INSTITUT FÜR ENERGIE- UND UMWELTFORSCHUNG HEIDELBERG

Comparative Life Cycle Assessment of Tetra Pak's® Tetra Recart and alternative packaging systems for liquid food on the Dutch market

Final report

commissioned by Tetra Pak

Heidelberg, May 2024

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Saskia Grünwasser and Frank Wellenreuther

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Abbreviations

ACE	Alliance for Beverage Cartons and the Environment
CARB	California Air Resources Board
CED	Cumulative energy demand
CML	Centrum voor Milieukunde (Center of Environmental Science), Leiden University, Netherlands
COD	Chemical oxygen demand
CRD	Cumulative raw material demand
EA	European Aluminium
EAA	European Environment Agency
EU27+2	European Union & Switzerland and Norway
FEFCO	Fédération Européenne des Fabricants de Carton Ondulé (Brussels)
FSC	Forest Stewardship Council™
FU	Functional unit
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
LCA	Life cycle assessment
LCI	Life cycle inventory
LDPE	Low density polyethylene
LPB	Liquid packaging board
MIR	Maximum Incremental Reactivity
MSWI	Municipal solid waste incineration
NL	Netherlands
NMIR	Nitrogen-Maximum Incremental Reactivity
NO_X	Nitrogen oxides

PA6	Polyamid 6
pc	packs
PET	Polyethylene terephthalate
PP	Polypropylene
PU	Polyurethane
rPET	recycled PET
SBM	Stretch blow moulding
SUP	Stand-up pouch
TiO_2	Titanium dioxide
TRC	Tetra Recart
UBA	Umweltbundesamt (German Federal Environmental Agency)
VOC	Volatile organic compounds
WASF OE	Wrap around side flap open ends, corrugated cardboard
WMO	World Meteorological Organization

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 has recently finalised LCA studies for several packaging formats including plant-based alternatives in several European markets. In this study liquid food packaging formats of Tetra Pak and competing packaging systems on the Dutch market are examined. Tetra Pak's liquid food packaging formats 'Tetra Recarts' are similar to beverage cartons. One main difference of the Tetra Recarts examined in this study is that they do not provide closures.

The main objectives of this study are:

(1) to assess the environmental performance of Tetra Pak's liquid food carton system Tetra Recart (200 mL and 390 mL) on the Dutch market.
(2) to provide knowledge of the environmental impact of the recycling on the environmental performance of Tetra Recart (200 mL and 390 mL) on the Dutch market, by considering in the study a range of recycling rates (rather than solely the current recycling rate).
(3) to compare the environmental performance of Tetra Recart (200 mL and 390 mL) with those of competing packaging systems with high market relevance on the Dutch market.

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

The examined liquid food carton systems are:

- Tetra Recart Mini (200 mL)
- Tetra Recart Midi (390 mL)

To examine the impact different recycling rates have on the LCA results of these cartons, three different recycling rates are applied in this study

- 0% recycling rate as worst-case-model if it wouldn't be recycled at all.
- 58% recycling rate as actual recycling rate of (beverage) cartons in the Netherlands (Ifeu calculation of recycling rate is based on the collection rate (Tetra Pak (based on HEDRA) 2023), data for 2020).
- 70% recycling rate as future-goal-model for the carton industry for 2030 (ACE 2021).

Competing liquid food packaging systems on the Dutch market include:

- Stand up pouches (SUP)
- Glass jar
- Steel cans made of tinplate.

All analysed packaging systems belong to the following segment:

- 'Liquid Food Portion Pack (ambient)' with volume of 200 mL – 500 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 2023. It is being conducted by the Institute for Energy and Environmental Research Heidelberg GmbH (ifeu).

The members of the project panel are:

- **Tetra Pak**: Magdalena Psuja, Yicheng Li, Nazanin Moradi, Patrick VantHoff
- **ifeu**: Frank Wellenreuther, Saskia Grünwasser

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). 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 disclosed.

Although this present study is not a full LCA because it only focuses on Climate Change and no other environmental impact categories, it is intended to be consistent with the ISO standards on LCA (ISO 14040: 2006; ISO 14044: 2006) except of the choice of impact categories. 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), France
- Dr. Leigh Holloway, eco3 Design Ltd., UK
- Dr. Alex Hetherington, 3keel, UK

Additional to the critical review panel no other interested parties were part in the conduction of the study.

Functional unit

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

For all packaging systems no packaging type specific differences in shelf life can be observed. The shelf life of all packaging systems is longer than required for the usual consumption period.

The primary packages examined are technically equivalent regarding the mechanical protection of the packaged liquid food 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. liquid food carton and the transport packaging (corrugated cardboard trays and shrink wrap, pallets), which are necessary for the packaging, filling and delivery of 1000 L liquid food.

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 foil, 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.

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 by Reinout Heijungs (Heijungs 1992) and Rolf Frischknecht (Frischknecht et al. 2007): Capital goods should be included if the costs of maintenance and depreciation are a substantial part of the product and if environmental hot spots within the supply chain can be identified. 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 liquid food and transport to fillers as no relevant differences between the systems under examination are to be expected.
- Distribution of liquid food from the filler to the point-of-sale (distribution of packages is included) as the same amount of beverage and liquid food 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 liquid food 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 liquid food 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 and liquid food losses in households is available, these losses though cannot be allocated to the different beverage and liquid food packaging systems. Further, no data is available for losses at the point of sale. Therefore, possible beverage and liquid food loss differences are not quantifiable. In consequence, a sensitivity analysis regarding liquid food 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 liquid food 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.
- 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 liquid food carton (**Figure 1**), SUP (**Figure 2**), glass jar (**Figure 3**) and steel can (**Figure 4**). 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 liquid food, only single use packaging systems are included in this study.

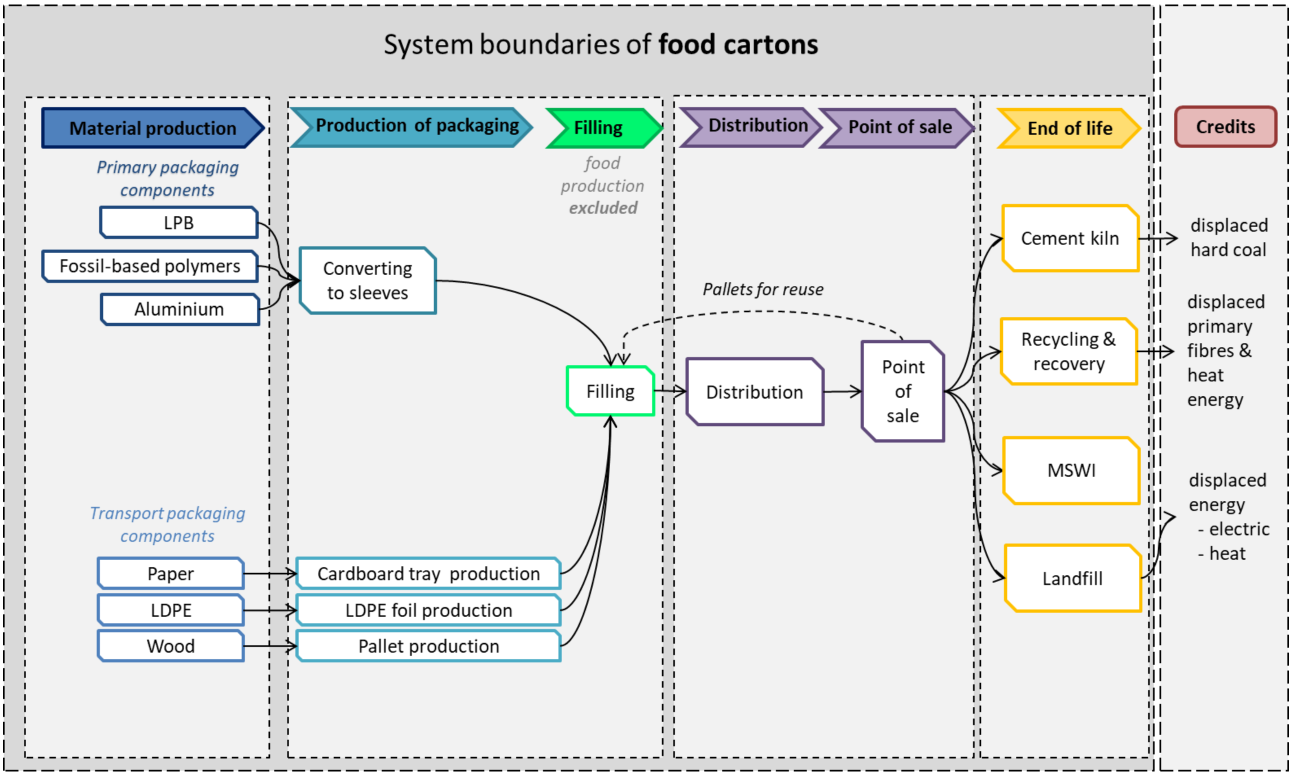

Figure 1: System boundaries of liquid food cartons

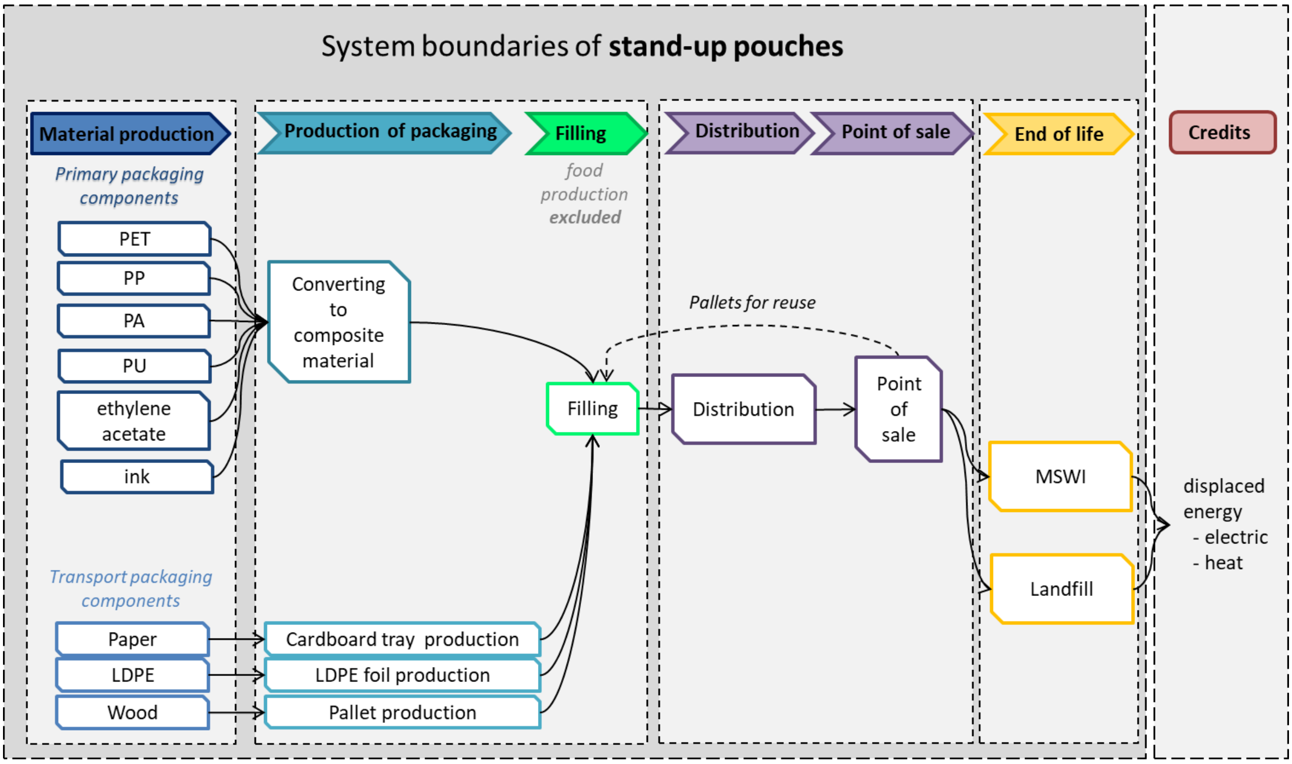

Figure 2: System boundaries of stand-up pouches

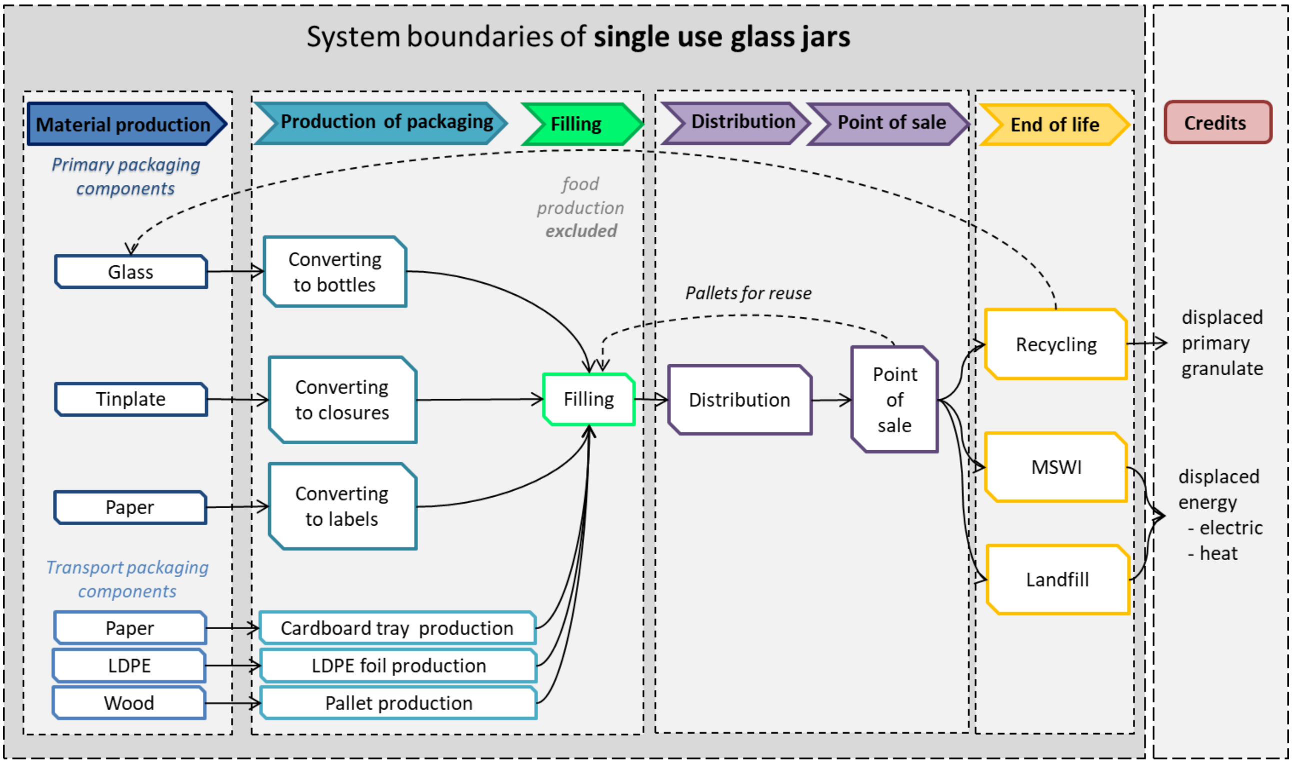

Figure 3: System boundaries of glass jars

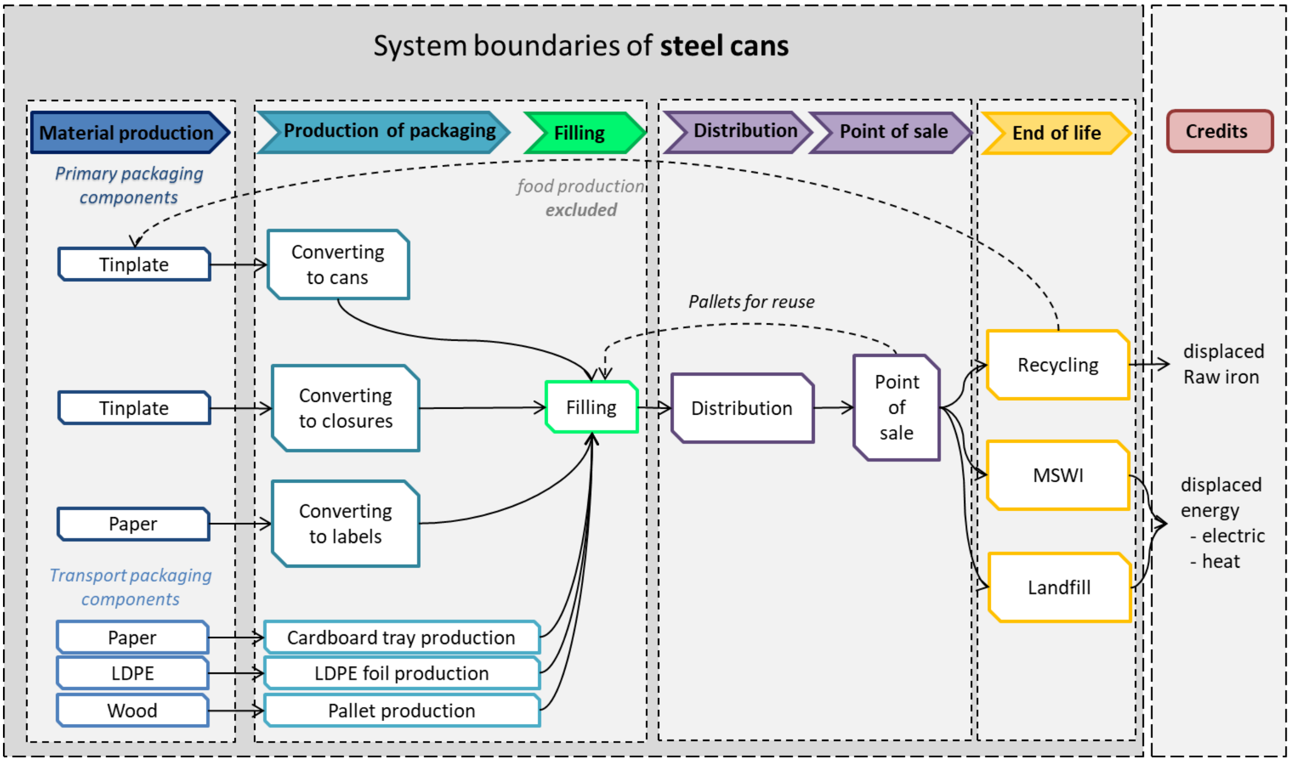

Figure 4: System boundaries of steel cans

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 liquid food cartons and labels of the cans and jars 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 liquid food 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 liquid food 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 liquid food 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.

In this study, ink is only considered for the pouch packaging systems (SUP 1, SUP 2). The ink of these pouches is more than 1% of the total mass of the packaging system. The solvent-based ink of pouches is considered based on the study of Sharma et al. (2021) with a thickness of 3.78 µm and area weight of 2.14 g/m^2.

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

In terms of the geographic scope, the LCA study focuses on the production, distribution and disposal of the packaging systems in the Netherlands. Country-specific data for the Netherlands is generated by using European process data as a proxy combined with the local electricity mixes. 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. In **Table 1** the geographic scope of the applied data is described.

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

Table 1: Geographic scope of applied process data and electricity prechains

		Liquid food cartons	SUP	Glass jar	Steel can
Materials	LPB	Sweden, Finland	-	-	-
	polymers	Europe[3]	Europe[3]	-	-
	aluminium	Europe[1]	-	-	-
	tinplate	-	-	Europe[4]	Europe
	glass	-	-	Netherlands / Germany[5]	-
Converting	bodies	Hungary / EU27+3[2]	Netherlands	Netherlands / Germany[5]	Netherlands
	closures	-	-	Netherlands / Germany[5]	Netherlands
End of Life		Netherlands / Germany	Netherlands	Netherlands	Netherlands

[1] EU27 + Norway, Switzerland, Iceland (EAA 2013), (EAA 2018). The applied dataset is only available as aggregated European dataset.
[2] EU27+3 process data combined with Hungarian electricity prechains.
[3] based on several plants in Europe (EcoInvent 3.10).
[4] based on several plants in Europe (worldsteel 2021).
[5] German process data combined with Dutch electricity prechains.

Time scope

The packaging specifications listed in **section 2** as well as the market situation for the choice of liquid food packaging systems refers to 2023. Therefore, the reference time for the study is 2023.

The applied data is as up-to-date as possible referring to the period between 2005 and 2020 (see **Table 12** in **section 3**). Exceptions are the data for steel can converting (1996) and PA6 (1999). In these 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 3.1.4**). If possible, always the most up to date pre-chains are used (for example electricity production for steel can 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

The study is designed as a 'cradle-to-grave' LCA and intended to be used in comparative assertions. To ensure that all the relevant data needed for the interpretation are available and complete, all life cycle steps of the packaging systems under study have been subjected to a plausibility and completeness check. The summary of the completeness check according to (ISO 14044: 2006) is presented in the following table:

Table 2: The summary of the completeness check according to (ISO 14044: 2006)

		Liquid food carton	SUP	steel can	Glass jar	Complete ?	Representative ?
Raw materials to consumer	Base material production	☑	☑	☑	☑	✔	✔
	Production of packaging (converting)	☑	☑	☑	☑	✔	✔
	Filling	☑	☑	☑	☑	✔	✔
	Distribution	☑	☑	☑	☑	✔	✔
	Transportation of materials to the single production steps	☑	☑	☑	☑	✔	✔
End of Life	Recycling processes	☑	☑	☑	☑	✔	✔
	MSWI	☑	☑	☑	☑	✔	✔
	Landfill	☑	☑	☑	☑	✔	✔
	Credits	☑	☑	☑	☑	✔	✔
Life Cycle Impact Assessment		☑	☑	☑	☑	✔	✔

☑ inventory data for all relevant processes available processes available

✔ Complete and representative data available

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 12** and described in **Section 3**.

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 can be considered a common practice for 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 liquid food 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 liquid food through all scenarios. Impacts related to transporting the liquid food itself would be the same in all scenarios. Thus, they don't need to be included in this comparative study of liquid food 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 5** illustrates the general allocation approach used for uncoupled systems and systems which are coupled through recycling. In **Figure 5** (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 5**. 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.

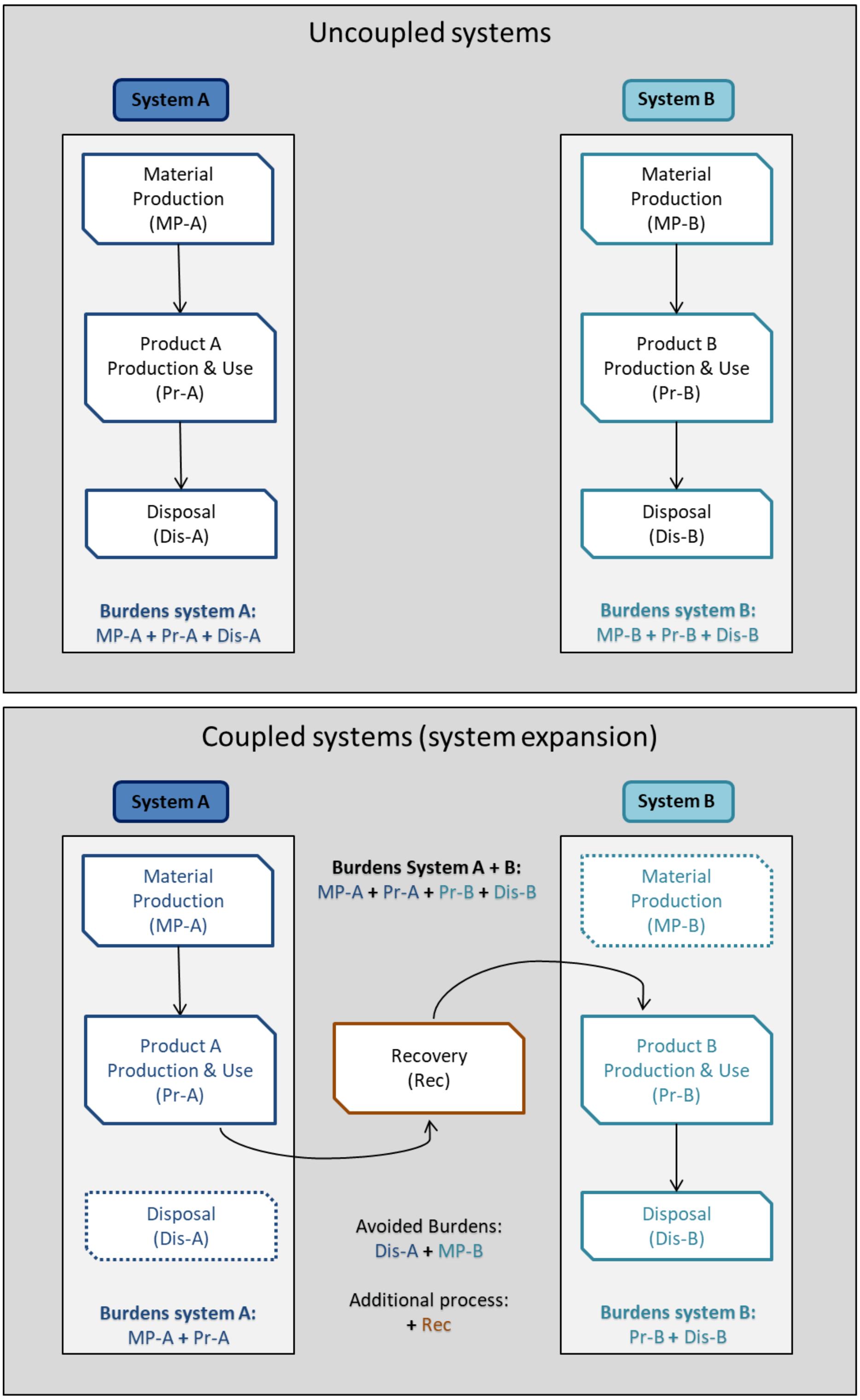

Figure 5: Additional system benefit/burden through recycling (schematic flow chart)[1]

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

[1] shaded boxes are avoided processes

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, 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 6** and **Figure 7**. 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.

