INSTITUT FÜR ENERGIE- UND UMWELTFORSCHUNG HEIDELBERG

SIG Terra portfolio

Analysis of *cb8/cf8 SIG beverage cartons* on the European market

Comparative life cycle assessment of *cb8/cf8 SIG beverage cartons* for liquid dairy and NCSD on the European market

Final report

CB-100740

commissioned by SIG Combibloc

Heidelberg, April 2025

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Andrea Drescher

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List of abbreviations

ACE	Alliance for Beverage Cartons and the Environment
AFFB	Alu-free Full barrier
cb8	SIG MidiBloc
cf8	SIG MidiFit
CH	Switzerland
CML	Centrum voor Milieukunde (Center of Environmental Science), Leiden University, Netherlands
COD	Chemical Oxygen Demand
DE	Germany
EAA	European Aluminium Association
EU27+3	European Union + Switzerland and Norway + UK
fbp	Forest-based polymers
FEFCO	Fédération Européenne des Fabricants de Carton Ondulé (Brussels)
FU	Functional unit
GWP	Global Warming Potential
HBEFA	Handbook emission factors for road transport
HDPE	High density polyethylene
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
LP	LightProof
LPB	Liquid packaging board
MIR	Maximum Incremental Reactivity
MSWI	Municipal solid waste incineration
NCSD	Non-carbonated soft drinks

NMIR	Nitrogen-Maximum Incremental Reactivity
NMVOC	Non-methane volatile organic compounds
NO_X	Nitrogen oxides
pc	packs
PET	Polyethylene terephthalate
PM 2.5	Particulate matter with an aerodynamic diameter of 2.5 µm or smaller
PolyAl	Polyethylene-Aluminium
PP	Polypropylene
rPET	recycled PET
RS	Robust structure
TC	Tethered cap
UBA	Umweltbundesamt (German Federal Environmental Agency)
VOC	Volatile Organic Compounds

1 Goal and Scope

1.1 Background and Objectives

For about 20 years SIG Combibloc commissions ifeu to do life cycle assessments of their packaging products. SIG aims to provide life cycle assessment results for all types of beverage cartons in its portfolio. The SIG Midi family consists of three different formats: SIG MidiBloc (cb), SIG MidiFit (cf) and SIG MidiStyle. These are aseptically filled carton packs with a wide range of filling sizes, different closure options and material structures. In addition to the standard robust structure (standard RS) for NCSD (non-carbonated soft drinks) and liquid dairy products, structures without aluminium foil and/or with forest-based polymers (SIG Terra line) are available.

The *SIG Terra Alu-free Full barrier (AFFB) beverage carton* line is the first aluminium foil-free full barrier solution for aseptic carton packaging. A further development of this aseptic beverage carton without aluminium foil is the *SIG Terra Alu-free Full barrier Forest-based polymers (AFFB + fbp)*, which contains polymers that originate from renewable European wood sources via a mass-balance approach. These polymers replace conventional fossil-based polymers, which usually are contained in most aseptic beverage cartons.

The SIG packaging line *SIG MidiFit (cf8) – 1000 ml* is identical to the *SIG MidiBloc (cb8) – 1000 ml* with regard to all packaging specifications (including secondary and tertiary packaging). Thus, in the following, they will be referred to as " *cb8/cf8 SIG beverage cartons*".

Table 1-1 shows the different *cb8/cf8 SIG beverage cartons* for liquid dairy and NCSD products for the European market (EU27+3) and how they are grouped together for the purpose of this LCA.

Table 1-1: List of cb8/cf8 SIG beverage cartons examined for the European market

Beverage carton with closure	Short name of beverage carton scenario
SIG MidiBloc (cb8) Standard RS - 1000 ml with SIG SwiftCap Linked	cb8/cf8 standard RS - 1000 ml SwiftCap Linked
SIG MidiFit (cf8) Standard RS - 1000 ml with SIG SwiftCap Linked	
SIG Terra MidiBloc (cb8) Alu-free Full barrier - 1000 ml with SIG SwiftCap Linked LightProof	cb8/cf8 SIG Terra AFFB - 1000 ml SwiftCap Linked LP
SIG Terra MidiFit (cf8) Alu-free Full barrier - 1000 ml with SIG SwiftCap Linked LightProof	
SIG Terra MidiBloc (cb8) Alu-free Full barrier Forest-based polymers - 1000 ml with SIG SwiftCap Linked LightProof	cb8/cf8 SIG Terra AFFB + fbp - 1000 ml SwiftCap Linked LP
SIG Terra MidiFit (cf8) Alu-free Full barrier Forest-based polymers - 1000 ml with SIG SwiftCap Linked LightProof	

The main objectives of this study are:

- To provide knowledge about the environmental strengths and weaknesses of the *cb8/cf8 SIG beverage carton* formats in the filling sizes 1000 ml for the packaging at European market conditions,
- To examine two different *cb8/cf8 SIG Terra Alu-free Full barrier beverage cartons* and
- To compare the environmental impact results with those of the respective *cb8/cf8 standard RS beverage carton* on European market conditions.

As the results of this study shall be used for internal and external communication, the study is also reviewed by a critical review panel.

1.2 Organisation of the study

This study was commissioned by SIG Combibloc in 2024. It is being conducted by ifeu.

The members of the project panel are:

- Frederic di Monte (SIG Combibloc)
- Udo Felten (SIG Combibloc)
- Frank Wellenreuther (ifeu)
- Andrea Drescher (ifeu)

1.3 Use of the study, target audience and critical review

The comparative results of this study are intended to be used by the commissioner (SIG Combibloc). Further they shall serve for information purposes of SIG Combibloc's customers, e.g. fillers and retail customers. The results are not intended to be considered for other geographical regions than Europe, not even for the same packaging systems. Nor are the results intended to be considered valid for (the same) packaging systems at any other time. According to the ISO standards on LCA (ISO 14040 2006; ISO 14044: 2006), this requires a critical review process undertaken by a critical review panel.

The members of the critical review panel are:

- Michael Sturges (chair; RISE Research Institutes of Sweden)
- Alex Hetherington (3keel Group Ltd, United Kingdom)
- Nicolas Cayé (GVM, Germany)

1.4 Functional unit

The function examined in this LCA study is the packaging for retail sale. The functional unit for this study is the provision of 1000 L beverage (liquid dairy or NCSD) at the point of sale. The packaging must protect these products for a sufficient period of time (minimum shelf life). It is assumed, that the primary packages examined is technically equivalent regarding the mechanical protection of the packaged beverage during transport, the storage at the point-of-sale and the use phase and that all packaging systems studied meet the required minimum shelf life. It should be noted, that beverage cartons generally exceed the minimum shelf life requirements.

The reference flow of the product system regarded here refers to the actually filled volume of the containers and includes all packaging systems, i.e., beverage carton and closures as well as the transport packaging (corrugated cardboard trays and shrink foil, pallets), which are necessary for the packaging, filling and delivery of 1000 L.

1.5 System boundaries

The study is designed as a 'cradle-to-grave' LCA without the use phase of the package by the consumers as no relevant differences between the systems under examination are to be expected. In other words, it includes the extraction and production of raw materials, converting processes, all transports and the final disposal in incineration plants or on landfills as well as the recycling of the packaging system.

In general, the study covers the following steps:

- Production of the primary base materials used in the primary packaging systems from the studied systems (incl. closures).
- Converting, recycling and final disposal of primary packaging systems and related transports.
- Production, converting, recycling and final disposal (incineration/landfill) of transport packaging (stretch foil, pallets, cardboard trays) and related transports.
- Production and disposal of process chemicals, as far as not excluded by the cut-off criteria (see below) and related transports.
- Transports of packaging material from producers to 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.
- In all manufacturing and filling processes for the primary and secondary packaging losses are included.

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 no significant impact is expected. 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. Considering relevant information about the supply chain from producers and retailers both criteria are considered to remain unfulfilled. An inclusion of capital goods might also lead to data asymmetries as data on infrastructure is not available for many production data sets.

- Production of beverage, and their transport to fillers as no relevant differences between the systems under examination are to be expected.
- Distribution of beverage from the filler to the point-of-sale (distribution of packages is included) as the same amount of beverage is transported for all regarded packaging systems (see transport allocation in **section 1.7.2**).
- Losses of beverage at different points in the supply and consumption chain which might occur for instance in the filling process, during handling and storage, etc. as they are considered to be roughly the same for all examined packaging systems. Significant differences in the amount of lost beverage between the regarded 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. Therefore, these possible beverage loss differences are not quantifiable as almost no data is available regarding these issues. In consequence a sensitivity analysis regarding beverage losses would be highly speculative and is not part of this study. This is indeed not only true for the availability of reliable data, but also uncertainties in inventory modelling methodology of regular and accidental processes and the allocation of potential beverage waste treatment aspects.
- 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 and the implementation would be highly speculative as no reliable data is available.

The following simplified flow charts (**Figure 1-1**) shall illustrate the system boundaries considered for the beverage cartons.

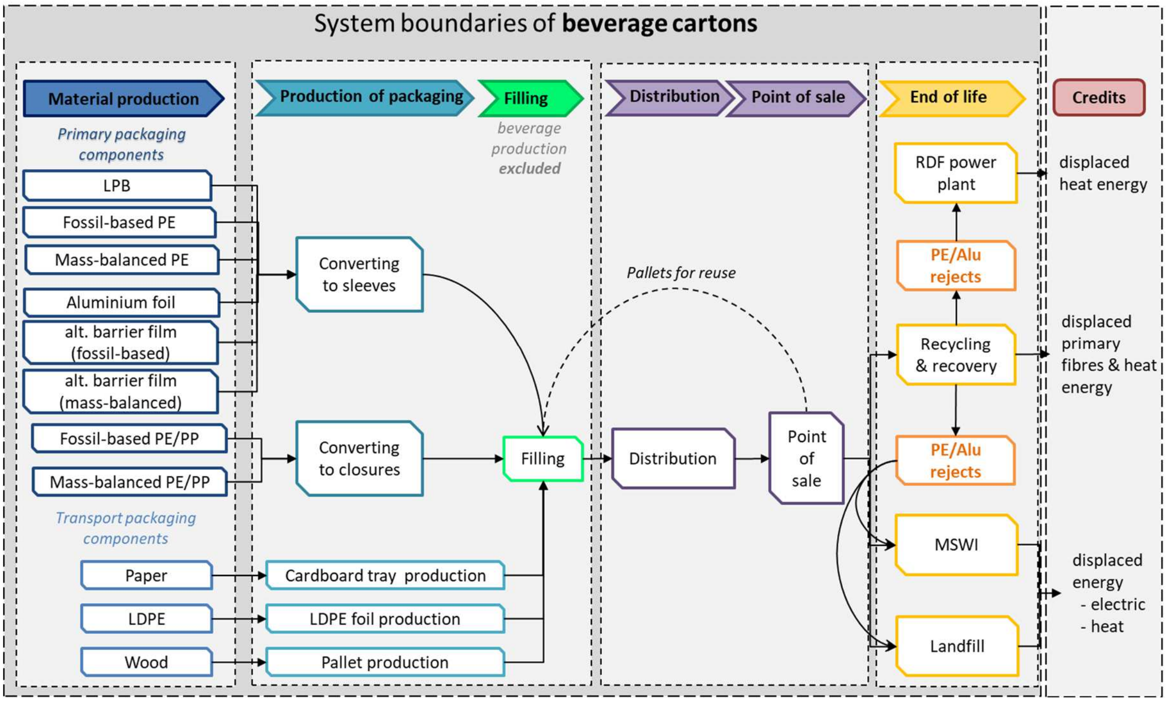

Figure 1-1: System boundaries of the *cb8/cf8 SIG beverage cartons* examined for the European market

For recycling and recovery routes the system boundary is set at the point where a secondary product (energy or recycled material) is obtained. The secondary products can replace primary energy generation processes and virgin materials, respectively. This effect is accounted for in the life cycle assessment by attributing credits for secondary products. These credits are calculated based on the environmental burdens of the corresponding primary energy generation process or material. The final disposal of those recycled materials undergoing another life cycle in a subsequent system is included in this study. Thus, all recycled materials finally end up in MSWI or landfills, depending on the municipal solid waste stream of the regarded country.

