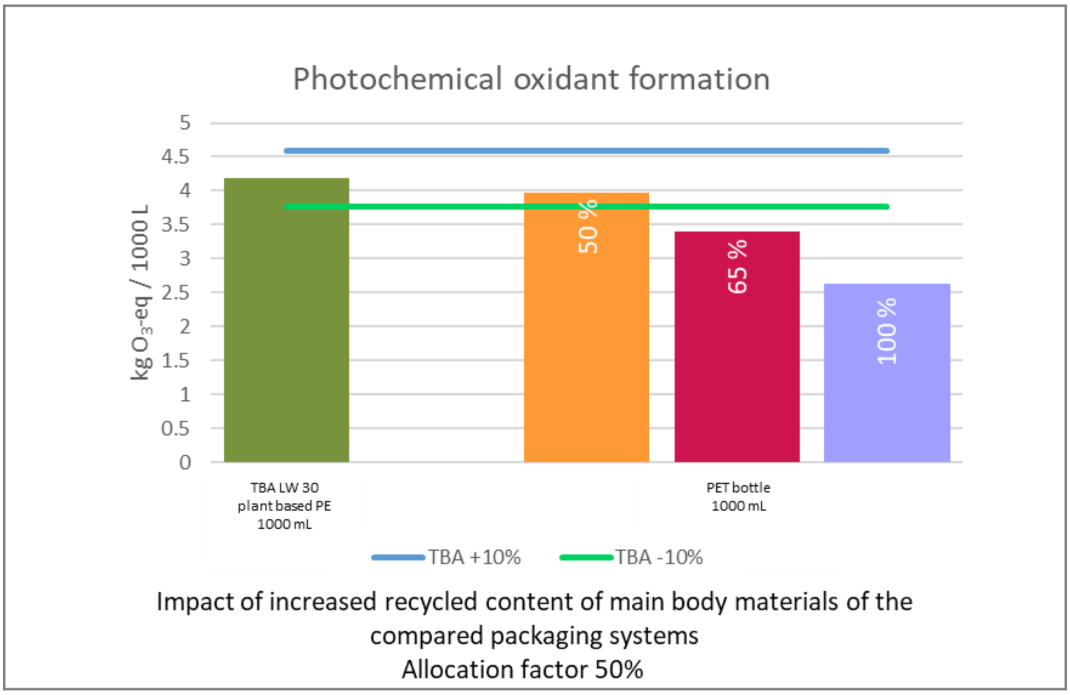


Figure 24: Tetra Brik® Aseptic 1000 Edge LightWing™ 30 with plant-based polymers: Acidification results for rPET sensitivity scenario, allocation factor 50% an 100%

In both scenarios (allocation factor 50% and 100%), the qualitative comparative results for 'Acidification' between the beverage carton and the *PET bottle* change from insignificant differences to higher net results for the beverage carton with increased recycled content from 50% rPET to 100%.

In the scenario allocation factor 50% the qualitative comparative results for 'Acidification' between the beverage carton and the *PET bottle* stay the same with increased recycled content from 65% rPET to 100% rPET.

In the scenario allocation factor 100% the qualitative comparative results for 'Acidification' between the beverage carton and the *PET bottle* change from insignificant differences to higher net results for the beverage carton with increased recycled content from 65% rPET to 100% rPET.



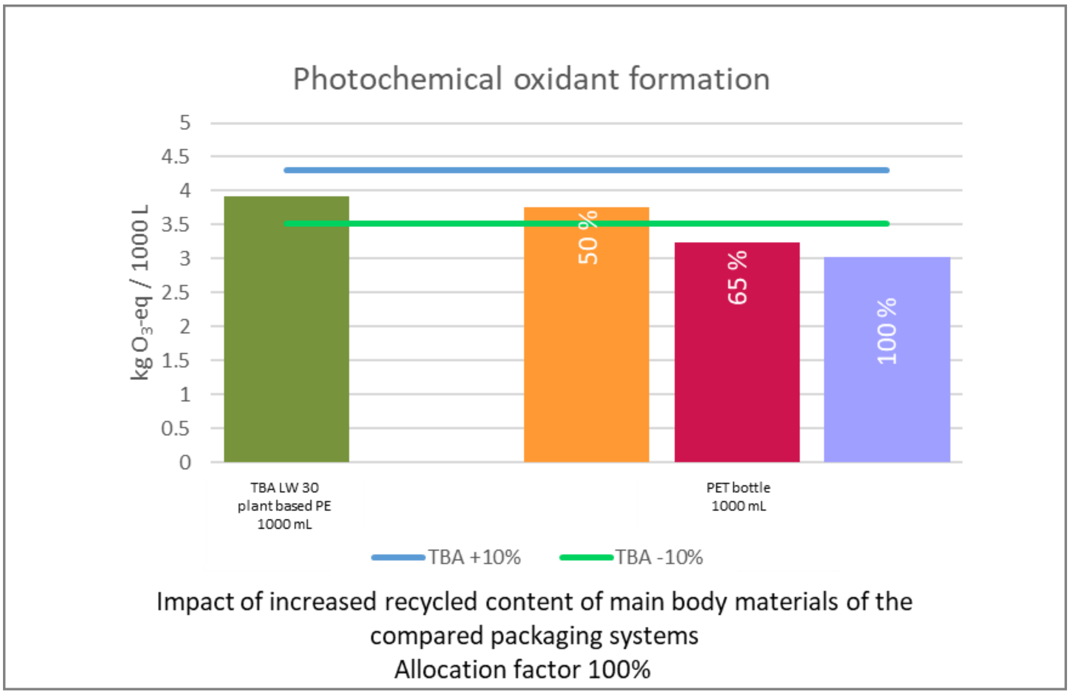
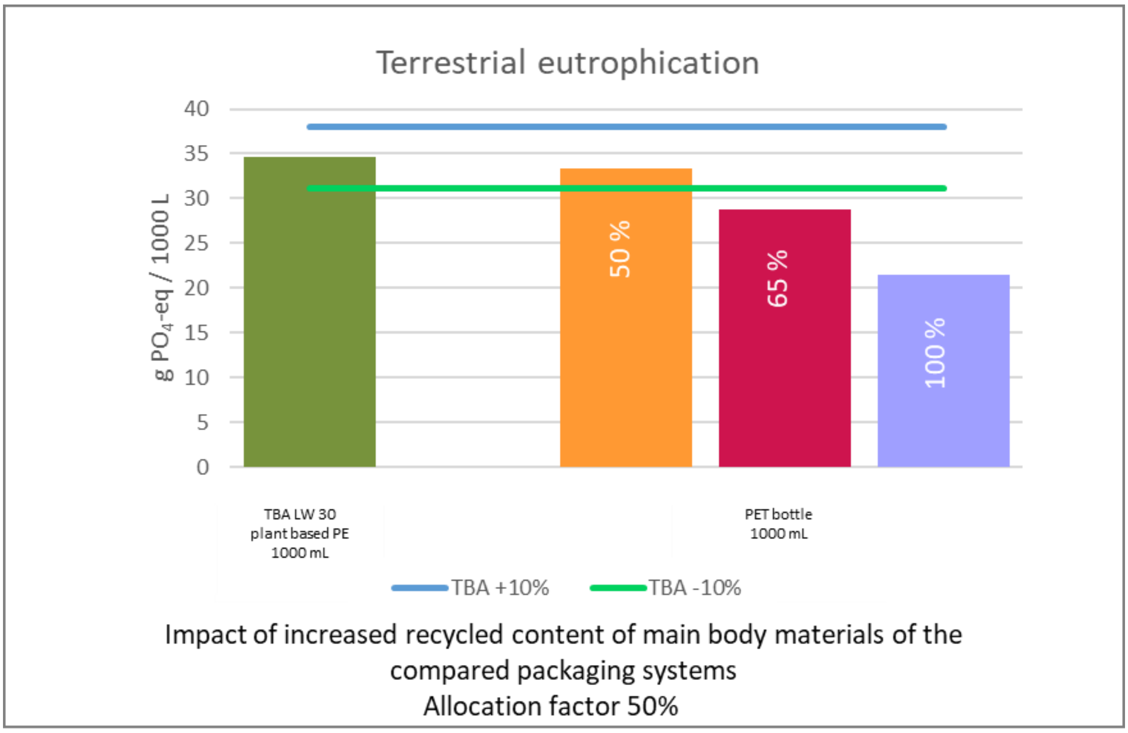


Figure 25: Tetra Brik® Aseptic 1000 Edge LightWing™ 30 with plant-based polymers: Photochemical oxidant formation results for rPET sensitivity scenario, allocation factor 50% an 100%

In both scenarios (allocation factor 50% and 100%), the qualitative comparative results for 'Photochemical oxidant formation' between the beverage carton and the *PET bottle* change from insignificant differences to higher net results for the beverage carton with increased recycled content from 50% rPET to 100% rPET.

In both scenarios (allocation factor 50% and 100%), the qualitative comparative results for 'Photochemical oxidant formation' between the beverage carton and the *PET bottle* stay the same with increased recycled content from 65% rPET to 100% rPET.



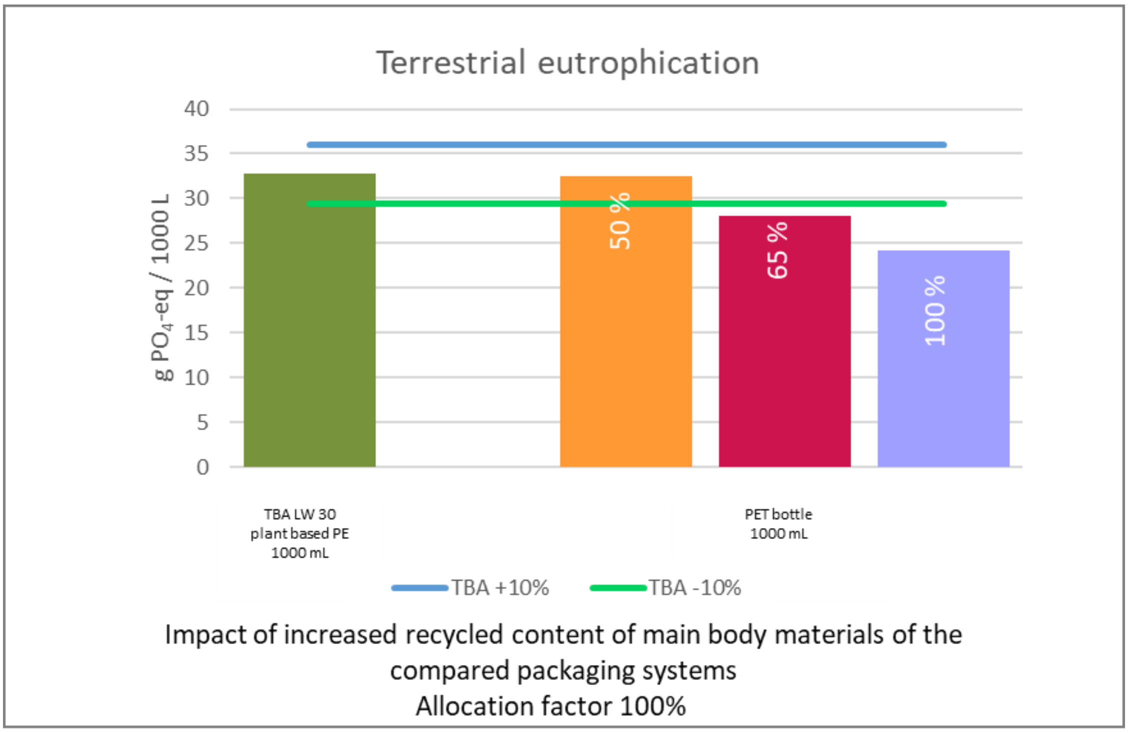
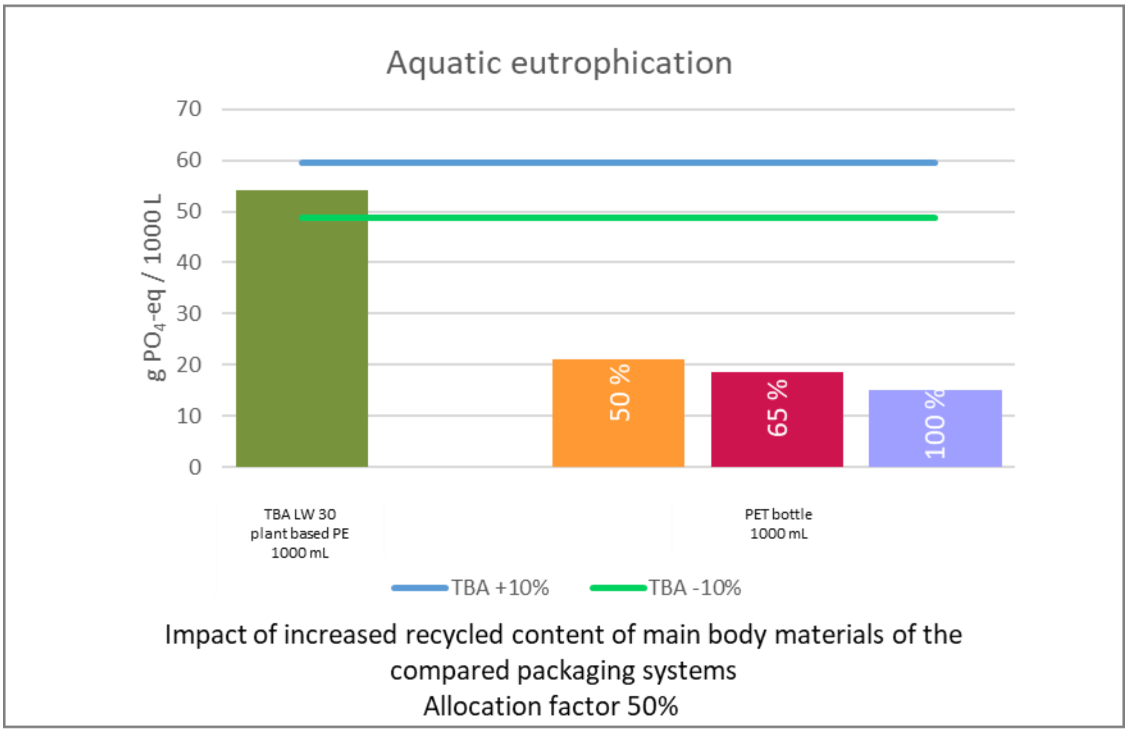


Figure 26: Tetra Brik® Aseptic 1000 Edge LightWing™ 30 with plant-based polymers: Terrestrial eutrophication results for rPET sensitivity scenario, allocation factor 50% an 100%

<u>In both scenarios (allocation factor 50% and 100%)</u>, the qualitative comparative results for 'Terrestrial eutrophication' between the beverage carton and the *PET bottle* change from insignificant differences to higher net results for the beverage carton with increased recycled content from 50% rPET to 100% rPET.

<u>In both scenarios (allocation factor 50% and 100%)</u>, the qualitative comparative results for 'Terrestrial eutrophication' between the beverage carton and the *PET bottle* stay the same with increased recycled content from 65% rPET to 100% rPET.