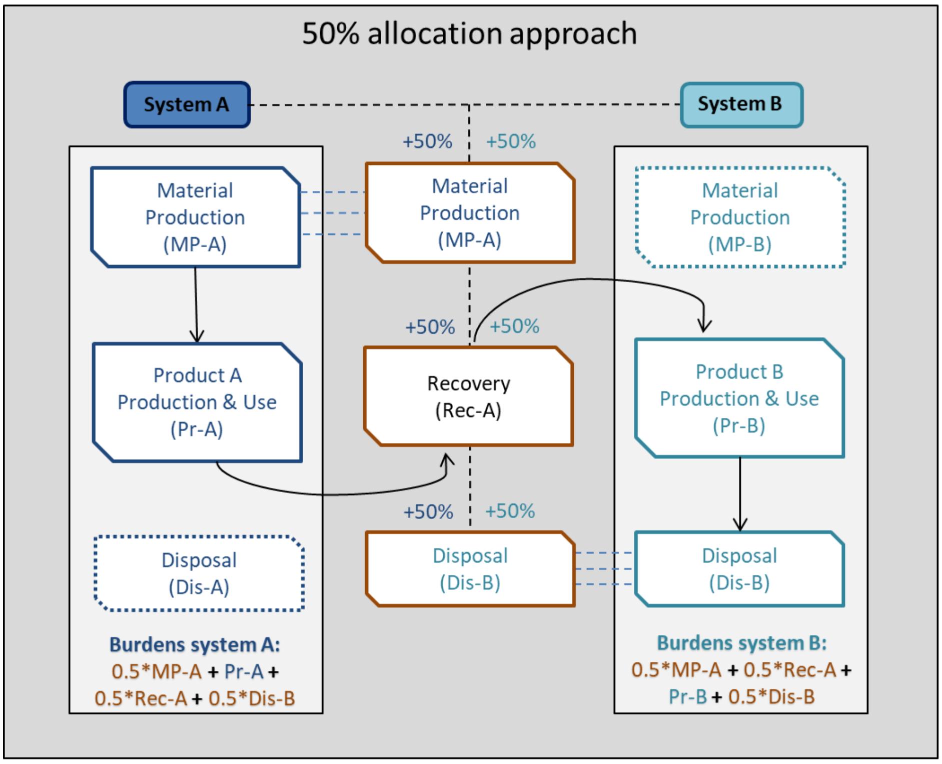

Figure 6: Principles of 50% allocation (schematic flow chart)[1]

Allocation with the 50% method (Figure 6)

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

[1] shaded boxes are avoided processes

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 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).

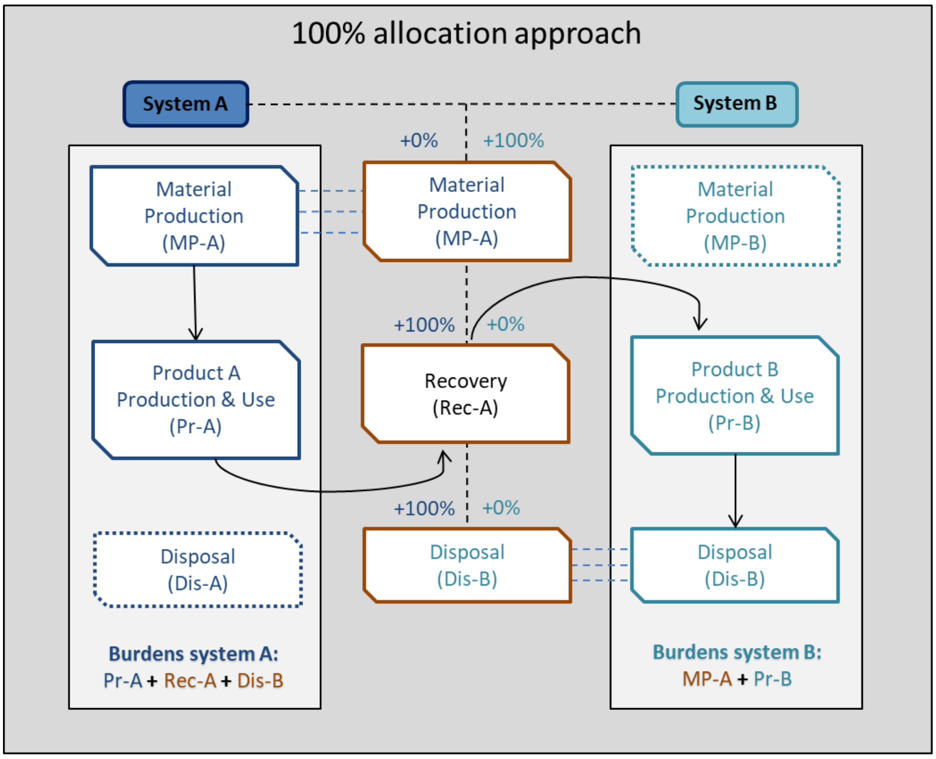

Figure 7: Principles of 100% allocation (schematic flow chart) [1]

Allocation with the 100% method (Figure 7)

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.

[1] shaded boxes are avoided processes

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 liquid food carton. It means that a comparatively unfavourable case for the liquid food cartons is chosen. For example, the steel can and the glass jar 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 steel cans and the glass jar.

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 5 to Figure 7

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 11**) 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 0.8 means that 1 kg of recycled (secondary) material replaces 0.8 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 expert judgments from German waste sorting operator "Der Grüne Punkt – Duales System Deutschland GmbH" from the year 2003 (DSD 2003). The substitution factor for PET from bottles has been raised to 1.0 since that date, as technical advancements made a bottle-to-bottle recycling process 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 recycled PET from PET bottles containing PA is reduced from 1 to 0.9. For the other substitution factors no newer data is available. The substitution factors apply to the secondary materials after the recycling processes with their production losses (see **section 3.12**).

- Paper fibres
  - from LPB (carton-based primary packaging): 0.9
  - in cardboard trays (secondary packaging): 0.9
- LDPE from foils: 0.94
- PET in bottles (bottle-to-bottle recycling): 1.0
- PET in bottles containing PA (bottle-to-bottle recycling): 0.9
- HDPE: 0.8
- Glass from bottles: 1
- Steel: 1 (substitution of raw iron)

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.

The carbon balance for the Tetra Recart 390 mL on the Dutch market is shown as an example in the following table.

Table 3: Carbon balance for Tetra Recart 390 mL, NL (per functional unit)

Biogenic carbon balance	CO_2 uptake	Carbon in CO_2 uptake	Carbon in biog. CO_2 and CH_4 emissions		Carbon sequestration in landfills	Carbon emissions and sequestration
Product systems	Tetra Recart Midi 390 mL *liquid food*	Tetra Recart Midi 390 mL *liquid food*	Tetra Recart Midi 390 mL *liquid food*	Subsequent system	Tetra Recart Midi 390 mL *liquid food*	Tetra Recart Midi 390 mL *liquid food* + Subsequent system
Allocation factor 50	**58.19 kg CO_2**	**15.87 kg C**	7.84 kg C	7.76 kg C	0.27 kg C	**15.87 kg C**
Allocation factor 100	**58.19 kg CO_2**	**15.87 kg C**	15.60 kg C	0.00 kg C	0.27 kg C	**15.87 kg C**

The difference between the emissions of Tetra Recart 390 mL and those of the following system when applying an allocation factor of 50% can be explained by the emissions from landfills as these are not affected by system allocation.

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 extra benefit for 'Climate Change' results, packaging systems with primary biogenic materials receive by only getting allocated 50% of the biogenic CO_2 emissions is gone.

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.

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.

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.

1.5.1 Impact categories

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).

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

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 the Acidification is kg SO_2-eq/FU.

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.

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 2015) is used as category indicator.

In reference to the functional unit, the unit for Ozone depletion is kg R-11-eq/FU.

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.

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 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

Human and Eco Toxicity (excl. Particulate Matter)

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 methods is clearly better than the others, although there is a slight preference for the consensus model USEtox. Based on comparisons among the different methods, the USEtox authors employ following residual errors (RE). The residual errors for the characterisation factors indicated in **Table 5**: are related to the square geometric standard deviation (GSD^2):

Table 5: Model uncertainty estimates for USEtox characterisation factors (reference: (Rosenbaum et al. 2008))

Characterisation factor	GSD^2
Human health, emission to rural air	77
Human health, emission to freshwater	215
Human health, emission to agricultural soil	2.189
Freshwater ecotoxicity, emission to rural air	176
Freshwater ecotoxicity, emission to freshwater	18
Freshwater ecotoxicity, emission to agricultural soil	103

To capture the 95% confidence interval, the mean value of each substance would have to be divided and multiplied by the GSD^2. (Sala et al. 2018) also concludes that the results for the impact categories human and eco toxicity are "not sufficiently robust to be included in external communications" before the robustness of the impact category was improved. Therefore, no assessment of human and eco toxicity is included in this study.

1.5.2 Additional categories at the inventory level

Inventory level categories differ from impact categories to the extent that no characterisation step using characterisation factors is used for assessment. The results of the categories at inventory level are presented and discussed in **section 4 and section 5** but are not intended to be used for comparison between systems and drawing of recommendations.

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 6: 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	hydro energy	biomass	wind energy	

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 on land use especially on different forest management types and ecoregions are not sufficient enough to apply 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 used for the following two reasons:

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

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

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 liquid food. 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 Selection of packaging systems

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

The choice of liquid food cartons has been made by Tetra Pak based on market relevance. Cartons of different volumes for the packaging of Liquid Food (ambient) have been chosen for examination. For this segment, typical competing packaging systems have been identified by Tetra Pak which represent the main competing packaging types in the Netherlands. The local marketing team of Tetra Pak has very detailed knowledge of the Dutch 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 segments. 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 systems are 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 Dutch market but aims to present comparative LCA environmental impact results for Tetra Pak's food cartons and their main competitors. Details regarding the chosen packaging systems and their reason for selection are shown in **Table 7**. On the liquid food market segment, plastic bottles are not considered as relevant packaging systems and are therefore not included in this study.

Table 7: Selection and reason of competing packaging systems

Segment	Geographic scope	Competing packaging system	Reason for selection
Liquid food Portion Pack (ambient)	NL	SUP 1 225 mL	The competitive packaging format constitutes a growing market share. The brand chosen is a representative mainstream brand in the long shelf-life food segment (ambient) in the Netherlands.
		SUP 2 500 mL	The competitive packaging format constitutes a growing market share. The brand chosen is a representative mainstream brand in the long shelf-life food segment (ambient) in the Netherlands.
		glass jar 1 350 mL	The common and competitive packaging format constitutes a significant market share. The brand chosen is neither premium nor low-cost (mid-market position) in the long shelf-life food segment (ambient) in the Netherlands.
		steel can 1 200 mL	A common and competitive packaging format. The brand chosen is neither premium nor low-cost (mid-market position) in the long shelf-life food segment (ambient) in the Netherlands.
		steel can 2 400 mL	A common and competitive packaging format. The brand chosen is neither premium nor low-cost (mid-market position) in the long shelf-life food segment (ambient) in the Netherlands.

The following table shows which liquid food cartons are compared with the selected competing systems. Similar volume sizes will be compared as listed in **Table 8**: 200-225 mL and 350-500 mL.

Table 8: List of Tetra Pak liquid food cartons in segment **Liquid food, Portion Pack (ambient)** and corresponding competing packaging systems

Carton based packaging systems (0%, 58%, 70% recycling rate)	ambient	Reference flow (systems / 1000 L)	Geographic scope	Competing packaging systems	ambient	Reference flow (systems / 1000 L)	Geographic scope
Tetra Recart (TRC) Mini 200 mL		5.000	NL	SUP 1 225 mL		4.444	NL
				steel can 1 200 mL		5.000	NL
Tetra Recart (TRC) Midi 390 mL		2.564	NL	SUP 2 500 mL		2.000	NL
				glass jar 1 350 mL		2.857	NL
				steel can 2 400 mL		2.500	NL

2.2 Packaging specifications

Specifications of liquid food carton packaging systems are listed in **Table 9** and 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 liquid food 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 liquid food 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 liquid food cartons, no materials with recycled content are used.

Data on secondary and tertiary packaging for liquid food 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 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 determined by ifeu in 2023 based on samples collected by Tetra Pak on the Dutch market. For steel cans and the glass jar, samples were assessed by ifeu regarding the type of materials and their quantified weights. Specifications were determined by weighting the separate parts of the packaging systems. Materials were classified by the declaration on the packaging parts. Specifications of pouches are based on laboratory analyses by Tetra Pak. Specifications of secondary packaging systems were determined by ifeu with the assumed surface of the secondary packaging based on similar packaging systems analysed in previous studies and the average weight per area for LDPE film and cardboard.

In case of primary packaging of glass packaging (white glass), recycled content (external cullet rate) of 69.5% (BVGlas 2012) is applied. In case of steel cans, recycled content (scrap input) of 7% (worldsteel 2021) is applied. The aluminium foil in the liquid food carton is too thin to be produced as recycled foil currently. Apart from bottle PET, closed-loop material recycling in food contact materials (FCM) is currently not possible for other plastics due to food safety regulations, technical questions and the small closed-loop recycling percentage of food packaging (De Tandt et al. 2021). Therefore, also for multilayer foils for pouches, no recycled content is applied.

Pallet configuration of competing packaging systems was calculated with the online tool *www.onpallet.com.* Euro pallets with a loading height of 1400mm are the base for the calculation. The weight of shrink foil per pallets is assumed to be the same as for pallets with liquid food cartons. Pallet configuration depends on the size of the bottles as well as the amount and arrangement of bottles in each secondary packaging.

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

2.2.1 Specifications of beverage and liquid food carton systems

Table 9: Packaging specifications for assessed carton systems for the packaging of **Liquid Food, Portion Pack (ambient)**

Food Portion Pack (ambient)

Specification	Unit	Packaging system	
		TRC Mini	TRC Midi
volume	mL	200	390
geographic Scope	-	NL	NL
ambient	-		
primary packaging (sum)[1]	**g**	**11.1**	**17.7**
primary packaging (per FU)	**g/FU**	**55500**	**45385**
composite material (sleeve)	g	11.1	17.7
- liquid packaging board	g	7.6	12.6
- fossil-based polymer	g	3.0	4.3
- virgin aluminium	g	0.5	0.8
secondary packaging (sum)[2]	**g**	**82.0**	**115.0**
- corr. cardboard WASF OE (wrap around side flap open ends)	g	82.0	115.0
tertiary packaging (sum)[3]	**g**	**26025.0**	**26025.0**
- pallet	g	25000.0	25000.0
number of use cycles	-	25	25
- cardboard layer (per pallet)	g	350.0	350.0
- number of cardboard layers	-	1	1
- stretch foil (per pallet) (LDPE)	g	675.0	675.0
pallet configuration			
Prim. packaging per sec. packaging	pc	16	16
sec. packaging per layer	pc	18	12
layers per pallet	pc	11	10
prim. packaging per pallet	pc	3168	1920

[1] per primary packaging unit
[2] per secondary packaging unit
[3] per tertiary packaging unit (pallet)

2.2.2 Specifications of alternative packaging systems

Table 10: Packaging specifications for assessed alternative systems in the segment **Liquid Food, Portion Pack (ambient)**

Liquid Food Portion Pack (ambient)						
Specification	**Unit**	**Packaging system**				
		SUP 1	**SUP 2**	**Glass jar 1**	**Steel can 1**	**Steel can 2**
volume	mL	225	500	350	200	400
geographic Scope	-	NL	NL	NL	NL	NL
clear / opaque	-	opaque	opaque	clear	-	-
ambient	-					
primary packaging (sum)[1]	g	**6.89**	**10.29**	**184.59**	**33.09**	**50.06**
primary packaging (per FU)	g/FU	**30622**	**20580**	**527400**	**165450**	**125150**
SUP, jar, can	g	6.89	10.29	172.41	26.88	41.60
- PET	g	1.06	3.10	-	-	-
- LDPE	g	4.16	4.81	-	-	-
- PA	g	1.08	1.30	-	-	-
- PU	g	0.32	0.64	-	-	-
- ethyl acetate	g	0.14	0.28	-	-	-
- print/ink	g	0.13	0.16	-	-	-
- glass	g	-	-	172.41	-	-
- tinplate	g	-	-	-	26.88	41.60
label	g	-	-	0.75	1.15	2.06
- paper	g	-	-	0.75	1.15	2.06
closure	g	-	-	11.43	5.06	6.40
- tinplate	g	-	-	11.43	5.06	6.40
secondary packaging (sum)[2]	g	**197.40**	**188.57**	**85.05**	**21.61**	**38.65**
- stretch foil per tray	g	-	-	-	3.67	7.83
- tray/box (corr.cardboard)	g	197.40	188.57	85.05	17.94	30.82
tertiary packaging (sum)[3]	g	**26025**	**26025**	**26025**	**26025**	**26025**
- pallet	g	25000	25000	25000	25000	25000
number of use cycles	-	25	25	25	25	25
- cardboard layer (per pallet)	g	350	350	350	350	350
- number of cardboard layers	-	1	1	1	1	1
- stretch foil (per pallet) (LDPE)	g	675	675	675	675	675
pallet configuration						
prim. packaging per sec. packaging	pc	16	12	6	3	6
sec. packaging per layer	pc	10	11	21	62	26
layers per pallet	pc	7	7	13	18	12
prim. packaging per pallet	pc	1120	924	1638	3348	1872

2.3 End-of-life

For each packaging system assessed in the study, the scenarios are modelled and calculated with average recycling rates for post-consumer packaging on the Dutch market. The applied recycling quotas are based on published quotas. The material recycling quotas represent the actual amount of material undergoing a material recycling process after sorting took place. The remaining part of the post-consumer packaging waste is modelled and calculated according to the average split between landfilling and incineration (MSWI) in the Netherlands. The applied end-of-life quotas and the related references are given in **Table 11**. Preferable local data sources are applied if possible.

Table 11: Applied end of life quotas for beverage and liquid food cartons and competing packaging systems in the Netherlands:

Geographical scope	Packaging system	EOL quota, source and reference year	Material recycling/recovery	MSWI	Landfill
NL		MSWI / landfill split		96.8%	3.2%
		source		(eurostat 2023)	
		reference year		2021	
	Liquid food carton	quota	57.6%	41.0%	1.4%
		source	(Tetra Pak (based on HEDRA) 2023)	(Tetra Pak (based on HEDRA) 2023), (eurostat 2023)	
		reference year	2022	2022, 2021	
	SUP[1]	quota	0%	96.8%	3.2%
		source	(Niaounakis 2019; Walker et al. 2020)	(eurostat 2023)	
		reference year	2019	2021	
	Glass jar[2]	quota	88.1%	11.5%	0.4%
		source	(afvalfonds verpakkingen 2022), (ifeu, 2023)	(afvalfonds verpakkingen 2022), (eurostat 2023)	
		reference year	2021, 2023	2021, 2021	
	Steel can[3]	quota	91.2%	8.5%	0.3%
		source	(afvalfonds verpakkingen 2022), (ifeu, 2023)	(afvalfonds verpakkingen 2022), (eurostat 2023)	
		reference year	2021, 2023	2021, 2021	

[1] multilayer pouches are not materially recycled (see section 3.12).
[2] recycling quota for all glass packaging (see section 3.12)
[3] recycling quota for all steel packaging (see section 3.12)

The following flow charts illustrate the applied specified end-of-life models for the Netherlands of liquid food carton, SUP, glass jar, and steel can. The percentages going into the recycling path as well going into MSWI and landfill from disposal in each flowchart corresponds to the material recycling quotas in Table 11. For the sorting process typical efficiencies from the internal ifeu database and insights of Tetra Pak are applied (liquid food cartons 90%, glass jars 99%, steel cans 96%).