Beverage cartons which are not collected and recycled are either burned in incineration plants (thermal recovery) or deposited on landfills. The collected beverage carton fraction is sent to a paper recycling facility for fibre recovery. That means that a true recycling only takes place for the fibre part of the beverage cartons. After this recycling process, an aluminium/polyethylene compound (PolyAl fraction) is left over. The individual materials of this aluminium/polyethylene compound are difficult to separate thus they have been used mainly in cement kilns or other power plants as refuse-derived fuel. In recent years, technologies to recycle these aluminium/plastic compounds have been further developed and applied in a small scale in different recycling plants. The actual share of these compounds undergoing a material recycling is not disclosed. Also, no inventory data for these recycling processes are yet available. However, as the creation of an inventory dataset is currently ongoing, there might be more details for modelling those processes in the future. For these reasons, in the current study it is still assumed, that a share of 50 % of the PolyAl fraction furthermore is used as refuse-derived fuel to generate heat energy. and 50 % undergoes the country-specific landfill-incineration split and will therefore not obtain material credits. This could be seen as a conservative approach from the perspective of the beverage cartons.

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, pre-chains from preceding systems with an input material share of less than 1 % of the total mass input of a considered process may be excluded from the present study. However, total cut-off is not to surpass 5 % of input materials as referred to the functional unit. All energy inputs are considered, except the energy related to the material inputs from pre-chains which are cut off according to the mass related rule. Pre-chains with low input material shares, which would be excluded by the mass criterion, are nevertheless included if they are of environmental relevance, e.g., flows that include known toxic substances. It has to be pointed out, that this is not the case for any pre-chain related to the packaging systems under examination. The environmental relevance (significant impact on any impact category) of material input flows was determined based on ifeu's expert judgement based on previous studies.

1.6 Data gathering and data quality

The datasets used in this study are described in **section 3** (**Life Cycle Inventory**). All data shall meet the general requirements and characteristics regarding data gathering and data quality as summarised in the following paragraphs.

Time scope

The reference time period for the comparison of packaging systems is 2024, as the packaging specifications listed in **section 2.2** (**Packaging specifications**) refer to 2024. Where no figures are available for these years, the used data shall be as up to date as possible. Particularly with regard to data on End of Life processes of the examined packages, the most current information available is used to correctly represent the recent changes in this area. As some of these data are not yet publicly available, expert judgements are applied in some cases, for example based on confidential exchanges with representatives from the logistics sector and retailers regarding distribution distances.
Most of the applied data refer to the period between 2005 and 2023. Parameters with an essential influence on the result, such as the electricity mix, are continuously updated. Older data have only been deemed acceptable for processes which do not show a high share on the overall impacts.

Geographic scope

In terms of the geographic scope, the LCA study focuses on the production, distribution, and disposal of beverage carton packages in Europe (EU27+3), respectively. A certain share of the raw material production as well as converting processes for packaging systems take place in specific European countries. For these, country-specific data is used as well as European averages depending on the availability of datasets. Examples are the liquid packaging board (LPB) production process (country-specific) and the production of plastics (available only as a European average, see **Table 3-1**).

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. The technical reference is intended to represent the average presently applied technology or presently applied technology.

Representativeness

Representativeness is addressed by looking at three indicators: temporal, geographical, and technological correlation. This evaluation aims to reflect how well the used inventory data represent the technology, geography, and time scopes of this study. These three indicators meet the (ISO 14044: 2006) standards and is carried out based on several guidelines for data quality assessment (Edelen and Ingwersen 2016; JRC 2010; Weidema et al. 2013; Zampori et al. 2016).

The representativity evaluation regarding the time scope indicates the correlation between the reference year of the used data and the time scope of this study. The qualitative evaluation shows that the reference year of the used data meet the time scope of this study, is close or close enough to the time scope of this study. It has to be noted, that a lower temporal correlation does not mean the data is not representative. “A more important reflection of correlation would be the technological correlation”. (Edelen and Ingwersen 2016)

The geographical representativeness of the used data identifies how well these inventory data represent the geographic scope of this study. The result of the evaluation is that the used data meet the geographic scope of this study.

The evaluation of the technological correlation shows differences that may be present between used data and the technology scope of this study. The used data covers either average of presently used technology or presently used technology.

The overall representative evaluation shows, that the used data can be regarded as representative for the intended purpose of this study.

Completeness

In general, the data collection and data implementation for the ifeu internal database takes place in four phases: In phase one, to understand the processes like filling, converting or plastics production, they are analysed based on available literature, discussions with the respective stakeholders or the production sites are directly visited. In this phase, the relevant flows of following flow types are identified: reference product, co-products, intermediate inputs, raw inputs, (material, energy, and water), waste to treatment (solid and hazardous and liquid), emissions to air (GHGs, Criteria Air Pollutants, Toxics + Other and Water), emissions to water (Nutrients and Toxics + Other), and emissions to soil (Nutrients and Toxics + Other). In phase 2, the respective companies provide data on the identified inputs (e.g., amount of raw materials, energy, or water) and main output products (e.g. emissions to air and water). In phase 3, a completeness check regarding all possible used impact and inventory categories are carried out based on information from phase 1. Based on this, additional relevant data are collected, concerning emissions to air and water, amounts of waste, and transport information. In phase 4, an additional completeness check is carried out, where the LCIA results of the implemented data are cross checked with available LCIA results (e.g., previous data, data from other geographic regions, similar processes). This procedure applies also for datasets implemented from industries except for the data collection phase. Missing information on land-use, water use, and toxicity are discussed in **section 1.8** (**Environmental Impact Assessment**) in the respective sections. The summary of the completeness check according to (ISO 14044: 2006) is presented in the following **Table 1-2**:

Table 1-2: Summary of the completeness check according to (ISO 14044: 2006)

		Beverage carton	Complete?	Representative?
	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 processes available
✔	Complete and representative data available

Consistency

To ensure consistency only data of the same level of detail were used. While building up the model, crosschecks concerning the plausibility of mass and energy flows were continuously conducted. The methodological framework is consistent throughout the whole model as the same methodological principles are used both in foreground and background system. An exception may be infrastructure which is generally excluded in this study. In case of some aggregated datasets taken from public databases it may be included without being probably documented. If these cases exist at all, then a slight inconsistency in regard to the exclusion of infrastructure may exist.

Reproducibility

All data and information used either are documented in this report or are available from the mathematical model of the processes and process plans designed within the Umberto 5.5 software. The reproducibility is given for internal use since the owners of the technology provided the data and the models are stored and available in a database. It is worth noting that for external audiences, it may be the case that full reproducibility in any degree of detail will not be available for confidentiality reasons. However, experienced experts would easily be able to recalculate and reproduce the product system models.

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 3-1** 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. For example, uncertainty measures like variances for elementary flows are not included in industry data sets as "the relevant foreground data is primary data or modelled based on primary information sources of the owner of the technology" (PlasticsEurope 2014).

However, to address potential uncertainties between the compared product systems, an estimated significance threshold of 10 % is chosen as pragmatic approach. This approach has been successfully applied in several LCA studies e.g. in (Kauertz et al. 2020). This LCA study meets the ISO standard for comparative life cycle assessments according to ISO 14040 ff and was the first LCA to meet the minimum requirements for beverage packaging LCAs in Germany published by the German Federal Environment Agency (UBA) in 2016. Applied to this study, this means that differences in the results of the impact category indicators between the comparative systems of ≤ 10 % are considered insignificant. Based on the data used for the impact categories considered in this study, the authors' point of view is that the significance threshold of 10 % is an appropriate size and guarantees consistency for all impact categories examined.

Modelling and calculation of inventories

For the implementation of the system models the computer tool Umberto® (version 5.5) is used. Umberto® is a standard software for mass flow modelling and LCA. It has been developed by the institute for environmental informatics (ifu) in Hamburg, Germany in collaboration with ifeu, Heidelberg.

1.7 Methodological aspects

1.7.1 Mass-balanced renewable material approach applied for the production of polymers in the *cb8/cf8 SIG Terra AFFB + fbp - 1000 ml SwiftCap Linked LP*

Mass balance-based polymers are polymers that are produced by using both, fossil and biogenic resources as input materials for the same production process. In practice the input of biogenic materials (in this case tall-oil, a by-product of the paper production processes) to the polymerisation process is done at the same production process where mainly fossil-based ethylene and naphtha are used. This leads to only one final product per production process which is neither 100 % fossil-based nor 100 % bio-based material. To allocate the specific characteristics of fossil-based or bio-based input materials to the final product the producers declare a certain share of their production as linked to renewable resources. That share, of course is dependent on the share of biogenic input material.

It is important to understand that in reality (in a physical sense) the $(C_2H_4)_n$ and $(C_3H_6)_n$ molecules of the tall oil-based polymers are in fact mainly non-bio-based, as the share of bio-based ethylene is below 1% of the total production. But as the polymers in the *cb8/cf8 SIG Terra AFFB + fbp - 1000 ml SwiftCap Linked LP* are the ones to which the tall-oil input is allocated to, they are modelled as if they would be 100 % tall-oil based for the purpose of this study. The allocation of inputs is certified by ISCC PLUS (International Sustainability & Carbon Certification) (ISCC 2019). The ISCC PLUS certificates are available on SIG Combibloc's website (https://www.sig.biz/en/about-sig/certifications?standards=iscc-plus) for all plants. The properties of the final mass-balanced material (beyond the nature of the molecules) are completely identical to those of a fossil-based material.

The LCA results for the *cb8/cf8 SIG Terra AFFB + fbp - 1000 ml SwiftCap Linked LP* will therefore not be directly connected to the physical products examined, but to the products of the production technology concept that lies behind it. In the authors' view the application of the mass balance approach in the production of polymers is an important driver to facilitate an increasing substitution of fossil resources by biogenic resources for the production of polymers. To model the examined products strictly on their physical properties would mean to not acknowledge this function of the mass balance approach.

Jeswani et al. published in 2019 a study investigating the methodology for integrating the biomass balance approach into life cycle assessment with an application in the chemicals sector. This study concludes that "a mass balance approach can be used in life cycle assessment while following the requirements set out in the ISO 14040 and 14044 standards" (Jeswani et al. 2019). Furthermore, this study highlights also that the mass balance approach is an applicable way to evaluate life cycle environmental impacts of bio-based products "without the need for building up the whole value chains separately from the fossil-based routes" (Jeswani et al. 2019).

1.7.2 Allocation

"Allocation refers to partitioning of 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. 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, the source is generally referred to.