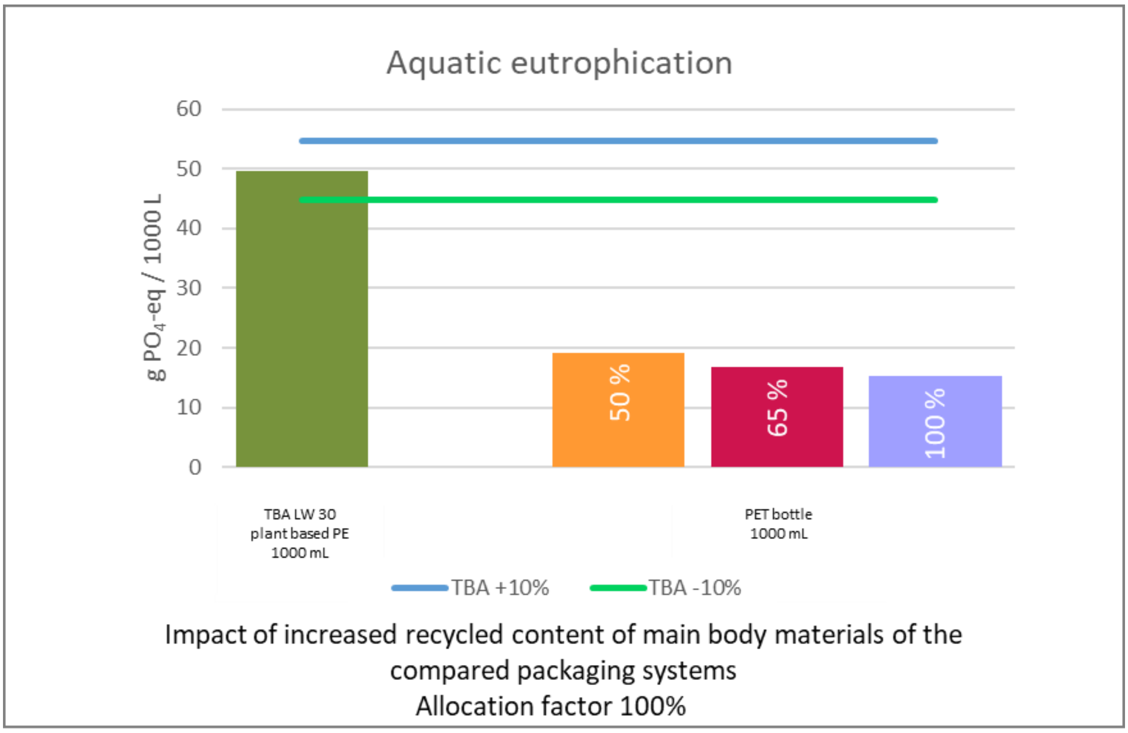
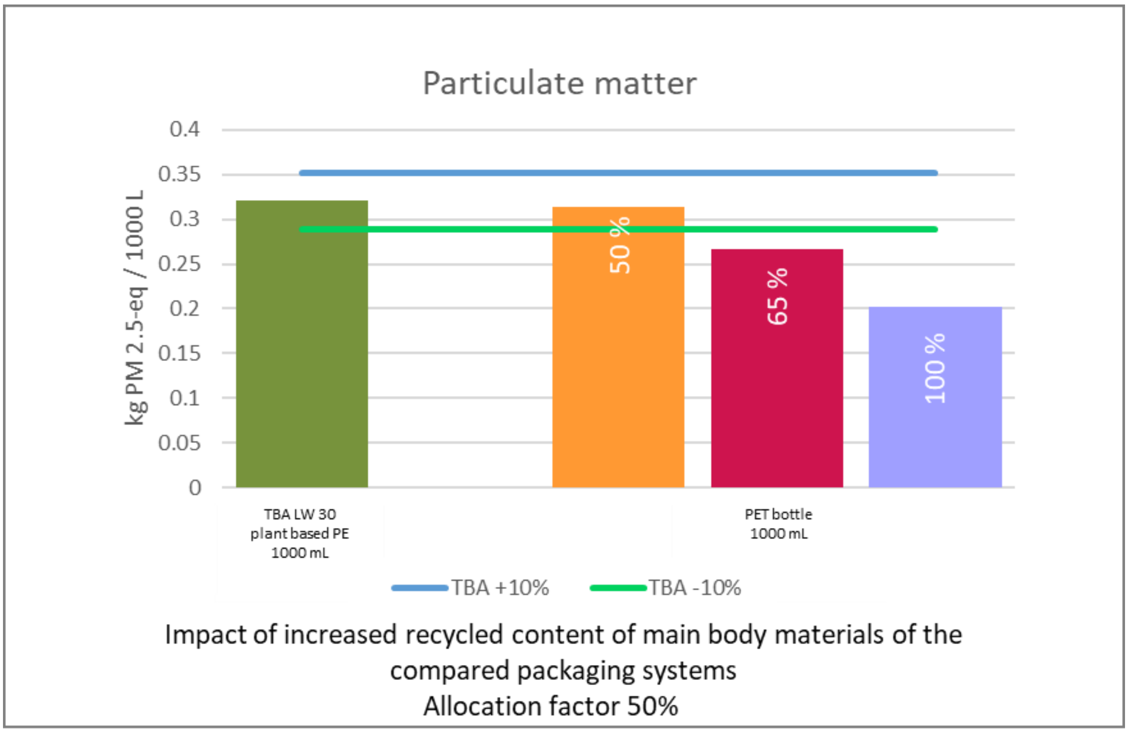


Figure 27: Tetra Brik® Aseptic 1000 Edge LightWing™ 30 with plant-based polymers: Aquatic eutrophication results for rPET sensitivity scenario, allocation factor 50% an 100%

In both scenarios (allocation factor 50% and 100%), the qualitative comparative results for 'Aquatic eutrophication' between the beverage carton and the *PET bottle* stay the same with increased recycled content from 50% rPET to 100% rPET and from 65% rPET to 100% rPET.



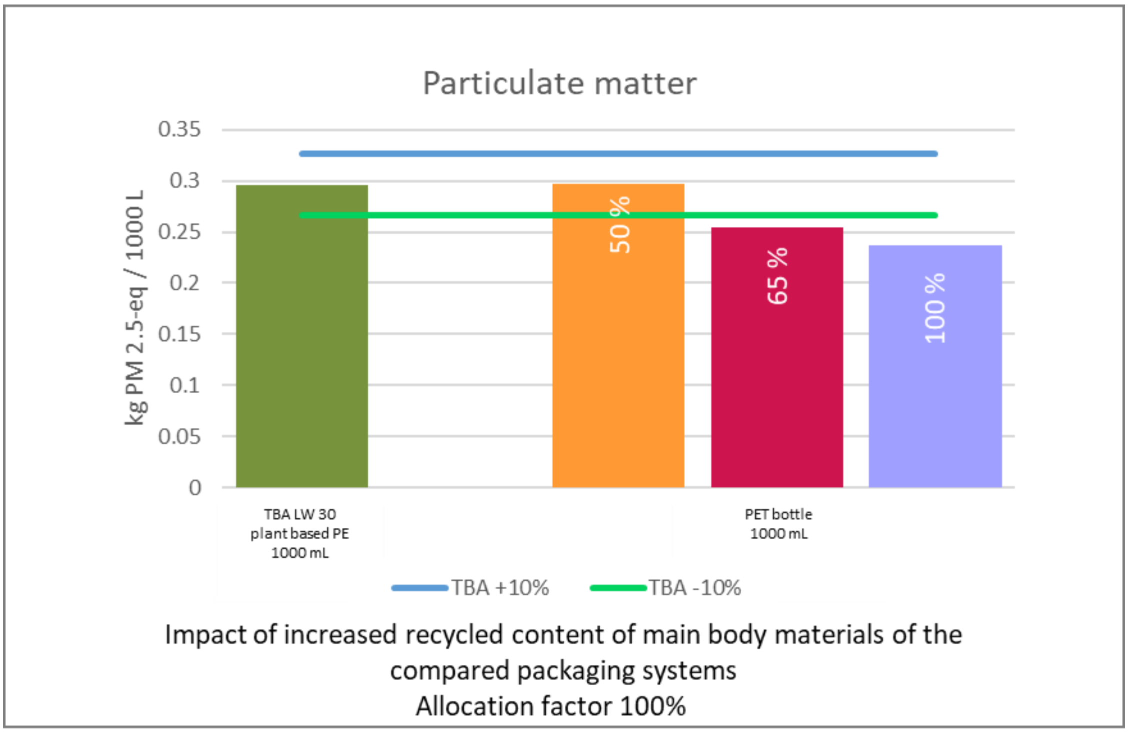
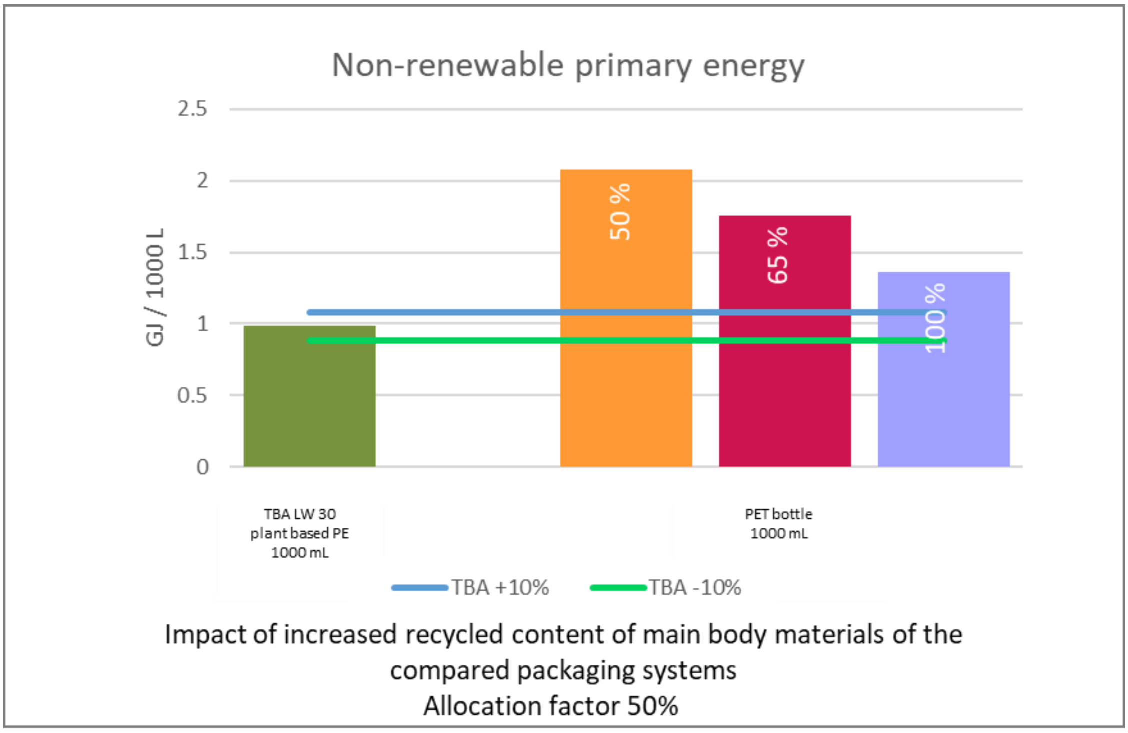


Figure 28: Tetra Brik® Aseptic 1000 Edge LightWing™ 30 with plant-based polymers: Particulate matter results for rPET sensitivity scenario, allocation factor 50% an 100%

In both scenarios (allocation factor 50% and 100%), the qualitative comparative results for 'Particulate matter' between the beverage carton and the *PET bottle* change from insignificant differences to higher net results for the beverage carton with increased recycled content from 50% rPET to 100% rPET.

In both scenarios (allocation factor 50% and 100%), the qualitative comparative results for 'Particulate matter' between the beverage carton and the *PET bottle* stay the same with increased recycled content from 65% rPET to 100% rPET.



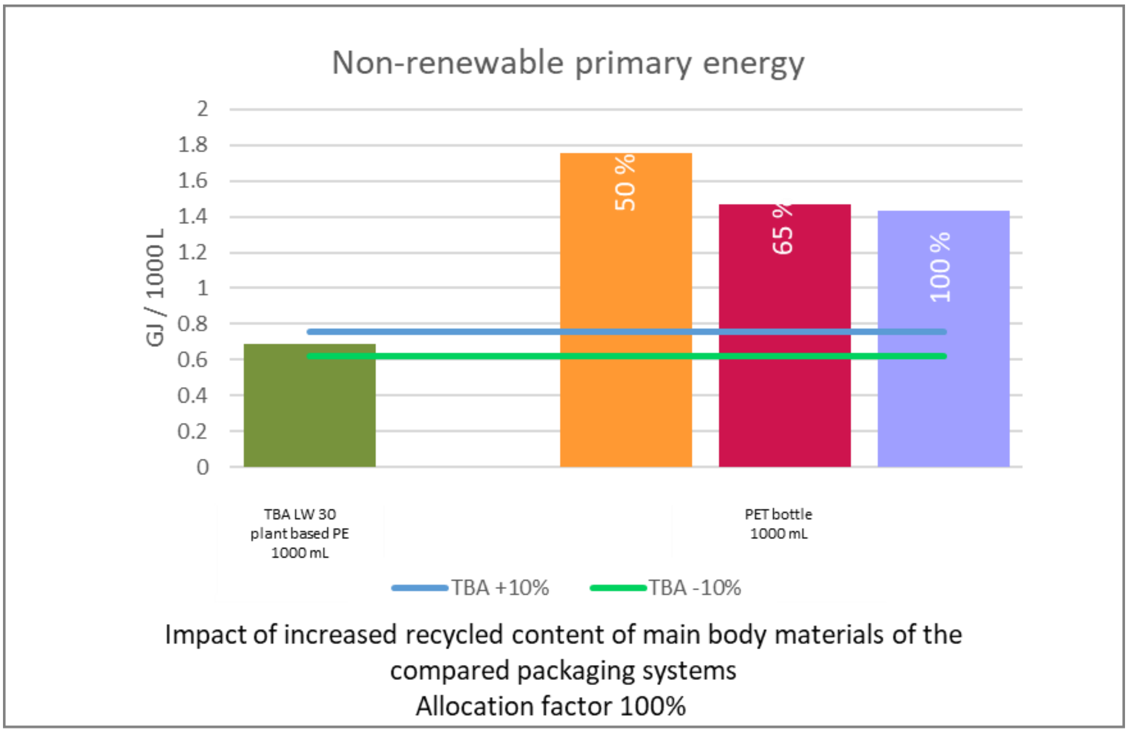
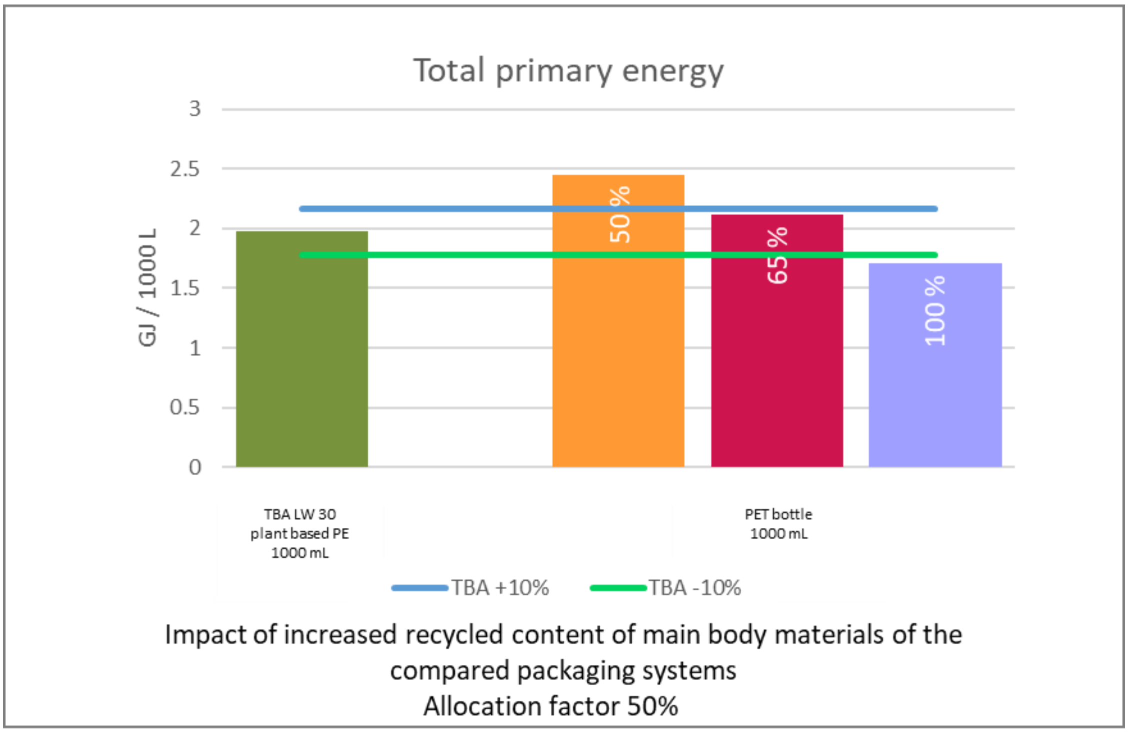


Figure 29: Tetra Brik® Aseptic 1000 Edge LightWing™ 30 with plant-based polymers: Non-renewable primary energy results for rPET sensitivity scenario, allocation factor 50% an 100%

In both scenarios (allocation factor 50% and 100%), the qualitative comparative results for 'Non-renewable primary energy' between the beverage carton and the *PET bottle* stay the same with increased recycled content from 50% rPET to 100% rPET and from 65% rPET to 100% rPET.