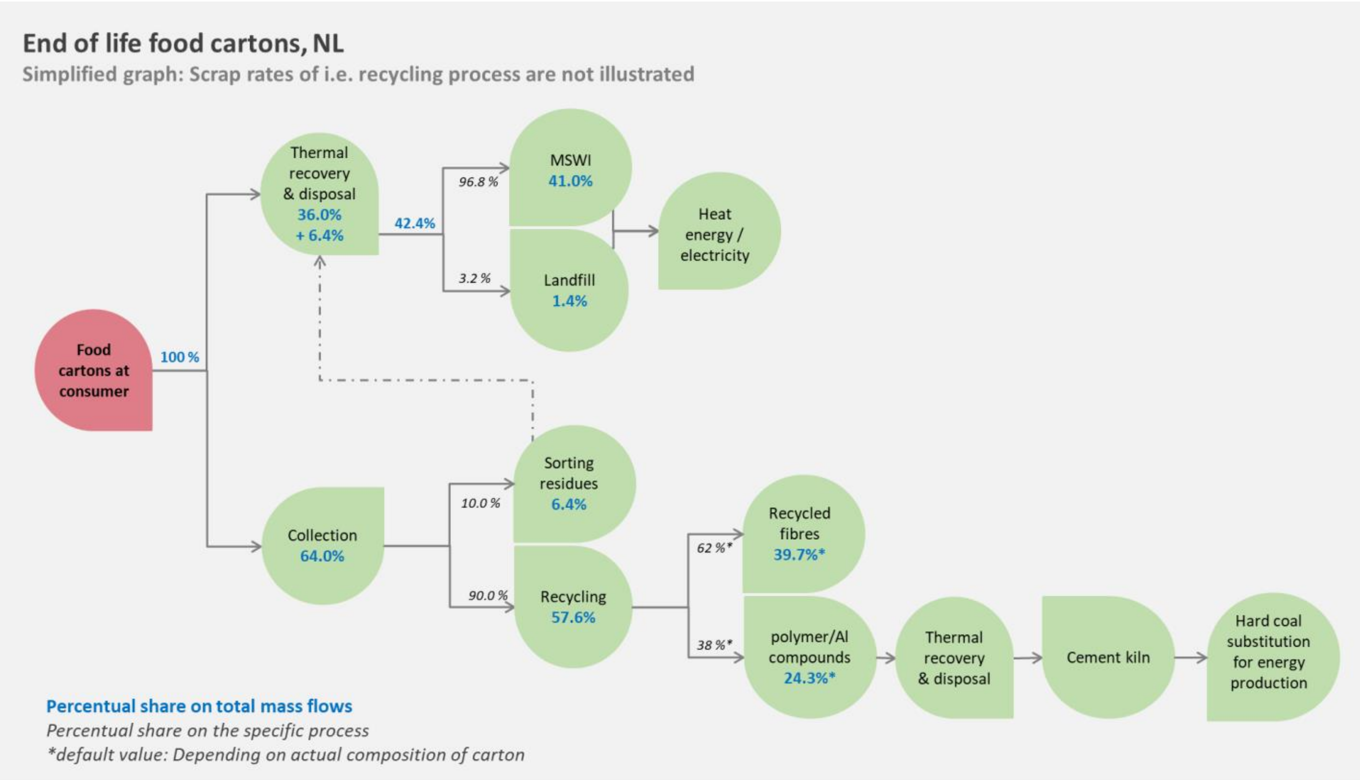

Figure 8: Applied end-of-life quotas for liquid food cartons in the Netherlands

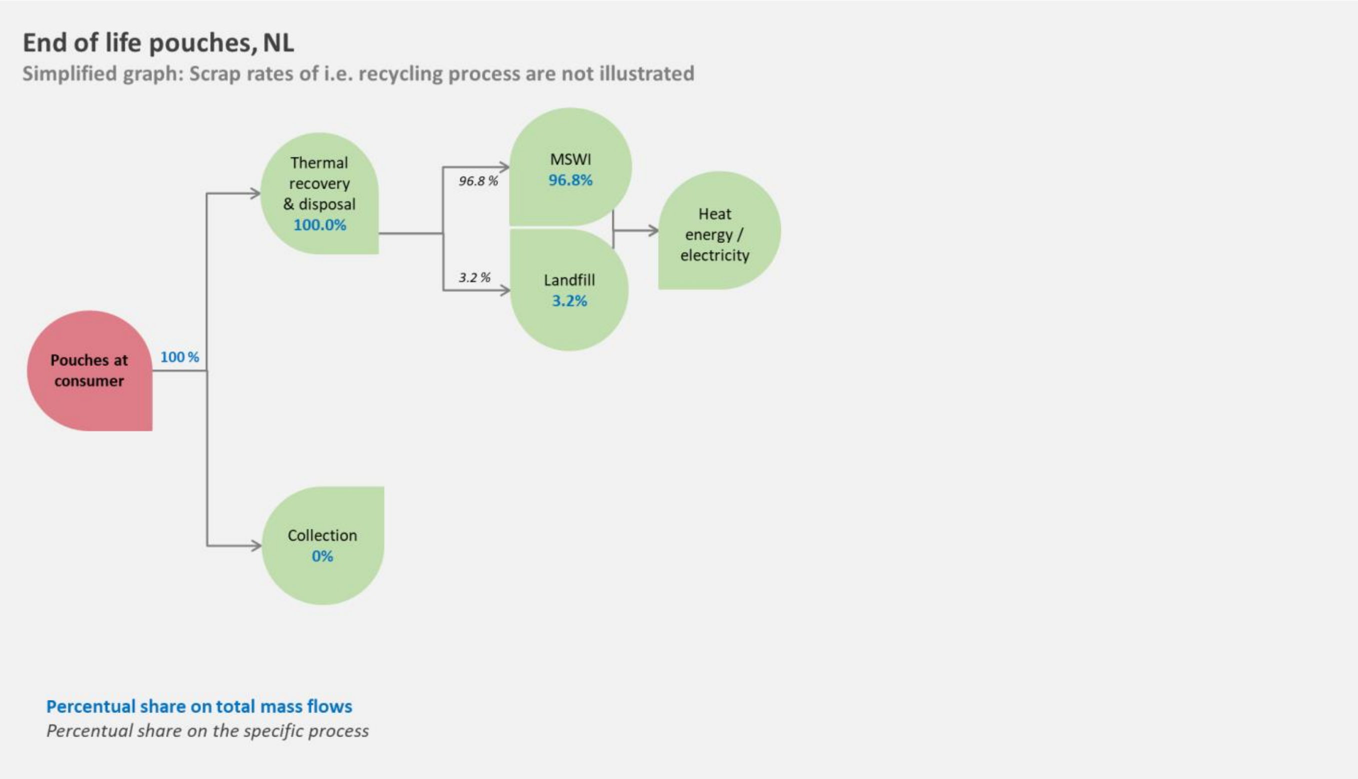

Figure 9: Applied end-of-life quotas for SUPs in the Netherlands

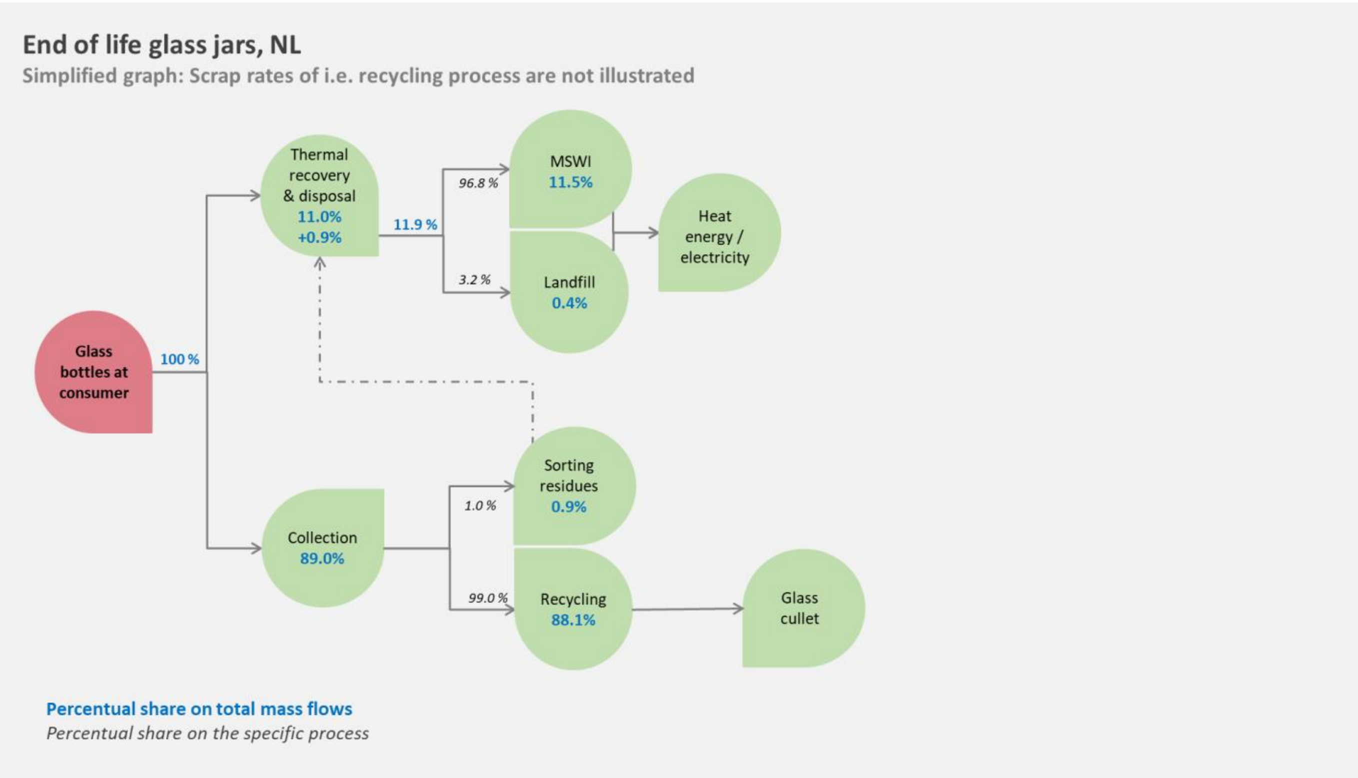

Figure 10: Applied end-of-life quotas for glass jars in the Netherlands

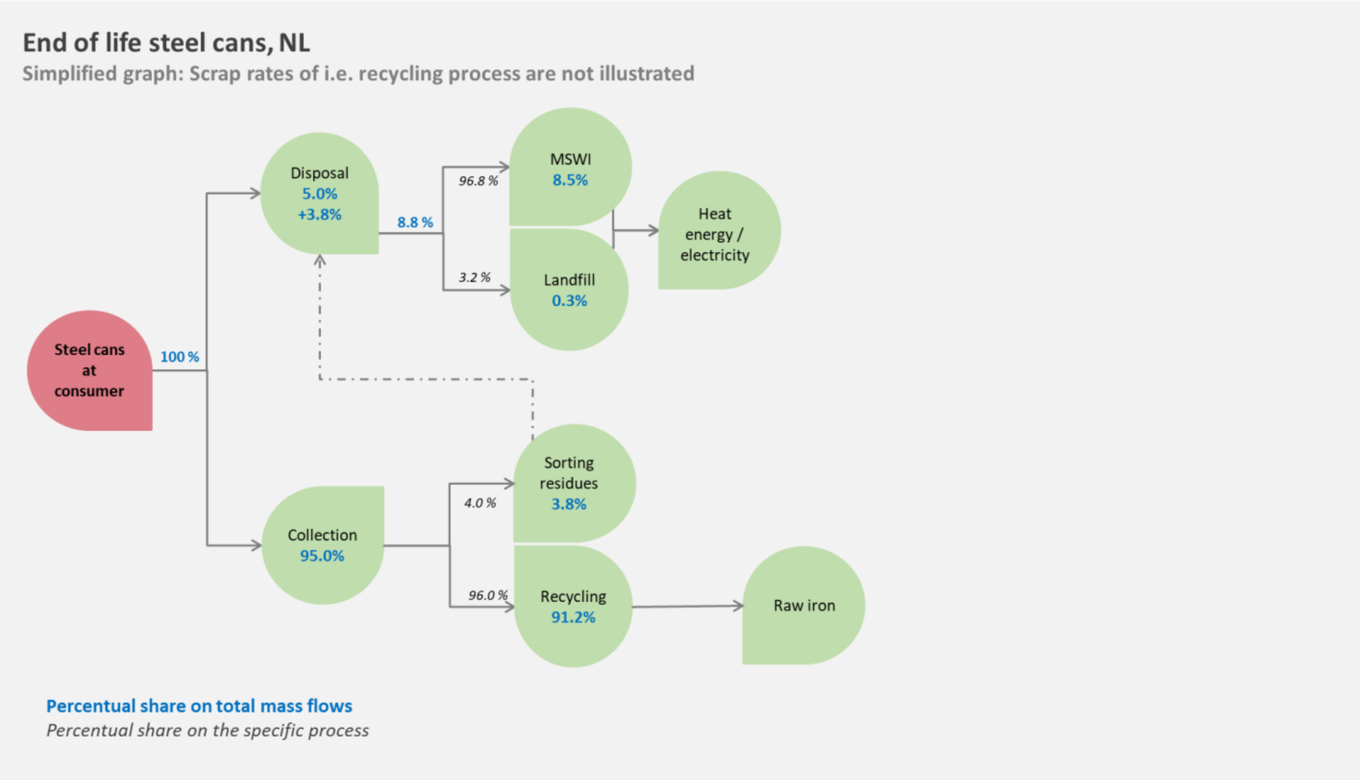

Figure 11: Applied end-of-life quotas for steel cans in the Netherlands

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. These scenarios are clustered into groups within the same segment and volume group. Following the ISO standard's recommendation, a variation of the allocation procedure shall be conducted. Therefore, two equal scenarios 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 %

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 12** gives an overview of important datasets applied in the current study. Primary data collected in 2019 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 12: 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	2011-2023	secondary
Fossil LDPE	EcoInvent 3.10	2011-2023	secondary
Fossil PET	EcoInvent 3.10	2015-2023	secondary
Fossil PA6	(PlasticsEurope 2005)	1999	secondary
Fossil PU	(PlasticsEurope 2021)	2019	secondary
Ethyl acetate	EcoInvent 3.9.1	1991-2023	secondary
Tinplate	(worldsteel 2021)	2017	secondary
Aluminium (primary)	(EAA 2018)	2015	secondary
Aluminium foil	(EAA 2013)	2010	secondary
Corrugated cardboard	(FEFCO and Cepi Container Board 2022)	2020	secondary
Liquid packaging board	ifeu data, obtained from ACE (ACE and ifeu 2020)	2018	secondary
Production			
Liquid food carton converting	(Tetra Pak 2019)	2017	primary
Pouch production	Ifeu database	2007/2018	primary
Glass jar converting including glass production	(BVGlas 2012)	2011/2018	secondary
Steel (tinplate) can converting	(BUWAL 1998), ifeu database	1996-2015	secondary
Filling			
Filling of liquid food cartons	Data provided by Tetra Pak	2020	primary
Filling Pouches	Data provided by Tetra Pak	2020	primary
Filling glass bottles	ifeu data obtained from various fillers	2011	primary

Material / process	Source	Reference year/ period	Collected data
Filling steel cans	ifeu data obtained from various fillers	2005	primary
Recovery			
Liquid food carton recycling	ifeu database, based on data from various European recycling plants	2004	primary
Glass jar	ifeu database, (FEVE 2006)	2004/2005	primary/ secondary
Steel can	ifeu database	2008	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	2016-2020	secondary
Landfill	ifeu database, based on statistics and landfill models	2019	secondary
Thermal recovery in cement kilns	ifeu database, German cement industry association (VDZ)	2006	primary
Lorry transport	ifeu database, based on statistics and transport models, emission factors based on HBEFA 4.1 (INFRAS 2019).	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)
- Polyethylene terephthalate (PET)
- Polyamide 6 (PA6)
- Polyurethane (PU)

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 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).

3.1.4 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.

3.1.5 Polyurethane (PU)

Polyurethane is a polymer composed of a chain of organic units joined by carbamate (urethane) links. Its precursors are polyol, diphenylmethane diisocyanate (MDI) and toluene diisocyanate (TDI). This ecoprofile is an inventory data set of flexible moulded polyurethane foam. The ecoprofile is published on the website of Plastics Europe (data last calculated September 2021), referring to the year 2019 (PlasticsEurope 2021).

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.

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 2015. The data are covering primary aluminium used in Europe consisting of 51% European aluminium data and 49% IAI data developed by the International Aluminium Institute (IAI) for imported aluminium (EAA 2018).

The data set for aluminium foil (5-200 µm) is based on data acquired by the EA together with EAFA covering the year 2010 for the manufacture of semi-finished products made of aluminium. For aluminium foils, this represents 51% of the total production in Europe (EU27 + EFTA countries). 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 57% of the production done through strip casting technology and 43% through classical production route. The dataset includes the electricity prechains, which are based on actual practice and are not a European average electricity mix.

3.4 Manufacture of tinplate

Data for the production of tinplate refer to the year 2017 and was provided by worldsteel (worldsteel 2021). The data set is based on a weighted average site-specific data (gate-to-gate) of European steel producers whereas the electricity grid mix included in the data is country-specific. According to worldsteel the dataset represents about 95% of the annual European supply or production volume. A recycled content of approximately 7% is reported for tinplate. The recycled content is based on the dataset provided by worldsteel.

3.5 Glass jars

The data used for the manufacture are data acquired by Bundesverband Glasindustrie e.V. (BVGlas) and represents the German production in 2012. The energy consumption and the emissions for the glass manufacturing process are determined by the composition of the raw mineral material and in particular by the scrubbing and the fossil energy resource used for the direct heating. The applied electricity prechains are modelled with the Dutch electricity mix based on 2018. As the production of glass bottle 1 takes place in Germany, the process data is coupled with the required prechain of the German electricity mix in order to adjust the process data to the production in Germany. A newer 2016 data set from FEVE (FEVE 2016) is not applied, because of its methodological approach of substituting gas, coal and oil based thermal energy on the market with sold heat surplus of the glass production process. As the dataset used in this study has lower impacts as the FEVE dataset from 2016, a conservative approach in the perspective of the beverage and liquid food carton systems is applied. As the dataset represents the German glass production the representativeness on the European market is not known.

3.6 Corrugated board and manufacture of cardboard trays

For the manufacture of corrugated cardboard and corrugated cardboard packaging the data sets published by FEFCO (FEFCO and Cepi Container Board 2022) 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 2020. All corrugated board and 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 (2022), this fraction on average is 12% in Europe. Due to a lack of more specific information this split was also used for this study.

3.7 Ethyl acetate

Ethyl acetate is the ester of ethanol and acetic acid. It is produced for use as a solvent and diluent. The ecoprofile is taken from EcoInvent 3.9.1, referring to the year 1991. This is the latest dataset available and has been partially updated in 2016.

3.8 Converting

3.8.1 Converting of liquid food cartons

The manufacture of composite board was modelled using European average converting data from Tetra Pak that refer to the year 2017. New converting data was collected after the study was finalised. It was shown that these emissions have only decreased slightly. For this reason, the present study was not updated with the more recent data. The converting process covers the lamination of LPB with LDPE and aluminium including, cutting, and packing of the composite material. The examined Tetra Recart beverage cartons are produced at an Hungarian converting side of Tetra Pak. 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, Hungarian electricity, and inventory data for transport packaging used for shipping the coated composite board to the filler.

3.8.2 Production of pouches

Data for the production of pouches are taken from the internal ifeu data base. These are based on data collected from various European pouch producers in the context of studies for flexible packaging and is considered to be representative for an average European pouch production. The dataset is based on data from 2007 and 2018. The process data is coupled with required prechains like the Dutch electricity mix.

3.8.3 Converting of steel can

Data gathering for the manufacturing of 3-piece tinplate food cans has been attempted within this study, but unfortunately without success. Thus, older food can manufacturing data had to be used. The converting dataset was taken from the literature (BUWAL 1998) and related prechains were taken in their most current version from the ifeu internal database. The process data refer to the year 1996. According to APEAL (APEAL 2008), the BUWAL converting process dataset is the only available food can converting dataset for the time being. 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.

3.9 Filling

Filling processes are similar for liquid food cartons and alternative packaging systems regarding material and energy flows. The respective data for Tetra Recart cartons and pouches were provided by Tetra Pak (ref. year 2019) 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. For the filling of glass bottles, data collected from various fillers (confidential) with a reference year of 2011 has been used. The data were still evaluated to be valid as filling machines and technologies have not changed since then. Filling data for the analysed steel can is based on the ifeu internal 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.

3.10 Transport settings

Table 13 provides an overview of the transport settings (distances and modes) applied for packaging materials. Data were obtained from Tetra Pak, ACE 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 location of the converted carton rolls is Hungary, Budaörs. Hence, it is assumed that the distance of the converted cardboard rolls to the filler is 1380 km (Hungary, Budaörs - Netherlands, Amsterdam).

Table 13: Transport distances and means of transports

Packaging element	Distance of material producer to converter	Distance of converter to filler (km)
Fossil polymers	500 km[1] (truck)	
Aluminium	500 km[1] (truck)	
Steel	500 km[1] (truck)	
Paperboard for composite board	300 km[2] (truck)	
	950 km[2] (ship)	
	800 km rail[2] (train)	
Cardboard for trays	**primary fibres:** 500 km[2] (ship) 400 km[2] (train) 250 km[2] (truck) **secondary fibres:** 300 /road[2] (truck)	
Wood for pallets	100 / road[1] (truck)	
LDPE stretch foil	500 km (material production site = converter)[1] (truck)	
Trays		500 km[1] (truck)
Pallets		100 km[1] (truck)
Converted carton rolls		1380 km[3] (truck)
Steel cans		500 km[1] (truck)
SUPs		500 km[1] (truck)
Glass jars	500 km (material production site = converter)[1] (truck)	

[1] ifeu assumption
[2] taken from published LCI reports
[3] Tetra Pak assumption (Converting location of carton rolls: Hungary, Budaörs)

3.11 Distribution of filled packs from filler to point of sale

Table 14 shows the applied distribution distances in this study. Distribution centres are the places where the products are temporarily stored and then distributed to the different point of sales (i.e. supermarkets). The distances are based on an LCA study on packaging for beverages on the European market for ACE (Busch and Wellenreuther 2018) as applied in the European baseline study (Schlecht and Wellenreuther 2020). 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. For this reason, an estimation of 33% of the delivery distance is calculated as an empty return trip. This estimation is based on expert judgement from ifeu's department for mobility and transport. This is only valid for the distribution steps to the distribution centres. Usually, no utilisation of lorries on their return trips from the point of sale to the warehouse is possible as the full return trip to the warehouse is attributed as an empty return trip to the examined system.

Table 14: Distribution distances in km for the according countries

	Distribution distance			
	Distribution Step 1		Distribution step 2	
Country and segment	**Filler → distribution centre** (delivery)	**Distribution centre → filler** (return trip)	**Distribution centre → POS** (delivery)	**POS → distribution centre** (return trip)
NL Liquid Food (ambient)	200 km	66 km	60 km	60 km

3.12 Recovery and recycling

Liquid food cartons

Liquid food cartons which are collected and sorted in Netherlands are subsequently exported to Germany and 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. A substitution factor 0.9 is applied. Rejects, in term of plastics and aluminium compounds are assumed to undergo a thermal treatment in cement kilns. Related process data used are taken from ifeu's internal database, referring to the year 2004 and are based on data from various European recycling plants collected by ifeu. The process data is coupled with the prechain of German electricity mix in order to represent the recycling in Germany.

Glass jars

The applied recycling rate of 88.1% for glass jars on the Dutch market is based on (afvalfonds verpakkingen 2022 and ifeu 2023).

The glass of collected glass jars is shredded and the ground glass serves as an input in the glass production, the share of external cullet is modelled as 69.5%. The data used in the current study is drawn from ifeu's internal database, and furthermore information received from BVGlas (2012). The reference period is 2012. Process data are coupled with required prechains and the market related electricity grid mix.

Steel cans

The applied recycling rate of 91.2% for steel cans on the Dutch market is based on (afvalfonds verpakkingen 2022 and ifeu 2023).

Steel cans, as a traditional food package, are sorted into a steel fraction in sorting plants. The sorted post-consumer steel packaging waste fraction is then assumed to substitute pig iron in the steelmaking process (without further pre-treatment). It is implemented in the life cycle model partly as closed-loop and partly as open-loop recycling with the criterion being the scrap input per ton steel product (as it is specified in the steel inventory dataset). Data are taken from the ifeu database based on collected data from the European Steel industry. If the recovery rate of steel packaging is higher than what is required to cover the defined scrap input the remaining post-consumer steel waste is assumed to leave the steel can system. In the model, it substitutes pig iron for a steelmaking process in a subsequent product system (Substitution factor 1.0).

Pouches

As multilayer films are currently not recycled (Niaounakis 2019), no recycling process for pouches is included in this study. Pouches are either incinerated or a minor share ends up in landfills, see **section 2.3**

3.13 Background data

3.13.1 Transport processes

Lorry 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 lorry size classes and road categories**.** Data are based on average fleet compositions within several lorry 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 – lorry 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. 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 3.13.2**).

3.13.2 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

[1] Twenty-foot Equivalent Unit

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)[1]. The Dutch electricity mix (2021) is applied as a prechain for most processes (see **Table 1** and **section 3**). Regarding liquid food cartons, electricity generation is considered using Swedish and Finnish mix of energy suppliers in the year 2018 for the production of LPB and the Hungarian mix of energy suppliers in the year 2021 for the converting of sleeves. The applied shares of energy sources to the related market are given in **Table 15**.

Table 15: Share of energy source to specific energy mix, reference year 2018 (SE and FI) and 2021.

Energy source	Geographic scope: Netherlands	EU 28	Sweden	Finland	Hungary	Germany
Hard coal	11.4%	6.4%	0.20%	8.11%	0.2%	9.4%
Brown coal	0.0%	7.8%	0.18%	4.86%	7.9%	18.9%
Fuel oil	0.0%	1.4%	0.18%	0.32%	0.2%	0.8%
Natural gas	50.1%	20.6%	0.56%	6.98%	27.5%	16.1%
Nuclear energy	3.1%	25.1%	41.00%	32.26%	44.1%	12.1%
Hydropower, wind, solar & geothermal	25.3%	32.4%	49.90%	28.66%	13.5%	33.2%
Hydropower	0.4%	38.6%	78.53%	69.18%	4.4%	10.5%
Wind power	60.9%	42.6%	20.98%	30.37%	14.1%	62.1%
Solar energy	38.7%	18.2%	0.49%	0.45%	81.5%	27.4%
Geothermal energy	0.0%	0.6%	0.00%	0.00%	0.0%	0.0%
Biomass energy	6.7%	4.9%	6.07%	17.15%	5.5%	7.5%
Waste	3.3%	1.4%	1.91%	1.66%	1.1%	1.7%

[1] http://www.iea.org/statistics/

3.13.3 Municipal waste incineration

The electrical and thermal efficiencies of the municipal solid waste incineration plants (MSWI) are shown in **Table 16**.

Table 16: Electrical and thermal efficiencies of the incineration plants for the Netherlands.

Geographic Scope	Electrical efficiency	Thermal efficiency	Reference period	Source
Netherlands	16%	8%	2012	(CEWEP 2012)

Compared with the electrical and thermal efficiencies for Europe, the Netherlands shows slightly higher electrical efficiencies and lower thermal efficiencies.

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. However, if thermal energy is provided, it is used 100%.

3.13.4 Landfill

The landfill model accounts for the emissions and the consumption of resources for the deposition of domestic wastes on a sanitary landfill site. As information regarding an average landfill standard in specific countries is hardly available, assumptions regarding the equipment with and the efficiency of the landfill gas capture system (the two parameters which determine the net methane recovery rate) had to be made.

Besides the parameters determining the landfill standard, another relevant system parameter is the degree of degradation of the beverage and liquid food carton material on a landfill. Empirical data regarding degradation rates of laminated cartons are not known to be available by the authors of the present study.

The following assumptions, especially relevant for the degradable board material, underlay the landfill model applied in this LCA study:

In this study the 100 years perspective is applied. The share of methane recovered via landfill gas capture systems (58.3% in the Netherlands) is based on data from National Inventory Reports (NIR 2022) under consideration of different catchment efficiencies at different stages of landfill operation. The majority of captured methane is used for energy conversion. The remaining share is flared.

Regarding the degradation of the carton board under landfill conditions, it is assumed that it behaves like coated paper-based material in general. According to (Micales and Skog 1997) 30% of paper is decomposed anaerobically on landfills. 70% remain in the landfill, while emissons from maintenance and operation are still allocated to them as well. Potential long-term emissions (i.e., >100a) are not considered anymore.

It is assumed that the degraded carbon is converted into landfill gas with 50% methane content by volume (IPCC 2006). Emissions of methane from biogenic materials (e.g. during landfill) are always accounted at the inventory level and in form of GWP.

3.13.5 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).

4 Results

4.1 Presentation of results

In this section, the results of the examined packaging systems for the Netherlands 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**.

Cradle to gate:

- Production and transport of liquid packaging board (**LPB**)
- Production and transport of plastics and additives for Tetra Recart food cartons (**plastics for sleeve**)
- Production and transport of aluminium & converting to foil for liquid food cartons (**aluminium foil for sleeve**)
- Production and transport of PET, PP (including additives, e.g., PA, PU, ethyl acetate) for the body of pouches), as well as steel for can bodies (**plastics for SUP/steel for body**)
- Production and transport of glass including converting to jar (**glass**)
- Converting processes of cartons, pouches and cans (**converting**)
- Production, converting and transport of closures & labels and their base materials (**closure & label**)

Gate to grave:

- Production of secondary and tertiary packaging: wooden pallets, LDPE shrink foil and corrugated cardboard trays **(transport packaging)**
- Filling process including packaging handling **(filling)**
- Retail of the packages from filler to the point-of-sale including cooling during transport if relevant **(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) **(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 food 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.

4.2 Allocation factor 50% of Liquid Food Portion Pack (ambient)

4.2.1 Presentation of results Liquid Food Portion Pack (ambient)

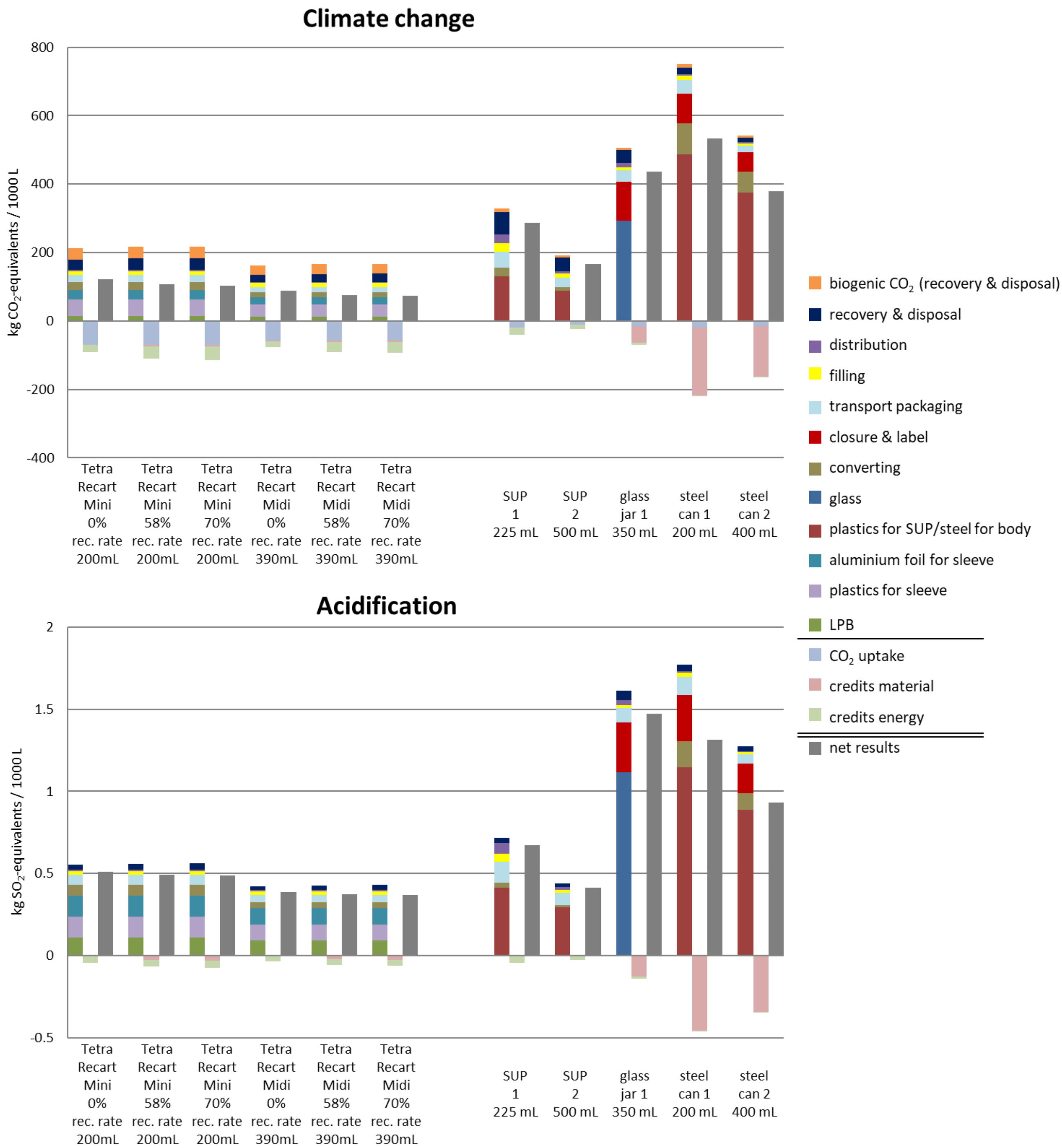

Figure 12: Indicator results of **segment Liquid Food Portion Pack (ambient)**, allocation factor 50% (Part 1/5)