Transport processes

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

System-related allocation

System-related allocation is applied in this study regarding open loop recycling and recovery processes. Recycling refers to material recycling, whereas recovery refers to energy 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 regarded system and processes regarding the use of recycled materials by the regarded system. System-related allocation is not applied regarding disposal processes like landfills with minor energy recovery possibilities. **Figure 1-2** illustrates the general allocation approach used for uncoupled systems and systems which are coupled through recycling. In **Figure 1-2** (upper graph) 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 graph of **Figure 1-2**. 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.

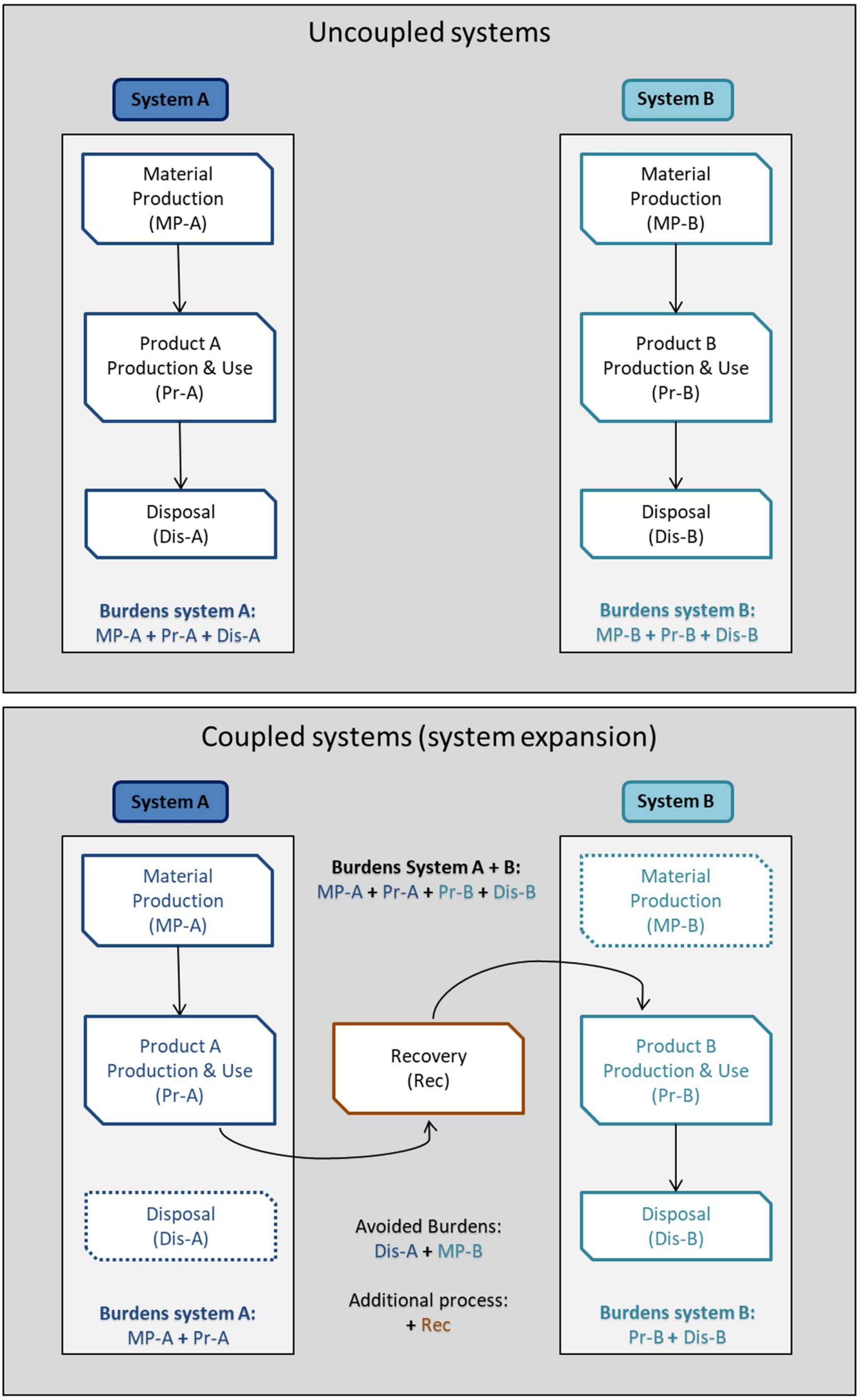

Figure 1-2: Additional system benefit/burden through recycling (schematic flow chart)[1]

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 polymer material recovery and recycling and the benefits and burdens of the use of recycled materials shall be allocated (i.e. accounted) to the regarded 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 1-3** and **Figure 1-4**. Both graphs 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.

Note: For systems including recycled packaging, the burdens associated with the ultimate landfill or MSWI of the secondary products produced from the recyclate are allocated to the primary system (50 % of the burdens of disposal in the 50 % allocation, 100 % of the burdens in the 100 % allocation).

[1] Dotted frames are avoided processes

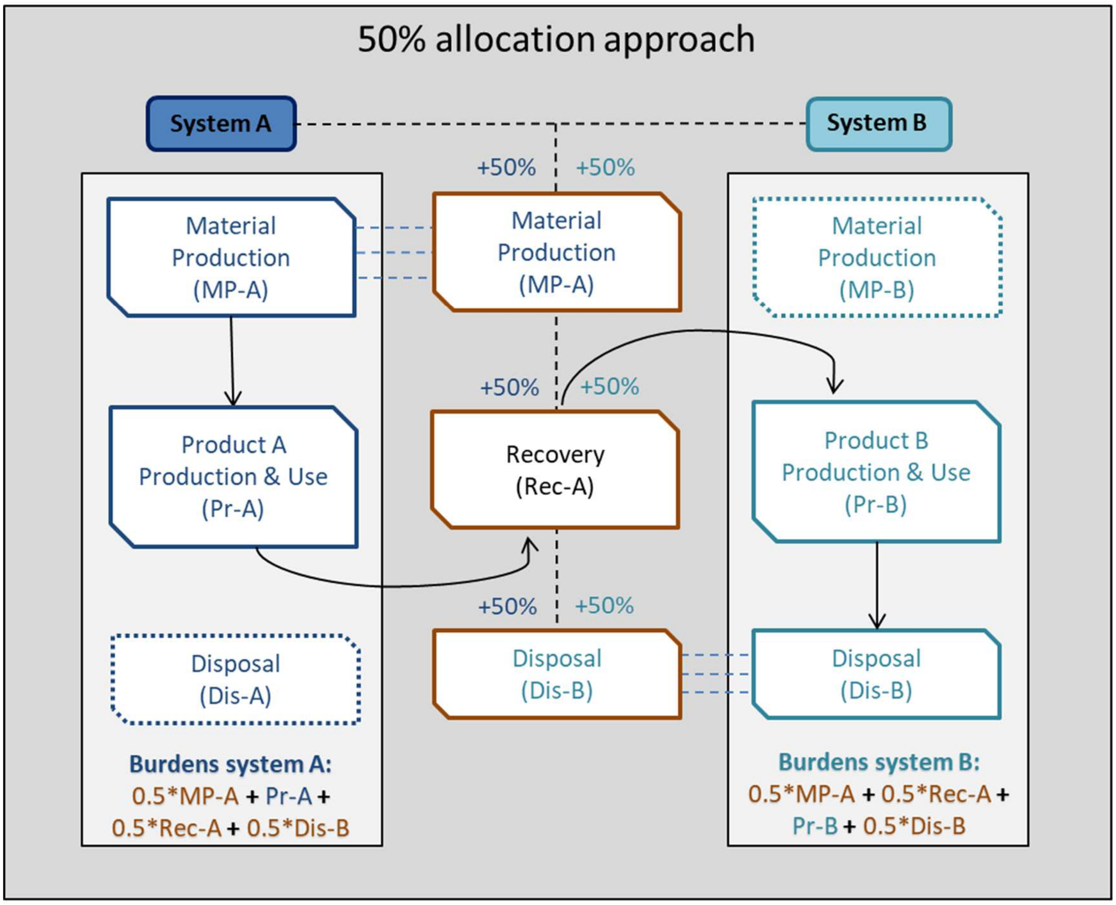

Figure 1-3: Scenario AF 50 %: Principles of 50 % allocation (schematic flow chart)[1]

Scenario AF 50 %: allocation with the 50% method (Figure 1-3)

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

Example 1 ('system A'), virgin beverage carton, which is recycled or thermally recovered after its use: All burdens from recycling and recovery processes are shared between the regarded beverage carton system and the following system (use of secondary material or energy production). Also, the benefits from replacing virgin materials or grid 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 the following references (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 example the European Packaging and Packaging Waste Directive (EU 2018) or the German packaging law (Verpackungsgesetz - VerpackG 2021).

The 50 % method has been used in numerous LCAs carried out by ifeu and is the standard approach applied in the packaging LCAs commissioned by the German Environment Agency (UBA). Additional background information on this allocation approach can be found in (UBA 2000, 2016).

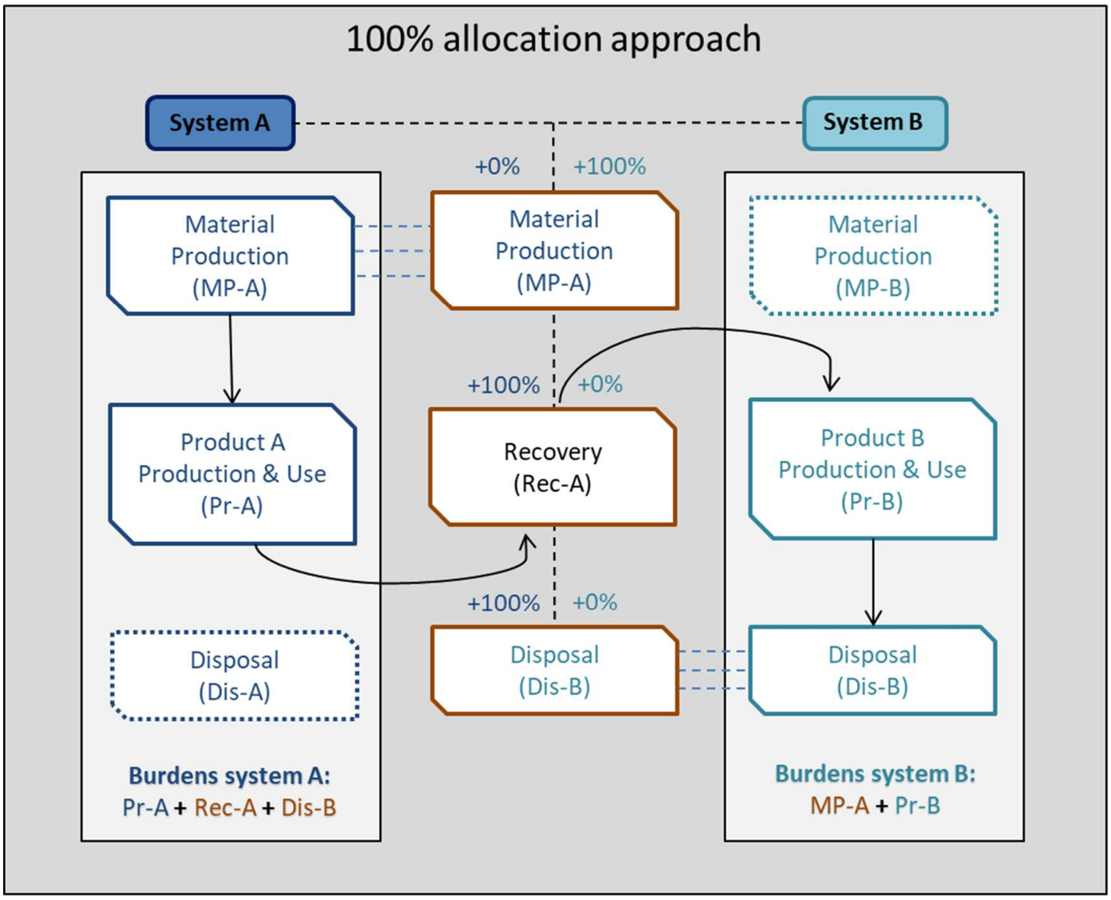

Figure 1-4: Scenario AF 100 %: Principles of 100% allocation (schematic flow chart)[1]

Scenario AF 100 %: Allocation with the 100 % method (Figure 1-4)

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

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

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

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

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 1-2 to Figure 1-4

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:
    - Virgin 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 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 graphs, among them the following:

- Material losses occur in both 'systems A and B', but are not shown in the graphs. 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 graphs may imply. Consequently only the effectively recycled and recovered material's life cycle steps are allocated between 'systems A and B'.
- The graphs 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 graphs. 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 virgin material it replaces, this translates to a loss in material quality. A substitution factor < 1 accounts for such effects.