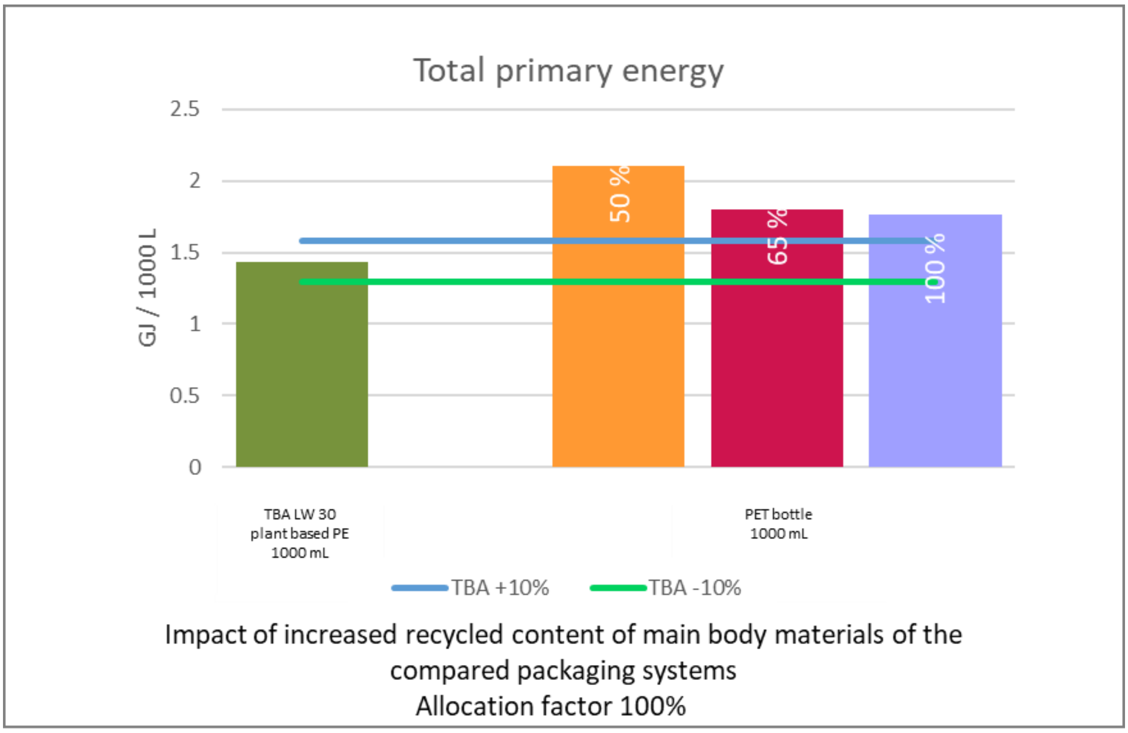


Figure 30: Tetra Brik® Aseptic 1000 Edge LightWing™ 30 with plant-based polymers: Total renewable primary energy results for rPET sensitivity scenario, allocation factor 50% an 100%

In the scenario allocation factor 50% the qualitative comparative results between the beverage carton and the *PET bottle* change from lower net results to higher net results for the beverage carton with increased recycled content from 50% rPET to 100% rPET and change from insignificant differences higher net results with increased recycled content from 65% rPET to 100% rPET.

In the scenario allocation factor 100% the qualitative comparative results between the beverage carton and the *PET bottle* stay the same with increased recycled content from 50% rPET to 100% rPET and from 65% rPET to 100% rPET.

Table 20: Net results of recycled content sensitivity scenarios: burdens, credits and net results per FU of 1000 L, allocation factor 50% (All figures are rounded to two decimal places.)

NL allocation factor 50 %		TBA LW 30 plant based PE 1000 mL	50% rPET bottle 1000 mL	65% rPET bottle 1000 mL	100% rPET bottle 1000 mL
Climate change [kg CO_2-equivalents]	burdens	89.84	134.13	118.97	98.62
	biogenic CO_2	23.98	1.29	1.29	1.29
	credits	-20.02	-16.25	-16.24	-16.23
	CO_2 uptake	-54.24	-2.58	-2.58	-2.58
	net results (∑)	**39.56**	**116.59**	**101.44**	**81.10**
Acidification [g SO_2-equivalents]	burdens	0.36	0.37	0.32	0.25
	credits	-0.04	-0.03	-0.03	-0.03
	net results (∑)	**0.32**	**0.34**	**0.29**	**0.22**
Photochemical oxidant formation [g O_3-equivalents]	burdens	4.74	4.37	3.80	3.03
	credits	-0.56	-0.40	-0.40	-0.40
	net results (∑)	**4.18**	**3.97**	**3.41**	**2.63**
Ozone depletion [g R-11-equivalents]	burdens	0.22	0.53	0.41	0.21
	credits	-0.02	-0.01	-0.01	-0.01
	net results (∑)	**0.20**	**0.52**	**0.40**	**0.20**
Terrestrial eutrophication [g PO_4-equivalents]	burdens	38.86	35.82	31.23	23.91
	credits	-4.26	-2.50	-2.50	-2.50
	net results (∑)	**34.60**	**33.32**	**28.73**	**21.41**
Aquatic eutrophication [g PO_4-equivalents]	burdens	59.25	23.26	20.72	17.20
	credits	-5.11	-2.11	-2.11	-2.11
	net results (∑)	**54.14**	**21.15**	**18.60**	**15.09**
Particulate matter [g PM 2.5- equivalents]	burdens	0.36	0.34	0.29	0.23
	credits	-0.04	-0.03	-0.03	-0.03
	net results (∑)	**0.32**	**0.31**	**0.27**	**0.20**
Non-renewable primary energy [GJ]	burdens	1.30	2.39	2.07	1.68
	credits	-0.32	-0.32	-0.32	-0.32
	net results (∑)	**0.98**	**2.07**	**1.75**	**1.36**
Total primary energy [GJ]	burdens	2.54	2.79	2.46	2.06
	credits	-0.57	-0.35	-0.35	-0.35
	net results (∑)	**1.97**	**2.45**	**2.12**	**1.71**

Table 21: Net results of recycled content sensitivity scenarios: burdens, credits and net results per FU of 1000 L, allocation factor 100% (All figures are rounded to two decimal places.)

NL allocation factor 100 %		TBA LW 30 plant based PE 1000 mL	50% rPET bottle 1000 mL	65% rPET bottle 1000 mL	100% rPET bottle 1000 mL
Climate change [kg CO_2-equivalents]	burdens	107.71	156.09	142.06	136.01
	biogenic CO_2	47.96	2.58	2.58	2.58
	credits	-40.06	-32.56	-32.55	-32.52
	CO_2 uptake	-54.24	-2.58	-2.58	-2.58
	net results (∑)	**61.37**	**123.54**	**109.52**	**103.49**
Acidification [g SO_2-equivalents]	burdens	0.38	0.38	0.33	0.31
	credits	-0.08	-0.06	-0.06	-0.06
	net results (∑)	**0.30**	**0.32**	**0.27**	**0.25**
Photochemical oxidant formation [g O_3-equivalents]	burdens	5.03	4.56	4.04	3.82
	credits	-1.11	-0.80	-0.80	-0.80
	net results (∑)	**3.91**	**3.76**	**3.25**	**3.02**
Ozone depletion [g R-11-equivalents]	burdens	0.22	0.53	0.42	0.29
	credits	-0.04	-0.02	-0.02	-0.02
	net results (∑)	**0.19**	**0.51**	**0.40**	**0.27**
Terrestrial eutrophication [g PO_4-equivalents]	burdens	41.25	37.45	33.13	29.17
	credits	-8.53	-5.01	-5.01	-5.01
	net results (∑)	**32.72**	**32.44**	**28.11**	**24.16**
Aquatic eutrophication [g PO_4-equivalents]	burdens	59.96	23.31	20.93	19.54
	credits	-10.23	-4.23	-4.23	-4.23
	net results (∑)	**49.74**	**19.08**	**16.70**	**15.31**
Particulate matter [g PM 2.5- equivalents]	burdens	0.38	0.35	0.31	0.29
	credits	-0.08	-0.05	-0.05	-0.05
	net results (∑)	**0.30**	**0.30**	**0.25**	**0.24**
Non-renewable primary energy [GJ]	burdens	1.33	2.40	2.10	2.07
	credits	-0.64	-0.64	-0.64	-0.64
	net results (∑)	**0.69**	**1.76**	**1.47**	**1.43**
Total primary energy [GJ]	burdens	2.57	2.80	2.50	2.47
	credits	-1.13	-0.70	-0.70	-0.70
	net results (∑)	**1.43**	**2.10**	**1.80**	**1.77**

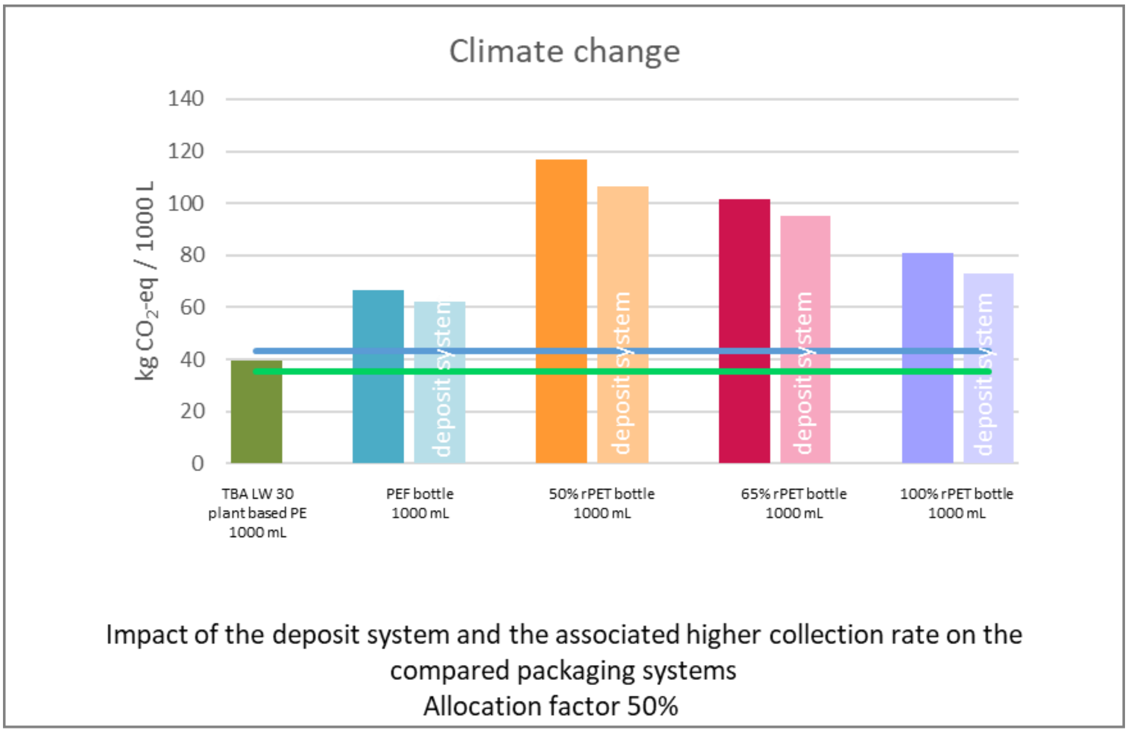
6 Results of the sensitivity analysis of collection rate

In this section the results of the examined beverage cartons and alternative packaging solutions are presented separately for the different categories in graphic form. In Figure 23 to Figure 30 the results for the sensitivity scenarios regarding the collection rate are shown for all impact categories. PET and PEF bottles in the base scenarios are modelled with 77% collection rate. This refers to the current collection status of plastic beverage bottles in the Netherlands being a mix of collection through a deposit system and through a collection of mixed packaging waste without deposit, as currently only a portion of JNSD packaging is part of the deposit refund system (verpact 2025). As a sensitivity the collection rate of 83% representing plastic beverage bottles collected exclusively with the deposit refund system (verpact 2025) is added for all rPET and PEF bottles. In these analyses, the allocation factor applied for open-loop-recycling is 50% and 100%. The net results of the scenario variants are presented in the following bar charts and shortly described. Additionally, in **Table 22** and **Table 23** the numerical results of the sensitivity scenarios are presented.

The constant lines in the figures indicate the significance thresholds of the alternative packaging systems in comparison to the beverage carton (+10% in blue and −10% in green), making it immediately visible from the graph whether significant differences to the beverage carton exist or not. Percentages lower than 10% are considered as insignificant differences. This can be considered a common practice for LCA studies comparing different product systems (Kupfer et al. 2017). The classification of the differences into lower/higher or insignificant is based on the significance which is described in **section 1.3**.

Please note: As described in **section 3.1.7**, this study utilizes an older dataset for PA6, with very high N_2O emissions. According to a more recent confidential PA dataset, N_2O emissions in present PA6 production are significantly lower. Since the N_2O emissions in the PA6 dataset are the main driver in the impact category ‘Ozone depletion’, comparative results for ‘Ozone depletion’ involving packaging systems containing PA6 are not considered reliable. In this section, the rPET bottles contain PA6. Therefore, results for ‘Ozone depletion’ are excluded from comparisons involving the rPET bottles.

6.1 Sensitivity scenarios collection rate – bar charts and description



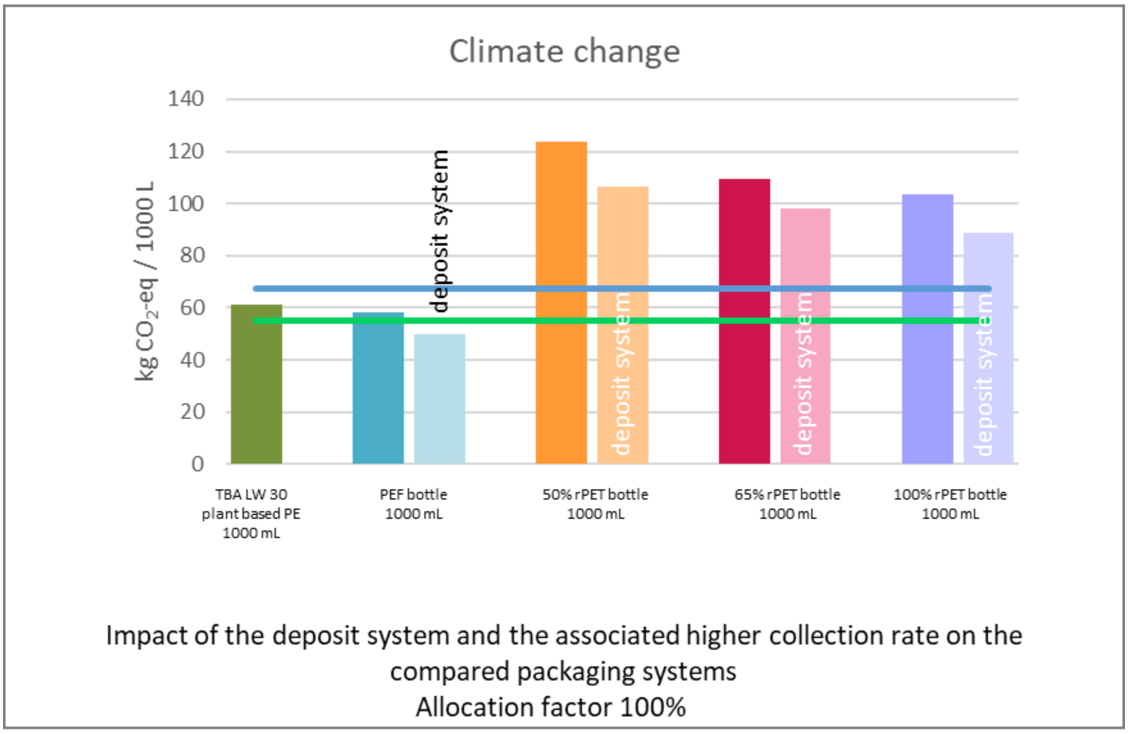


Figure 31: Tetra Brik® Aseptic 1000 Edge LightWing™ 30 with plant-based polymers: Climate change results for collection rate sensitivity scenario, allocation factor 50% an 100%

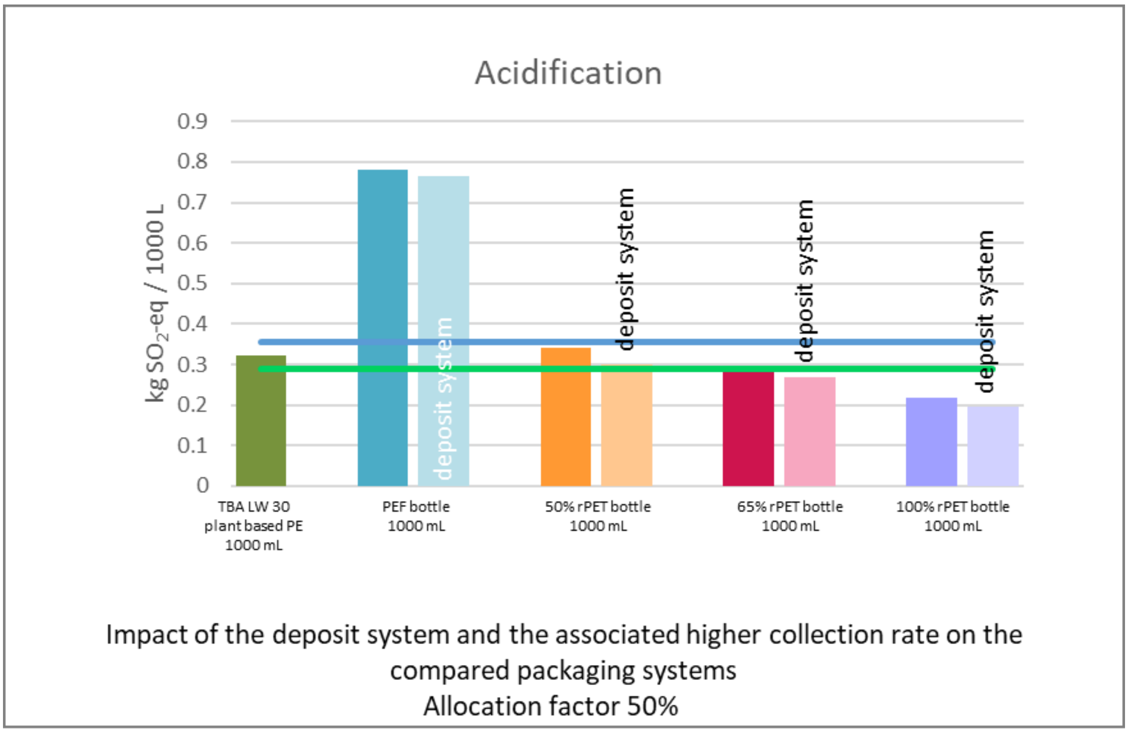
In the scenario allocation factor 50% the qualitative comparative results for 'Climate change' between the beverage carton and the *PEF bottle* stay the same with increased collection rate from 77% to 83% (only deposit system).