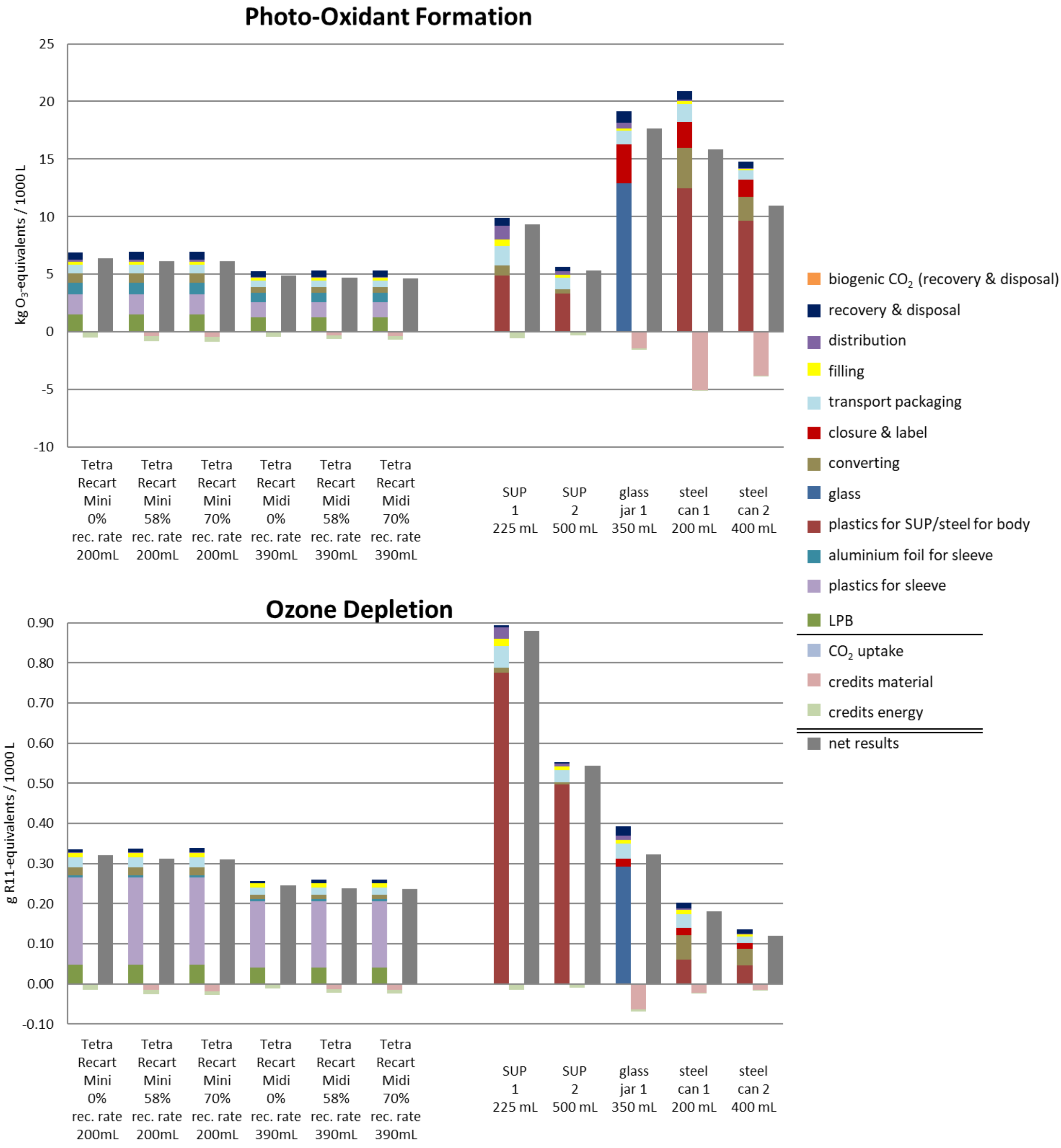

Figure 13: Indicator results of **segment Liquid Food Portion Pack (ambient)**, allocation factor 50% (Part 2/5)

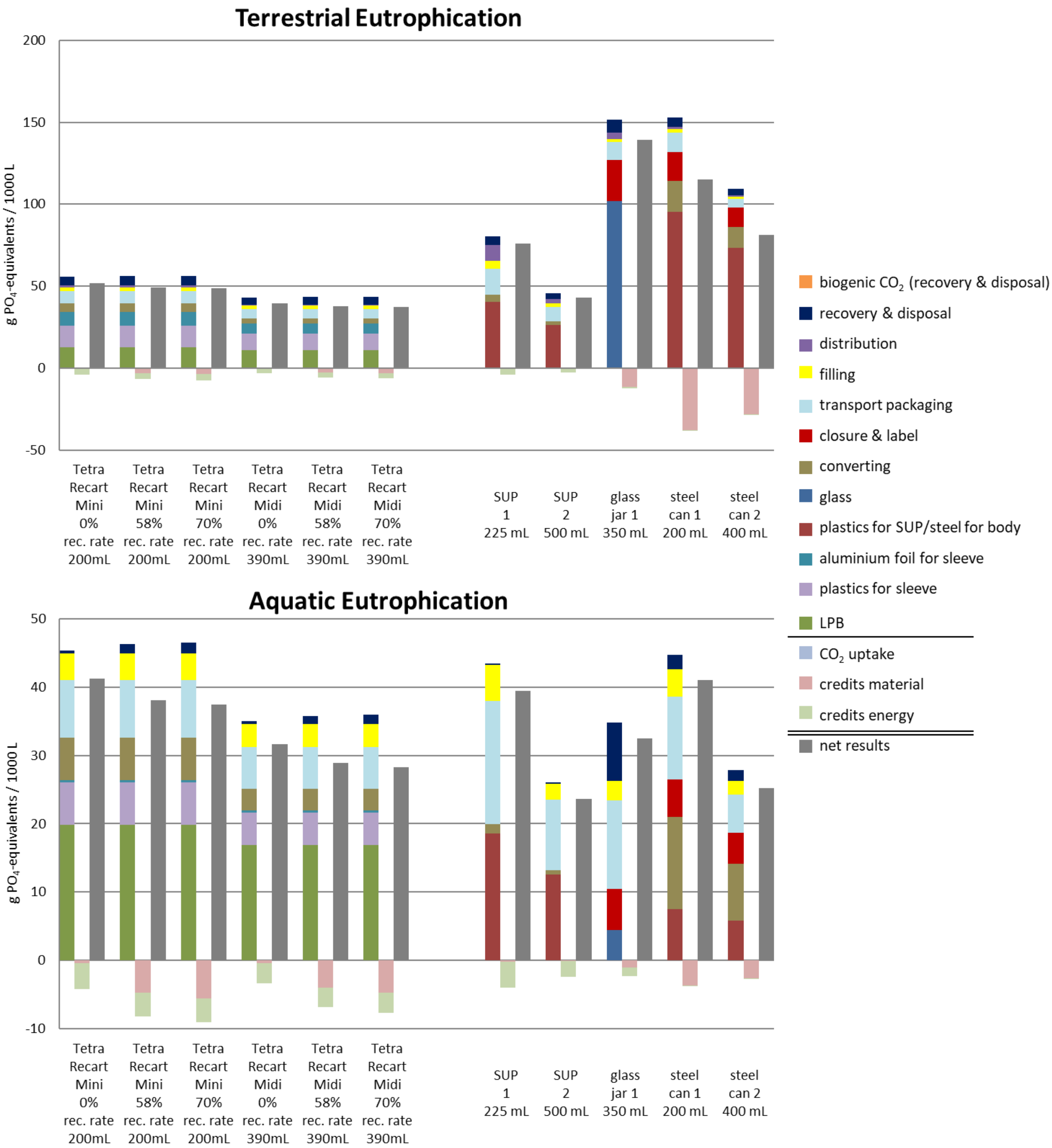

Figure 14: Indicator results of **segment Liquid Food Portion Pack (ambient)**, allocation factor 50% (Part 3/5)

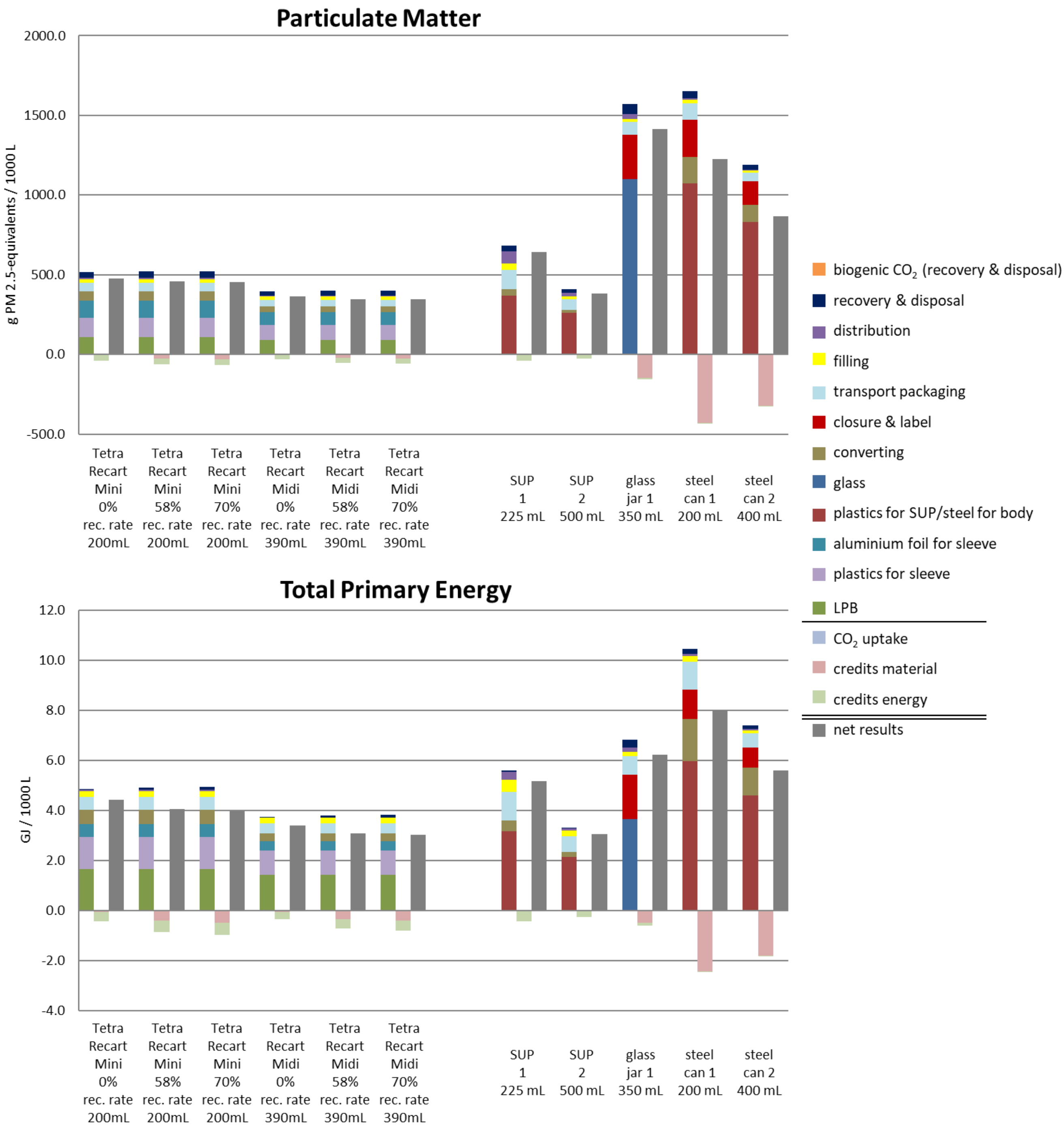

Figure 15: Indicator results of **segment Liquid Food Portion Pack (ambient)**, allocation factor 50% (Part 4/5)

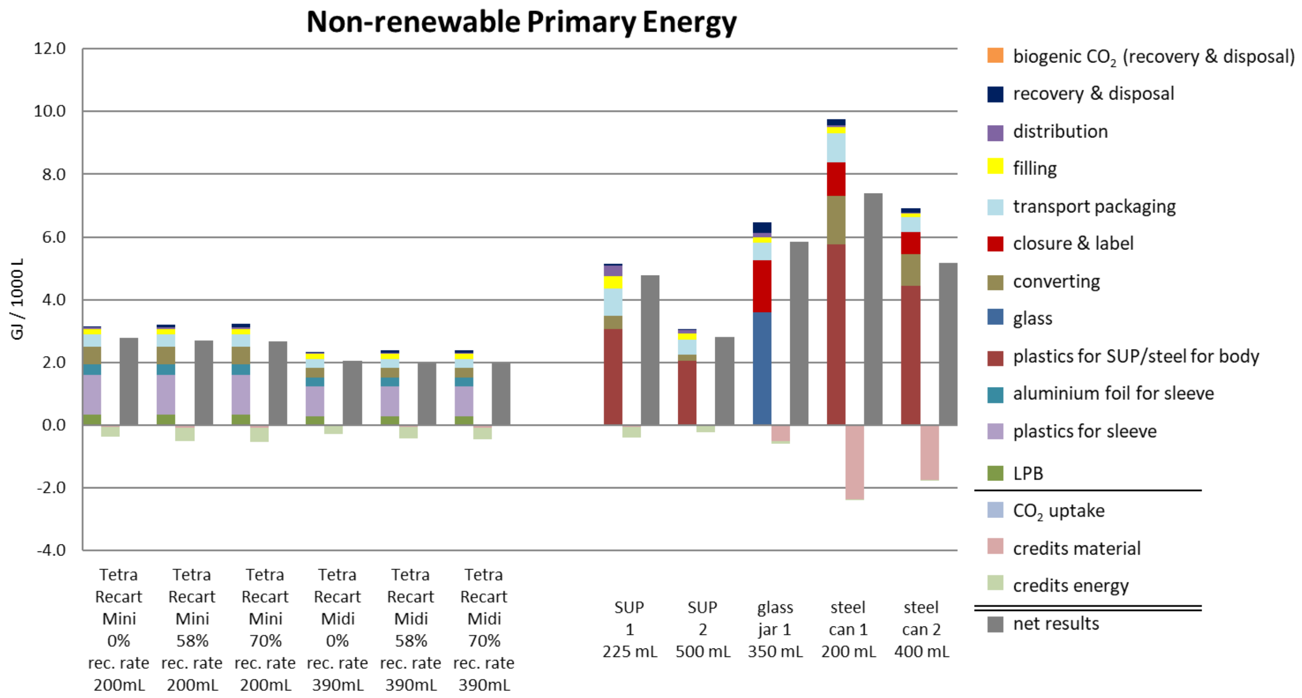

Figure 16: Indicator results of **segment Liquid Food Portion Pack (ambient)**, allocation factor 50% (Part 5/5)

Table 17: Category indicator results of **segment Liquid Food Portion Pack (ambient)** - burdens, credits and net results per FU of 1000 L, allocation factor 50% (All figures are rounded to two decimal places.)

Food Portion Pack (ambient) Allocation 50 Netherlands		Tetra Recart Mini 0% recycling rate 200mL	Tetra Recart Mini 58% recycling rate 200mL	Tetra Recart Mini 70% recycling rate 200mL	Tetra Recart Midi 0% recycling rate 390mL	Tetra Recart Midi 58% recycling rate 390mL	Tetra Recart Midi 70% recycling rate 390mL	SUP 1 225 mL	SUP 2 500 mL	glass jar 1 350 mL	steel can 1 200 mL	steel can 2 400 mL
Climate Change [kg CO_2-e/1000 L]	burdens	178.32	182.13	182.95	134.25	137.35	138.02	319.03	185.72	498.50	740.53	535.10
	CO_2 (reg)	34.32	34.33	34.33	28.74	28.74	28.74	9.05	5.09	7.64	9.40	6.86
	credits	-21.77	-40.23	-44.20	-17.42	-31.87	-34.98	-22.11	-13.33	-54.84	-197.79	-148.23
	CO_2 uptake	-69.44	-69.44	-69.44	-58.19	-58.19	-58.19	-18.54	-10.43	-15.59	-19.59	-14.33
	net results	**121.43**	**106.79**	**103.64**	**87.39**	**76.04**	**73.60**	**287.44**	**167.05**	**435.71**	**532.54**	**379.40**
Acidification [kg SO_2-e/1000 L]	burdens	0.55	0.56	0.56	0.42	0.43	0.43	0.72	0.44	1.61	1.77	1.27
	credits	-0.04	-0.07	-0.07	-0.03	-0.06	-0.06	-0.05	-0.03	-0.14	-0.46	-0.34
	net results	**0.51**	**0.49**	**0.49**	**0.39**	**0.37**	**0.37**	**0.67**	**0.41**	**1.47**	**1.31**	**0.93**
Photo-Oxidant Formation [kg O_3-e/1000 L]	burdens	6.90	6.95	6.95	5.28	5.32	5.33	9.88	5.66	19.17	20.90	14.75
	credits	-0.49	-0.77	-0.83	-0.39	-0.64	-0.69	-0.52	-0.31	-1.54	-5.07	-3.78
	net results	**6.41**	**6.17**	**6.12**	**4.88**	**4.68**	**4.64**	**9.35**	**5.34**	**17.63**	**15.83**	**10.97**
Ozone Depletion [g R11-e/1000 L]	burdens	0.33	0.34	0.34	0.26	0.26	0.26	0.89	0.55	0.39	0.20	0.14
	credits	-0.01	-0.03	-0.03	-0.01	-0.02	-0.02	-0.01	-0.01	-0.07	-0.02	-0.02
	net results	**0.32**	**0.31**	**0.31**	**0.24**	**0.24**	**0.24**	**0.88**	**0.54**	**0.32**	**0.18**	**0.12**
Terrestrial Eutrophication [g PO_4-e/1000 L]	burdens	55.75	56.22	56.32	42.79	43.24	43.34	80.35	45.54	151.71	152.98	109.45
	credits	-4.03	-6.84	-7.44	-3.24	-5.66	-6.18	-4.21	-2.53	-12.53	-37.82	-28.33
	net results	**51.72**	**49.38**	**48.88**	**39.55**	**37.58**	**37.16**	**76.13**	**43.01**	**139.19**	**115.16**	**81.12**
Aquatic Eutrophication [g PO_4-e/1000 L]	burdens	45.37	46.35	46.56	34.97	35.77	35.94	43.50	26.03	34.79	44.70	27.83
	credits	-4.18	-8.25	-9.12	-3.36	-6.91	-7.67	-4.05	-2.42	-2.29	-3.70	-2.65
	net results	**41.19**	**38.10**	**37.44**	**31.61**	**28.86**	**28.27**	**39.45**	**23.62**	**32.50**	**41.00**	**25.18**
Particulate Matter [g PM 2.5-e/1000 L]	burdens	516.54	521.29	522.31	394.83	399.16	400.09	681.83	407.80	1571.39	1652.78	1189.75
	credits	-38.48	-62.45	-67.60	-30.88	-51.43	-55.85	-40.78	-24.50	-158.75	-429.36	-321.32
	net results	**478.06**	**458.85**	**454.71**	**363.95**	**347.73**	**344.24**	**641.05**	**383.30**	**1412.64**	**1223.42**	**868.43**
Total Primary Energy [GJ/1000 L]	burdens	4.84	4.91	4.93	3.74	3.80	3.82	5.60	3.31	6.83	10.44	7.38
	credits	-0.43	-0.87	-0.97	-0.34	-0.72	-0.80	-0.43	-0.26	-0.62	-2.44	-1.80
	net results	**4.41**	**4.04**	**3.96**	**3.40**	**3.09**	**3.02**	**5.16**	**3.05**	**6.21**	**8.00**	**5.58**
Non-renewable Primary Energy [GJ/1000 L]	burdens	3.15	3.21	3.22	2.34	2.39	2.40	5.15	3.05	6.46	9.75	6.92
	credits	-0.36	-0.52	-0.55	-0.29	-0.41	-0.44	-0.38	-0.23	-0.60	-2.36	-1.75
	net results	**2.79**	**2.69**	**2.67**	**2.05**	**1.98**	**1.96**	**4.77**	**2.82**	**5.86**	**7.38**	**5.17**

4.3 Allocation factor 100% of Liquid Food Portion Pack (ambient)

4.3.1 Presentation of results Liquid Food Portion Pack (ambient)

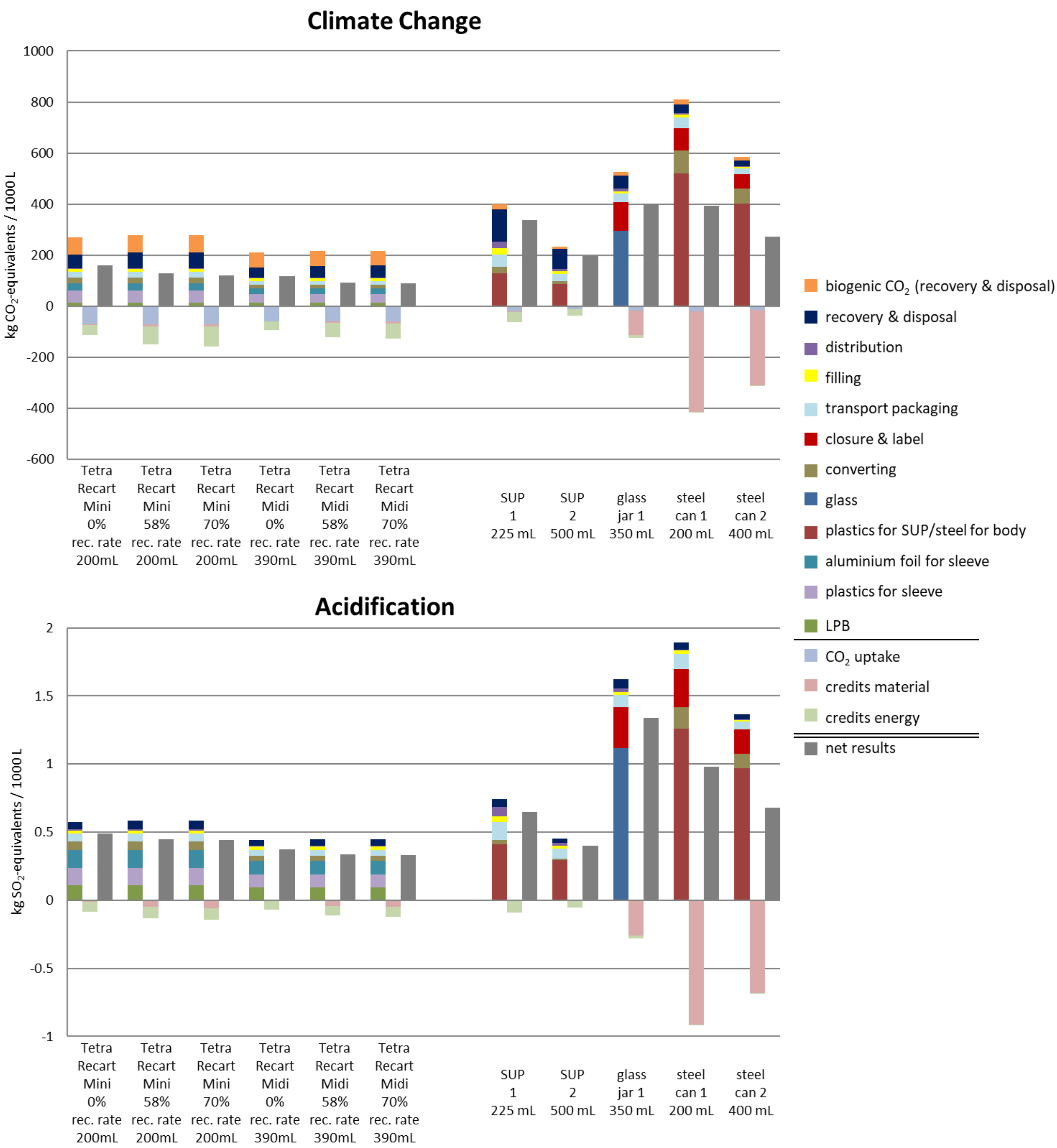

Figure 17: Indicator results of **segment Liquid Food Portion Pack (ambient)**, allocation factor 100% (Part 1/5)

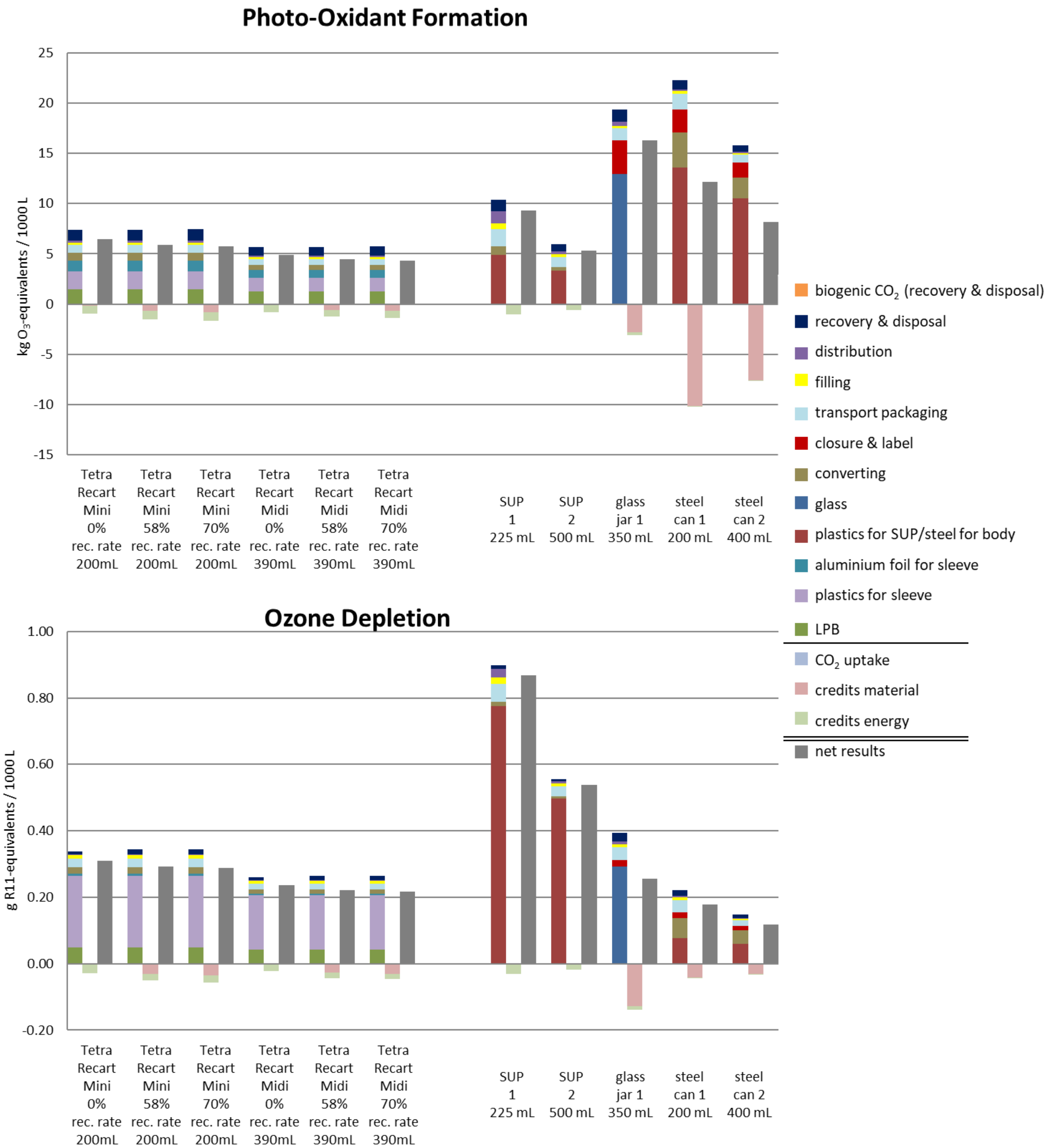

Figure 18: Indicator results of **segment Liquid Food Portion Pack (ambient)**, allocation factor 100% (Part 2/5)