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 virgin material. For example, a substitution factor of 0.9 means that 1 kg of recycled (secondary) material replaces 0.9 kg of virgin 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 the default values reported in Annex C by the European Commission and as proposed for the Product Environmental Footprint (PEF) method (Nessi et al. 2021). The substitution factors apply to the secondary materials after the recycling processes with their production losses (see **section 3.8**).

- Paper fibres
  - from LPB (carton-based primary packaging): 1.0
  - in cardboard trays (secondary packaging): 1.0
- LDPE from films: 0.75
- HDPE: 0.9

1.7.3 Biogenic CO_2

Renewable materials like paper fibres or mass-balanced plastics 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 binding of CO_2 by 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 reg. (EOL).

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 Global Warming Potential (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) or the German packaging law (Verpackungsgesetz - VerpackG 2021) 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 1.7.1** 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 regarded packaging systems containing regenerative 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 renewable 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 regarded packaging systems containing regenerative materials would not be reduced.

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

Using the example of mainly renewable materials like LPB, the application of the CO_2 uptake in credits would deter from recycling efforts of packaging containing renewable 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 renewable 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 renewable materials sourced from recycling processes would not be benefited. As no packaging systems which contain recycled renewable materials are analysed in this study, this approach of not considering CO_2 uptake in credits is seen suitable within this study. 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’ (*cb8/cf8 SIG Terra AFFB + fbp - 1000 ml SwiftCap Linked LP*) and ‘system B’ (subsequent system) together stays the same.

As described in **section 1.7.1** system-related allocation is applied in this study for energy 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 energy recovery of renewable 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 regarded 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 renewable 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 renewable materials can promote the increase of use of renewable materials in packaging system.

In case of applying allocation 100 % for recovery processes all the biogenic CO_2 emissions (recovery & disposal) are attributed to the regarded system. Therefore, in this case the extra benefit for ‘Climate Change’ results, packaging systems with primary renewable materials receive by only getting allocated 50 % of the biogenic CO_2 emissions, is gone.

As these decisions and conventions applied in this study have to be considered as subjective choices, 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.

1.8 Environmental Impact Assessment

The environmental impact assessment phase is intended to increase the understanding and evaluating 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 the present 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 both on the current practice in LCA and the applicability of as less as uncertain characterisation models also with regard to 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, CML or UBA.

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.

1.8.1 Impact categories related to emissions

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.

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 g R-11-eq/FU.

Summer smog (Photochemical Oxidant formation)

Summer smog (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.

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.

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) 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 g 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[2]. 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 1-3** summarises some examples of elementary flows and their classification to the impact categories included in the study and described before.

[2] In previous LCA studies commissioned by SIG and conducted by ifeu the contribution to the 'fine Particulate Matter Potential' was calculated by summing the products of the amounts of the individual harmful substances and the respective PM10 equivalent. According to Detzel et al. (2016) the characterisation factors of de Leeuw (2002) shall now be related to PM2.5 equivalent. This recommendation is based on the respective guidelines of WHO (2021) WHO: It states that the fraction PM2.5 is mainly responsible for toxic effects.

Table 1-3: Examples of elementary flows and their classification to emission related impact categories

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

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

1.8.2 Impact categories related to the use/consumption of resources

Abiotic resource depletion

The consumption of resources is deemed adverse for human society. In all considerations regarding sustainable, environmentally compatible commerce, the conservation of resources plays a key role. The safeguard subject of this category is the reduction of depletion and dissemination of abiotic resources (fossil fuels and minerals) that can be extracted from the lithosphere.

For this study the approach of (Guinée 2002) based on parameters on ultimate reserves and extraction rates by (Guinée 2002; Heijungs 1992) are applied. This model considers the scarcity of materials as a function of the natural reserve of the resource in connection with the annual extraction rate. The natural reserve of raw materials is based on ultimate reserves, i.e., on concentrations of elements and fossil carbon in the Earth's crust. The quotients of extraction and ultimate reserve of a resource are related to the corresponding quotient of the reference antimony to express the abiotic resource depletion (ADP) as antimony equivalents (Sb-eq/kg resource). With the approach of (Guinée 2002) both, the fossil and mineral/metal resources are addressed together in one impact category.

The characterisation factors for abiotic resource depletion elements (minerals and metals) are taken from (CML 2016). The annual extraction rate of the elements is based on USGS (U.S. Geological Survey) with the reference year 2011. Mineral and metals that consist of more than one element like barium sulphate, characterisation factors have been recalculated based on the factors from (CML 2016). **Table 1-4** gives some examples of mineral and metal resources included in this impact category.

Table 1-4: Examples of elementary flows and their classification to resource related impact category.

Impact category	Elementary flow examples							Unit
Abiotic resource depletion	Crude oil	Natural gas	Hard coal	Soft coal	Al	Ab	Fe	kg Sb-eq

The method by CML (2016) separates abiotic resource depletion into two single impact categories. Nevertheless, the authors of this study are not going along with this change as the assessment of abiotic resources is only complete when all abiotic resources are included. Therefore, the approach of (Guinée 2002) without separating abiotic resource depletion in two categories is applied. The characterisation factors for the fossil abiotic resource depletion have been updated to the same reference year as for element resources (2011) based on the calculation method described in (Guinée 2002). The quotients of extraction and ultimate reserve of the fossil resources are related to the corresponding quotient of the reference antimony. This calculation results in the following characterisation factor: 0.000093 kg Sb-eq/MJ fossil fuel.

Nevertheless, the Abiotic Resource Depletion of mineral and metal resources (Abiotic Resource Depletion elements) is presented as additional information at the end of each set of results.

In reference to the functional unit, the unit for Abiotic Resource Depletion is kg Sb-eq/FU.

1.8.3 Further impact categories not included in the study

Use of nature

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

The currently available methodology by (Beck et al. 2010; Chaudhary and Brooks 2018; Fehrenbach et al. 2015) on land use especially on different forest management types and ecoregions are only well applicable in geographical context of Europe, but with regard to the supply chains under study, global resource chains are relevant. Therefore, no assessment of the use of nature is included in this study.

Water scarcity footprint

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.

However, 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. Nevertheless, some of the qualitative aspects are considered in this report in the impact category "Aquatic Eutrophication".

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 1-5** are related to the square geometric standard deviation (GSD^2):

Table 1-5: 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.

1.8.4 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** (**Results and discussion of base scenarios)** 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 GJ/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 GJ/FU.

Table 1-6: 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	GJ
	Renewable primary energy	hydro energy	solar energy	geo-energy	biomass	wind energy	

2 Packaging systems and scenarios

2.1 Selection and description of packaging systems

The choice of beverage cartons to be examined for this LCA study has been made by SIG Combibloc. The focus lies on the *cb8/cf8 SIG beverage cartons* line for which this study aims to provide knowledge of its strengths and weaknesses regarding environmental aspects.

The beverage cartons examined differ in their materials but are essentially identical in their shape and functionality. As the SIG packaging line *SIG MidiFit (cf8) 1000 ml* is identical to the *SIG MidiBloc (cb8) 1000 mL* with regard to all packaging specifications (including secondary and tertiary packaging), they are grouped together under the designation "*cb8/cf8 SIG beverage cartons*".

The *cb8/cf8 standard RS - 1000 ml SwiftCap Linked* is a standard beverage carton which sleeve consist of about 76 % LPB, 19 % fossil-based PE and 5 % aluminium foil. For the *cb8/cf8 SIG Terra AFFB - 1000 ml SwiftCap Linked LP* line the aluminium layer is replaced by an alternative barrier film. In the *cb8/cf8 SIG Terra AFFB + fbp - 1000 ml SwiftCap Linked LP beverage carton*, all fossil-based plastic components (PE, PP) in the sleeve and closure are replaced by mass-balanced plastic components (mass-balanced PE, mass-balanced PP). The material composition (except the replaced PE, PP) and the weight of both *cb8/cf8 SIG Terra AFFB beverage cartons* is exactly the same.

The Directive (EU) 2019/904 Single-use plastic articles on tethered caps has been in force since 2024: from now on, closures and lids may be placed on the market only if the closures and lids remain attached to the one-way beverage packaging during the period of intended use of the articles with a volume of up to three litres. The aim is to recycle the caps together with the containers and to avoid littering of the environment by discarded caps. All beverage cartons examined in this LCA study are equipped with a tethered cap (SIG SwiftCapLinked and SIG SwiftCapLinked LightProof).

2.2 Packaging specifications

The packaging specifications of the beverage cartons under examination were provided by SIG Combibloc and are shown in **Table 2-1Table 2-1**. In both *cb8/cf8 SIG Terra Alu-free Full barrier beverage cartons,* the aluminium foil is replaced by an alternative barrier film. The composition of those alternative barrier films is confidential and is therefore not shown in **Table 2-1**. For transparency reason, the authors of the study ensured, that the critical review committee has access to the underlying data and relevant information during the review process.