In the scenario allocation factor 100% the qualitative comparative results for ‘Climate change’between the beverage carton and the *PEF bottle* change from insignificant differences to higher net results for the beverage carton with increased collection rate from 77% to 83% (only deposit system).

In both scenarios (allocation factor 50% and 100%), the qualitative comparative results for ‘Climate change’between the beverage carton and the *50% rPET* stay the same with increased collection rate from 77% to 83% (only deposit system).

In both scenarios (allocation factor 50% and 100%), the qualitative comparative results for ‘Climate change’between the beverage carton and the *65% rPET* stay the same with increased collection rate from 77% to 83% (only deposit system).

In both scenarios (allocation factor 50% and 100%), the qualitative comparative results for ‘Climate change’between the beverage carton and the *100% rPET* stay the same with increased collection rate from 77% to 83% (only deposit system).



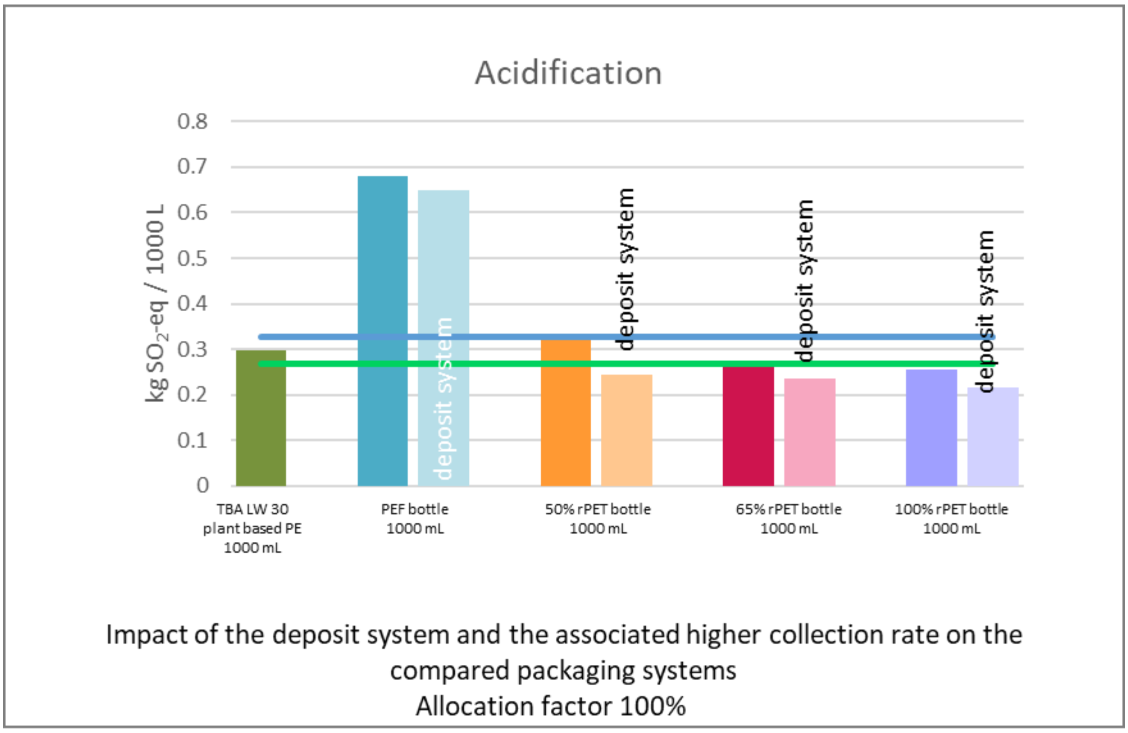


Figure 32: Tetra Brik® Aseptic 1000 Edge LightWing™ 30 with plant-based polymers: Acidification results for collection rate sensitivity scenario, allocation factor 50% an 100%

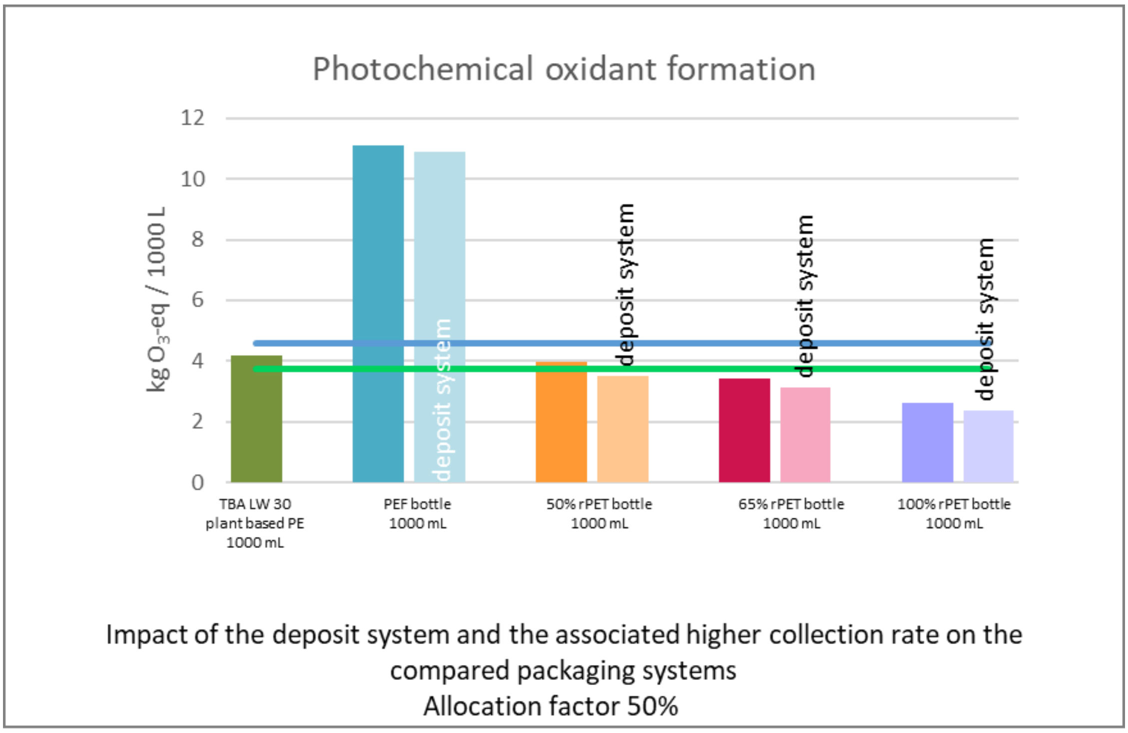
In both scenarios (allocation factor 50% and 100%), the qualitative comparative results for 'Acidification'between the beverage carton and the *PEF bottle* stay the same with increased collection rate from 77% to 83% (only deposit system).

In the scenario allocation factor 50% the qualitative comparative results for 'Acidification' between the beverage carton and the *50% rPET* stay the same with increased collection rate from 77% to 83% (only deposit system).

In the scenario allocation factor 100% the qualitative comparative results for 'Acidification' between the beverage carton and the *50% rPET* change from insignificant differences to higher net results with increased collection rate from 77% to 83% (only deposit system).

In both scenarios (allocation factor 50% and 100%), the qualitative comparative results for 'Acidification' between the beverage carton and the *65% rPET* stay the same with increased collection rate from 77% to 83% (only deposit system).

In both scenarios (allocation factor 50% and 100%), the qualitative comparative results for 'Acidification' between the beverage carton and the *100% rPET* stay the same with increased collection rate from 77% to 83% (only deposit system).



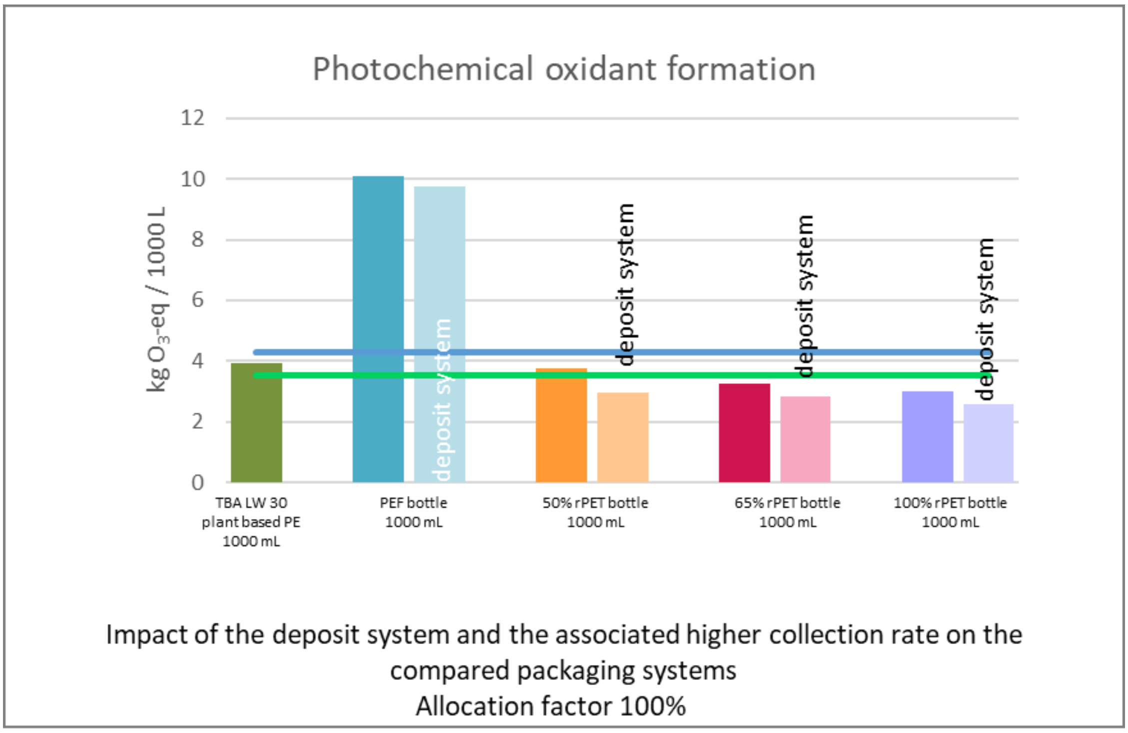


Figure 33: Tetra Brik® Aseptic 1000 Edge LightWing™ 30 with plant-based polymers: Photochemical oxidant formation results for collection rate sensitivity scenario, allocation factor 50% an 100%

In both scenarios (allocation factor 50% and 100%), the qualitative comparative results for 'Photochemical oxidant formation' between the beverage carton and the *PEF bottle* stay the same with increased collection rate from 77% to 83% (only deposit system).

In both scenarios (allocation factor 50% and 100%), the qualitative comparative results for 'Photochemical oxidant formation' between the beverage carton and the *50% rPET* change from insignificant differences to higher net results for the beverage carton with increased collection rate from 77% to 83% (only deposit system).

In both scenarios (allocation factor 50% and 100%), the qualitative comparative results for 'Photochemical oxidant formation' between the beverage carton and the *65% rPET* stay the same with increased collection rate from 77% to 83% (only deposit system).

In both scenarios (allocation factor 50% and 100%), the qualitative comparative results for 'Photochemical oxidant formation' between the beverage carton and the *100% rPET* stay the same with increased collection rate from 77% to 83% (only deposit system).