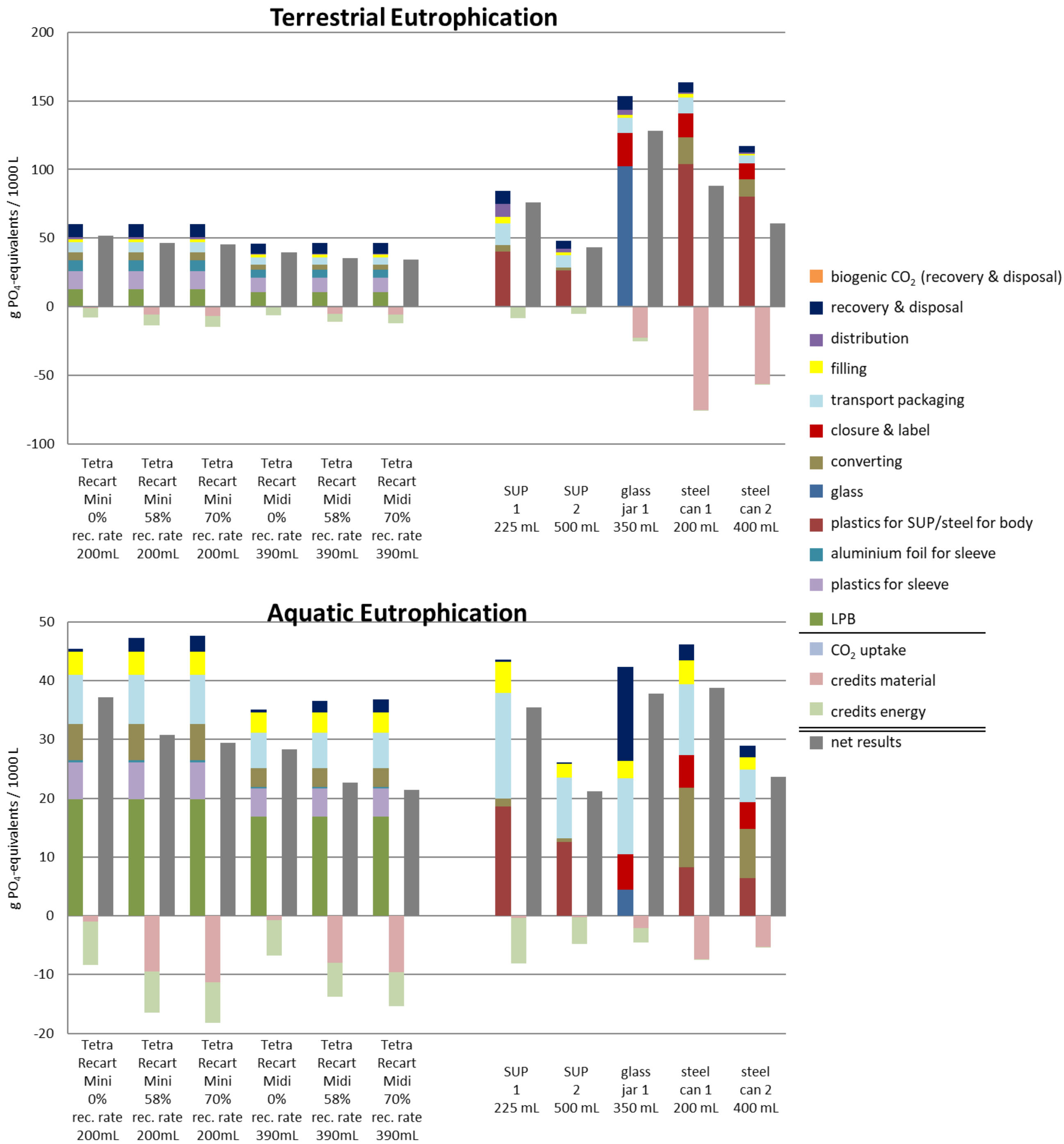

Figure 19: Indicator results of **segment Liquid Food Portion Pack (ambient)**, allocation factor 100% (Part 3/5)

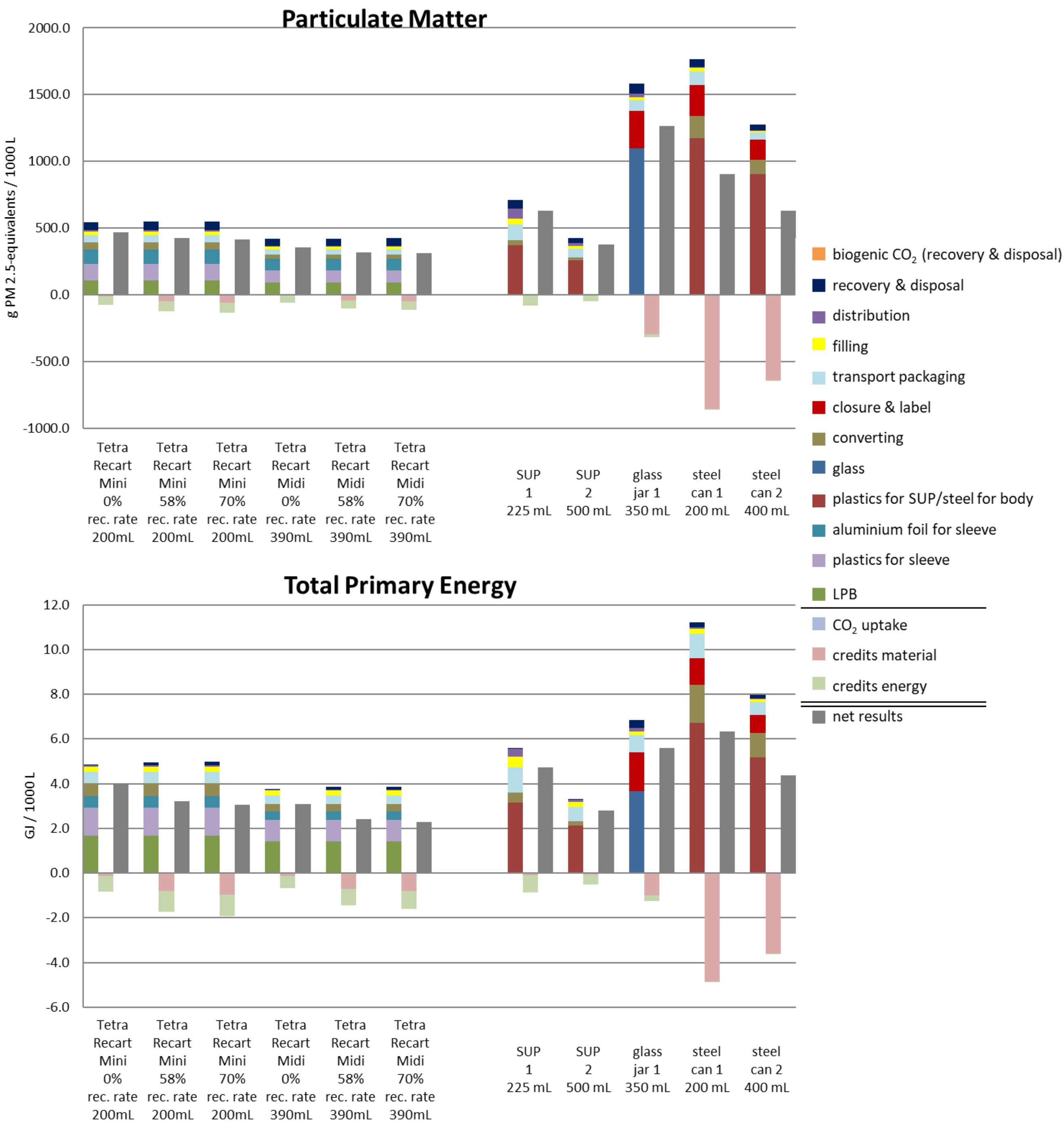

Figure 20: Indicator results of **segment Liquid Food Portion Pack (ambient)**, allocation factor 100% (Part 4/5)

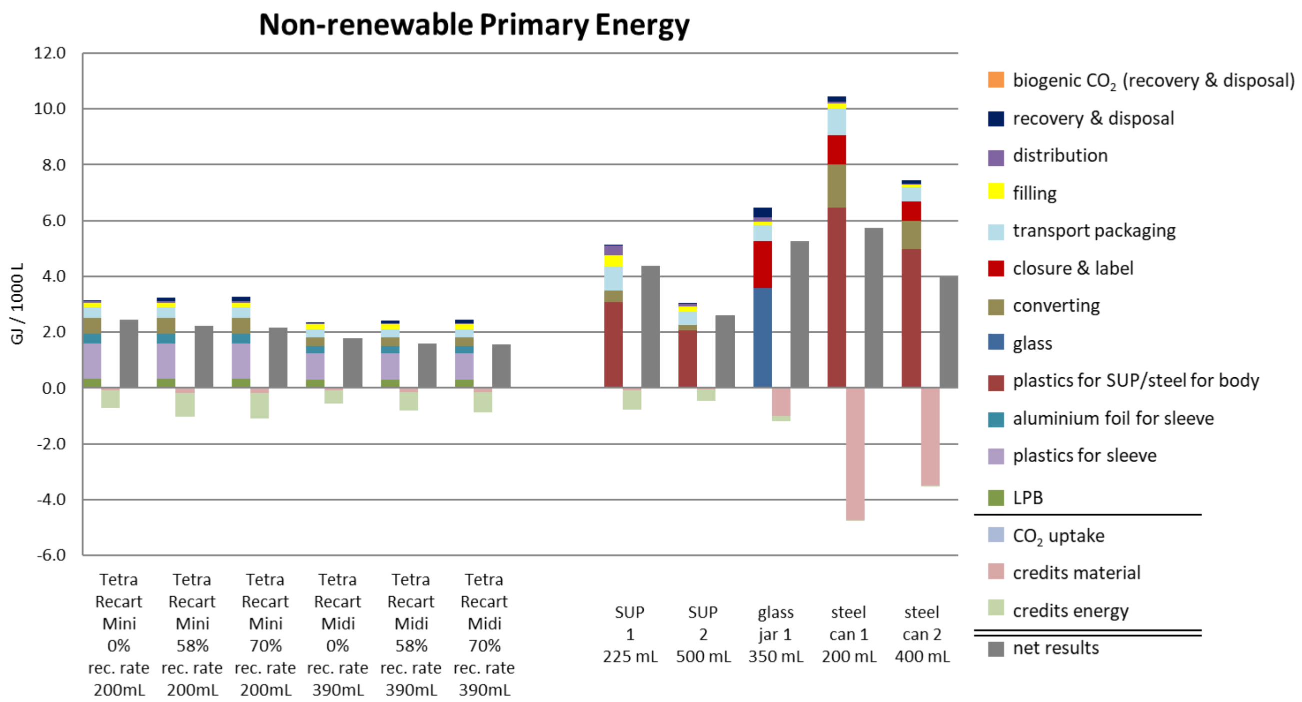

Figure 21: Indicator results of **segment Liquid Food Portion Pack (ambient)**, allocation factor 100% (Part 5/5)

Table 18: Category indicator results of **segment Liquid Food Portion Pack (ambient)** burdens, credits and net results per FU of 1000 L, allocation factor 100% (All figures are rounded to two decimal places.)

Food Portion Pack (ambient) Allocation 100 Netherlands		Tetra Recart Mini 0% recycling rate 200mL	Tetra Recart Mini 58% recycling rate 200mL	Tetra Recart Mini 70% recycling rate 200mL	Tetra Recart Midi 0% recycling rate 390mL	Tetra Recart Midi 58% recycling rate 390mL	Tetra Recart Midi 70% recycling rate 390mL	SUP 1 225 mL	SUP 2 500 mL	glass jar 1 350 mL	steel can 1 200 mL	steel can 2 400 mL
Climate Change [kg CO_2-e/1000 L]	burdens	203.05	209.82	211.28	152.98	158.50	159.69	380.72	223.80	511.42	791.13	570.45
	CO_2 (reg)	67.99	68.27	68.33	56.95	57.18	57.23	18.11	10.18	15.27	19.02	13.92
	credits	-42.77	-80.16	-88.21	-34.19	-63.49	-69.80	-44.20	-26.67	-109.64	-395.73	-296.53
	CO_2 uptake	-69.44	-69.44	-69.44	-58.19	-58.19	-58.19	-18.54	-10.43	-15.59	-19.59	-14.33
	net results	**158.83**	**128.49**	**121.96**	**117.55**	**94.01**	**88.94**	**336.09**	**196.88**	**401.46**	**394.83**	**273.52**
Acidification [kg SO_2-e/1000 L]	burdens	0.58	0.58	0.59	0.44	0.45	0.45	0.74	0.45	1.62	1.89	1.37
	credits	-0.08	-0.14	-0.15	-0.07	-0.11	-0.12	-0.09	-0.05	-0.28	-0.91	-0.68
	net results	**0.49**	**0.45**	**0.44**	**0.37**	**0.34**	**0.33**	**0.65**	**0.40**	**1.34**	**0.98**	**0.68**
Photo-Oxidant Formation [kg O_3-e/1000 L]	burdens	7.39	7.41	7.42	5.67	5.70	5.71	10.38	5.96	19.38	22.27	15.76
	credits	-0.98	-1.54	-1.66	-0.78	-1.27	-1.38	-1.05	-0.63	-3.09	-10.15	-7.56
	net results	**6.42**	**5.87**	**5.75**	**4.89**	**4.43**	**4.33**	**9.33**	**5.33**	**16.29**	**12.12**	**8.19**
Ozone Depletion [g R11-e/1000 L]	burdens	0.34	0.34	0.34	0.26	0.26	0.26	0.90	0.56	0.39	0.22	0.15
	credits	-0.03	-0.05	-0.06	-0.02	-0.04	-0.05	-0.03	-0.02	-0.14	-0.04	-0.03
	net results	**0.31**	**0.29**	**0.29**	**0.24**	**0.22**	**0.22**	**0.87**	**0.54**	**0.26**	**0.18**	**0.12**
Terrestrial Eutrophication [g PO_4-e/1000 L]	burdens	59.87	60.26	60.34	46.09	46.54	46.64	84.61	48.13	153.43	163.74	117.33
	credits	-8.03	-13.66	-14.87	-6.45	-11.30	-12.35	-8.42	-5.07	-25.05	-75.67	-56.68
	net results	**51.84**	**46.60**	**45.47**	**39.64**	**35.24**	**34.29**	**76.19**	**43.06**	**128.38**	**88.07**	**60.65**
Aquatic Eutrophication [g PO_4-e/1000 L]	burdens	45.45	47.25	47.63	35.04	36.50	36.82	43.53	26.05	42.34	46.20	28.94
	credits	-8.33	-16.48	-18.23	-6.71	-13.81	-15.34	-8.10	-4.83	-4.57	-7.40	-5.29
	net results	**37.12**	**30.77**	**29.40**	**28.33**	**22.69**	**21.48**	**35.43**	**21.22**	**37.77**	**38.80**	**23.65**
Particulate Matter [g PM 2.5-e/1000 L]	burdens	543.90	548.93	550.01	416.73	421.72	422.79	709.70	424.74	1583.07	1764.86	1272.77
	credits	-76.59	-124.73	-135.09	-61.45	-102.72	-111.61	-81.54	-49.01	-317.45	-859.07	-642.83
	net results	**467.31**	**424.21**	**414.93**	**355.28**	**318.99**	**311.18**	**628.15**	**375.73**	**1265.62**	**905.79**	**629.93**
Total Primary Energy [GJ/1000 L]	burdens	4.85	4.96	4.99	3.75	3.84	3.86	5.60	3.31	6.84	11.21	7.97
	credits	-0.84	-1.74	-1.94	-0.68	-1.43	-1.59	-0.87	-0.52	-1.24	-4.88	-3.60
	net results	**4.00**	**3.22**	**3.05**	**3.07**	**2.41**	**2.27**	**4.73**	**2.79**	**5.60**	**6.34**	**4.37**
Non-renewable Primary Energy [GJ/1000 L]	burdens	3.15	3.25	3.27	2.34	2.42	2.44	5.15	3.05	6.46	10.46	7.46
	credits	-0.71	-1.03	-1.10	-0.57	-0.82	-0.88	-0.76	-0.46	-1.20	-4.73	-3.49
	net results	**2.44**	**2.22**	**2.18**	**1.77**	**1.60**	**1.57**	**4.39**	**2.60**	**5.26**	**5.73**	**3.96**

4.4 Description and interpretation

The following five subsections describe the results of the life cycle steps for Tetra Recart, pouches, glass jars, and steel cans. In addition, the effect of the allocation factors is explained regarding the Dutch market.

4.4.1 Tetra Recart (specifications see **section 2.2.1**)

For the Tetra Recarts, in 8 impact categories a considerable part of the environmental burdens is caused by the production of the material components of the liquid food carton.

The **LPB** shows the largest contribution in the results of 'Photochemical oxidant formation', 'Terrestrial eutrophication', 'Aquatic eutrophication', 'Particulate matter', 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 **plastic for sleeve** of Tetra Recart shows considerable shares on the environmental burdens in all categories.

The production of **aluminium foil** for the sleeves of the ambient liquid food cartons 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.

The **converting** and **filling** processes generally play a small role. The largest contribution by these processes is observed in 'Climate change', 'Acidification', 'Photochemical oxidant formation', 'Terrestrial eutrophication', 'Particulate matter', 'Non-renewable primary energy' and 'Total primary energy'. This results from the thermal energy and electricity input.

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 foil production play a minor role.

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

The end-of-life phase **recovery & disposal** of the considered Tetra Recarts 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. 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 liquid food 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 incineration plants, where energy recovery takes place and from the use of the rejects 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. This amount of carbon can be re-emitted in the end-of-life either by landfilling or incineration or be forwarded to the next product system in a recycled product.

4.4.2 Pouches (specifications see **section 2.2.2**)

For stand-up pouches, the biggest part of the environmental burdens is caused by the production of the base materials (plastics for SUP) in most categories. These base materials often 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 stand-up pouches show an increased consumption of 'Acidification', 'Photochemical oxidant formation', 'Ozone depletion', 'Aquatic eutrophication', 'Particulate matter', 'Total primary energy' and 'Non-renewable primary energy'. 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 pouches, 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).

Thermal energy and electricity are the main inputs for the life cycle steps **converting** and **filling**. Therefore, they show considerable contributions in categories that are driven by energy generation: 'Climate change', 'Acidification' 'Photochemical oxidant formation', 'Terrestrial eutrophication', 'Particulate matter', 'Total primary energy' and 'Non-renewable primary energy'.

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

The life cycle step **distribution** shows small burdens in all impact categories for the stand-up pouches.

The impact of the stand-up pouches' **recovery & disposal** life cycle step is most important regarding 'Climate change'. The incineration of stand-up pouches in MSWIs causes high greenhouse gas emissions.

The influence of **credits** on the net result is low in most categories. With no recycling of stand-up pouches all stand-up pouches are incinerated or landfilled. The energy credits mainly originate from the incineration plants.

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.

4.4.3 Glass jar (specifications see section 2.2.2)

Even more than for the other regarded packaging systems, the production of the **glass** material is the main contributor to the overall burdens for the glass bottle. The production of glass clearly dominates the results in all categories apart from 'Aquatic eutrophication'. The highest share of emissions from the glass production of total emissions is shown in the category 'Ozone depletion': The substitution of primary material increases the material credits when comparing allocation factor 50% to 100% (see also **section 4.4.5**).

The life cycle step **distribution** shows small burdens in all impact categories for the glass jar.

In the impact category 'Aquatic eutrophication' the impact of **recovery & disposal** plays a major role for glass packaging due to the recycling process, whereby the emissions (allocation factor 50% to 100%) increase strongly (see also **section 4.4.5**).

All other life cycle steps play only a minor role compared to the glass production. For the impact category 'Aquatic eutrophication', **transport packaging** also plays a visible role due to the cardboard used for secondary and tertiary packaging.

Energy credits play only a minor role for the glass bottle, as the little energy that can be generated in end-of-life mainly comes from the incineration of secondary and tertiary packaging.

Material credits from glass recycling have a small impact on the overall net results as the cullet is used in a closed loop. The use of closed loop cullet can be seen in the reduced impacts of the life cycle step for the production of glass.

4.4.4 Steel cans (specifications see section 2.2.2)

For steel cans, the biggest parts of the environmental burdens in most categories is caused by the production of the **steel for body**.

The **converting** process for the can body shows small to minor share of burdens for most categories.

The life cycle step **closure & label** shows small to considerable impact shares attributed to the steel production and converting of the cap of the can as well as the production of the paper label.

The life cycle step **distribution** shows small burdens in all impact categories for the steel cans.

The life cycle step **transport packaging** shows only small shares of burdens in most categories. The exception is 'Aquatic eutrophication' which shows higher shares of burdens from the production of cardboard for the secondary packaging.

The life cycle step **filling** shows only small shares of burdens for the steel cans.

The steel cans' **recovery & disposal** life cycle step shows small shares of burdens regarding most categories.

The influence of **material credits** on the net result is relevant for most categories. They reduce the overall burdens due to the substitution of raw steel with recycled steel from the cans. The influence of **energy credits** on the net result is low due to the low share of MSWI and the low heating value of steel.

4.4.5 Allocation factors

If an allocation factor of 100 % is applied, all burdens from recovery processes (i.e., emissions from incineration, emissions from the production of electricity for recycling processes) and all credits for the substitution of other processes (i.e., avoided electricity generation due to energy recovery at MSWIs, avoided virgin material production due to recycling) are allocated to the examined system.

In general, in the Dutch market for **liquid food cartons, stand-up pouches, glass jars and steel cans** the net results are slightly lower with an applied allocation factor of 100 % compared to allocation factor 50% apart from 'Climate change'. For 'Climate change' the absolute value of the credits is lower than that of the burdens from recovery & disposal regardless of the allocation factor. In addition, the allocation factor does not affect the CO_2 uptake. Biogenic CO_2 (recovery & disposal) emissions are accounted for 'Climate change' in the same way as fossil CO_2 emissions.

4.5 Comparison between systems

The net result comparison of the food cartons Tetra Recart Mini and Tetra Recart Midi and alternative packaging solutions (SUPs, steel cans, glass jars) 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 red illustrate the distinction between lower (green) and higher (red) net results in the respective categories. The packaging system on the left is the 'reference', which is being compared with the packaging system on the right. Red bar charts mean that the packaging system on the left has higher impacts, green bar charts mean that the packaging system on the left 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.** In **section 1.1** it is described where the recycling rates (0%, 58% and 70%) of Tetra Recarts come from.

The percentages in **Figure 22** to **Figure 24** show the difference of net results of Tetra Recart Mini (200 mL) in the three different recycling scenarios:

- Tetra Recart Mini 0% recycling rate compared with Tetra Recart Mini 58% recycling rate
- Tetra Recart Mini 0% recycling rate compared with Tetra Recart Mini 70% recycling rate
- Tetra Recart Mini 58% recycling rate compared with Tetra Recart Mini 70% recycling rate

The percentages in **Figure 25** to **Figure 27** show the difference of net results of Tetra Recart Midi (390 mL) in the three different recycling scenarios:

- Tetra Recart Midi 0% recycling rate compared with Tetra Recart Midi 58% recycling rate
- Tetra Recart Midi 0% recycling rate compared with Tetra Recart Midi 70% recycling rate
- Tetra Recart Midi 58% recycling rate compared with Tetra Recart Midi 70% recycling rate

The percentages in **Figure 28** to **Figure 33** show the difference of net results between Tetra Recart Mini (200 mL) in the different recycling scenarios and the competing packaging systems:

- Tetra Recart Mini 0% recycling rate compared with stand-up pouch 1 (225 mL)
- Tetra Recart Mini 0% recycling rate compared with steel can 1 (200 mL)
- Tetra Recart Mini 58% recycling rate compared with stand-up pouch 1 (225 mL)

- Tetra Recart Mini 58% recycling rate compared with steel can 1 (200 mL)
- Tetra Recart Mini 70% recycling rate compared with stand-up pouch 1 (225 mL)
- Tetra Recart Mini 70% recycling rate compared with steel can 1 (200 mL)

The percentages in **Figure 34** to **Figure 42** show the difference of net results between Tetra Recart Midi (390 mL) in the different recycling scenarios and the competing packaging systems:

- Tetra Recart Midi 0% recycling rate compared with stand-up pouch 2 (500 mL)
- Tetra Recart Midi 0% recycling rate compared with glass jar 1 (350 mL)
- Tetra Recart Midi 0% recycling rate compared with steel can 2 (400 mL)
- Tetra Recart Midi 58% recycling rate compared with stand-up pouch 2 (500 mL)
- Tetra Recart Midi 58% recycling rate compared with glass jar 1 (350 mL)
- Tetra Recart Midi 58% recycling rate compared with steel can 2 (400 mL)
- Tetra Recart Midi 70% recycling rate compared with stand-up pouch 2 (500 mL)
- Tetra Recart Midi 70% recycling rate compared with glass jar 1 (350 mL)
- Tetra Recart Midi 70% recycling rate compared with steel can 2 (400 mL)

4.5.1 Comparisons of Tetra Recarts

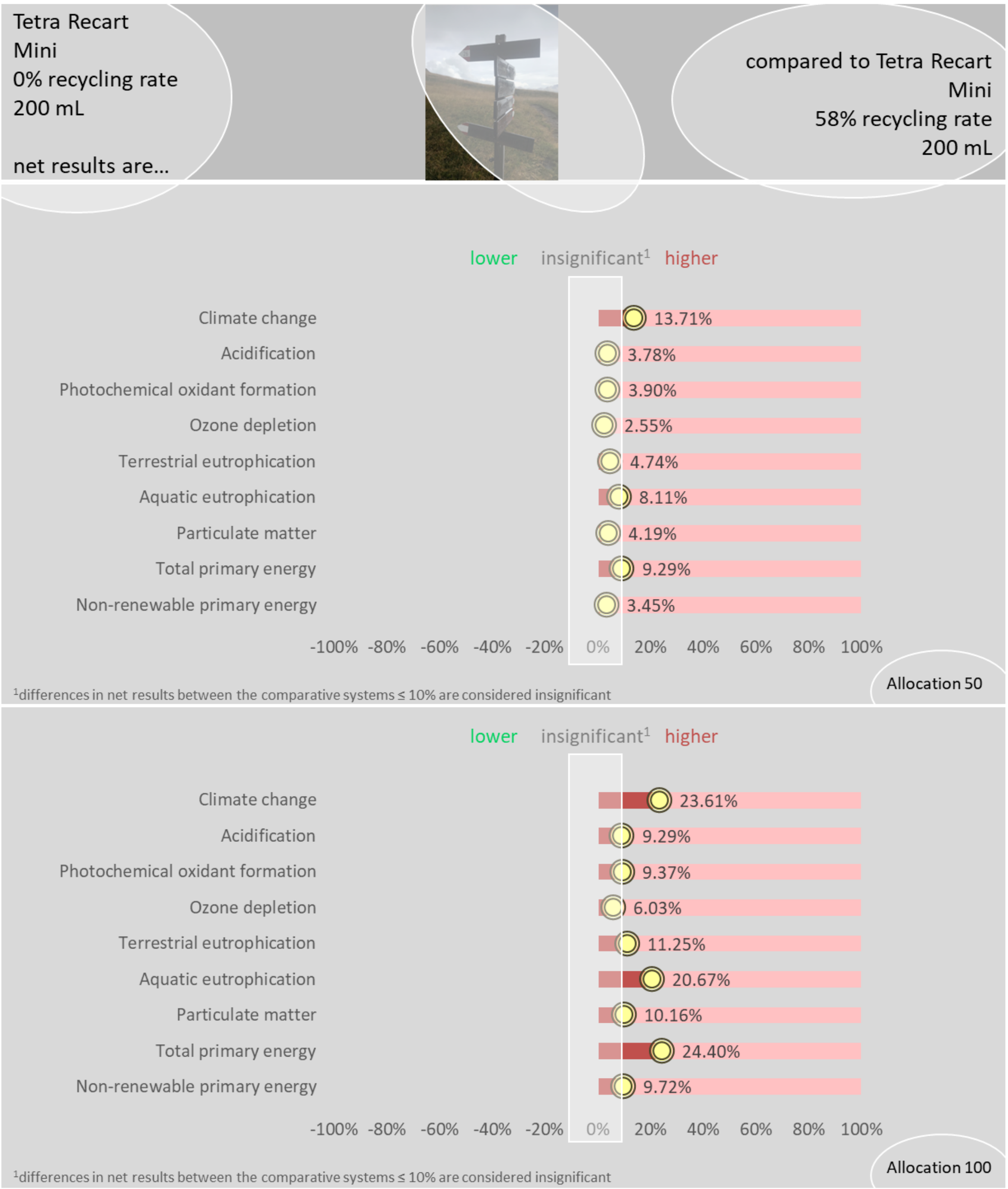

Figure 22: Comparison of net results Tetra Recart Mini 0% recycling rate and Tetra Recart Mini 58% recycling rate (Netherlands); allocation factor 50% and 100%

In both scenarios, the ***Tetra Recart Mini 0% rec. rate*** shows higher net results than the ***Tetra Recart Mini 58% rec. rate*** in the impact category 'Climate change'.