Table 2-1: Packaging specifications of the examined *cb8/cf8 SIG beverage cartons* on the European market

Specification	Unit	Packaging system		
		cb8/cf8 standard RS – 1000 ml SwiftCap Linked	*cb8/cf8 SIG Terra AFFB – 1000 ml SwiftCap Linked LP*	*cb8/cf8 SIG Terra AFFB + fbp – 1000 ml SwiftCap Linked LP*
volume	mL	1000	1000	1000
geographic scope	-	EU	EU	EU
primary packaging (sum)[3]	g	**29.52**	**32.03**	**32.03**
primary packaging (per FU)	**g/F**	**29520**	**32030**	**32030**
composite material (sleeve)	g	26.72	29.15	29.15
- liquid packaging board	g	20.278	23.661	23.661
- fossil PE	g	5.045	4.263	-
- mass-balanced PE	g	-	-	4.263
- aluminium foil	g	1.392	-	-
- barrier film (fossil-based)	g	-	1.227	-
- barrier film (mass-balanced)	g	-	-	1.227
closure	g	2.80	2.88	2.88
- fossil PP	g	1.54	1.58	-
- mass-balanced PP	g	-	-	1.58
- fossil PE	g	1.26	1.30	-
- mass-balanced PE	g	-	-	1.30
secondary packaging (sum)[4]	g	204	204	204
- tray/box (corrugated cardboard)	g	204	204	204
tertiary packaging (sum)[5]	g	**22350**	**22350**	**22350**
- Wooden pallet	g	22000	22000	22000
- type of pallet	-	EURO	EURO	EURO
number of use cycles	-	25	25	25
- cardboard layer (per pallet)	g	1750	1750	1750
- stretch film (per pallet) (LDPE)	g	350	350	350
pallet configuration				
prim. packaging per sec. packaging	pc	12	12	12
sec. packaging per layer	pc	13	13	13
layers per pallet	pc	5	5	5
prim. packaging per pallet	pc	780	780	780

[3] per primary packaging unit
[4] per secondary packaging unit
[5] per tertiary packaging unit (pallet)

2.3 Distribution of filled packages from filler to point of sale

Table 2-2 shows the applied distribution distances in this LCA study. The distribution distances for the European market from filling to point of sale were determined by SIG Combibloc based on the existing bottling locations for the examined beverage segment filled. The provided transport distances have been cross-checked by ifeu based on internal and confidential studies on distribution.

For the distribution in Europe, a total distribution distance of 530 km has been assumed. In addition to regional and nationwide filling and distribution in Europe also cross-national distribution is considered which leads to a longer average distance. Since the packaging weights of the beverage cartons studied are comparable, changes in transport distances do not have a significant impact on the comparison of the packaging systems. The transport distance is implemented in the model as a two-stage delivery to retailers, where the first step indicates the transport to a central warehouse, and the second represents the delivery from a central warehouse to the supermarket (point-of-sale). For distribution step 2 as an expert estimate based on the same data mentioned above, a minimum empty transport distance of 30 km is assumed. The distance for distribution step 1 is obtained by subtracting the 30 km from the total distribution distance.

As no first-hand information was available on average empty return distances of lorries for the respective markets, it was assumed that lorries have an empty return trip with 30 % of the distance of the fully loaded trip. This assumption is supported by information provided to the ifeu its mobility department by various fillers and retailers through various projects.

In the life cycle model, environmental burdens related to distribution have been allocated between beverage and packaging based on respective masses and on the degree of utilisation of the lorry. The distribution distances for the markets considered in this study are summarised in **Table 2-2**.

Table 2-2: Distribution distances in Europe for the examined beverage cartons

	Distribution distance			
	Distribution step 1		Distribution step 2	
Market	**Filler → distribution centre** (delivery)	**Distribution centre → filler** (return trip)	**Distribution centre → POS** (delivery)	**POS → distribution centre** (return trip)
Europe liquid dairy and NCSD	500 km	150 km	30 km	30 km

2.4 End of Life

To model the end-of-life of the examined beverage cartons one needs to know their fate after their use by the consumers. The applied recycling rate and the disposal split for the European market are listed in **Table 2-3** and **Table 2-4**. These data have been collected from different waste management reports and statistics and are partly publicly available. The recycling rate represents the actual amount of material undergoing a material recycling process after sorting took place. The collection rate represents the amount of material before sorting. The assumption of sorting losses including those due to moisture and residues is 10 %. The recyclability of the *SIG Terra Alu-free Full barrier (AFFB) beverage carton* has been tested by SIG in several trials. No negative impact on the recyclability of these beverage cartons was observed. Thus, the same recycling rate is applied for all beverage carton systems studied.

Table 2-3: End of Life split of packaging systems examined in Europe

	Recycling rate	Reference
Beverage cartons	confidential[6]	EXTR:ACT 2025, data for 2022

The remaining part of the post-consumer packaging waste is modelled and calculated according to the average rates for landfilling and incineration (MSWI) in the European market. The disposal split (100 %) is divided into landfilling, approximate 47.4 % and incineration, approximate 52.6 %. This disposal split is also applied for the final disposal of recycled materials undergoing another life cycle in a subsequent system.

Table 2-4: Disposal split in the regarded market

		Europe	
Disposal split	Landfill	47.4 %	(eurostat 2024) municipal waste statistic, data for 2022
	Incineration	52.6 %	

[6]Due to confidentiality reason the data cannot disclosed within this study but have been made available to the critical review committee.

2.5 Scenario overview

2.5.1 Base scenario AF 50 % and base scenario AF 100 %

For each of packaging system a base scenario for the European market is defined, which is intended to reflect the most realistic situation under the described scope. Following the ISO standard's recommendation, a variation of the allocation procedure shall be conducted. Therefore, for each packaging system, there are two equal base scenarios regarding the open-loop allocation defined for the European market- once with system allocation factor 50 % and once with system allocation factor 100 %. For further details on allocation factors and system allocation see **section 1.7.2**.

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. The use of different sources of the data sets can be justified methodologically by the fact that there is a conflict - the choice of consistently the same source often does not mean high quality. Therefore, the choice was made to always use the data sets with comparable background systems or system assumptions in combination with the best available data quality. **Table 3-1** gives an overview of important datasets applied in the current study.

Table 3-1: Overview on inventory/process datasets used in the current study

Material / process	Reference	Reference year/ period	Geographic scope
Intermediate goods			
Fossil PP	(Ecoinvent 3.10)	2011-2023	Europe
Fossil LDPE	(Ecoinvent 3.10)	2011-2023	Europe
Fossil HDPE	(Ecoinvent 3.10)	2011-2023	Europe
Mass-balanced- PE	Based on information provided by SIG Combibloc, literature (Cashman et al. 2016) and ifeu database	2016	Finland/Europe
Mass-balanced PP	Based on information provided by SIG Combibloc, literature (Cashman et al. 2016) and ifeu database	2016	Finland/Europe
Titanium dioxide	(Ecoinvent 3.10)	2011-2023	Europe
Aluminium (primary)	(EAA 2018)	2015	Europe
Aluminium foil	(EAA 2013)	2010	Europe
Alternative barrier film	SIG Combibloc (confidential data)	2022	Europe
Corrugated cardboard	(FEFCO and Cepi Container Board 2022)	2020	Europe
Liquid packaging board	ifeu data, obtained from ACE (ACE and ifeu 2020)	2018	Finland/Sweden
Production			
Beverage carton converting	SIG Combibloc	2019	Germany
Injection moulding of caps	SIG Combibloc	2019	Europe
Filling			
Filling of beverage cartons	SIG Combibloc	2022	Europe

Material / process	Reference	Reference year/ period	Geographic scope
Recovery			
Beverage carton recycling	ifeu database, based on data from various European recycling plants	2004	Europe
Background data			
Electricity production	ifeu database, based on statistics and power plant models	2021	Europe
Municipal waste incineration	ifeu database, based on statistics and incineration plant models	2016-2022	Europe
Landfill	ifeu database, based on statistics and landfill models	2019	Europe
Thermal recovery in cement kilns	ifeu database, German cement industry association (VDZ)	2006	Europe
Lorry transport	ifeu database, based on statistics and transport models, emission factors based on HBEFA 4.1 (INFRAS 2017).	2017	Europe
Rail transport	(EcoTransIT World 2016)	2016	Europe
Sea ship transport	(EcoTransIT World 2016)	2016	Europe

3.1 Manufacture of plastic raw materials

The following plastics are used within the beverage cartons under study:

- Polypropylene (PP)
- Low density polyethylene (LDPE)
- High density polyethylene (HDPE)
- Mass-balanced PE and mass-balanced PP

3.1.1 PP (polypropylene)

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 (EI version 3.10). 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 underlying Plastics Europe data set hence represented 77 % of PP production in Europe.

3.1.2 LDPE (low density polyethylene)

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 eco-profile published by Ecoinvent (EI version

3.10). 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 year 2011. Data from a total of 22 participating polymerisation units were collected. The data set represents 72% of LDPE production in Europe (EU27+2).

3.1.3 HDPE (high density polyethylene)

HDPE is produced by a variety of low-pressure methods and has fewer side-chains than LDPE. The present LCA study uses the eco-profile published by Ecoinvent (EI version 3.10). The dataset covers the production of HDPE-granulate from the extraction of the raw materials from the natural environment, including processes associated with this. The data refer to the year 2011 and were acquired from a total of 21 participating polymerisation units. The data set represents 68% of HDPE production in Europe (EU27+2).

3.1.4 Mass-balanced PE and mass-balanced-PP dataset based on tall oil pitch

The production processes of mass-balanced PE and mass-balanced PP are based on tall oil pitch. Tall oil pitch is a wood-based by-product from pulp production. Carbon stored in wood, the base input material for the production processes of the mass-balanced plastics, has been absorbed from the atmosphere during plant growth and is referred as biogenic carbon. As there is no additional carbon added in the production processes of mass-balanced plastics the carbon stored mass-balanced HDPE, LDPE and PP is biogenic. In order to derive the biogenic carbon content of the mass-balanced plastics, the carbon content is calculated with the corresponding chemical formulas of HDPE, LDPE and PP.

The production of tall oil pitch is modelled as described in (Cashman et al. 2016) covering the production steps kraft pulping, acidulation and distillation and their related transportation. During the kraft pulping process, wood is converted into pulp ready for papermaking. Black Liquor Soap (BLS) is recovered as a by-product of this process. In a next step, BLS is reacted with sulfuric acid to produce CTO (acidulation step). After this, the crude tall oil is distilled and fractionated into higher-quality products (distillation step). Tall oil pitch is one of them. Consequently, a share of the burdens from the pulping and the distillation step s is assigned to the tall oil. The allocation is done on mass basis.

For kraft pulping a kraftliner pulp process based on (FEFCO 2012) is used. The share of BLS in kraft pulp production is 4 % (Cashman et al. 2016). By applying mass allocation 4 % of pulp production’s burdens are taken for BLS.

The acidulation step to produce crude tall oil from BLS is modelled with the in- and outputs of Table 2 in Cashman et al. (2016) (see **Table 3-2**)

Table 3-2: In- and outputs Acidulation. Table 2 in Cashman et al. (2016)

Inputs			**Outputs**		
Black Liquor Soap (BLS)	2,000.00	kg	Crude tall oil	1,000.00	kg
electric energy	110,000.00	kJ			
heat energy from oil[7]	50,164.92	kJ			
heat energy from natural gas[8]	8,114.40	kJ			
steam (process)	1,623.000.00	kJ			
sodium hydroxide, 50% in H2O, production mix, at plant [RER]	25.00	kg			
sulfuric acid, liquid, at plant [RER]	200.00	kg			

Based on table 1a in (Cashman et al. 2016), tall oil pitch is only one product of the crude tall oil distillation process. 27 % of the total output mass of all distillation products is tall oil pitch (see **Table 3-3**). The distillation process is modelled with the in- and outputs of Table 1b in (Cashman et al. 2016) (see

Table 3-4). As these in- and outputs apply for the sum of all distillation products they are multiplied in this study with the mass allocation factor of 0.27 in order to account only the burdens of the tall oil pitch production.