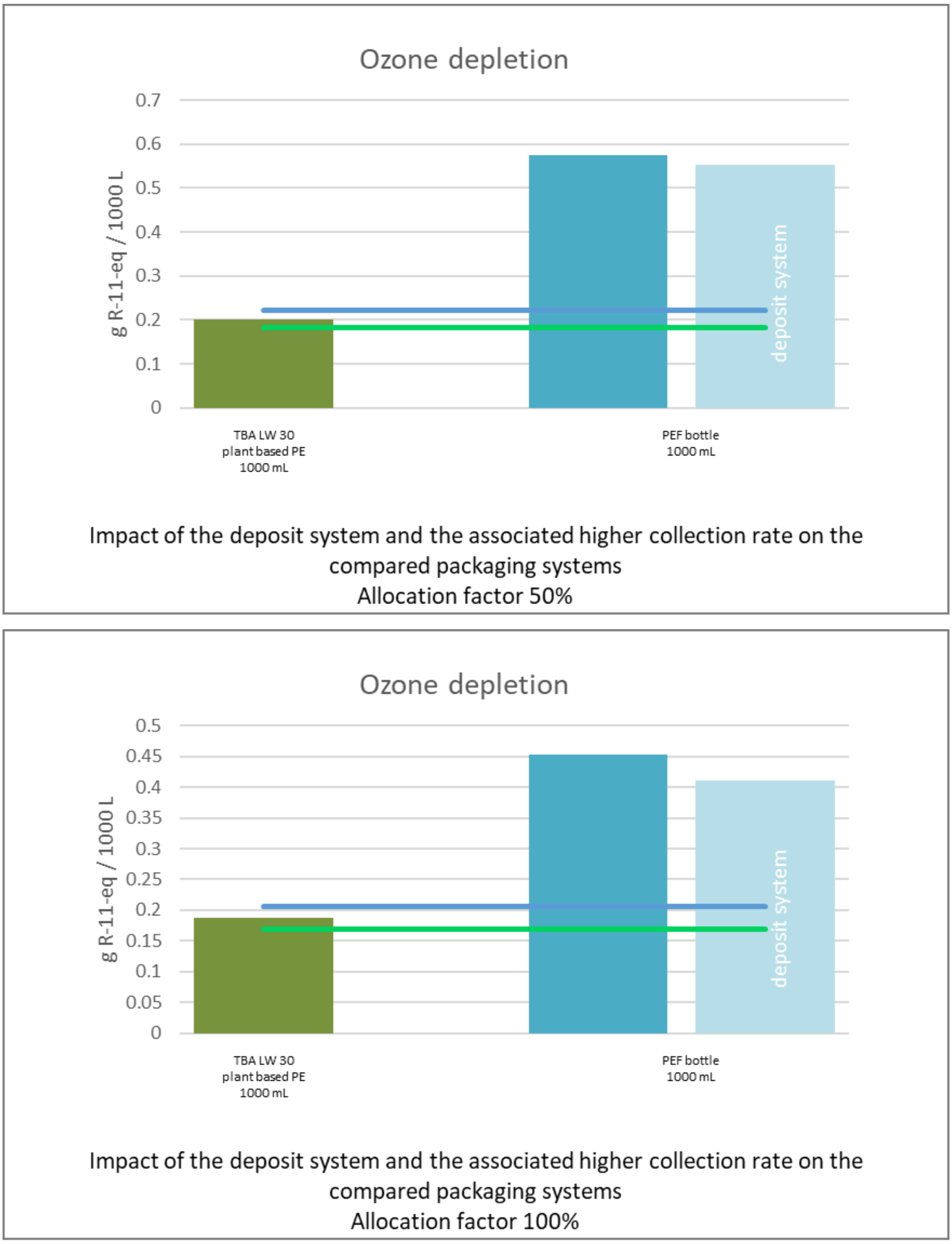
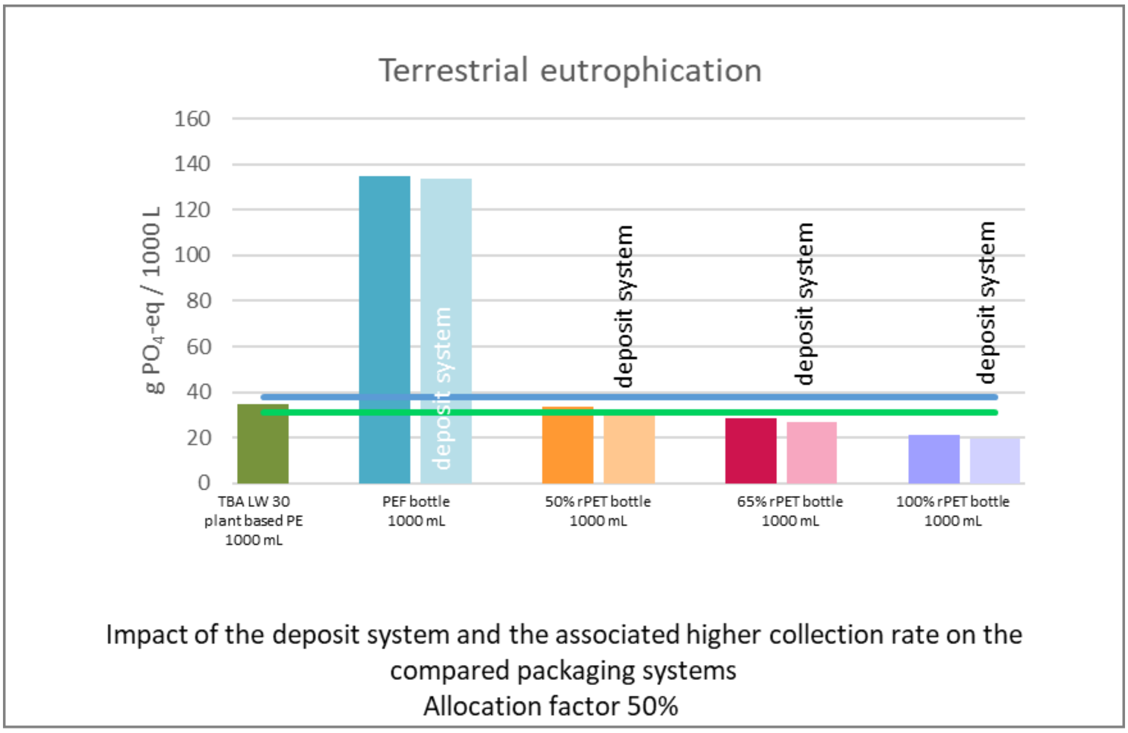


Figure 34: Tetra Brik® Aseptic 1000 Edge LightWing™ 30 with plant-based polymers: Ozone depletion results for collection rate sensitivity scenario, allocation factor 50% an 100%

In both scenarios (allocation factor 50% and 100%), the qualitative comparative results for 'Ozone depletion' between the beverage carton and the *PEF bottle* stay the same with increased collection rate from 77% to 83% (only deposit system).



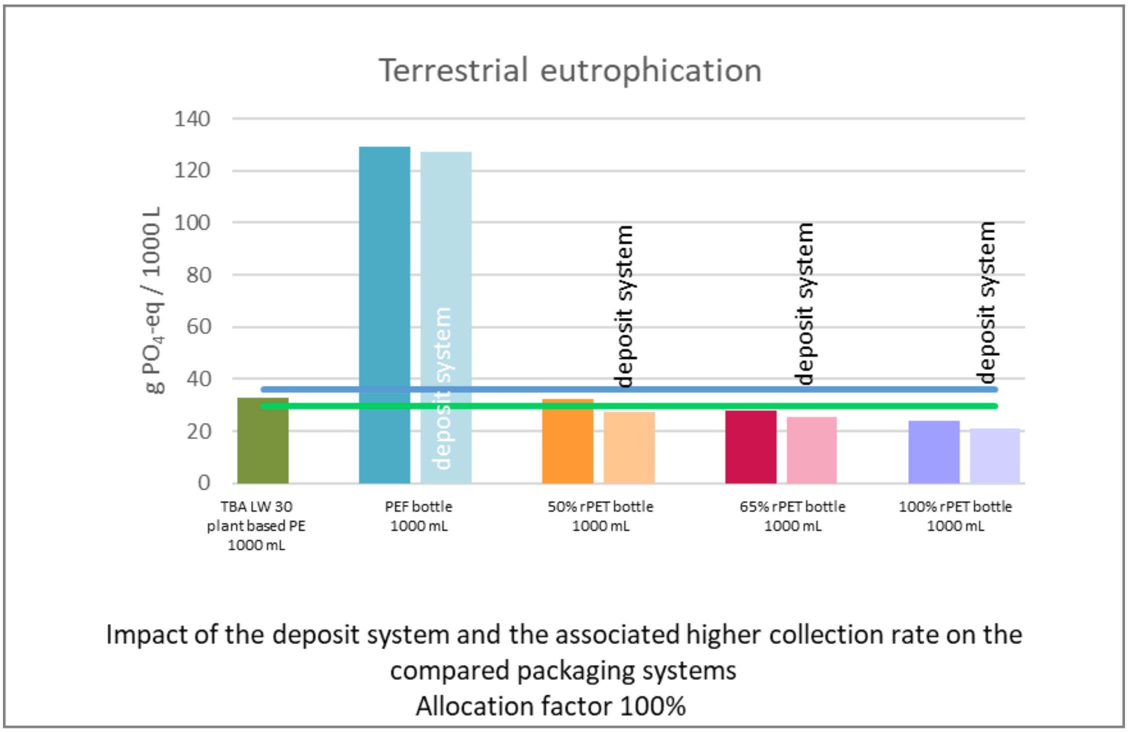


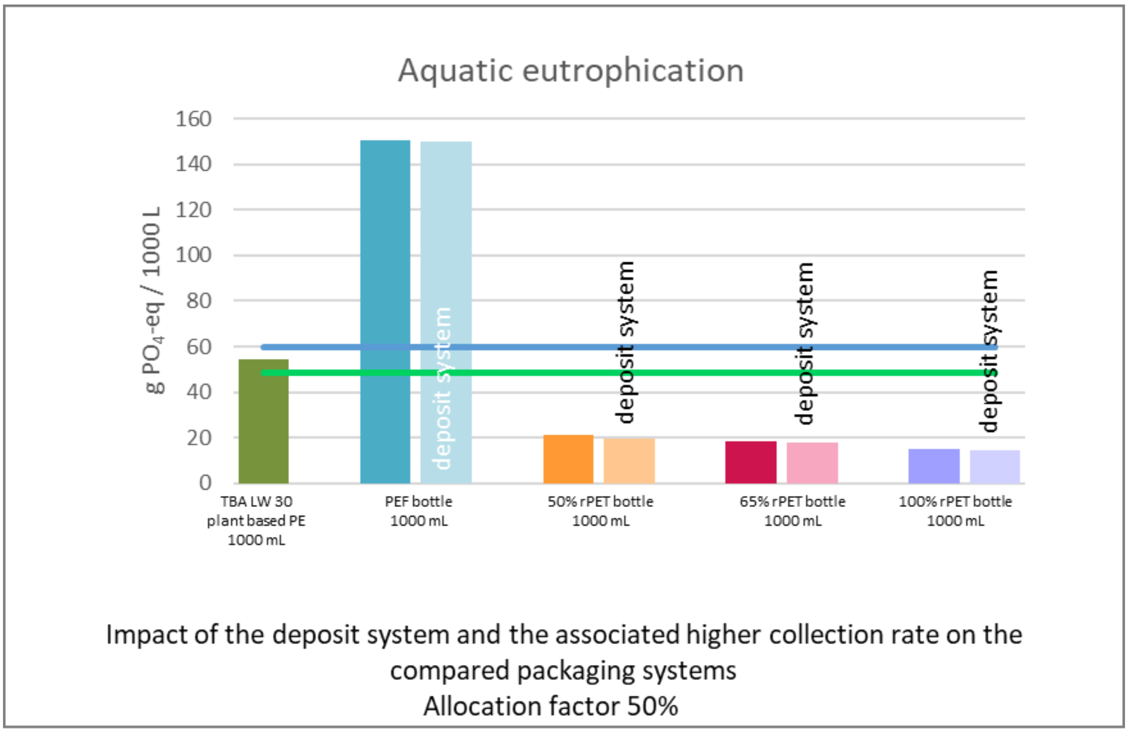
Figure 35: Tetra Brik® Aseptic 1000 Edge LightWing™ 30 with plant-based polymers: Terrestrial eutrophication results for collection rate sensitivity scenario, allocation factor 50% an 100%

In both scenarios (allocation factor 50% and 100%), the qualitative comparative results for 'Terrestrial eutrophication' between the beverage carton and the *PEF bottle* stay the same with increased collection rate from 77% to 83% (only deposit system).

In both scenarios (allocation factor 50% and 100%), the qualitative comparative results for 'Terrestrial eutrophication' between the beverage carton and the *50% rPET* change from insignificant differences to higher net results for the beverage carton with increased collection rate from 77% to 83% (only deposit system).

In both scenarios (allocation factor 50% and 100%), the qualitative comparative results for 'Terrestrial eutrophication' between the beverage carton and the *65% rPET* stay the same with increased collection rate from 77% to 83% (only deposit system).

In both scenarios (allocation factor 50% and 100%), the qualitative comparative results for 'Terrestrial eutrophication' between the beverage carton and the *100% rPET* stay the same with increased collection rate from 77% to 83% (only deposit system).



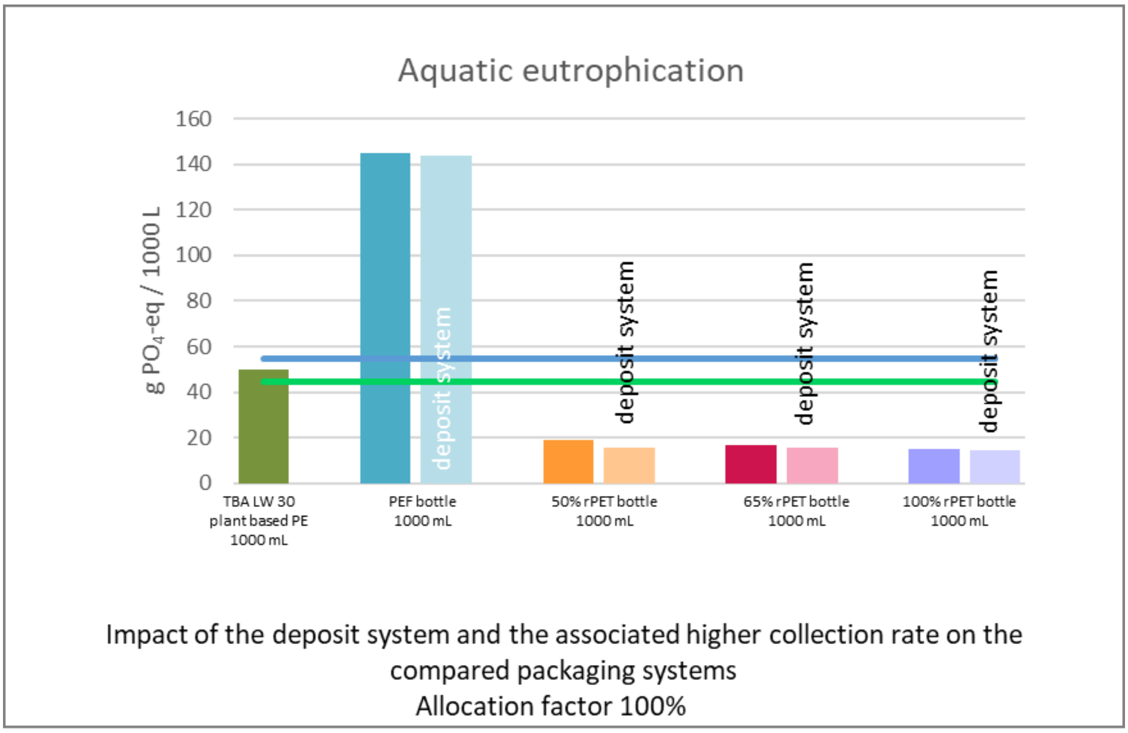


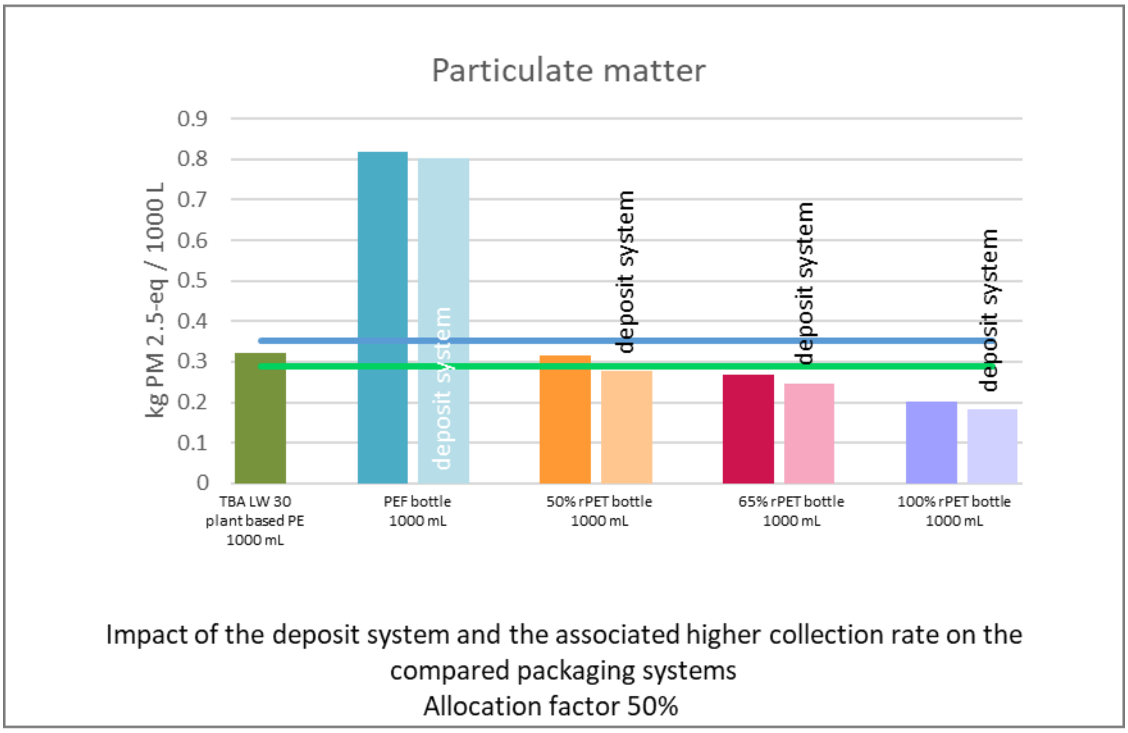
Figure 36: Tetra Brik® Aseptic 1000 Edge LightWing™ 30 with plant-based polymers: Aquatic eutrophication results for collection rate sensitivity scenario, allocation factor 50% an 100%

In both scenarios (allocation factor 50% and 100%), the qualitative comparative results for 'Aquatic eutrophication' between the beverage carton and the *PEF bottle* stay the same with increased collection rate from 77% to 83% (only deposit system).

In both scenarios (allocation factor 50% and 100%), the qualitative comparative results for 'Aquatic eutrophication' between the beverage carton and the *50% rPET* stay the same with increased collection rate from 77% to 83% (only deposit system).