In scenario AF 100% the ***Tetra Recart Mini 0% rec. rate*** measures higher net results compared to ***Tetra Recart Mini 58% rec. rate*** in the impact categories 'Terrestrial eutrophication', 'Aquatic eutrophication' and 'Particulate matter' and in the inventory category 'Total primary energy'.

No significant differences are measured in the impact categories 'Acidification', 'Photochemical oxidant formation' and 'Ozone depletion' and in the inventory category 'Non-renewable primary energy'.

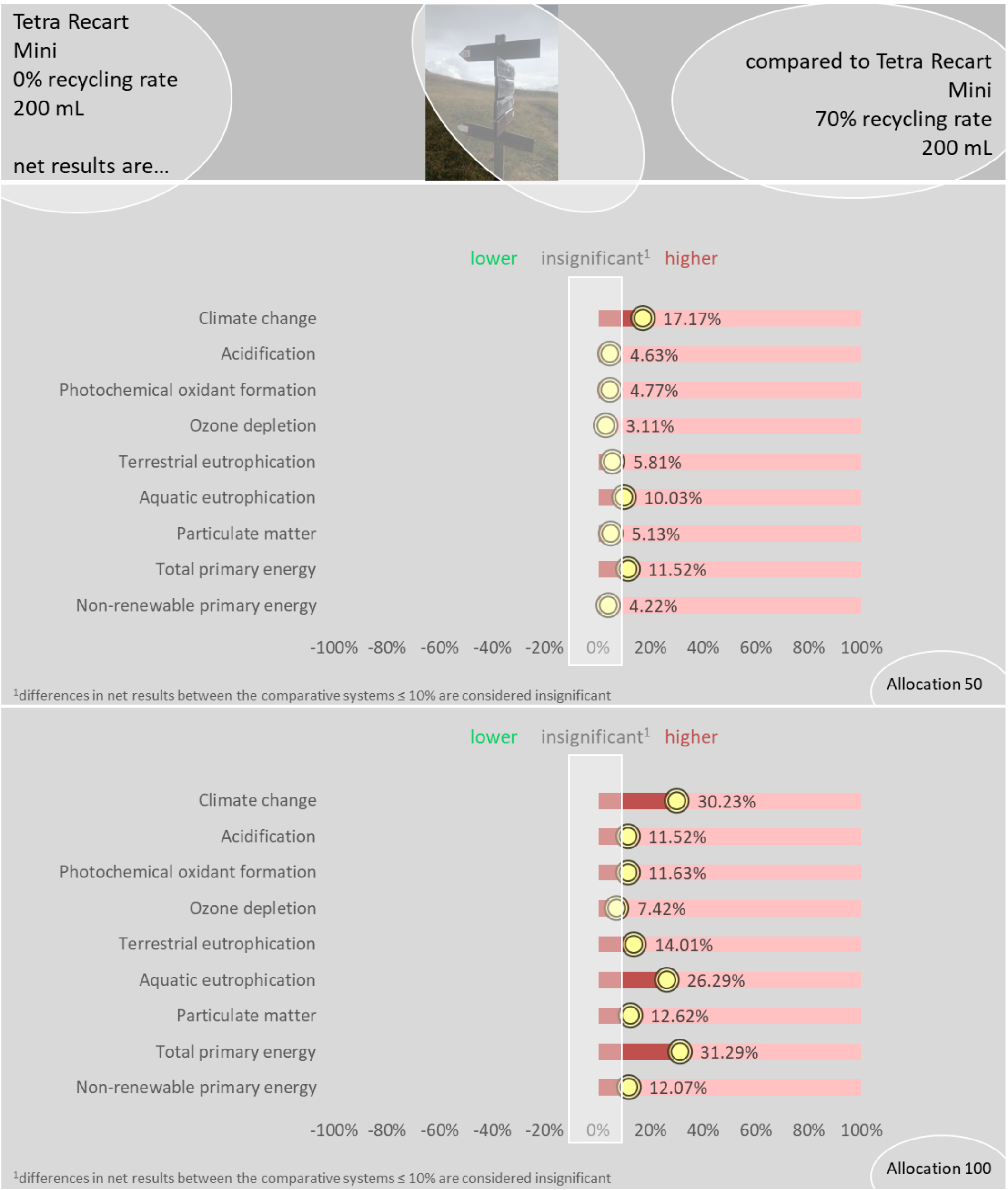

Figure 23: Comparison of net results Tetra Recart Mini 0% recycling rate and Tetra Recart Mini 70% recycling rate (Netherlands); allocation factor 50% and 100%

In both scenarios, the ***Tetra Recart Mini 0% rec. rate*** shows higher net results than the ***Tetra Recart Mini 70% rec. rate*** in the impact categories 'Climate change' 'Aquatic eutrophication' and in the inventory category 'Total primary energy'.

In scenario AF 100% the ***Tetra Recart Mini 0% rec. rate*** measures higher net results compared to ***Tetra Recart Mini 70% rec. rate*** in the impact categories 'Acidification', 'Photochemical oxidant formation', 'Terrestrial eutrophication' and 'Particulate matter' and in the inventory category 'Non-renewable primary energy'.

No significant differences are measured in the impact category 'Ozone depletion'.

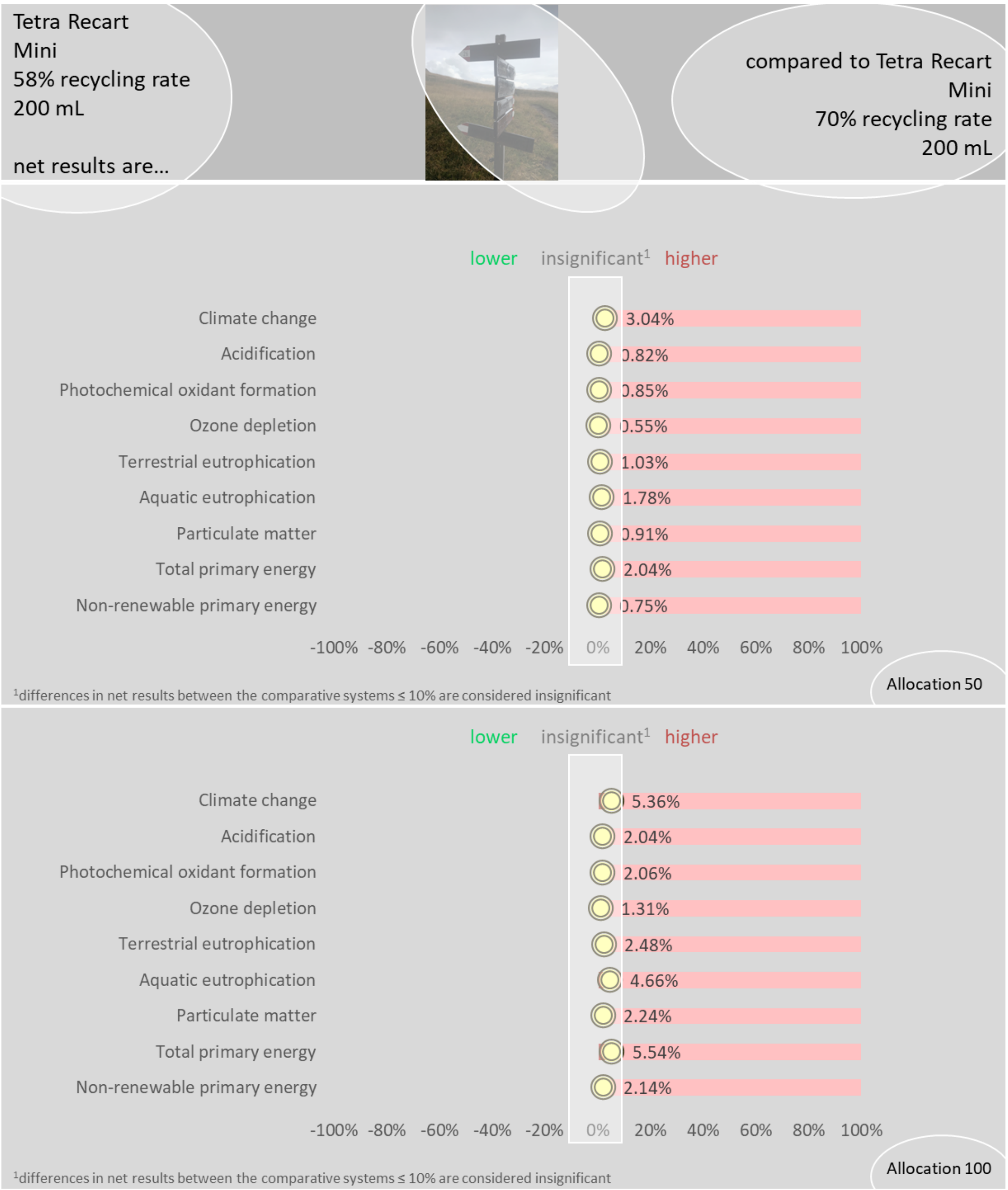

Figure 24: Comparison of net results Tetra Recart Mini 58% recycling rate and Tetra Recart Mini 70% recycling rate (Netherlands); allocation factor 50% and 100%

No significant differences are shown in the comparison of the net results of ***Tetra Recart Mini 58% rec. rate*** and the ***Tetra Recart Mini 70% rec. rate***.

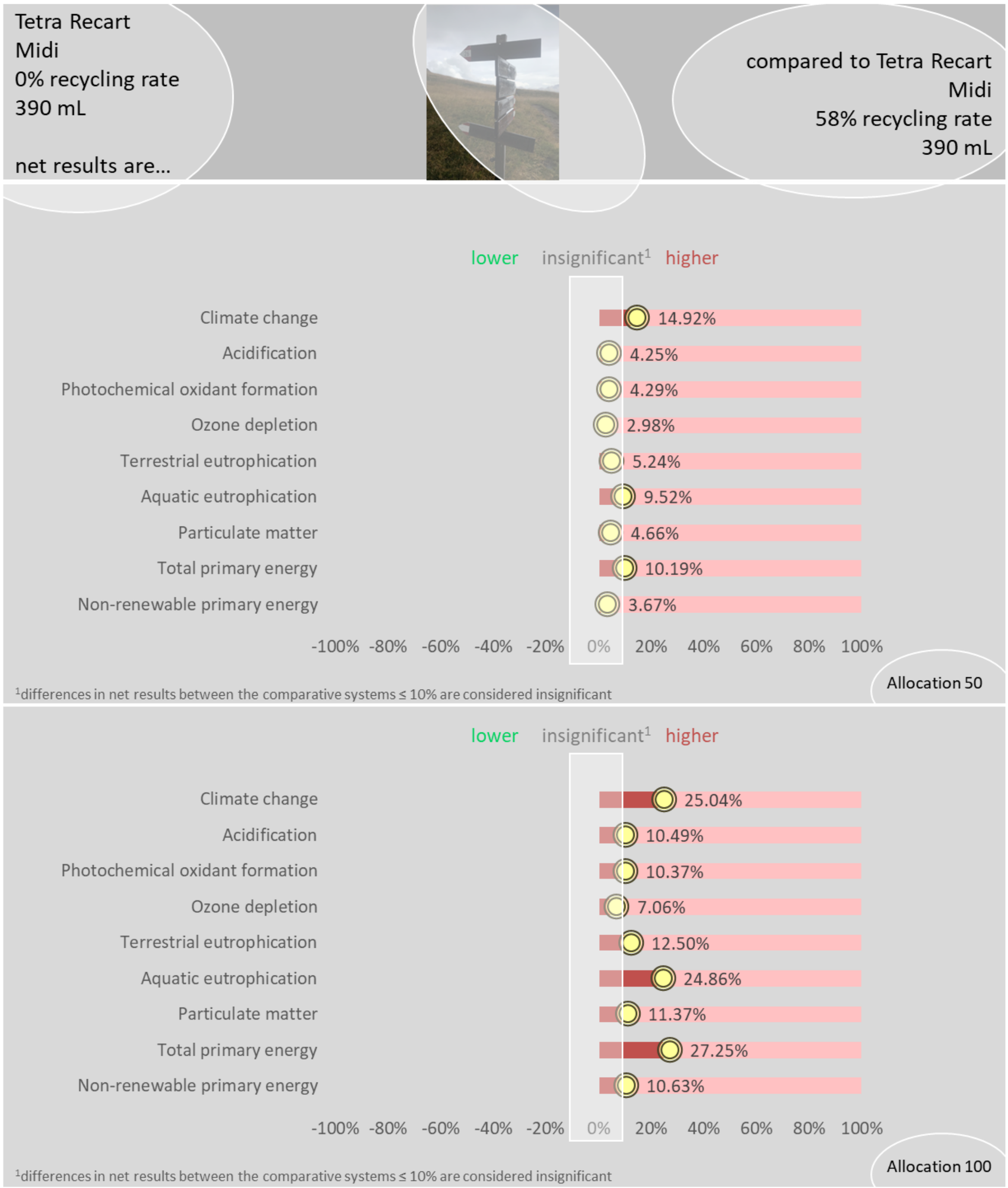

Figure 25: Comparison of net results Tetra Recart Midi 0% recycling rate and Tetra Recart Midi 58% recycling rate (Netherlands); allocation factor 50% and 100%

In both scenarios, the ***Tetra Recart Midi 0% rec. rate*** shows higher net results than the ***Tetra Recart Midi 58% rec. rate*** in the impact category 'Climate change' and in the inventory category 'Total primary energy'.

In scenario AF 100% the ***Tetra Recart Midi 0% rec. rate*** measures higher net results compared to ***Tetra Recart Midi 58% rec. rate*** in the impact categories 'Acidification', 'Photochemical oxidant formation', 'Terrestrial eutrophication', 'Aquatic eutrophication' and 'Particulate matter', and in the inventory category 'Non-renewable primary energy'.

No significant differences are measured in the impact category 'Ozone depletion'.

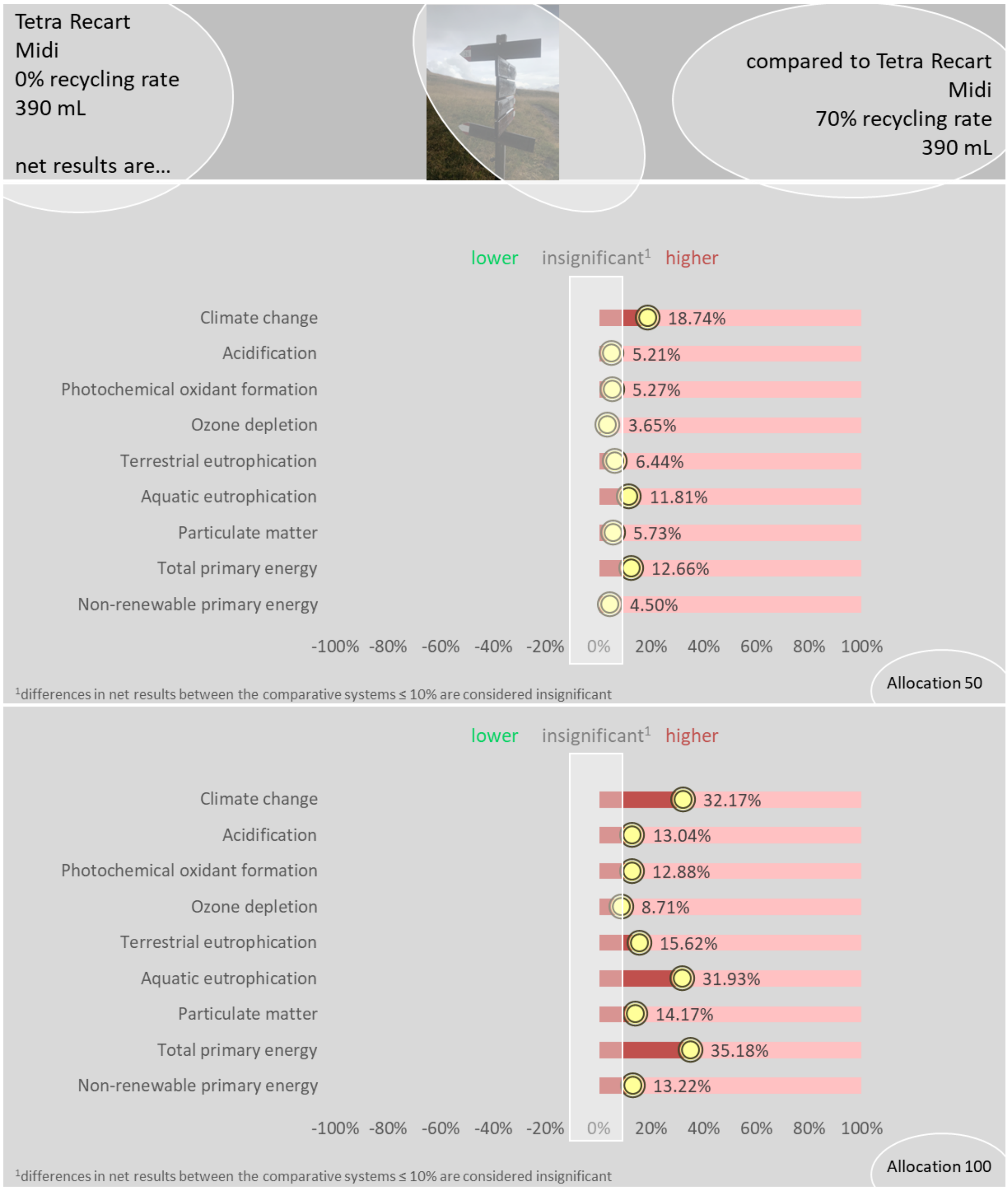

Figure 26: Comparison of net results Tetra Recart Midi 0% recycling rate and Tetra Recart Midi 70% recycling rate (Netherlands); allocation factor 50% and 100%

In both scenarios, the ***Tetra Recart Midi 0% rec. rate*** shows higher net results than the ***Tetra Recart Midi 70% rec. rate*** in the impact categories 'Climate change' and 'Aquatic eutrophication' and in the inventory category 'Total primary energy'.

In scenario AF 100% the ***Tetra Recart Midi 0% rec. rate*** measures higher net results compared to ***Tetra Recart Midi 70% rec. rate*** in the impact categories 'Acidification', 'Photochemical oxidant formation', 'Terrestrial eutrophication' and 'Particulate matter', and in the inventory category 'Non-renewable primary energy'.

No significant differences are measured in the impact category 'Ozone depletion'.

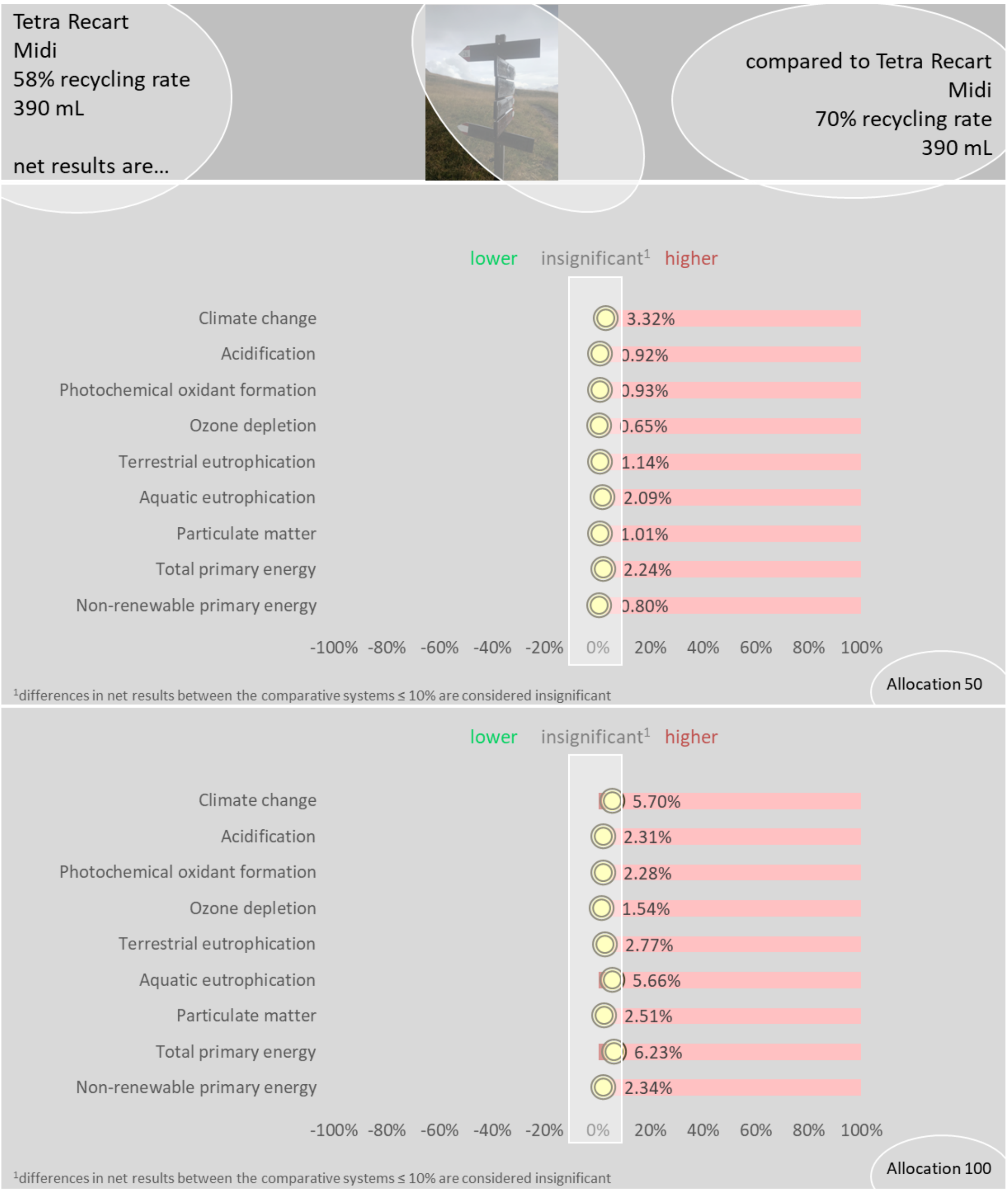

Figure 27: Comparison of net results Tetra Recart Midi 58% recycling rate and Tetra Recart Midi 70% recycling rate (Netherlands); allocation factor 50% and 100%

No significant differences are shown in the comparison of the net results of ***Tetra Recart Midi 58% rec. rate*** and the ***Tetra Recart Midi 70% rec. rate***.

4.5.2 Comparisons of Tetra Recart Mini with competing packaging systems

Figure 28: Comparison of net results Tetra Recart Mini 0% recycling rate and stand-up pouch 1 (225 mL) (Netherlands); allocation factor 50% and 100%

In both scenarios, the ***Tetra Recart Mini 0% rec. rate*** shows lower net results than ***stand-up pouch 1*** in the impact categories 'Climate change', 'Acidification', 'Photochemical oxidant formation', 'Ozone depletion', 'Terrestrial eutrophication', 'Particulate matter' and in the inventory categories 'Total primary energy' and 'Non-renewable primary energy'.

No significant differences are measured in the impact category 'Aquatic eutrophication'.