Table 3-3: Products of the distillation step and product allocation according to table 1a in Cashman et al. (2016)

Products from the distillation of 1000 kg crude tall oil			**Product allocation**	
Heads	0.048	t	4.8	%
Pitch	0.27	t	27.0	%
Tall oil rosin	0.27	t	27.0	%
Tall oil fatty acids	0.34	t	34.0	%
Distilled tall oil	0.072	t	7.2	%

[7] converted from kg to kJ with calorific value: 11.91 kWh/kg
[8] converted from m³ to kJ with calorific value: 46MJ/kg and density of natural gas: 0.84 kg/m³ (ifeu)

Table 3-4: In- and outputs distillation. Table 1b in (Cashman et al. 2016)

Inputs			Outputs		
Crude Tall Oil	1,110.00	kg	Tall oil distillation products	1,000.00	kg
electric energy	622,800.00	kJ	sewage (process) Sweden, Finland	21.00	kg
heat energy from oil[7]	182,223.00	kJ			
heat energy from natural gas[8]	253,864.80	kJ			
steam (process)	584,000.00	kJ			
nitrogen	8.41	kg			

Mass-balanced PE and PP are produced by cracking and polymerization of biodiesel. The biodiesel is based on tall oil pitch. It is a distillation product of crude tall oil, gained through acidulation of BLS which is a by-product of paper pulp production (as described above).

Biodiesel is produced from tall oil pitch by hydrotreatment. The confidential dataset of this process is based on the studies (Reinhardt et al. 2006) and (Nikander 2008). Both studies provide process data of the so-called NExBTL process of Neste Oil. According to several press releases[9] of Neste Oil biodiesel based on tall oil pitch is produced in its plant in Finland. The location of the plant was therefore set accordingly. The co-products fuel gas and bio-gasoline are produced as well. Bio-gasoline is internally used as thermal energy. Allocation was done by mass and calorific value of biodiesel and fuel gas. Biodiesel accounts for 93.5 % of the processes in- and outputs.

The cracking and polymerization processes for PE and PP are taken from the ifeu database. They are based on data representing the average from several polymerisation units in Europe.

3.2 Production of liquid packaging board (LPB)

LPB production dataset represents the LPB production in Europe and is produced by ifeu (ACE and ifeu 2020). The production of LPB was modelled using data gathered from 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.

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 including a forestry model to calculate inventories for this sub-system. Energy required is supplied by electricity as well as by renewable

[9] https://www.neste.com/en/neste-oil-uses-tall-oil-pitch-produce-traffic-fuel

on-site energy production by incineration of wood, bark and black liquor. The specific energy sources were taken into account.

3.3 Production of virgin 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 Association (EAA) 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 EAA 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 are assumed to be sourced in Europe. According to 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 upstream chains which are specific for the actual practice and are not an European average electricity mix.

3.4 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 card-board trays. According to FEFCO / Cepi Container Board (2018), this fraction on average is 12 % in Europe. Due to a lack of more specific information this split was also used for this study.

3.5 Converting

Converting of beverage cartons

The manufacture of composite board was modelled using data provided by the commissioner of the current study, SIG Combibloc, and refers to the year 2019. Process data has been collected from the converting site in Linnich, Germany. Due to very similar technology at other (and smaller) converting sites the collected data is considered as representative for all European converting sites by SIG Combibloc. The converting process covers the lamination of LPB, LDPE and aluminium or alternative barrier film respectively, printing, cutting, and packing of the composite material. The examined beverage cartons are produced at a German converting site of SIG Combibloc and printed with a rotogravure process.

Process data provided by SIG Combibloc was then coupled with required upstream chains, such as process heat, grid electricity, and inventory data for transport packaging used for shipping the coated composite board to the filler (**Table 3-5**).

Closure production

The closures made of fossil and mass-balanced PP and HDPE are produced by injection moulding. The data for the production were provided by SIG Combibloc and are based on values measured in SIG's plant in Switzerland and Europe. The process data were coupled with required upstream chains such as the production of PE and grid electricity.

3.6 Filling

The respective data for this study was provided by SIG Combibloc. A cross-check has been conducted with filling data from ifeu's internal database, which relies on information from different fillers and filling machine manufacturers. Data provided by SIG Combibloc are similar and therefore considered plausible.

3.7 Transport settings

The following **Table 3-5** provides an overview of the transport settings (distances and modes) applied for packaging materials. Data were obtained from SIG Combibloc and several producers of raw materials. Where no such data were available expert judgements were made, e.g., exchanges with representatives from the logistic sector and supplier.

Table 3-5: Transport distances and means: Transport defined by distance and mode (km/mode)

Packaging element	Distance of material producer to converter (km)	Distance of converter to filler (km)
Fossil polymers **Mass-balanced polymers** **Aluminium**	500 / road[10] 45 / road[11] 500 / road[10]	
Paper board for composite board	300 / road[12] 950 / sea[12] 800 / rail[12]	
Cardboard for trays	primary fibres: 500 / sea, 400 / rail, 250 / road[12] secondary fibres: 300 /road[12]	
Wood for pallets	100 / road[10]	
LDPE stretch film	500 /road (material production site = converter)[10]	
Trays		500 / road[10]
Pallets		100 / road[10]
Converted cartons		500 / road[13]
Closures beverage cartons		500 / road[13]

3.8 Recovery and recycling

3.8.1 Beverage cartons

Beverage cartons are typically positively sorted into a beverage carton fraction, which subsequently is sent to a paper recycling facility for fibre recovery. The recovered paper fibres are used for new paper products, like tissues, boxes or strong kraft papers. A substitution factor 1 is applied. 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 remaining material fraction in term of plastics and aluminium compounds (PolyAl fraction) have so far been used mainly in cement klins or other power plants as a refuse-derived fuels. However, these material fraction can be also mechanically recycled into new materials at specialised facilities. Due to the lack of process and mass flow data (how much PolyAl material is sent to a recycling facility) it is assumed that, in the European scope, 50 % of the PolyAl fraction is used as refuse-derived fuels in power plants to generate process heat. The

[10] ifeu assumption
[11] SIG 2023
[12] taken from published LCI reports
[13] SIG assumption

other 50 % undergo a thermal treatment in a MSWI plant or are finally disposed on a landfill according to the average disposal split in Europe (**Table 2-4**.). This could be considered as a conservative approach from the viewpoint of the PolyAl treatment.

3.8.2 Closures

HDPE and PP closures are mostly collected and sorted with the primary packaging body. A specialized process for the recycling of closures has not yet been established on a large scale. In this study, closure recycling is modeled as follows: the collected and sorted plastic closures are undergoing a regranulation process which results into secondary raw materials for further use. The data used in the current study is based on ongoing primary data collection from various European recycling companies. Those data reflect the average state of the art, however country-specific representativeness cannot be assessed. The process data is coupled with the required pre-chain of the market specific electricity mix in order to adjust the process data to the recycling location.

3.9 Background data

3.9.1 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 referring to the year 2017 and 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. 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. 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[14]) and an utilisation capacity of 70 %. 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.

[14] Twenty-foot Equivalent Unit

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 (see also **section 3.9.2**).

3.9.2 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 base network for grid power modelling maintained and annually updated at ifeu as described in (Fehrenbach et al. 2016). It is based on national electricity mix data by the International Energy Agency (IEA)[15]. The European electricity mix is applied as a prechain for most processes. Regarding beverage cartons, electricity generation is considered using Swedish and Finnish mix of energy suppliers in the year 2018 for the production of LPB. The applied shares of energy sources to the related market are given in **Table 3-6**. It has to be pointed out, that no supplier's specific electricity mixes were applied for any process along the entire value chain of the packaging systems regarded. As those are already included in the country-specific mixes, residual electricity mixes would have to be applied to all other processes within the system boundaries. This is not possible for many processes, for example polymer production as these are modelled with aggregated data that already include electricity inputs. Therefore, applying supplier specific electricity mixes would lead to a double counting that has to be avoided. If, however, for example green electricity is produced on-site, this would be taken into account. According to SIG Combibloc, all its beverage cartons are produced using 100 % renewable energy at production sites worldwide. As mentioned above, this is not taken into account.

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

Table 3-6: Share of energy source to specific energy mix, reference year 2021, based on IEA.

		Geographic scope			
		EU 27+3	Germany	Sweden	Finland
Energy source	Hard coal	6.36 %	9.42 %	0.01%	3.59%
	Brown coal	7.84 %	18.90 %	0.05%	2.81%
	Fuel oil	1.38 %	0.76 %	0.20%	0.22%
	Natural gas	20.56 %	16.15 %	0.53%	6.60%
	Nuclear energy	25.14 %	12.08 %	30.04%	32.68%
	Hydropower, wind, solar & geothermal	32.36 %	33.23 5	61.08 %	35.23 %
	Hydropower	38.47	10.52 %	71.93%	64.83%
	Wind power	42.76	62.12 %	26.57%	33.94%
	Solar energy	18.09	27.25 %	1.50%	1.23%
	Geothermal energy	0.68	0.10 %	0.00%	0.0 %
	Biomass energy	4.97 %	7.73 %	6.18 %	1.91 %
	Waste	1.36 %	1.71 %	1.92 %	1.47 %

3.9.3 Municipal waste incineration

The electrical and thermal efficiencies of the municipal solid waste incineration plants (MSWI) are shown in **Table 3-7**.

Table 3-7: Electrical and thermal efficiencies of the incineration plants for the examined markets

Geographic Scope	Electrical efficiency	Thermal efficiency	Reference period	Reference
Europe	15.0%	32.0%	2018	(CE Delft and prognos 2022, data provided by CEWEP 2021)

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, ([EC 2000] Council Directive 2000/76/EC).

It is assumed that the electrical energy generated in MSWI plants substitute the market specific grid electricity and that the thermal energy recovered in MSWI plants serves as process heat. The model takes into account that there are MSWI plants which do not provide thermal energy. However, if thermal energy is provided, it is used 100 %.

3.9.4 Landfill

The landfill model accounts for the emissions and the consumption of resources for the deposition of domestic wastes on a sanitary landfill site. Besides electric and mechanical energy for maintenance and operation of the landfill, burdens from treatment of short-term leakage (0-100a) in a waste treatment plant are included in the model. As information regarding an average landfill standard in Europe is currently not 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 carton material on a landfill. Empirical data regarding degradation rates of laminated beverage 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:

Regarding the degradation of the beverage 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 emissions 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.

3.9.5 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). Germany is the largest cement market within the European Union and an important trading partner for many EU countries. According to the Federal Statistical Office, German cement manufacturers exported around 6.2 million tonnes of cement in 2022 (VDZ 2023). Thus, the respective dataset is considered to be a suitable proxy for the thermal recovery in cement kilns in any European country. The applied process data cover emissions from the treatment in the clinker burning process. Parameters are restricted to those which change compared to the use of primary fuels. The output cement clinker is a function of the energy potential of the fuel and considers the demand of base material. According to VDZ (2021), cement plants have thermal efficiencies of 70-80 %.The primarily substitution of hard coal in cement kilns was confirmed by the economic, technical and scientific association for the German cement industry (VDZ e.V.) (VDZ 2019). However, in this study it is assumed that the cement kiln is only a suitable substitute for high-efficiency thermal recovery, and therefore heat energy is credited.

4 Results and discussion of base scenarios

4.1 Presentation of results

In this section the results of the examined beverage cartons are presented separately for the different impact and inventory categories in graphic form. **Figure 4-1** to **Fehler! Verweisquelle konnte nicht gefunden werden.** show the results for the base scenarios with allocation factor 50 % and 100 % across all impact and inventory categories.