In both scenarios (allocation factor 50% and 100%), the qualitative comparative results for 'Aquatic eutrophication' between the beverage carton and the *65% rPET* stay the same with increased collection rate from 77% to 83% (only deposit system).

In both scenarios (allocation factor 50% and 100%), the qualitative comparative results for 'Aquatic eutrophication' between the beverage carton and the *100% rPET* stay the same with increased collection rate from 77% to 83% (only deposit system).



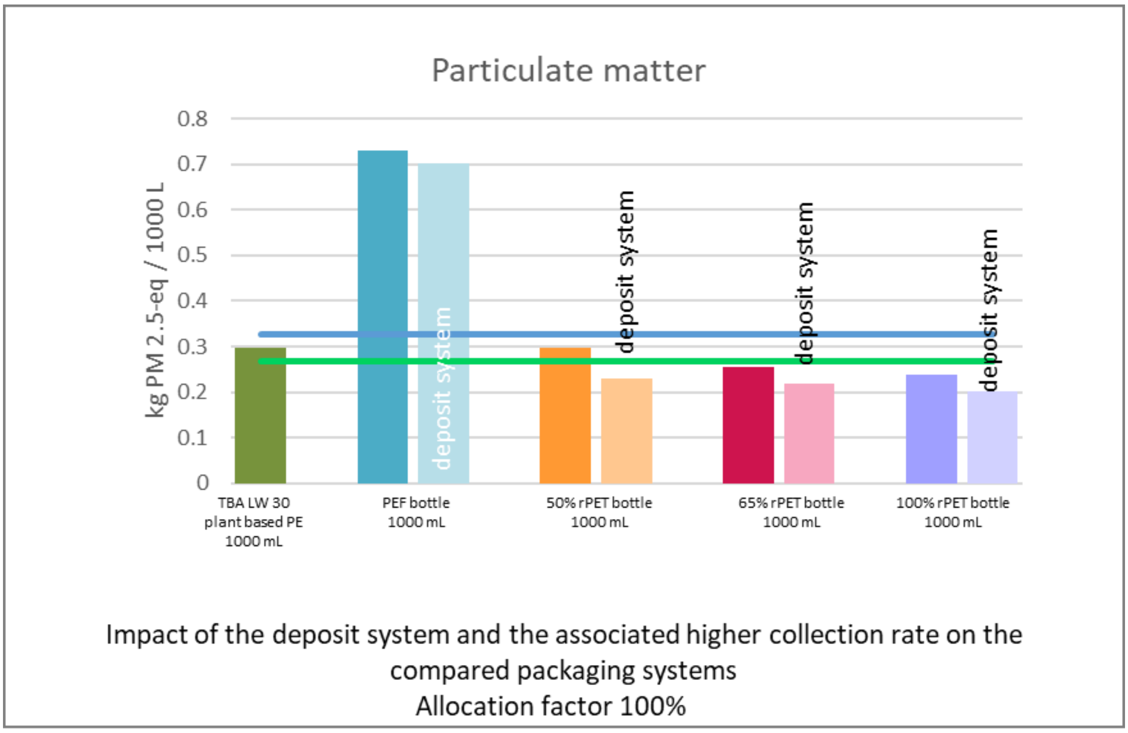


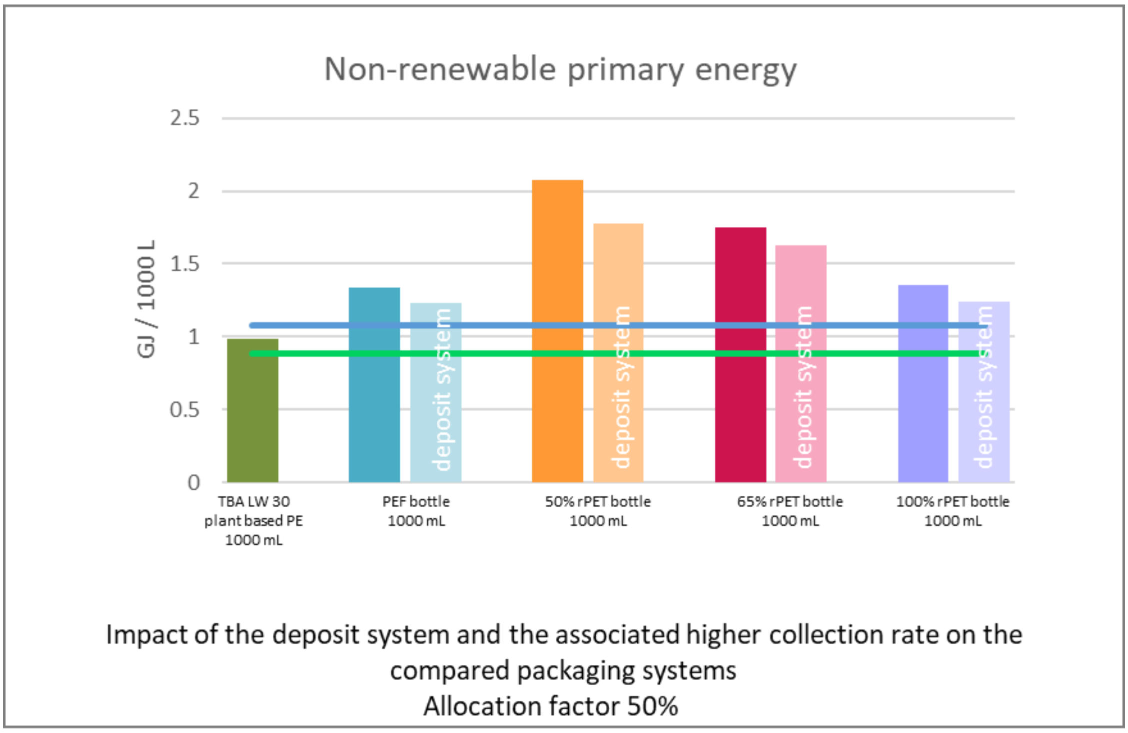
Figure 37: Tetra Brik® Aseptic 1000 Edge LightWing™ 30 with plant-based polymers: Particulate matter results for collection rate sensitivity scenario, allocation factor 50% an 100%

In both scenarios (allocation factor 50% and 100%), the qualitative comparative results for 'Particulate matter' between the beverage carton and the *PEF bottle* stay the same with increased collection rate from 77% to 83% (only deposit system).

In both scenarios (allocation factor 50% and 100%), the qualitative comparative results for 'Particulate matter' between the beverage carton and the *50% rPET* change from insignificant differences to higher net results for the beverage carton with increased collection rate from 77% to 83% (only deposit system).

In both scenarios (allocation factor 50% and 100%), the qualitative comparative results for 'Particulate matter' between the beverage carton and the *65% rPET* stay the same with increased collection rate from 77% to 83% (only deposit system).

In both scenarios (allocation factor 50% and 100%), the qualitative comparative results for 'Particulate matter' between the beverage carton and the *100% rPET* stay the same with increased collection rate from 77% to 83% (only deposit system).



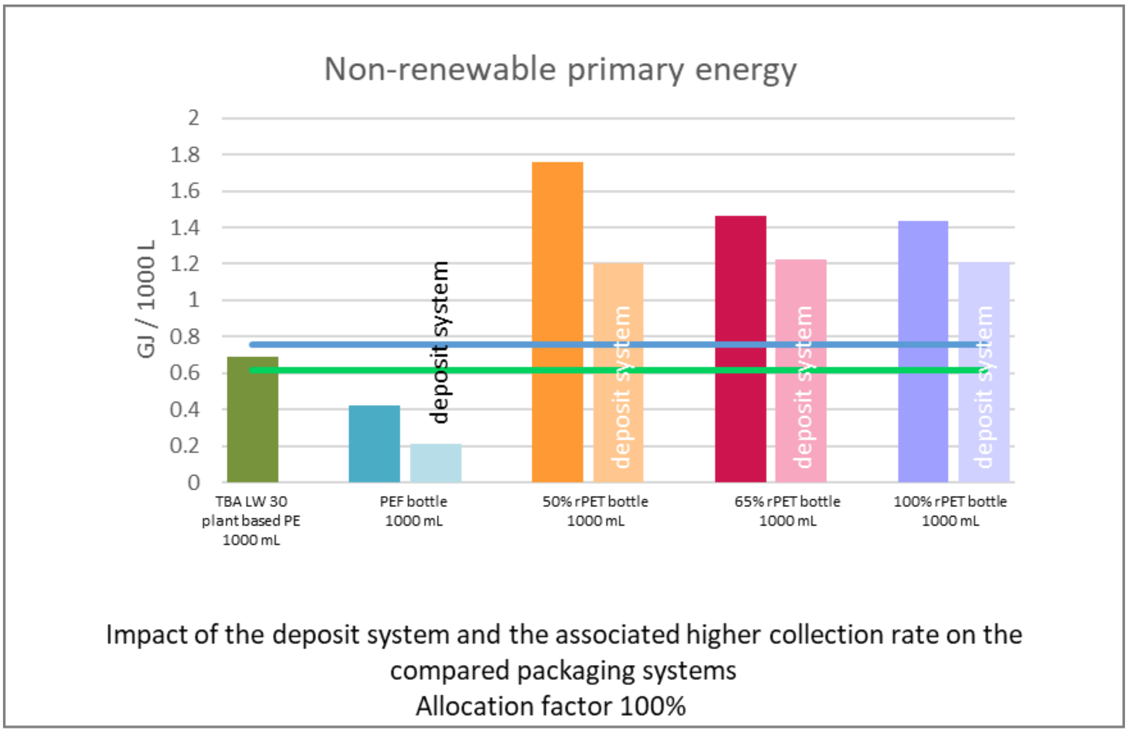


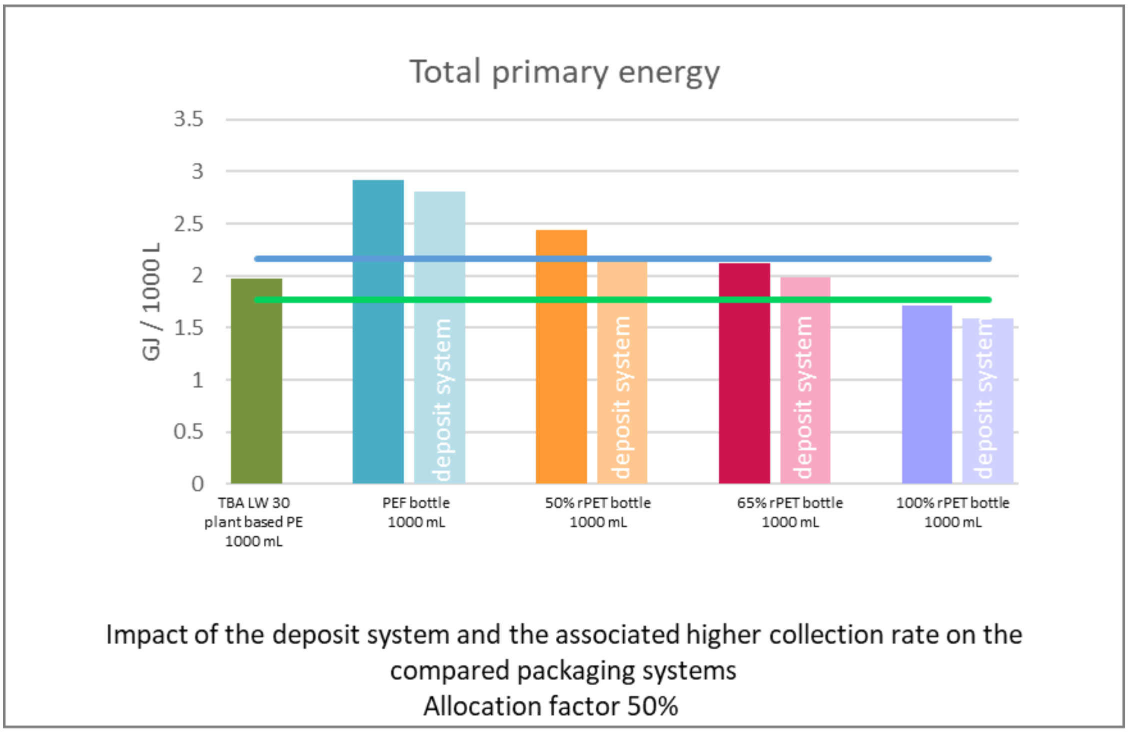
Figure 38: Tetra Brik® Aseptic 1000 Edge LightWing™ 30 with plant-based polymers: Non-renewable primary energy results for collection rate sensitivity scenario, allocation factor 50% an 100%

In both scenarios (allocation factor 50% and 100%), the qualitative comparative results for 'Non-renewable primary energy' between the beverage carton and the *PEF bottle* stay the same with increased collection rate from 77% to 83% (only deposit system).

In both scenarios (allocation factor 50% and 100%), the qualitative comparative results for 'Non-renewable primary energy' between the beverage carton and the *50% rPET* stay the same with increased collection rate from 77% to 83% (only deposit system).

In both scenarios (allocation factor 50% and 100%), the qualitative comparative results for 'Non-renewable primary energy' between the beverage carton and the *65% rPET* stay the same with increased collection rate from 77% to 83% (only deposit system).

In both scenarios (allocation factor 50% and 100%), the qualitative comparative results for 'Non-renewable primary energy' between the beverage carton and the *100% rPET* stay the same with increased collection rate from 77% to 83% (only deposit system).



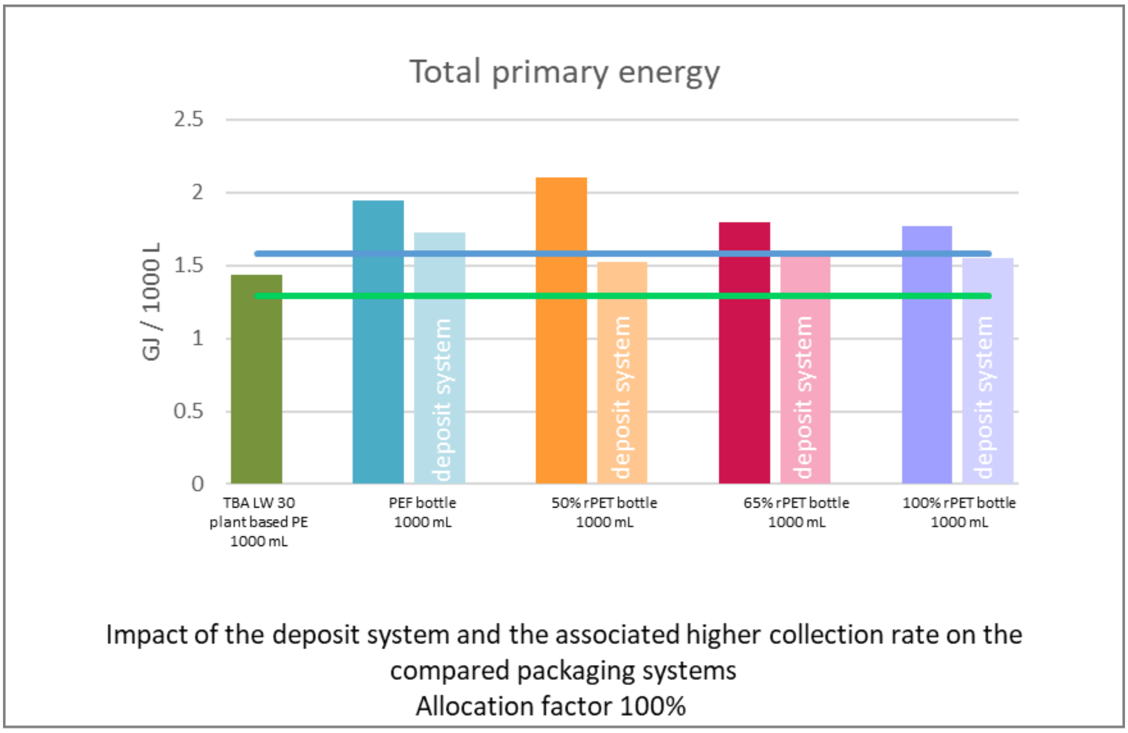


Figure 39: Tetra Brik® Aseptic 1000 Edge LightWing™ 30 with plant-based polymers: Total primary energy results for collection rate sensitivity scenario, allocation factor 50% an 100%

In both scenarios (allocation factor 50% and 100%), the qualitative comparative results for ‘Total primary energy’ between the beverage carton and the *PEF bottle* stay the same with increased collection rate from 77% to 83% (only deposit system).