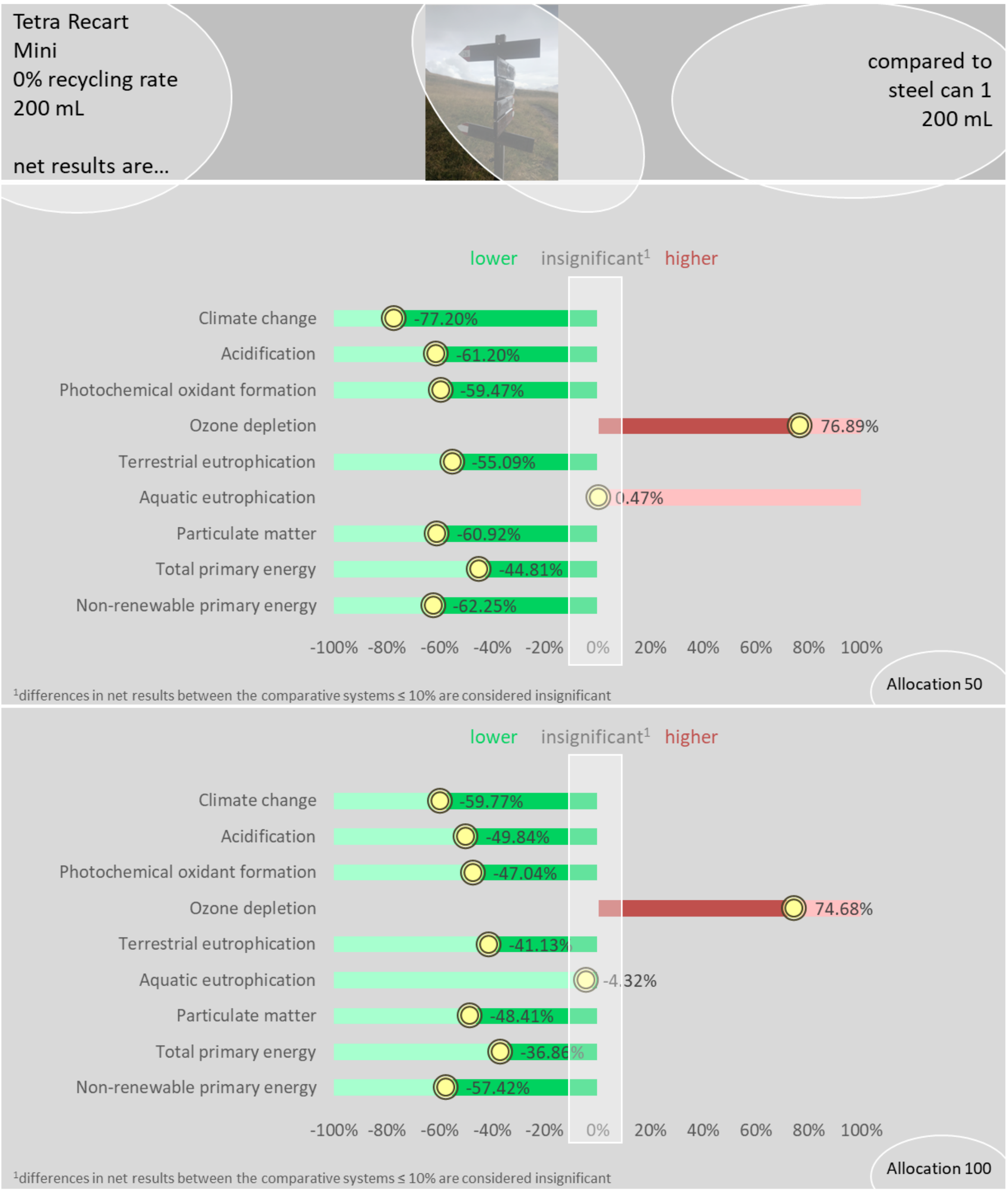

Figure 29: Comparison of net results Tetra Recart Mini 0% recycling rate and steel can 1 (200 mL) (Netherlands); allocation factor 50% and 100%

In both scenarios, the ***Tetra Recart Mini 0% rec. rate*** shows lower net results than ***steel can 1*** in the impact categories 'Climate change', 'Acidification', 'Photochemical oxidant formation', 'Terrestrial eutrophication' and 'Particulate matter' and in the inventory categories 'Total primary energy' and 'Non-renewable primary energy'.

In both scenarios, the ***Tetra Recart Mini 0% rec. rate*** measures higher net results than ***steel can 1*** in the impact category 'Ozone depletion'.

No significant differences are measured in the impact category 'Aquatic eutrophication'.

Figure 30: Comparison of net results Tetra Recart Mini 58% recycling rate and stand-up pouch 1 (225 mL) (Netherlands); allocation factor 50% and 100%

In both scenarios, the ***Tetra Recart Mini 58% rec. rate*** shows lower net results than ***stand-up pouch 1*** in the impact categories 'Climate change', 'Acidification', 'Photochemical oxidant formation', 'Ozone depletion', 'Terrestrial eutrophication' and 'Particulate matter' and in the inventory categories 'Total primary energy' and 'Non-renewable primary energy'.

In scenario AF 100% the ***Tetra Recart Mini 58% rec. rate*** measures lower net results compared to ***stand-up pouch 1*** in the impact category 'Aquatic eutrophication'.

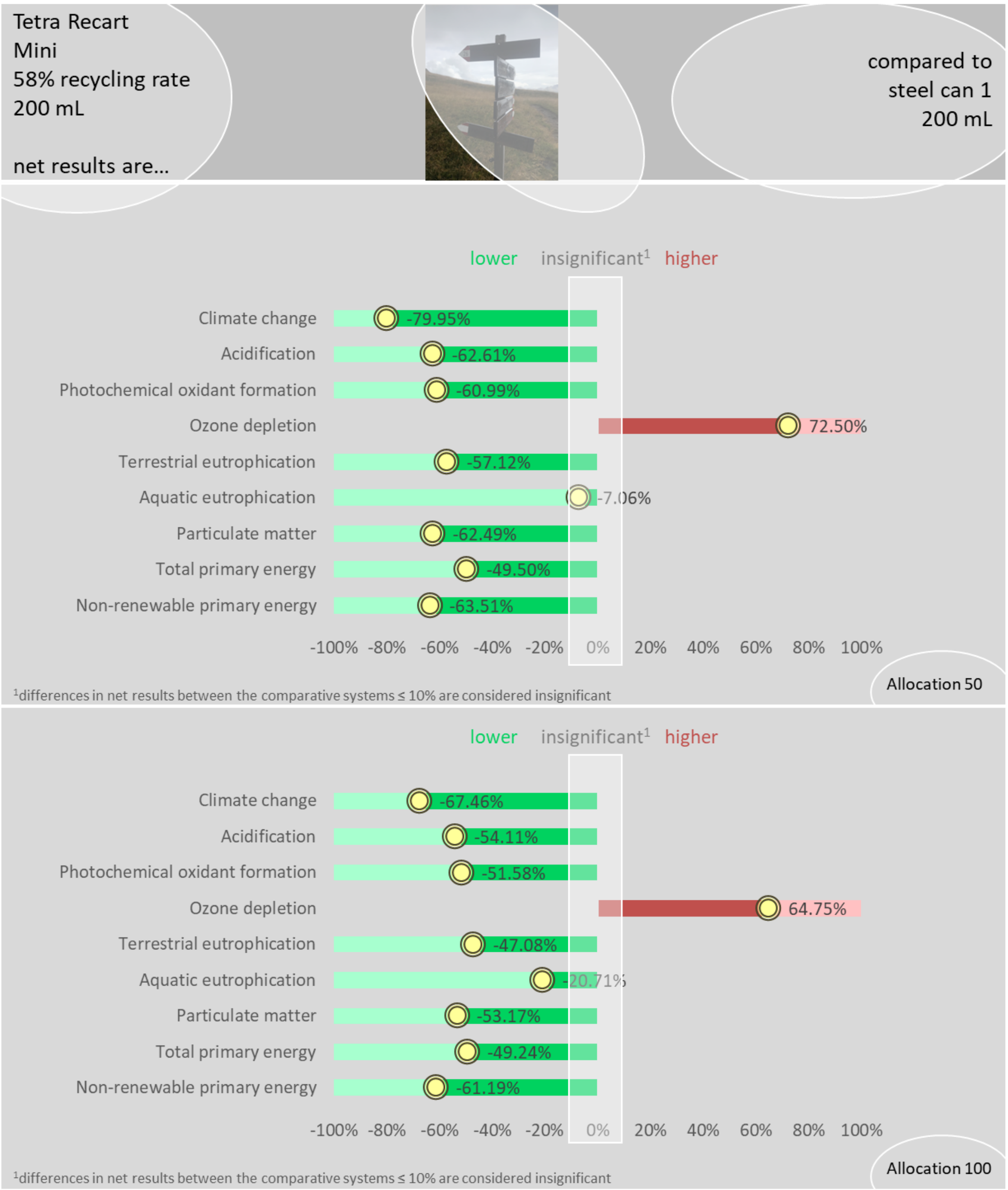

Figure 31: Comparison of net results Tetra Recart Mini 58% recycling rate and steel can 1 (200 mL) (Netherlands); allocation factor 50% and 100%

In both scenarios, the ***Tetra Recart Mini 58% rec. rate*** shows lower net results than ***steel can 1*** in the impact categories 'Climate change', 'Acidification', 'Photochemical oxidant formation', 'Terrestrial eutrophication' and 'Particulate matter' and in the inventory categories 'Total primary energy' and 'Non-renewable primary energy'.

In both scenarios, the ***Tetra Recart Mini 58% rec. rate*** measures higher net results than ***steel can 1*** in the impact category 'Ozone depletion'.

In scenario AF 100% the ***Tetra Recart Mini 58% rec. rate*** measures lower net results compared to ***steel can 1*** in the impact category 'Aquatic eutrophication'.

Figure 32: Comparison of net results Tetra Recart Mini 70% recycling rate and stand-up pouch 1 (225 mL) (Netherlands); allocation factor 50% and 100%

In both scenarios, the ***Tetra Recart Mini 70% rec. rate*** shows lower net results than ***stand-up pouch 1*** in the impact categories 'Climate change', 'Acidification', 'Photochemical oxidant formation', 'Ozone depletion', 'Terrestrial eutrophication' and 'Particulate matter' and in the inventory categories 'Total primary energy' and 'Non-renewable primary energy'.

In scenario AF 100% the ***Tetra Recart Mini 70% rec. rate*** measures lower net results compared to ***stand-up pouch 1*** in the impact category 'Aquatic eutrophication'.

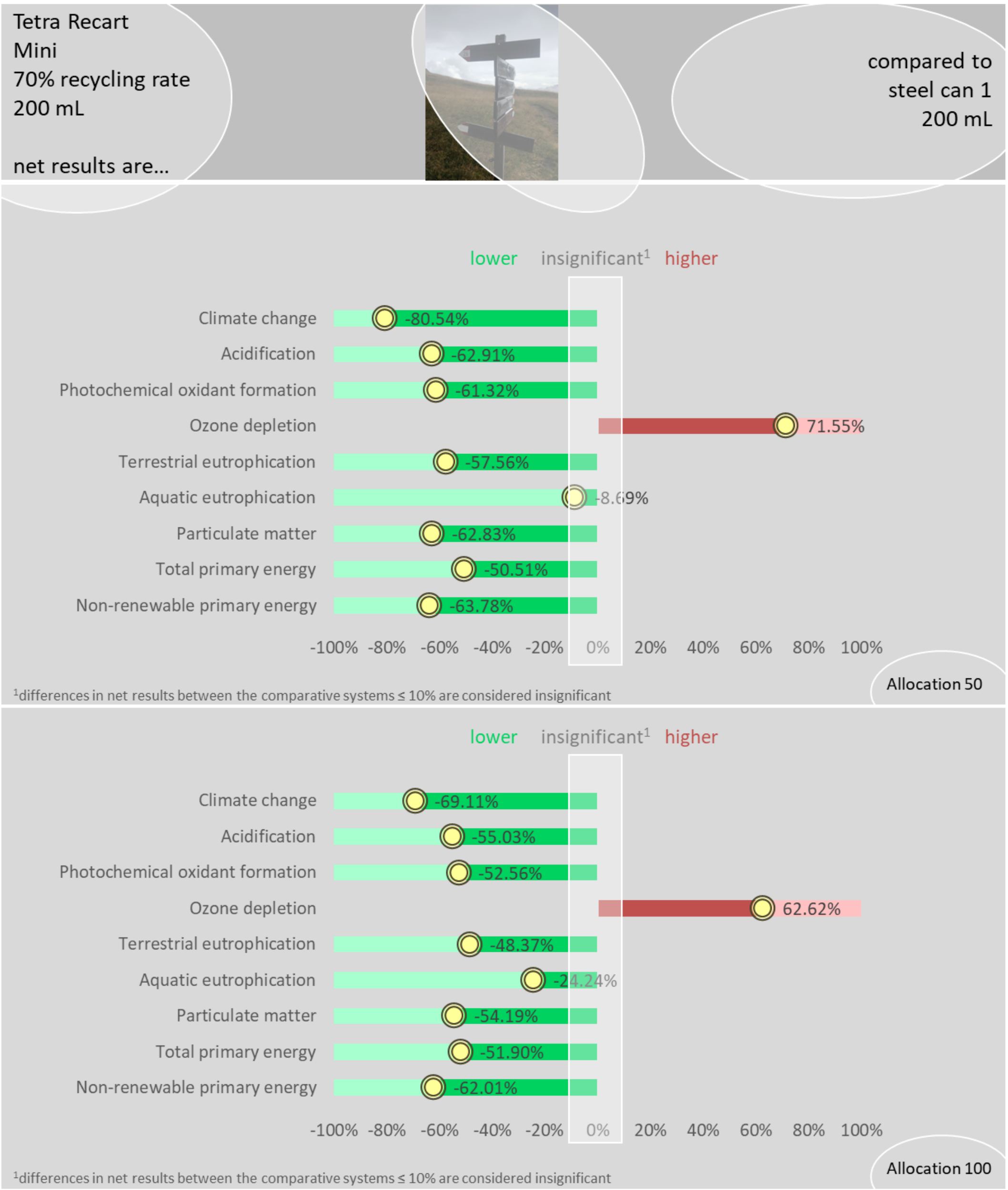

Figure 33: Comparison of net results Tetra Recart Mini 70% recycling rate and steel can 1 (200 mL) (Netherlands); allocation factor 50% and 100%

In both scenarios, the ***Tetra Recart Mini 70% rec. rate*** shows lower net results than ***steel can 1*** in the impact categories 'Climate change', 'Acidification', 'Photochemical oxidant formation', 'Terrestrial eutrophication' and 'Particulate matter' and in the inventory categories 'Total primary energy' and 'Non-renewable primary energy'.

In both scenarios, the ***Tetra Recart Mini 70% rec. rate*** measures higher net results than ***steel can 1*** in the impact category 'Ozone depletion'.

In scenario AF 100% the ***Tetra Recart Mini 70% rec. rate*** measures lower net results compared to ***steel can 1*** in the impact category 'Aquatic eutrophication'.

4.5.3 Comparison of Tetra Recart Midi with competing packaging systems

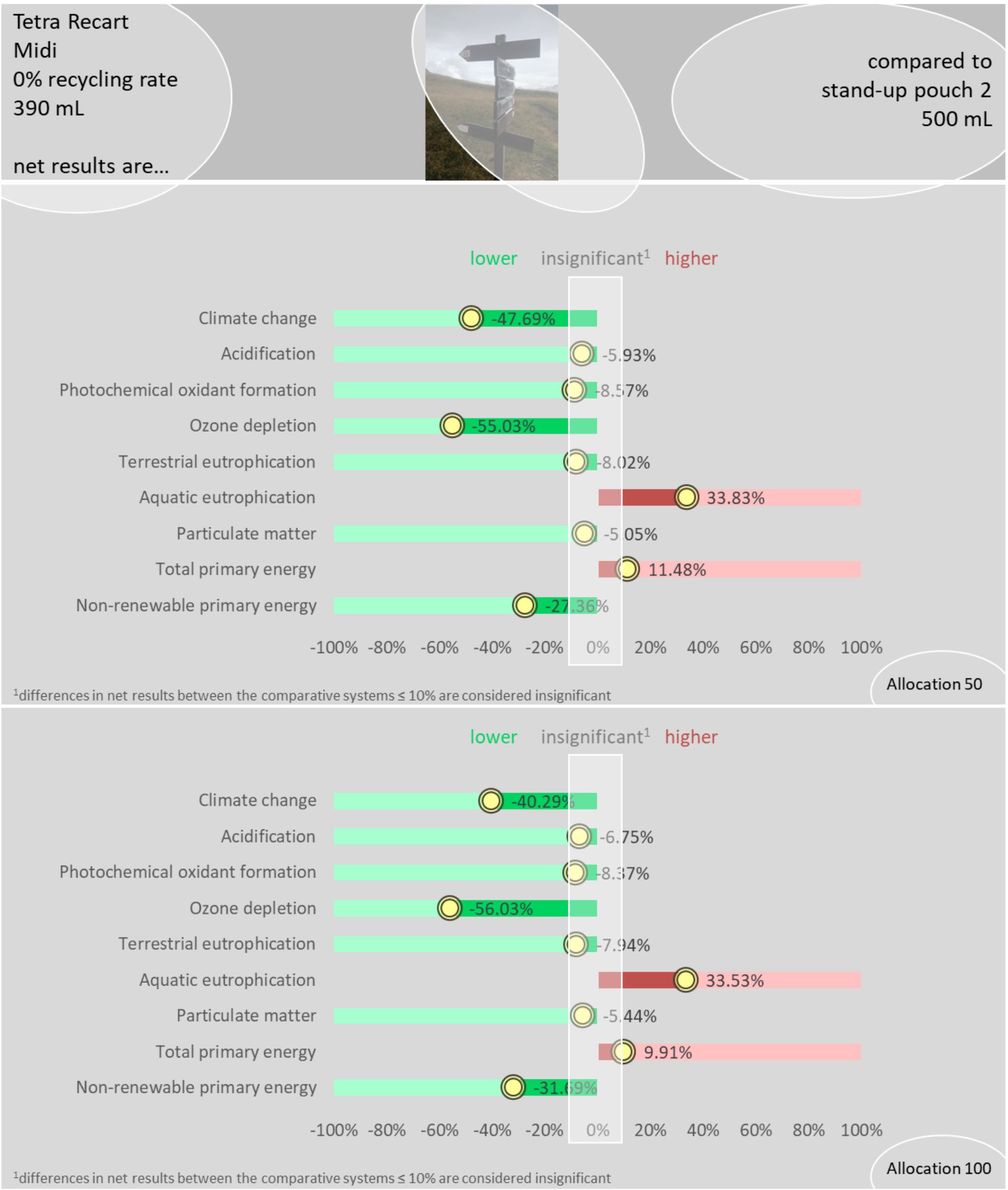

Figure 34: Comparison of net results Tetra Recart Midi 0% recycling rate and stand-up pouch 2 (500 mL) (Netherlands); allocation factor 50% and 100%

In both scenarios, the ***Tetra Recart Midi 0% rec. rate*** shows lower net results than ***stand-up pouch 2*** in the impact category 'Climate change', 'Ozone depletion' and in the inventory category 'Non-renewable primary energy'.

In both scenarios, the ***Tetra Recart Midi 0% rec. rate*** shows higher net results than ***stand-up pouch 2*** in the impact category, 'Aquatic eutrophication'.

Also, in scenario AF 50% the ***Tetra Recart Midi 0% rec. rate*** measures higher net results compared to ***stand-up pouch 2*** in the inventory category 'Total primary energy'.

No significant differences are measured in the impact categories 'Acidification', 'Photochemical oxidant formation', 'Terrestrial eutrophication' and 'Particulate matter'.

Figure 35: Comparison of net results Tetra Recart Midi 0% recycling rate and glass jar 1 (350 mL) (Netherlands); allocation factor 50% and 100%

In both scenarios, the ***Tetra Recart Midi 0% rec. rate*** shows lower net results than ***glass jar 1*** in the impact categories 'Climate change', 'Acidification', 'Photochemical oxidant formation', 'Terrestrial eutrophication' and 'Particulate matter' and in the inventory categories 'Total primary energy' and 'Non-renewable primary energy'.

In scenario AF 50% the ***Tetra Recart Midi 0% rec. rate*** measures lower net results compared to ***glass jar 1*** in the impact category 'Ozone depletion'.

In scenario AF 100% the ***Tetra Recart Midi 0% rec. rate*** measures lower net results compared to ***glass jar 1*** in the impact category 'Aquatic eutrophication'.

Figure 36: Comparison of net results Tetra Recart Midi 0% recycling rate and steel can 2 (400 mL) (Netherlands); allocation factor 50% and 100%

In both scenarios, the ***Tetra Recart Midi 0% rec. rate*** shows lower net results than ***steel can 2*** in the impact categories 'Climate change', 'Acidification', 'Photochemical oxidant formation', 'Terrestrial eutrophication' and 'Particulate matter' and in the inventory categories 'Total primary energy' and 'Non-renewable primary energy'.

In both scenarios, the ***Tetra Recart Midi 0% rec. rate*** measures higher net results than ***steel can 2*** in the impact categories 'Ozone depletion' and 'Aquatic eutrophication'.

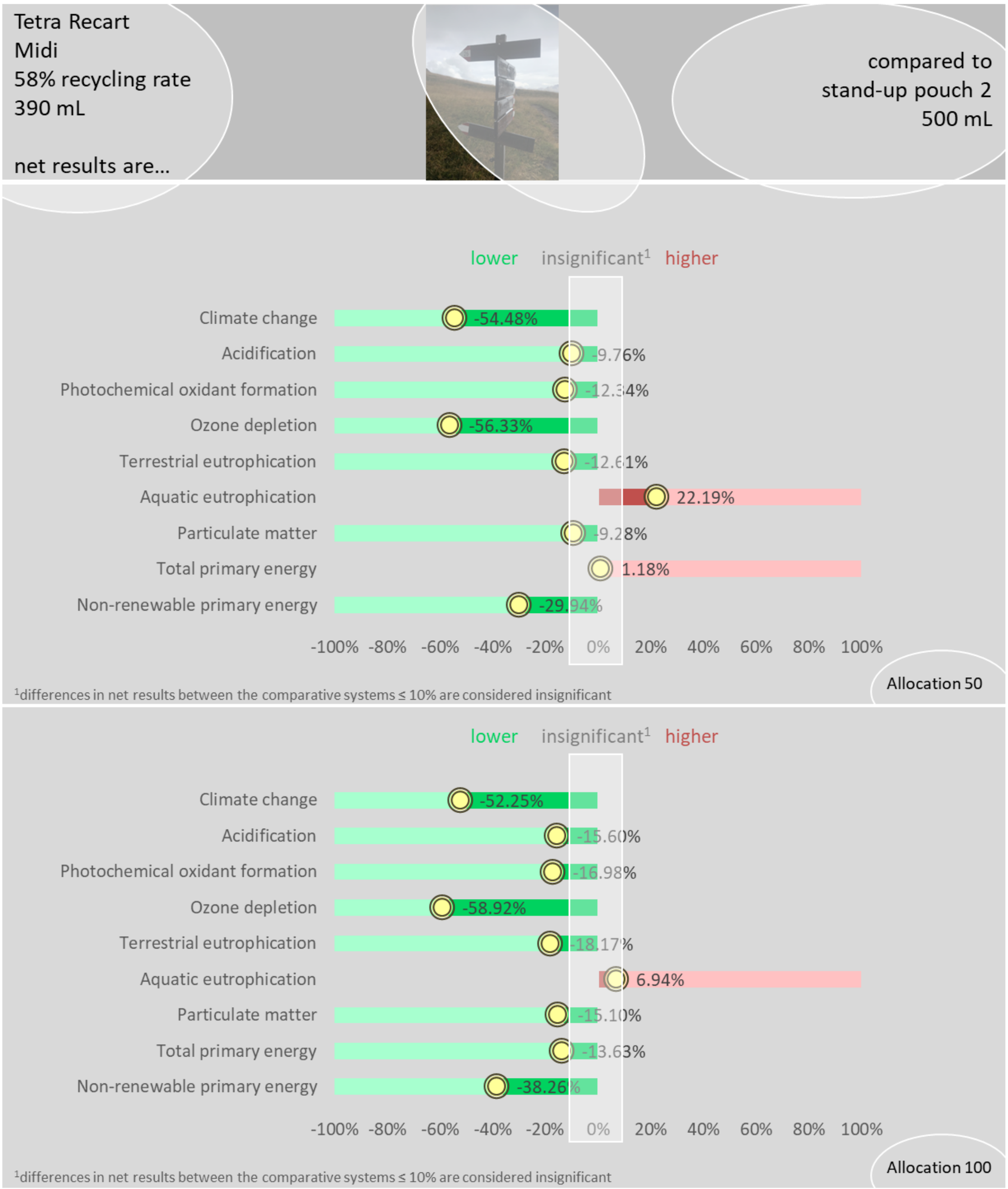

Figure 37: Comparison of net results Tetra Recart Midi 58% recycling rate and stand-up pouch 2 (500 mL) (Netherlands); allocation factor 50% and 100%

In both scenarios, the ***Tetra Recart Midi 58% rec. rate*** shows lower net results than ***stand-up pouch 2*** in the impact categories 'Climate change', 'Photochemical oxidant formation', 'Terrestrial eutrophication' and 'Ozone depletion' and in the inventory category 'Non-renewable primary energy'.

Also, in scenario AF 100% the ***Tetra Recart Midi 58% rec. rate*** measures lower net results compared to ***stand-up pouch 2*** in the impact categories 'Acidification' and 'Particulate matter' and in the inventory category 'Total primary energy'.

In scenario AF 50% the ***Tetra Recart Midi 58% rec. rate*** measures higher net results compared to ***stand-up pouch 2*** in the impact category 'Aquatic eutrophication'.

Figure 38: Comparison of net results Tetra Recart Midi 58% recycling rate and glass jar 1 (350 mL) (Netherlands); allocation factor 50% and 100%

In both scenarios, the ***Tetra Recart Midi 58% rec. rate*** shows lower net results than ***glass jar 1*** in all impact and inventory categories.

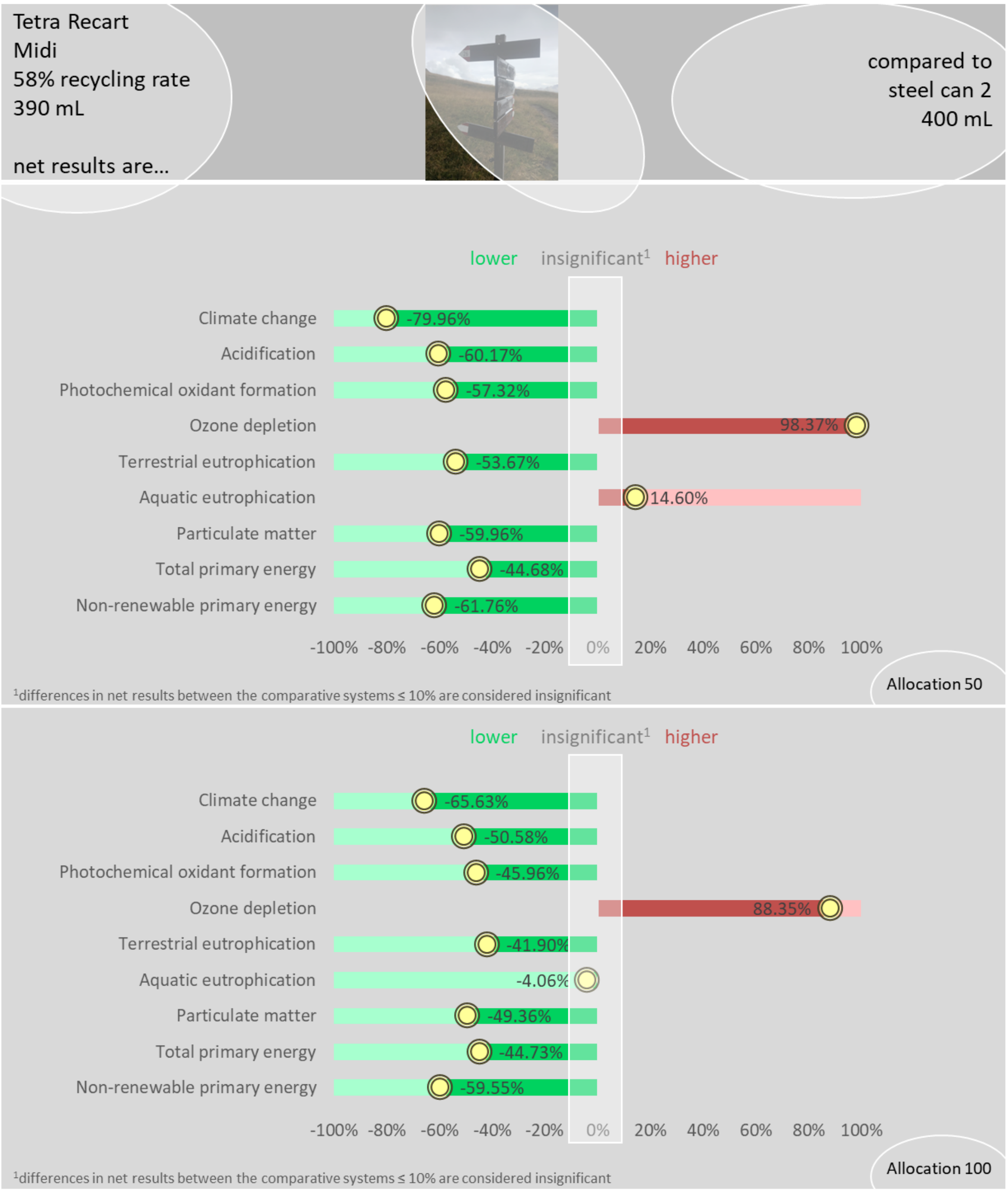

Figure 39: Comparison of net results Tetra Recart Midi 58% recycling rate and steel can 2 (400 mL) (Netherlands); allocation factor 50% and 100%

In both scenarios, the ***Tetra Recart Midi 58% rec. rate*** shows lower net results than ***steel can 2*** in the impact categories 'Climate change', 'Acidification', 'Photochemical oxidant formation', 'Terrestrial eutrophication' and 'Particulate matter' and in the inventory categories 'Total primary energy' and 'Non-renewable primary energy'.