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 for beverage cartons (**Plastics for sleeve**)
- Production and transport of aluminium/base material and converting to foil/barrier film (**Aluminium foil/barrier film**)
- Converting processes of beverage cartons **(Converting)**
- Production and transport of base materials for closure and related converting **(Closure)**

Gate to grave:

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

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 1.7**). 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, thermal energy from recovery processes) **(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 systems flows required for the delivery of 1000 L beverage to the point of sale including the end-of-life of the packaging systems.

4.2 Results of base scenarios

4.2.1 Base scenarios with 50 % allocation: numerical values and graphs

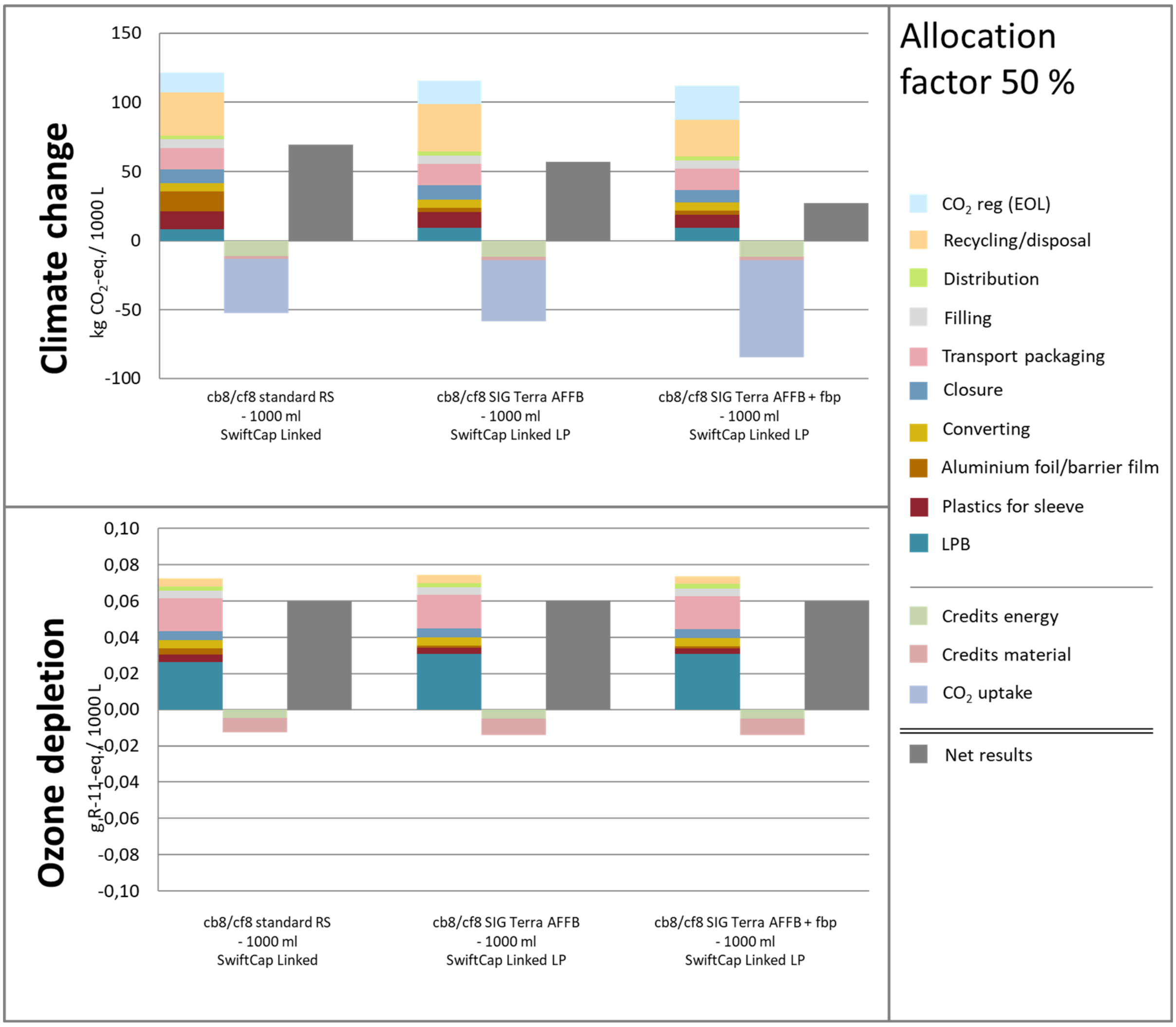

Figure 4-1: Indicator results for base scenarios with allocation factor 50 % (Part 1/4)

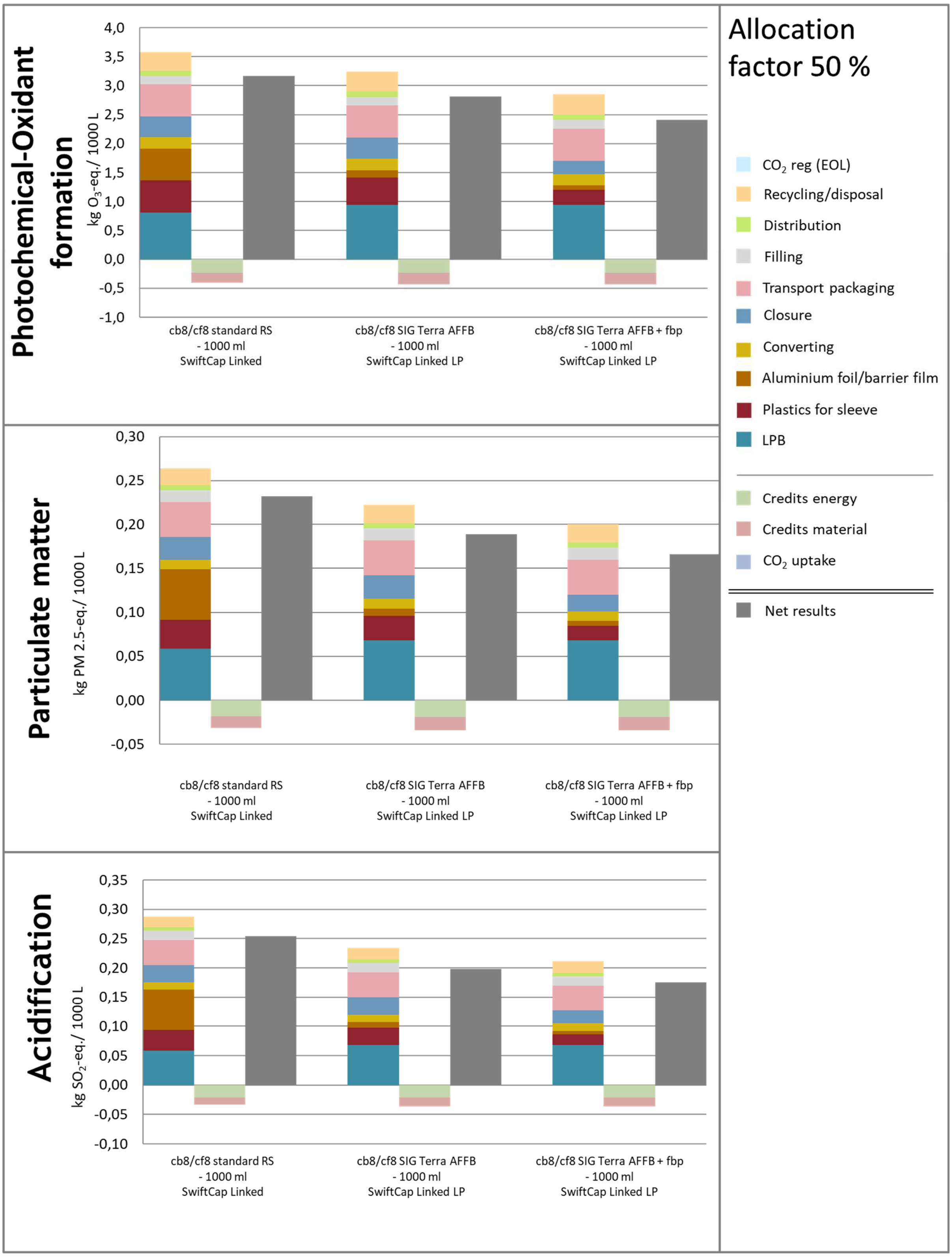

Figure 4-2: Indicator results for base scenarios with allocation factor 50 % (Part 2/4)

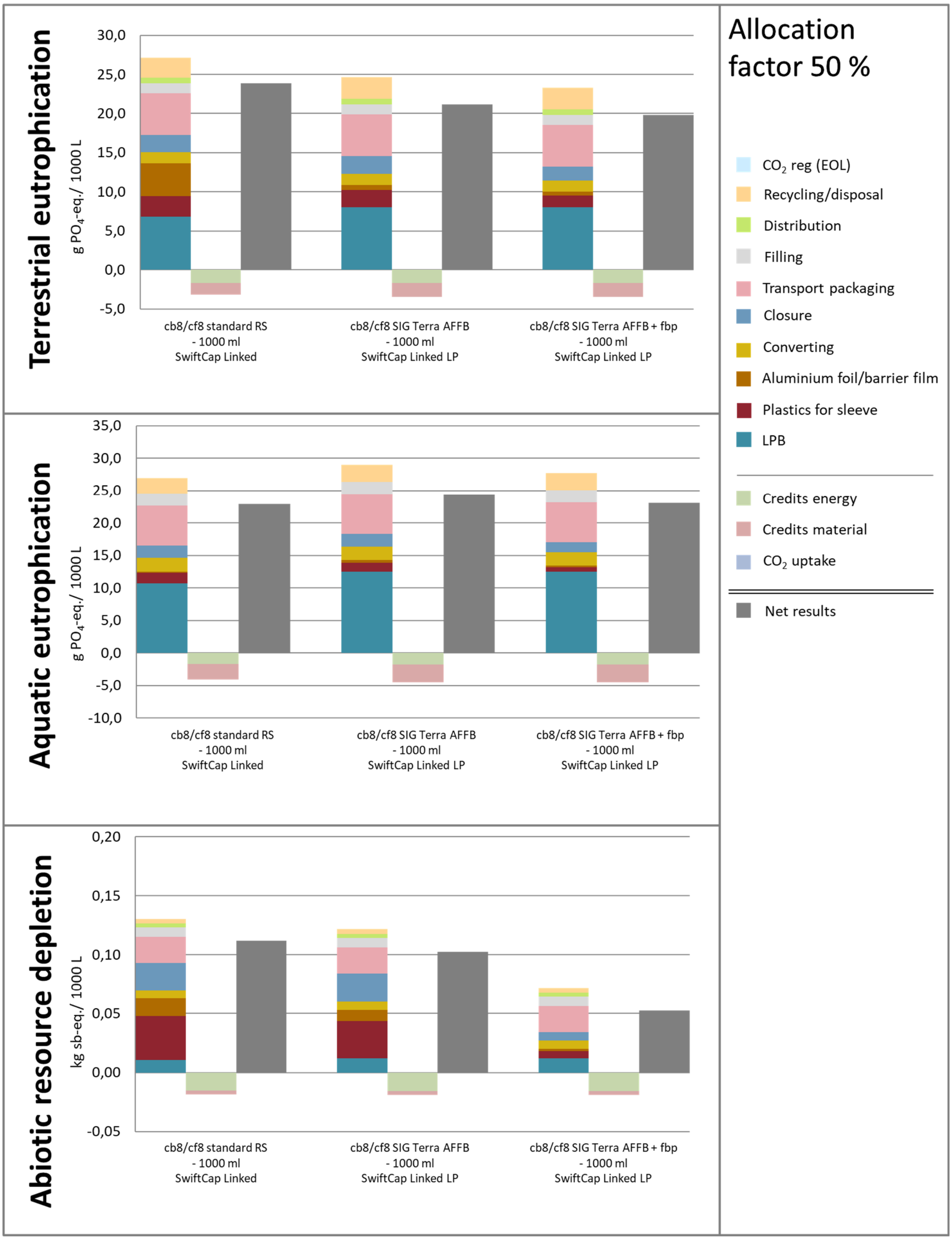

Figure 4-3: Indicator results for base scenarios with allocation factor 50 % (Part 3/4)