In both scenarios (allocation factor 50% and 100%), the qualitative comparative results for ‘Total primary energy’ between the beverage carton and the *50% rPET* change from lower net results to insignificant differences with increased collection rate from 77% to 83% (only deposit system).

In the scenario allocation factor 50% the qualitative comparative results for 'Total primary energy' between the beverage carton and the *65% rPET* stay the same with increased collection rate from 77% to 83% (only deposit system).

In the scenario allocation factor 100% the qualitative comparative results for 'Total primary energy' between the beverage carton and the *65% rPET* change from lower net results to insignificant differences with increased collection rate from 77% to 83% (only deposit system).

In the scenario allocation factor 50% the qualitative comparative results for 'Total primary energy' between the beverage carton and the *100% rPET* stay the same with increased collection rate from 77% to 83% (only deposit system).

In the scenario allocation factor 100% the qualitative comparative results for 'Total primary energy' between the beverage carton and the *100% rPET* change from lower net results to insignificant differences with increased collection rate from 77% to 83% (only deposit system).

Table 22: Net results of collection rate sensitivity scenarios: burdens, credits and net results per FU of 1000 L, allocation factor 50% (All figures are rounded to two decimal places.)

NL allocation factor 50 %		TBA LW 30 plant based PE 1000 mL	PEF bottle 1000 mL	PEF bottle 1000 mL *deposit system*	50% rPET bottle 1000 mL	50% rPET bottle 1000 mL *deposit system*	65% rPET bottle 1000 mL	65% rPET bottle 1000 mL *deposit system*	100% rPET bottle 1000 mL	100% rPET bottle 1000 mL *deposit system*
Climate change [kg CO_2-equivalents]	burdens	89.84	136.20	136.54	134.13	136.10	118.97	116.11	98.62	89.16
	biogenic CO_2	23.98	24.58	24.58	1.29	1.29	1.29	1.29	1.29	1.29
	credits	-20.02	-45.15	-49.73	-16.25	-28.23	-16.24	-19.77	-16.23	-14.81
	CO_2 uptake	-54.24	-49.15	-49.15	-2.58	-2.58	-2.58	-2.58	-2.58	-2.58
	net results (∑)	**39.56**	**66.47**	**62.24**	**116.59**	**106.58**	**101.44**	**95.04**	**81.10**	**73.06**
Acidification [g SO_2-equivalents]	burdens	0.36	0.90	0.90	0.37	0.37	0.32	0.31	0.25	0.22
	credits	-0.04	-0.12	-0.14	-0.03	-0.07	-0.03	-0.04	-0.03	-0.03
	net results (∑)	**0.32**	**0.78**	**0.76**	**0.34**	**0.30**	**0.29**	**0.27**	**0.22**	**0.20**
Photochemical oxidant formation [g O_3-equivalents]	burdens	4.74	12.46	12.44	4.37	4.31	3.80	3.69	3.03	2.74
	credits	-0.56	-1.37	-1.54	-0.40	-0.81	-0.40	-0.54	-0.40	-0.37
	net results (∑)	**4.18**	**11.09**	**10.90**	**3.97**	**3.50**	**3.41**	**3.15**	**2.63**	**2.36**
Ozone depletion [g R-11-equivalents]	burdens	0.22	0.70	0.70	0.53	0.52	0.41	0.40	0.21	0.18
	credits	-0.02	-0.13	-0.15	-0.01	-0.06	-0.01	-0.03	-0.01	-0.01
	net results (∑)	**0.20**	**0.57**	**0.55**	**0.52**	**0.46**	**0.40**	**0.37**	**0.20**	**0.17**
Terrestrial eutrophication [g PO_4-equivalents]	burdens	38.86	143.54	143.39	35.82	35.42	31.23	30.38	23.91	21.95
	credits	-4.26	-8.63	-9.68	-2.50	-5.09	-2.50	-3.34	-2.50	-2.32
	net results (∑)	**34.60**	**134.90**	**133.72**	**33.32**	**30.33**	**28.73**	**27.04**	**21.41**	**19.63**
Aquatic eutrophication [g PO_4-equivalents]	burdens	59.25	157.03	157.19	23.26	23.26	20.72	20.66	17.20	16.50
	credits	-5.11	-6.49	-7.19	-2.11	-3.93	-2.11	-2.66	-2.11	-1.91
	net results (∑)	**54.14**	**150.53**	**150.00**	**21.15**	**19.33**	**18.60**	**18.00**	**15.09**	**14.59**
Particulate matter [g PM 2.5- equivalents]	burdens	0.36	0.93	0.93	0.34	0.34	0.29	0.29	0.23	0.21
	credits	-0.04	-0.11	-0.12	-0.03	-0.06	-0.03	-0.04	-0.03	-0.03
	net results (∑)	**0.32**	**0.82**	**0.80**	**0.31**	**0.28**	**0.27**	**0.25**	**0.20**	**0.18**
Non-renewable primary energy [GJ]	burdens	1.30	2.31	2.32	2.39	2.37	2.07	2.03	1.68	1.54
	credits	-0.32	-0.97	-1.08	-0.32	-0.60	-0.32	-0.41	-0.32	-0.30
	net results (∑)	**0.98**	**1.34**	**1.23**	**2.07**	**1.78**	**1.75**	**1.62**	**1.36**	**1.24**
Total primary energy [GJ]	burdens	2.54	3.95	3.96	2.79	2.77	2.46	2.43	2.06	1.92
	credits	-0.57	-1.03	-1.15	-0.35	-0.64	-0.35	-0.44	-0.35	-0.33
	net results (∑)	**1.97**	**2.91**	**2.81**	**2.45**	**2.14**	**2.12**	**1.98**	**1.71**	**1.59**

Table 23: Net results of collection rate sensitivity scenarios: burdens, credits and net results per FU of 1000 L, allocation factor 100% (All figures are rounded to two decimal places.)

NL allocation factor 100 %		TBA LW 30 plant based PE 1000 mL	PEF bottle 1000 mL	PEF bottle 1000 mL *deposit system*	50% rPET bottle 1000 mL	50% rPET bottle 1000 mL *deposit system*	65% rPET bottle 1000 mL	65% rPET bottle 1000 mL *deposit system*	100% rPET bottle 1000 mL	100% rPET bottle 1000 mL *deposit system*
Climate change [kg CO_2-equivalents]	burdens	107.71	148.52	149.42	156.09	163.04	142.06	137.77	136.01	118.44
	biogenic CO_2	47.96	49.15	49.15	2.58	2.58	2.58	2.58	2.58	2.58
	credits	-40.06	-90.36	-99.52	-32.56	-56.52	-32.55	-39.60	-32.52	-29.68
	CO_2 uptake	-54.24	-49.15	-49.15	-2.58	-2.58	-2.58	-2.58	-2.58	-2.58
	net results (∑)	**61.37**	**58.15**	**49.90**	**123.54**	**106.52**	**109.52**	**98.17**	**103.49**	**88.76**
Acidification [g SO_2-equivalents]	burdens	0.38	0.92	0.92	0.38	0.38	0.33	0.32	0.31	0.27
	credits	-0.08	-0.24	-0.27	-0.06	-0.14	-0.06	-0.08	-0.06	-0.05
	net results (∑)	**0.30**	**0.68**	**0.65**	**0.32**	**0.25**	**0.27**	**0.24**	**0.25**	**0.22**
Photochemical oxidant formation [g O_3-equivalents]	burdens	5.03	12.84	12.83	4.56	4.58	4.04	3.89	3.82	3.32
	credits	-1.11	-2.74	-3.08	-0.80	-1.63	-0.80	-1.07	-0.80	-0.75
	net results (∑)	**3.91**	**10.10**	**9.76**	**3.76**	**2.95**	**3.25**	**2.82**	**3.02**	**2.57**
Ozone depletion [g R-11-equivalents]	burdens	0.22	0.70	0.70	0.53	0.53	0.42	0.40	0.29	0.24
	credits	-0.04	-0.25	-0.29	-0.02	-0.12	-0.02	-0.06	-0.02	-0.02
	net results (∑)	**0.19**	**0.45**	**0.41**	**0.51**	**0.41**	**0.40**	**0.35**	**0.27**	**0.22**
Terrestrial eutrophication [g PO_4-equivalents]	burdens	41.25	146.60	146.59	37.45	37.63	33.13	32.09	29.17	25.88
	credits	-8.53	-17.27	-19.36	-5.01	-10.19	-5.01	-6.69	-5.01	-4.64
	net results (∑)	**32.72**	**129.32**	**127.22**	**32.44**	**27.44**	**28.11**	**25.40**	**24.16**	**21.24**
Aquatic eutrophication [g PO_4-equivalents]	burdens	59.96	157.67	157.95	23.31	23.59	20.93	20.81	19.54	18.14
	credits	-10.23	-12.99	-14.39	-4.23	-7.86	-4.23	-5.32	-4.23	-3.83
	net results (∑)	**49.74**	**144.68**	**143.56**	**19.08**	**15.73**	**16.70**	**15.49**	**15.31**	**14.31**
Particulate matter [g PM 2.5- equivalents]	burdens	0.38	0.95	0.95	0.35	0.35	0.31	0.30	0.29	0.25
	credits	-0.08	-0.22	-0.25	-0.05	-0.12	-0.05	-0.08	-0.05	-0.05
	net results (∑)	**0.30**	**0.73**	**0.70**	**0.30**	**0.23**	**0.25**	**0.22**	**0.24**	**0.20**
Non-renewable primary energy [GJ]	burdens	1.33	2.36	2.38	2.40	2.40	2.10	2.05	2.07	1.81
	credits	-0.64	-1.94	-2.17	-0.64	-1.19	-0.64	-0.82	-0.64	-0.60
	net results (∑)	**0.69**	**0.42**	**0.21**	**1.76**	**1.20**	**1.47**	**1.23**	**1.43**	**1.21**
Total primary energy [GJ]	burdens	2.57	4.01	4.03	2.80	2.81	2.50	2.44	2.47	2.20
	credits	-1.13	-2.07	-2.30	-0.70	-1.28	-0.70	-0.89	-0.70	-0.65
	net results (∑)	**1.43**	**1.94**	**1.73**	**2.10**	**1.53**	**1.80**	**1.56**	**1.77**	**1.55**

7 Conclusions

In this section, conclusions are drawn from the results presented and described in the previous sections, taking into account the limitations outlined in **section 8**. This means the results and conclusions are only valid for the regarded scenarios, for example. the application of most currently available electricity mixes. The conclusions consider the results of both respective sets of base results, meaning the results of the 50% allocation scenarios and the 100% allocation scenarios are taken into account to the same degree. A conclusion regarding lower or higher net results is only drawn if the same conclusion applies for allocation 50% and 100%. Results of the sensitivity analysis regarding recycled PET content and PET/PEF bottle collection rate with only deposit system are also considered.

The results are valid only for the exact packaging systems, which have been chosen by Tetra Pak taking into account the customers' preferences. Even though this selection is based on market data it does not represent the whole Dutch market.

The beverage carton systems analysed in this study show different environmental performances compared to the different competing packaging systems depending on their packaging specifications.

The following applies to the comparison of the beverage carton with the PEF bottle:

- The beverage carton shows **lower net results** compared to the PEF bottle considering the base scenarios and the collection rate sensitivity scenarios in the categories 'Ozone depletion', 'Photochemical oxidant formation', 'Particulate matter', 'Acidification', 'Terrestrial eutrophication', 'Aquatic eutrophication' and 'Total primary energy'.
- No conclusions regarding lower or higher net results can be drawn in the categories 'Climate change' and 'Non-renewable primary energy'.

The following applies to the comparison of the beverage carton with the 50% rPET bottle:

- The beverage carton shows **lower net results** compared to the 50% rPET bottle considering the base scenarios and the collection rate sensitivity scenarios in the categories 'Climate change' and 'Non-renewable primary energy'.
- The beverage carton shows **higher net results** compared to the 50% rPET bottle considering the base scenarios and the collection rate sensitivity scenarios in the category 'Aquatic eutrophication'.
- No conclusions regarding lower or higher net results a can be drawn in the categories 'Photochemical oxidant formation', 'Particulate matter', 'Acidification', 'Terrestrial eutrophication, and 'Total primary energy'.

The following applies to the comparison of the beverage carton with the 65% rPET bottle:

- The beverage carton shows **lower net results** compared to the 65% rPET bottle considering the base scenarios and the collection rate sensitivity scenarios in the categories 'Climate change' and 'Non-renewable primary energy'.

- The beverage carton shows **higher net results** compared to the 65% rPET bottle considering the base scenarios and the collection rate sensitivity scenarios in the categories ‘Photochemical oxidant formation’, ‘Terrestrial eutrophication’, 'Aquatic eutrophication' and ‘Particulate matter’.
- No conclusions regarding lower or higher net results a can be drawn in the categories ‘Acidification’ and ‘Total primary energy’.

The following applies to the comparison of the beverage carton with the 100% rPET bottle:

- The beverage carton shows **lower net results** compared to the 100% rPET bottle considering the collection rate sensitivity scenarios in the categories 'Climate change' and ‘Non-renewable primary energy’.
- The beverage carton shows **higher net results** compared to the 100% rPET bottle considering the collection rate sensitivity scenarios in the categories ‘Acidification’, ‘Photochemical oxidant formation’, ‘Terrestrial eutrophication’, 'Aquatic eutrophication' and ‘Particulate matter’.
- No conclusions regarding lower or higher net results a can be drawn in the category ‘Total primary energy’.

While the individual comparative results vary with the regarded categories it can be noted though that regarding ‘Climate change’ the beverage carton shows lower impacts than every respective rPET bottle scenario. The more renewable materials are used (either carton or plant-based polymers), the lower is the ‘Climate change’ impact of a pack assessed. On the other hand, the usage of plant-based polymers leads to higher impacts in categories like ‘Ozone depletion’, ‘Acidification’, ‘Aquatic eutrophication’ and ‘Terrestrial eutrophication’ mainly due to the field emissions of N_2O from the use of nitrogen fertilisers on agriculture fields. Bagasse combustion in case of plant-based PE and humin combustion in case of PEF contributes to categories like ‘Photochemical oxidant formation’ and ‘Particulate matter’. Humin combustion in case of PEF contributes additionally to ‘Terrestrial eutrophication’.

Compared to the PEF bottle in which PEF is a plant-based plastic the beverage carton shows insignificant differences regarding ‘Climate change’ as both materials benefit from they plant-based materials. Especially in case of allocation factor 100% the PEF bottle benefits from high material credits being treated like a PET bottle in the end of life. As the PEF bottle contains higher amounts of plant-based plastic based on agricultural sources than the beverage carton the PEF bottle shows higher impacts in categories like ‘Ozone depletion’, ‘Acidification’, ‘Aquatic eutrophication’ and ‘Terrestrial eutrophication’ resulting from field emissions and ‘Photochemical oxidant formation’ and ‘Particulate matter’ resulting from bagasse or humin combustion.

8 Limitations

The results of the base scenarios and analysed packaging systems and the respective comparisons between packaging systems are valid within the framework conditions described in sections 1 and 2. The following limitations must be taken into account however.

Limitations arising from the selection of **market segments**:
The results are valid only for the filled product in the specific segment. Even though carton packaging systems and assessed competing packaging systems are common in other market segments, other filling products create different requirements towards their packaging and thus certain characteristics may differ strongly, e.g. barrier functions.

Limitations concerning **selection of packaging systems:**
The results are valid only for the exact packaging systems, which have been chosen by Tetra Pak taking into account the customers' preferences. Even though this selection is based on market data it does not represent the whole Dutch market.

Limitations concerning **packaging system specifications:**
The results are valid only for the examined packaging systems as defined by the specific system parameters, since any alternation of the latter may potentially change the overall environmental profile.

The filling volume and weight of a certain type of packaging can vary considerably for all packaging types that were studied. The volume of each selected packaging system chosen for this study represents the predominant packaging size on the market. It is not possible to transfer the results of this study to packages with other filling volumes or weight specifications.

Each packaging system is defined by multiple system parameters, which may potentially alter the overall environmental profile. All packaging specifications of the carton packaging systems were provided by Tetra Pak® and are to represent the typical packaging systems used in the analysed market segment. These data have been cross-checked by ifeu.

To some extent, there may be a certain variation of design (i.e. specifications) within a specific packaging system. Packaging specifications different from the ones used in this study cannot be compared directly with the results of this study.