In both scenarios, the ***Tetra Recart Midi 58% rec. rate*** measures higher net results than ***steel can 2*** in the impact category 'Ozone depletion'.

Also, in scenario AF 100% the ***Tetra Recart Midi 58% rec. rate*** measures higher net results than ***steel can 2*** in the impact category 'Aquatic eutrophication'.

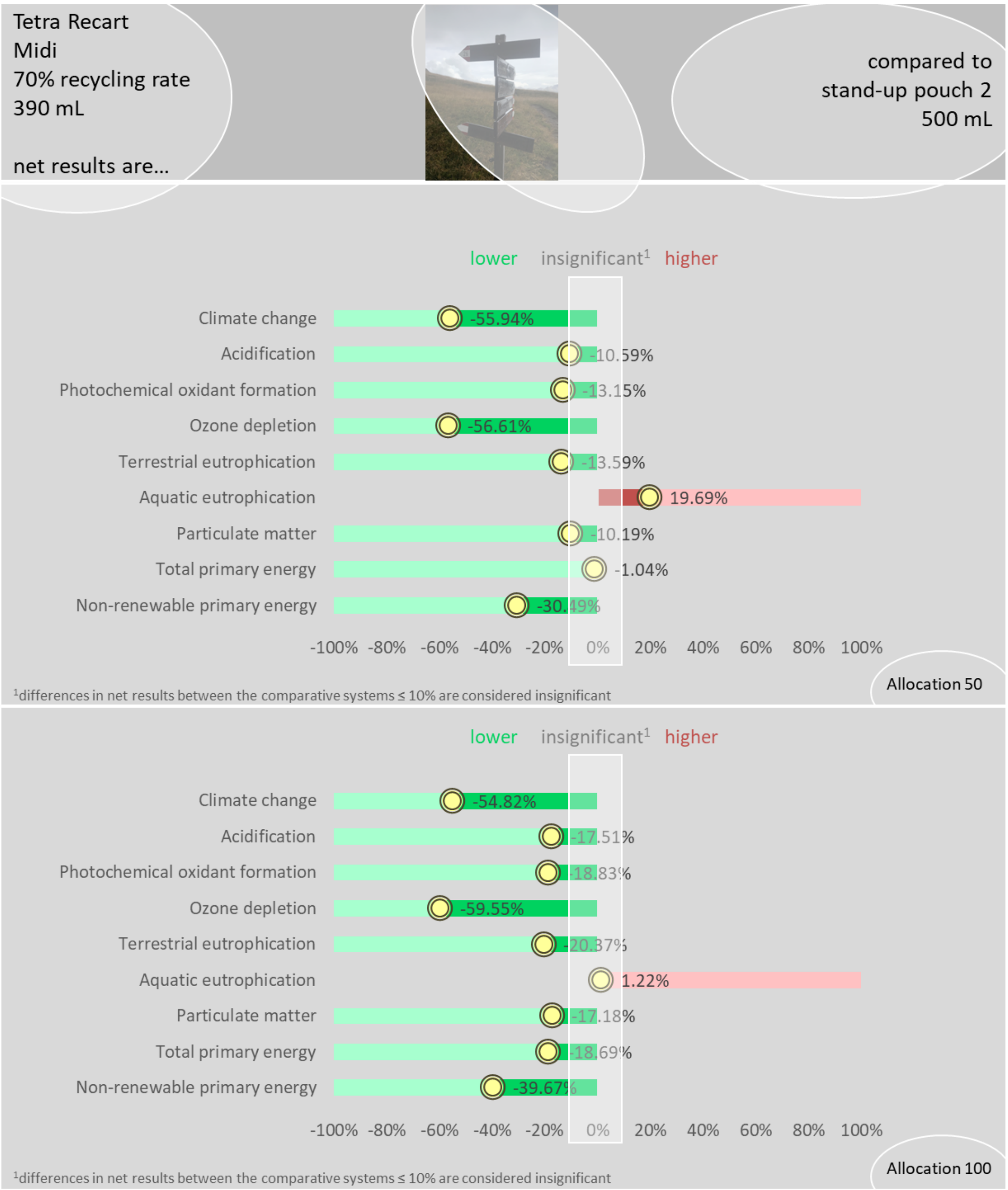

Figure 40: Comparison of net results Tetra Recart Midi 70% recycling rate and stand-up pouch 2 (500 mL) (Netherlands); allocation factor 50% and 100%

In both scenarios, the ***Tetra Recart Midi 70% rec. rate*** shows lower net results than ***stand-up pouch 2*** in the impact categories 'Climate change', 'Acidification', 'Photochemical oxidant formation', 'Ozone depletion', 'Terrestrial eutrophication' and 'Particulate matter' and in the inventory category 'Non-renewable primary energy'.

Also, in scenario AF 100% the ***Tetra Recart Midi 70% rec. rate*** measures lower net results compared to ***stand-up pouch 2*** in the inventory category 'Total primary energy'.

In scenario AF 50% the ***Tetra Recart Midi 70% rec. rate*** measures higher net results compared to ***stand-up pouch 2*** in the impact category 'Aquatic eutrophication'.

Figure 41: Comparison of net results Tetra Recart Midi 70% recycling rate and glass jar 1 (350 mL) (Netherlands); allocation factor 50% and 100%

In both scenarios, the ***Tetra Recart Midi 70% rec. rate*** shows lower net results than ***glass jar 1*** in all impact and inventory categories.

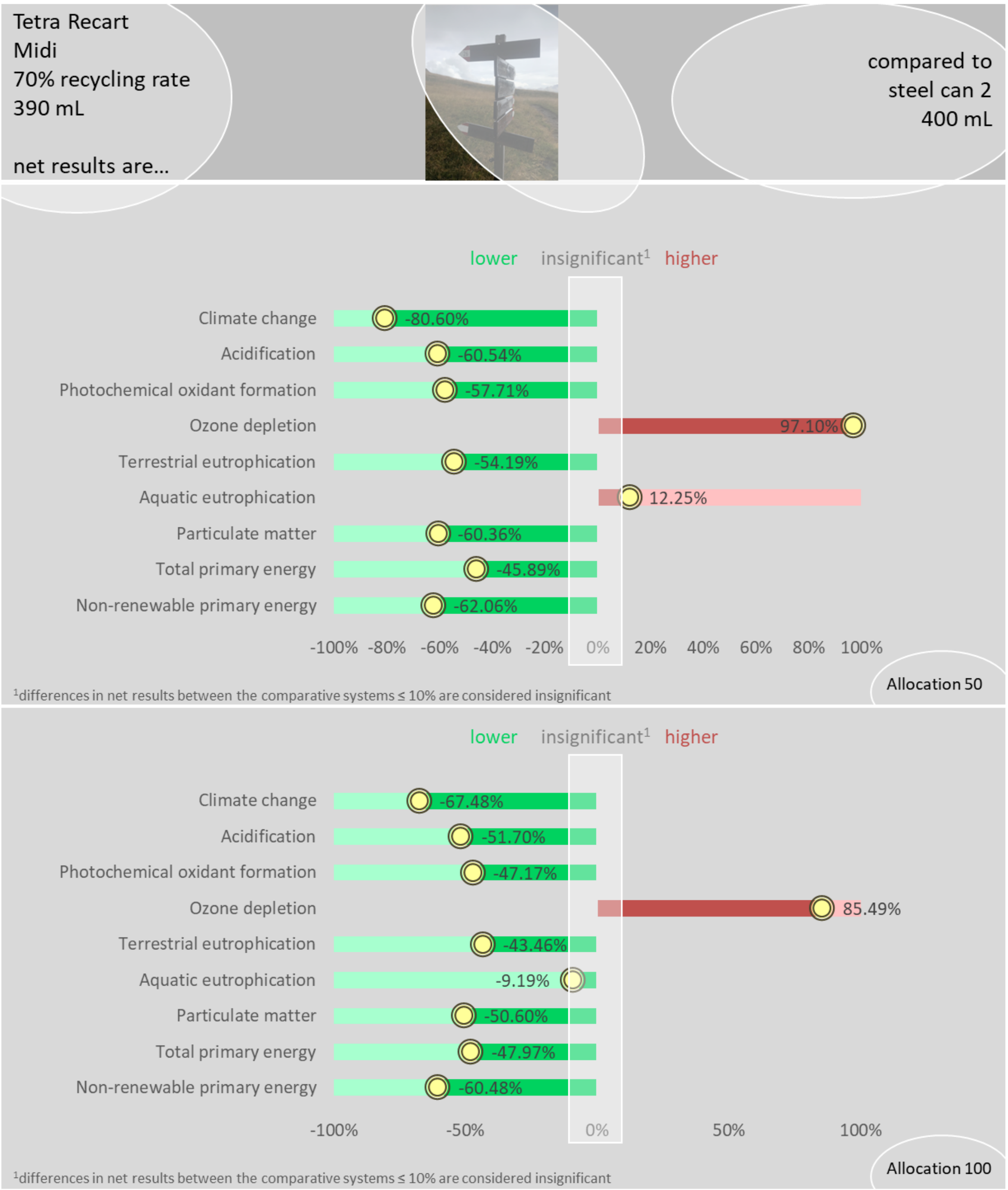

Figure 42: Comparison of net results Tetra Recart Midi 70% recycling rate and steel can 2 (400 mL) (Netherlands); allocation factor 50% and 100%

In both scenarios, the ***Tetra Recart Midi 70% rec. rate*** shows lower net results than ***steel can 2*** in the impact categories 'Climate change', 'Acidification', 'Photochemical oxidant formation', 'Terrestrial eutrophication' and 'Particulate matter' and in the inventory categories 'Total primary energy' and 'Non-renewable primary energy'.

In both scenarios, the ***Tetra Recart Midi 70% rec. rate*** measures higher net results than ***steel can 2*** in the impact category 'Ozone depletion'.

Also, in scenario AF 50% the ***Tetra Recart Midi 70% rec. rate*** measures higher net results compared to ***steel can 2*** in the impact category 'Aquatic eutrophication'.

5 Description and conclusions

The following sections describe and summarise the results of the packaging systems on the Dutch market regarding the different recycling rates of the Tetra Recart packaging system and the comparison with stand-up pouches, glass jar and steel cans. Conclusions are drawn from the results presented in the previous sections. In this section results with the 50% allocation factor and the 100% allocation factor are taken into account to the same degree. Differences of 10% and lower are considered to be insignificant (please see also **section 1.3** on precision and uncertainty).

5.1 Environmental impacts of different recycling rates

Recycling rates of Tetra Recart Mini (200 mL): 0% vs. 58%

For Tetra Recart Mini, a recycling rate of 0% leads to significantly higher emissions in the impact category 'Climate change' with both allocation factors (50%, 100%) than with a recycling rate of 58%.

Furthermore, regarding allocation factor 100%, a recycling rate of 0% leads to significantly higher emissions in the impact categories 'Terrestrial eutrophication', 'Aquatic eutrophication' and 'Particulate matter' and in the inventory category 'Total primary energy' than with a recycling rate of 58%.

Recycling rates of Tetra Recart Mini (200 mL): 0% vs. 70%

For Tetra Recart Mini, a recycling rate of 0% leads to significantly higher emissions in the impact categories 'Climate change', 'Aquatic Eutrophication' and in the inventory category 'Total primary energy' with both allocation factors (50%, 100%) than with a recycling rate of 70%.

Furthermore, regarding allocation factor 100%, a 0% recycling rate of Tetra Recart Mini shows significantly higher emissions in the impact categories 'Acidification', 'Photochemical oxidant formation', 'Terrestrial eutrophication' and 'Particulate matter' and in the inventory category 'Non-renewable primary energy' than with a 70% recycling rate of Tetra Recart Mini.

Recycling rates of Tetra Recart Mini (200 mL): 58% vs. 70%

No significant differences are measured for both allocation factors (50%, 100%) in the comparison with a recycling rate of 58% and a recycling rate of 70%.

Recycling rates of Tetra Recart Midi (390 mL): 0% vs. 58%

A recycling rate of 0% leads to significantly higher emissions in the impact category 'Climate change' and and in the inventory category' Total primary energy' with both allocation factors (50%, 100%) than with a recycling rate of 58%.

Furthermore, regarding allocation factor 100%, a 0% recycling rate of Tetra Recart Midi shows significantly higher emissions in the impact categories 'Acidification', 'Photochemical oxidant formation', 'Terrestrial eutrophication', 'Aquatic eutrophication' and 'Particulate matter' and in the inventory category 'Non-renewable primary energy' than with a 58% recycling rate of Tetra Recart Midi.

Recycling rates of Tetra Recart Midi (390 mL): 0% vs. 70%

For Tetra Recart Midi, a recycling rate of 0% leads to significantly higher emissions in the impact categories 'Climate change' and 'Aquatic eutrophication' and in the inventory category 'Total primary energy' with both allocation factors (50%, 100%) than with a recycling rate of 70%.

Furthermore, regarding allocation factor 100%, a 0% recycling rate of Tetra Recart Midi shows significantly higher emissions in the impact categories 'Acidification', 'Photochemical oxidant formation', 'Terrestrial eutrophication' and 'Particulate matter', and in the inventory category 'Non-renewable primary energy' than a 70% recycling rate of Tetra Recart Midi.

Recycling rates of Tetra Recart Midi (390 mL): 58% vs. 70%

No significant differences are measured for both allocation factors (50%, 100%) in the comparison with a recycling rate of 58% and a recycling rate of 70%.

5.2 Competing packaging systems

Tetra Recart Mini (200 mL) vs. stand-up pouch 1 (225 mL)

For 'Climate change', 'Acidification', 'Photochemical oxidant formation', 'Ozone depletion', 'Terrestrial eutrophication', 'Particulate matter', 'Total primary energy' and 'Non-renewable primary energy', Tetra Recart Mini shows throughout all examined recycling rates (0%, 58%, 70%) lower impacts with both, the 50% and the 100% allocation factor than the compared **stand-up pouch 1.**

The pattern of the results when comparing Tetra Recart Mini 0% rec. rate and Tetra Recart Mini 70% rec. rate to stand-up pouch 1 with 100% allocation factor changes: Insignificant impacts of Tetra Recart Mini in the category 'Aquatic eutrophication' change to significant lower impacts with a 70% recycling rate.

Tetra Recart Mini (200 mL) vs. steel can 1 (200 mL)

For 'Climate change', 'Acidification', 'Photochemical oxidant formation', 'Terrestrial Eutrophication', 'Particulate matter', 'Total primary energy' and 'Non-renewable primary energy' the Tetra Recart Mini shows throughout all examined recycling rates (0%, 58%, 70%) lower impacts with both, the 50% and the 100% allocation factor than the compared **steel can 1.** For 'Ozone depletion' the Tetra Recart Mini shows throughout all examined recycling rates (0%, 58%, 70%) higher impacts with both, the 50% and the 100% allocation factor than the compared steel can 1 (200 mL).

The pattern of the results when comparing Tetra Recart Mini 0% rec. rate and Tetra Recart Mini 70% rec. rate to steel can 1 with 100% allocation factor changes: Insignificant impacts of Tetra Recart Mini in the category 'Aquatic eutrophication' change to significant lower impacts with a 70% recycling rate.

Tetra Recart Midi (390 mL) vs. stand-up pouch 2 (500 mL)

For 'Climate change', 'Ozone depletion' and 'Non-renewable primary energy' the Tetra Recart Midi shows throughout all examined recycling rates (0%, 58%, 70%) lower impacts with both, the 50% and the 100% allocation factor than the compared **stand-up pouch 2.**

The pattern of the results when comparing Tetra Recart Midi 0% rec. rate and Tetra Recart 70% rec. rate to stand-up pouch 2 with 50% allocation factor changes: Insignificant differences of Tetra Recart Midi 0% recycling rate in the categories 'Acidification', 'Photochemical oxidant formation', Terrestrial eutrophication' and 'Particulate matter' show lower impacts with a 70% recycling rate.

Furthermore, the pattern of the results when comparing Tetra Recart Midi 0% rec. rate and Tetra Recart Midi 70% rec. rate to stand-up pouch 2 with 100% allocation factor changes: Significant higher impacts of Tetra Recart Midi 0% recycling rate in the category 'Aquatic eutrophication' change to significant insignificant differences with a 70% recycling rate. Insignificant impacts of Tetra Recart Midi 0% recycling rate in the categories 'Acidification', 'Photochemical oxidant formation', 'Terrestrial eutrophication', 'Particulate matter' and 'Total primary energy' change to significant lower impacts with a 70% recycling rate.

Tetra Recart Midi (390 mL) vs. glass jar 1 (350 mL)

For 'Climate change', 'Acidification', 'Photochemical oxidant formation', 'Terrestrial eutrophication', 'Particulate matter', 'Total primary energy' and 'Non-renewable primary energy' the Tetra Recart Midi shows throughout all examined recycling rates (0%, 58%, 70%) lower impacts with both, the 50% and the 100% allocation factor than the compared **glass jar 1.**

The pattern of the results when comparing Tetra Recart Midi 0% rec. rate and Tetra Recart 70% rec. rate to glass jar 1 with 50% allocation factor changes: Insignificant differences of Tetra Recart Midi 0% recycling rate in the category 'Aquatic eutrophication' shows lower impacts with a 70% recycling rate.

Furthermore, the pattern of the results when comparing Tetra Recart Midi 0% rec. rate and Tetra Recart Midi 70% rec. rate to glass jar 1 with 100% allocation factor changes: Insignificant differences of Tetra Recart Midi 0% recycling rate in the category 'Ozone depletion' changes to significant lower impacts with a 70% recycling rate.

Tetra Recart Midi (390 mL) vs. steel can 2 (400 mL)

For 'Climate change', 'Acidification', 'Photochemical oxidant formation', 'Terrestrial eutrophication', 'Particulate matter', 'Total primary energy' and 'Non-renewable primary energy' the Tetra Recart Midi shows throughout all examined recycling rates (0%, 58%, 70%) lower impacts with both, the 50% and the 100% allocation factor than the compared **steel can 2.** For 'Ozone depletion' the Tetra Recart Midi shows throughout all examined recycling rates (0%, 58%, 70%) higher impacts with both, the 50% and the 100% allocation factor than the compared steel can 2 (400 mL).

The pattern of the results when comparing Tetra Recart Midi 0% rec. rate and Tetra Recart Midi 70% rec. rate to steel can 2 with 100% allocation factor changes: Higher impacts of Tetra Recart Midi 0% recycling rate in the category 'Aquatic eutrophication' changes to insignificant differences with a 70% recycling rate.

5.3 Conclusions

General

The Tetra Recarts analysed in this study show different environmental performances depending on their packaging specifications.

In general, Tetra Recarts, as well as alternative packaging systems benefit from a larger filling volume leading to lower impacts per functional unit as in most cases the amount of packaging material per functional unit decreases with higher filling volumes.

Alternative packaging systems examined in this study show high burdens from the production of their base materials, like plastics, glass, or steel. For Tetra Recarts on the other hand the production of liquid packaging board (LPB) does not contribute as much to the environmental impact, as its production utilises mainly renewable energy leading to lower environmental impacts.

Recycling rate

The application of different recycling rates to Tetra Recart Mini and Tetra Recart Midi has an impact on the environmental results.

Generally, for Tetra Recart Mini and Tetra Recart Midi on the Dutch market, a higher recycling rate leads to lower environmental impacts in the environmental impact categories 'Climate change' and 'Aquatic Eutrophication' and in the inventory category 'Total primary energy' (with allocation factor 50% and allocation factor 100%).

In all other categories the different recycling rates do not lead to significant changes in impact results (if significance threshold of 10% applied).

Competing packaging systems

Tetra Recarts show lower environmental impacts than their compared packaging systems regarding 'Climate change' and 'Non-renewable primary energy'.

The results of the comparisons with competing packaging systems for the other categories are more diverse between the different segments and packaging systems. Therefore, for conclusions regarding the comparative performances of Tetra Recarts beyond 'Climate change' and 'Non-renewable primary energy', the detailed description in **section 5.2** should be consulted.

The pattern of the results when comparing Tetra Recart Mini to steel can 1 remains the same, regardless of the applied recycling rate in all impact and inventory categories examined, also with a 0% recycling rate.

When comparing Tetra Recart Mini 0% recycling rate and Tetra Recart Mini 70% recycling rate to stand-up pouch 1, the pattern of results remains the same, regardless of the applied recycling rate in all impact categories examined, also with a 0% recycling rate.

When comparing Tetra Recart Midi 0% recycling rate and Tetra Recart Midi 70% recycling rate to stand-up pouch 2, the pattern of results changes in the impact categories 'Acidification', 'Photochemical oxidant formation', 'Terrestrial eutrophication', 'Aquatic eutrophication' and 'Particulate matter' and in the inventory category 'Total primary energy'.

When comparing Tetra Recart Midi 0% recycling rate and Tetra Recart Midi 70% recycling rate to glass jar 1, the pattern of results changes in the impact categories 'Ozone depletion' and 'Aquatic eutrophication'.

When comparing Tetra Recart Midi 0% recycling rate and Tetra Recart Midi 70% recycling rate to steel can 2, the pattern of results changes in the impact categories 'Aquatic eutrophication'.

6 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 products from the segment Liquid Food (ambient). 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.

Limitations concerning **conventions**:
Conventions are required to take biogenic carbon into account in calculations. The results of this study are only valid for the conventions explained and justified in detail in section 1.7.2.

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.

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 available and most appropriate data for the purpose of this study. It is based on figures provided by the commissioner and data from ifeu's internal database. In addition, the different quality level of the data does not affect the results of the study and the 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.

7 Recommendations

Since the environmental result of the Tetra Recart is significantly influenced by the production of its main component, the sleeve, measures to ensure the same functionality by using less material would be recommended.

Based on the conclusions of this study, that a higher recycling rate leads to significantly lower impacts in the categories 'Climate change', 'Aquatic Eutrophication' and 'Total primary energy' it is recommended to assess possibilities which provoke an increase of recycling rate by

- an increase of collection rates
- a reduction of sorting residues.

No general recommendation from an environmental viewpoint can be given for one type of packaging that is valid for the entire segment Liquid Food Portion Pack (ambient).

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Critical Review Statement according to ISO 14040 and 14044

of the study

Comparative Life Cycle Assessment of Tetra Pak's® Tetra Recart and alternative packaging systems for liquid food 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)
Leigh Holloway
Alex Hetherington

21/05/2024

1. Procedural Aspects of the Critical Review

This Critical Review (CR) was commissioned by Tetra Pak® (commissioner) via Magdalena Psuja, Sustainability Transformation Manager, Tetra Pak Sp. z o.o., Poland, in late 2023. The Life Cycle Assessment (LCA) study was conducted by 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 Final Draft Report was submitted on 29 January 2024. This was later than expected, wherefore the CR panel had to reorganize the time schedule originally foreseen for the review. Thus, initial comments by the panel were sent only on March 4th 2024 and discussed in a visio-conference on March 19th 2024. During the conference call the comments were elaborated by the panel members and discussed with the practitioner IFEU and the commissioner Tetra Pak (TP) in detail.

The review panel received a revised version of the Final Draft Report of the study on April 12th 2024. The panel sent further comments back on May 4th 2024. On May 13th 2024 IFEU delivered a revised Final Report with the consideration of the second-round comments that then 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 May 21st 2024. 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 necessary data, including confidential ones were presented to the reviewers and all issues 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's® Tetra Recart and alternative packaging systems for liquid food on the Dutch market" – Final Report in the version of May 13th 2024 - 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 CR panel are specific to the context and content of the present study only and shall not be generalised any further.

2. General Comments

This study, which has been carried out for liquid food and the Dutch market, is one of the regional studies commissioned by Tetra Pak, similar to the European study [Tetra Pak EU 2020]. The European Study is a full LCA according to ISO 14040 and ISO 14044 (cf. Critical Review Statement in [Tetra Pak

EU 2020]). In the study for the Dutch market, a further elaborated LCA model is used as in the European baseline study with region-specific Dutch data like packaging solutions for liquid food and end-of-life data and more recent data for the electricity mixes. Several impact categories are considered making it an assessment study of potential environmental impacts. In addition to climate change with the impact category indicator Global Warming Potential (GWP), which nowadays seems to be the most relevant one considering the current climate challenges, acidification, photo-oxidant formation, ozone depletion, terrestrial and aquatic eutrophication and particulate matter are considered in the study. Moreover, the indicators total primary energy and non-renewable primary energy at inventory level are systematically assessed throughout the results.

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

In this study liquid food packaging formats of Tetra Pak and competing packaging systems on the Dutch market are examined. TetraPak's liquid food packaging formats 'Tetra Recarts' are similar to beverage cartons. One main difference of the Tetra Recarts examined in this study is that they do not provide closures. The main objectives of this study are:

(1) to assess the environmental performance of Tetra Pak's liquid food carton system Tetra Recart (200 mL and 390 mL) on the Dutch market.
(2) to provide knowledge of the environmental impact of the recycling on the environmental performance of Tetra Recart (200 mL and 390 mL) on the Dutch market, by considering in the study a range of recycling rates (rather than solely the current recycling rate).
(3) to compare the environmental performance of Tetra Recart (200 mL and 390 mL) with those of competing packaging systems with high market relevance on the Dutch market.

The functional unit is meaningfully defined for packaging of beverages and liquid foods 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 and are clearly interpreted.

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 presents the total primary energy and non-renewable at inventory level and the panel agreed with this.

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 CO2 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 CO2 uptake is released at the end of life, because the allocation factor is not applied for the CO2 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 background 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 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 segment 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.

The conclusions, limitations the 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.

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.

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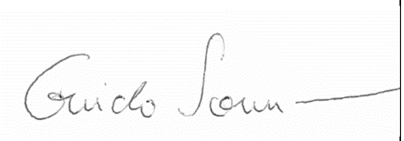		
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