Limitations concerning the chosen **environmental impact potentials** and applied **assessment methods**:
The selection of the environmental categories applied in this study covers impact categories and assessment methods considered by the authors to be the most appropriate to assess the potential environmental impacts of the product system studied. It should be noted that the use of different impact assessment methods could lead to other results concerning the environmental ranking of packaging systems. The results are valid only for the specific characterisation model used for the step from inventory data to impact assessment.

Limitations concerning the analysed impact **categories**:
The results are valid only for the environmental impact categories, which were examined. They are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins or risks. This means that the potential damage caused by the substances is not taken into account. In this study, bio-sourced products were examined. It is important to note that these materials are often associated with specific

environmental impacts, particularly concerning land use and water use. However, these impacts were not analysed in the present study due to the limitations outlined in **section 1.5**.

Limitation concerning the **exclusion of impact categories**:

The environmental impact of plastic littering, particularly marine pollution, was not examined in this study. Although robust methodologies for quantifying these impacts in life cycle assessments are currently lacking, this issue remains a critical consideration for comprehensive environmental evaluations. Future research should aim to develop and incorporate standardized methods for assessing littering impacts to provide a more holistic understanding of the overall environmental performance of plastic products. Furthermore, this study did not assess the environmental impact of land use, abiotic resources and water scarcity. The assessment of these categories was omitted due to insufficiently reliable data or evaluation methods. However, since the potential impacts related to land use, resources, and water are highly relevant for the analysed product systems, their inclusion may be considered in the future as methods and data become available.

Limitations concerning **conventions**:
Conventions are required to take biogenic carbon into account in calculations. The results of the allocation factor 50% scenarios in this study are only valid for the conventions explained and justified in detail in **section 1.4.2.** They don't pose a relevant limitation for the 100% allocation factor scenarios and therefore also not for the conclusions of the study.

Limitations concerning **geographic boundaries**:
The results are valid only for the indicated geographic scope and cannot be assumed to be valid in geographic regions other than the Netherlands, even for the same packaging systems.

This applies particularly for the end-of-life settings as the mix of waste treatment routes (recycling and incineration) and specific technologies used within these routes may differ, e.g., in other countries.

Limitations concerning the **reference period**:
The results are valid only for the indicated time scope and the adequateness of the data chosen to the reference period and cannot be assumed to be valid for (the same) packaging systems at a different point in time. No future scenarios, for example regarding potential future electricity mixes have been considered.

Limitations concerning **allocation**:
The results are only valid for the applied allocation approaches in this study. Allocation approaches other than those used in this study can lead to different results.

Limitations concerning **data**:
The results are valid only for the data used and described in this report: To the knowledge of the authors, the data mentioned in **section 3** represents the best most appropriate data available for the purpose of this study. These data are based on figures provided by the commissioner, data and information from ifeu's internal database, and assumptions. However, it has to be noted that the age and quality of certain datasets, such as the electricity, PA6 and bio-PE, which play a relevant role on overall results, present some limitations on the representativeness of the data.

While the practical scope for addressing these limitations remains restricted, even small changes in the datasets stated above could affect the results and conclusions.

Limitations concerning **uncertainty**:

Data uncertainties of applied data sets are often unknown, therefore no quantitative uncertainty analysis was carried out, and a general significance threshold of 10% was applied (Detzel et al. 2016). For all packaging systems, the same methodological choices were applied concerning allocation rules, system boundaries and the calculation of environmental categories.

9 Recommendations

Based on the LCA results, the limitations listed in **section 8** and the methodological choices including the selection of impact categories the authors develop the following recommendations:

- Since the environmental results of the Tetra Pak beverage carton are significantly influenced by the production of its main component, the sleeve, measures to ensure the same functionality by using less material would be recommended.
- From an environmental viewpoint no general recommendation for one type of packaging can be given that is valid for all segments.
- Only if there is a strong focus on climate change mitigation, the beverage carton can be recommended over all regarded rPET bottles as the packaging of choice for the packaging of JNSD on the Dutch market. In any case the consequences for the environmental performance in other impact categories should never be disregarded completely.
- The use of PEF bottles carries the risk that, should the share of PEF bottles rise to such an extent that they constitute more than 5% of the total of PET and PEF bottles combined, they can no longer be recycled within the PET recycling infrastructure. If that happens, recycling credits will get lost and the net results of most impact categories including climate change of PEF bottles will likely become much higher. It is therefore recommended to bear this in mind when considering using PEF bottles on the Dutch market.
- It is recommended to the industries and related associations in general to provide more comprehensive process inventory data, especially for production processes to reduce the level of data asymmetries that could lead to misinterpreted results. This is required to allow recently developed methods such as assessment methods for water consumption and UseTox to be successfully applicable.

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Critical Review Statement according to ISO 14040 and 14044

of the study

Comparative Life Cycle Assessment of Tetra Pak® beverage carton with rPET and PEF bottles on the Dutch market

Conducted by
IFEU - Institut für Energie- und Umweltforschung Heidelberg gGmbH (the "Practitioner")

Performed for
Tetra Pak® (the "Commissioner")

by

Guido Sonnemann (chairman)
Meis Uijttewaal
Alex Hetherington

11/12/2025

1. Procedural Aspects of the Critical Review

This Critical Review (CR) was commissioned by Tetra Pak® (commissioner) via Magdalena Psuja, Sustainability Transformation Manager, and Maren Fuhrich, Marketing Manager, Tetra Pak B.V., The Netherlands, in August 2025. The Life Cycle Assessment (LCA) study was conducted by Samuel Mahami, Saskia Grünwasser, Andrea Drescher and Frank Wellenreuther from IFEU - Institut für Energie- und Umweltforschung Heidelberg gGmbH, Germany (practitioner). The review process included three rounds of commenting. In the last round this critical review statement was prepared since no further comments remained to be considered.

The first draft report was submitted on 29 October 2025. Initial comments by the Panel were discussed among the CR Panel members online on 11 November 2025. Afterwards the Panel chair sent to IFEU and Tetra Pak the first round of comments, which were discussed in a video-conference on 25 November 2025. During the conference call the comments were elaborated by the Panel members and discussed with the practitioner IFEU and the commissioner Tetra Pak in detail.

The review Panel received a second draft report of the study on 3 December 2025. The Panel sent further comments back on 5 December 2025, which were discussed with IFEU and Tetra Pak in a second video-conference on 8 December 2025. On 9 December 2025 IFEU delivered a revised final report with the consideration of the second-round comments. The modifications made were reviewed again by the Panel. The Panel accepted the replies to the remaining comments and this information together with a critical review statement was sent back to IFEU on 11 December 2025. IFEU and Tetra Pak agreed on the statement without further comments.

Formally this critical review is a review by “interested parties” (Panel method) according to ISO 14040 section 7.3.3 [2] and ISO 14044 section 4.2.3.7 and 6.3 [3] because the study includes comparative assertions of competing packaging systems and is intended to be disclosed to third parties. Despite this title, however, the inclusion of further representatives of "interested parties" is optional and was not explicitly intended in this study. The review panel is neutral with regard to and independent from any commercial interests of the commissioner. The Panel was not aware of issues relevant to other interested parties, as it was outside the scope of the present project to invite governmental or non-governmental organisations or other interested parties, e.g. competitors or consumers.

The reviewers emphasise the open and constructive atmosphere of the project. All requested data, including those referring to IFEU’s internal database and those confidential to Tetra Pak, were presented to the reviewers. Related issues of data quality were discussed openly. All comments of the Panel have been treated by the practitioner with sufficient detail in the final report. The resulting critical review statement represents the consensus between the reviewers.

The present CR statement is delivered to Tetra Pak. The CR Panel cannot be held responsible of the use of its work by any third party and not for a potential misuse in communication done by the commissioner itself. The conclusions of the CR Panel cover the full report from the study “Comparative Life Cycle Assessment of Tetra Pak® beverage carton with rPET and PEF bottles on the Dutch market” – Final report in the version of 9 December 2025 – and no other report, extract or publication which may eventually be undertaken. The CR Panel conclusions are given regarding the current state of the art and the information received. The conclusions expressed by the Panel are specific to the context and content of the present study only and shall not be generalised any further.

2. General Comments

Tetra Pak has recently finalised LCA studies for several packaging formats including plant-based polymers alternatives in several European markets. This study compares one beverage packaging format of Tetra Pak, PET bottles with recycled content (rPET) and bottles made of plant-based polyethylene furanoate (PEF) in the segment Juice, Nectars and Still Drinks (JNSD) Family Pack (ambient) on the Dutch market.

The review was performed according to ISO/TS 14071 (2014): Environmental management – Life cycle assessment - Critical review processes and reviewer competencies: Additional requirements and guidelines to ISO 14044 (2006). The goal of the review was:

- To validate the functional unit, reference flows and system boundaries as well as allocation and calculation rules chosen for the study,
- To oversee if the life cycle impact assessment indicators and additional environmental information used are appropriate for the product,
- To verify if data, literature sources and review quality are appropriate in relation to the goal of the study,
- To assess if the interpretations reflect the limitations identified and the goal of the study,
- To check the study with regard to transparency, and
- To analyse the overall consistency of the study and to evaluate if the LCA descriptions and analysis of improvement potentials are scientifically and technically valid.

The analysis and the verification of the software model used and the individual datasets are outside the scope of this review.

Based on the intensive review process, we have agreed with the commissioner and practitioner that we have a few specific comments that we will highlight in this statement.

3. Specific Comments

3.1 Consistency of the methods with ISO 14040 and 14044

As indicated before, in this study on beverage packaging format of Tetra Pak, PET bottles with recycled content (rPET) and bottles made of plant-based polyethylene furanoate (PEF) are examined in the segment JNSD Family Pack (ambient) on the Dutch market. All relevant packaging formats analysed have been selected by Tetra Pak. The main objectives of this study are:

(1) to compare the environmental performance of Tetra Pak's beverage carton system with rPET bottles on the Dutch market,
(2) to compare the environmental performance of Tetra Pak's beverage carton system with PEF bottles on the Dutch market, and
(3) to assess the impact of the deposit system and the associated higher collection rate on the compared packaging systems.

The functional unit is meaningfully defined for packaging of beverages and the system boundaries of the examined packaging systems are reasonably defined and presented transparently.

ISO 14040 and ISO 14044 include no obligation to consider any specific impact categories, but the choice of impact categories must be substantiated, meaningful and support the goal and scope of the study. The choice is reasonable against the backdrop of the goal, well explained and critically discussed.

In order to check the influence of the allocation method on the results, two base scenarios were examined (50:50 and 100:0) and discussed transparently and critically in the interpretation, taking into account the limitations of allocation in general. The two allocation methods examined were not referred to as the "base method" and "sensitivity analysis" to emphasise that no method is "truer" than another and, thus, is prioritised. The Panel welcomes the equal treatment of the two allocation methods examined, as this approach underlines that any choice of an allocation method can only be interpreted within the given framework. The practitioner has clearly specified that they prefer this approach to the Circular Footprint Formula proposed by the European Commission. The results obtained with the allocation methods are presented in a transparent manner.

3.2 Scientific and technical validity of the methods used

The methods used represent the scientific and technical state-of-the-art for such analyses. Three aspects are highlighted below:

The selection of the impact categories considered, and the characterisation models used in the study follow essentially the specifications in [UBA 2016], which are compatible with ISO 14040 (2006) and 14044 (2006). Due to methodological uncertainties of the currently available indicator models for mapping the impacts of resource consumption, the study does not cover land use and water use, which however are especially relevant for biobased products, but presents the total primary energy and non-renewable at inventory level, and the Panel accepts this choice by the practitioner.

The handling of biogenic carbon in product systems containing plant-based materials requires utmost attention to avoid misinterpretations:

- The study treats the CO_2 uptake due to photosynthesis during the growth phase of the plants as negative CO_2 value and if CO_2 is emitted at the end of the life cycle a positive value is assigned. This approach allows for more transparency than the general assumption that biogenic CO_2 is neutral – or not considered - during its life cycle.
- Particular difficulties of interpretation arise when biogenic CO_2 has to be allocated in a cradle-to-grave system considering open-loop-recycling. In the study, two equally applied allocation approaches are analysed: 50:50 allocation and 100:0 allocation. The preconditions and implications of both allocation methods are presented transparently and comprehensibly in a separate chapter. However, it should be mentioned here, that with a 50:50 allocation (open loop recycling) only half of the CO_2 uptake is released at the end of life, because the allocation factor is not applied for the CO_2 uptake. This is done, because the authors consider it as fair that the party that originally and consciously brings the renewable material to the market should get the benefit. As this is a subjective choice also the 100:0 allocation is included, in which this convention does not play a role.
- It is extremely important that the results of the Global Warming Potential (GWP) with consideration of plant-based materials are only communicated in the context of the methodological framework. In order to prevent misinterpretations, the Panel expressly points out that readers of the study shall carefully consider the respective statements of the study. The reviewers would like to explicitly point out that with the selected consideration of biogenic resources in the product in combination with incineration with energy recovery at the end of the life a negative net result can come out in the carbon footprint. Provided that sufficient biogenic material is used, it can fully compensate for the process related GHG emissions. This effect is even boosted with a 50:50 allocation and the consideration of CO_2 uptake. Whether this approach is suitable for comparing a product made from biogenic raw materials with a product made from fossil raw materials could not be conclusively assessed during the review process.

3.3 Appropriateness of data in relation to the goal of the study

As is normal practice for Critical Reviews, it was not possible to check the correctness of all items of primary and other data, and the whole background datasets belonging largely to IFEU's internal database, but the data used in the study were reviewed for appropriateness and plausibility. The use of the Umberto® 5.5 software facilitates an appropriate modelling of the systems investigated. The reviewers appreciate that an effort was made to evaluate the data quality with the Pedigree matrix approach and conclude that the data used are appropriate and reasonable in relation to the goal of the study.

3.4 Assessment of interpretation referring to limitations and goal of the study

The interpretation is integrated into the presentation of the results and their discussion, which is very useful for traceability due to the number of packaging systems examined. For each product examined, the Life Cycle Inventory and Life Cycle Impact Assessment results of the packaging systems considered are carefully and clearly evaluated with reference to the documented result data. This is done for both allocation procedures examined. However, no sensitivity analysis for different electricity mixes was included.

The conclusions, limitations and recommendations, which are respectively presented in separate chapters, are comprehensibly derived and transparently discussed based on the presented evaluation of the results without any over-interpretation. The Panel appreciates in particular the detailed discussion of the limitations in a separate chapter, which very clearly points out once again that the results of an LCA apply exclusively to the selected framework conditions and cannot be transferred from one framework to another. The impact assessment of plastics littering might for example be considered in the future once a method becomes available that addresses this issue in a robust way.

In order to avoid that LCA results are misinterpreted by the public, it is of central importance that a clear distinction is made between an environmental statement and the significance of a numerical value as a result of the application of a characterisation model in the LCA. The study addresses this aspect and thus integrates the greatest possible transparency.

The reviewers conclude that the interpretations reflect the limitations identified and the goal of the study.

3.5 Transparency and consistency of study report

The study is intended to be communicated to third parties. The report meets the requirements of ISO 14044 (clause 5.2) for third-party reports.

The study is transparently structured. Inconsistencies in the report could not be identified. The line of argument is transparent and comprehensible.

The reviewers conclude that the report is transparent and consistent.

4 Conclusion

To conclude we can state, that it is usually not easy to perform an LCA based on somehow limited industry data obtained from different sites and estimated data of the products compared, but as far as we can say, this study is well done. Thus, we can confirm that the LCA study is performed in a professional and scientifically sound way, compliant with ISO 14040 (2006): Environmental Management - Life Cycle Assessment - Principles and Framework and ISO 14044 (2006): Environmental Management - Life Cycle Assessment - Requirements and Guidelines.

References:

[ISO 14040] ISO 14040:2006. Environmental management - Life cycle assessment - Principles and framework

[ISO 14044] ISO 14044:2006. Environmental management - Life cycle assessment - Requirements and guidelines

[ISO 14067] ISO 14067:2018. Greenhouse gases — Carbon footprint of products — Requirements and guidelines for quantification

[Tetra Pak EU 2020] Comparative Life Cycle Assessment of Tetra Pak® carton packages and alternative packaging systems for beverages and liquid food on the European market – Final Report – 9th Mach 2020". Critical Review included

[UBA 2016] UBA (2016): Prüfung und Aktualisierung der Ökobilanzen für Getränkeverpackungen. 19/2016. UBA. S. 492.

Pessac, 11/12/2025	Delft, 11/12/2024	Long Hanborough, 11/12/2025
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