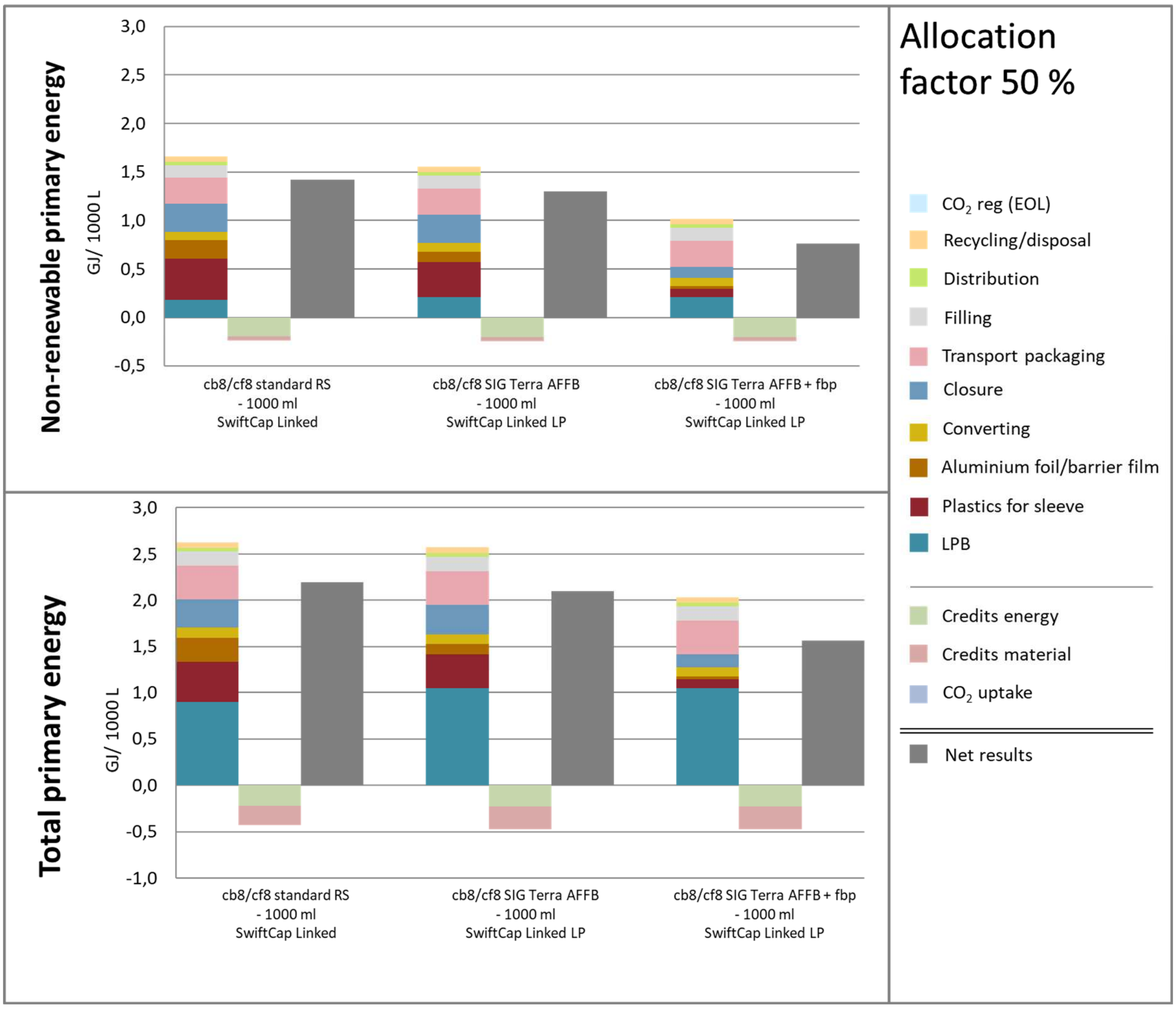

Figure 4-4: Indicator results for base scenarios with allocation factor 50 % (Part 4/4)

Table 4-1: Category indicator results for **base scenarios** with allocation factor 50 %: burdens, credits and net results per functional unit of 1000 L beverage

Base scenarios: allocation factor 50 %		**cb8/cf8 standard RS - 1000 ml SwiftCap Linked**	**cb8/cf8 SIG Terra AFFB - 1000 ml SwiftCap Linked LP**	**cb8/cf8 SIG Terra AFFB + fbp - 1000 ml SwiftCap Linked LP**
Climate Change [kg CO_2-equivalents]	Burdens	107,20	98,89	87,26
	CO2 (reg)	14,54	16,47	24,62
	Credits	-13,35	-13,89	-13,89
	CO_2 uptake	-39,12	-44,58	-70,97
	Net results (∑)	69,26	56,90	27,02
Acidification [kg SO_2-equivalents]	Burdens	0,29	0,23	0,21
	Credits	-0,03	-0,04	-0,04
	Net results (∑)	0,25	0,20	0,18
Photochemical-Oxidant formation [kg O_3-equivalents]	Burdens	3,58	3,25	2,85
	Credits	-0,41	-0,44	-0,44
	Net results (∑)	3,17	2,81	2,41
Ozone Depletion [g R-11-equivalents]	Burdens	0,07	0,07	0,07
	Credits	-0,01	-0,01	-0,01
	Net results (∑)	0,06	0,06	0,06
Terrestrial eutrophication [g PO_4-equivalents]	Burdens	27,11	24,64	23,29
	Credits	-3,21	-3,47	-3,47
	Net results (∑)	23,89	21,17	19,82
Aquatic eutrophication [g PO_4-equivalents]	Burdens	26,98	28,95	27,67
	Credits	-4,06	-4,53	-4,53
	Net results (∑)	22,93	24,42	23,14
Particulate matter [kg PM 2,5- equivalents]	Burdens	0,26	0,22	0,20
	Credits	-0,03	-0,03	-0,03
	Net results (∑)	0,23	0,19	0,17
Abiotic resource depletion [kg sb-equivalents]	Burdens	0,13	0,12	0,07
	Credits	-0,02	-0,02	-0,02
	Net results (∑)	0,11	0,10	0,05
Non-renewable primary energy [GJ]	Burdens	1,66	1,55	1,01
	Credits	-0,24	-0,25	-0,25
	Net results (∑)	1,42	1,30	0,76
Total Primary Energy [GJ]	Burdens	2,63	2,57	2,04
	Credits	-0,43	-0,47	-0,47
	Net results (∑)	2,19	2,10	1,57

4.2.2 Base scenarios with 100 % allocation: numerical values and graphs

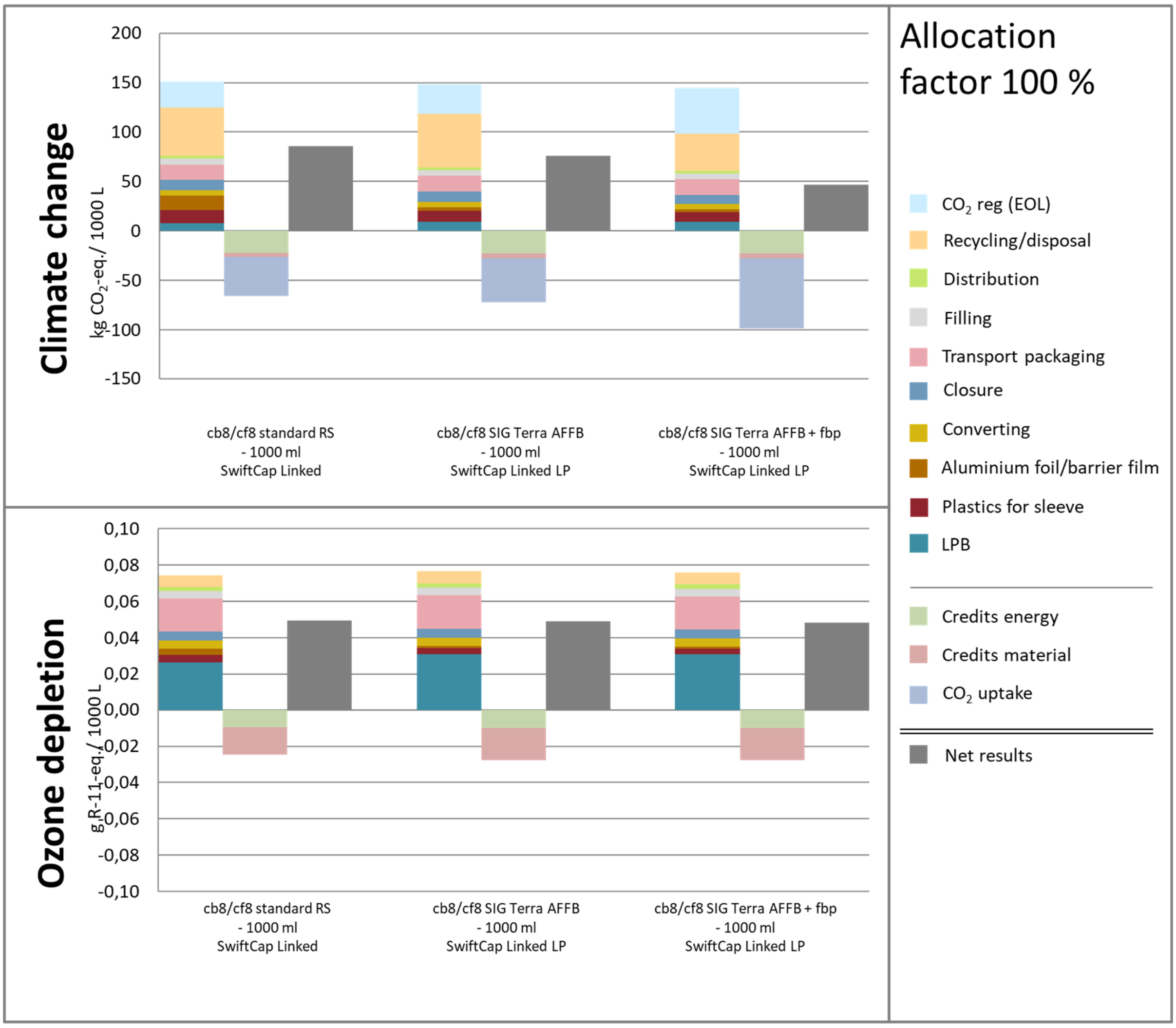

Figure 4-5: Indicator results for base scenarios with allocation factor 100 % (Part 1/4)

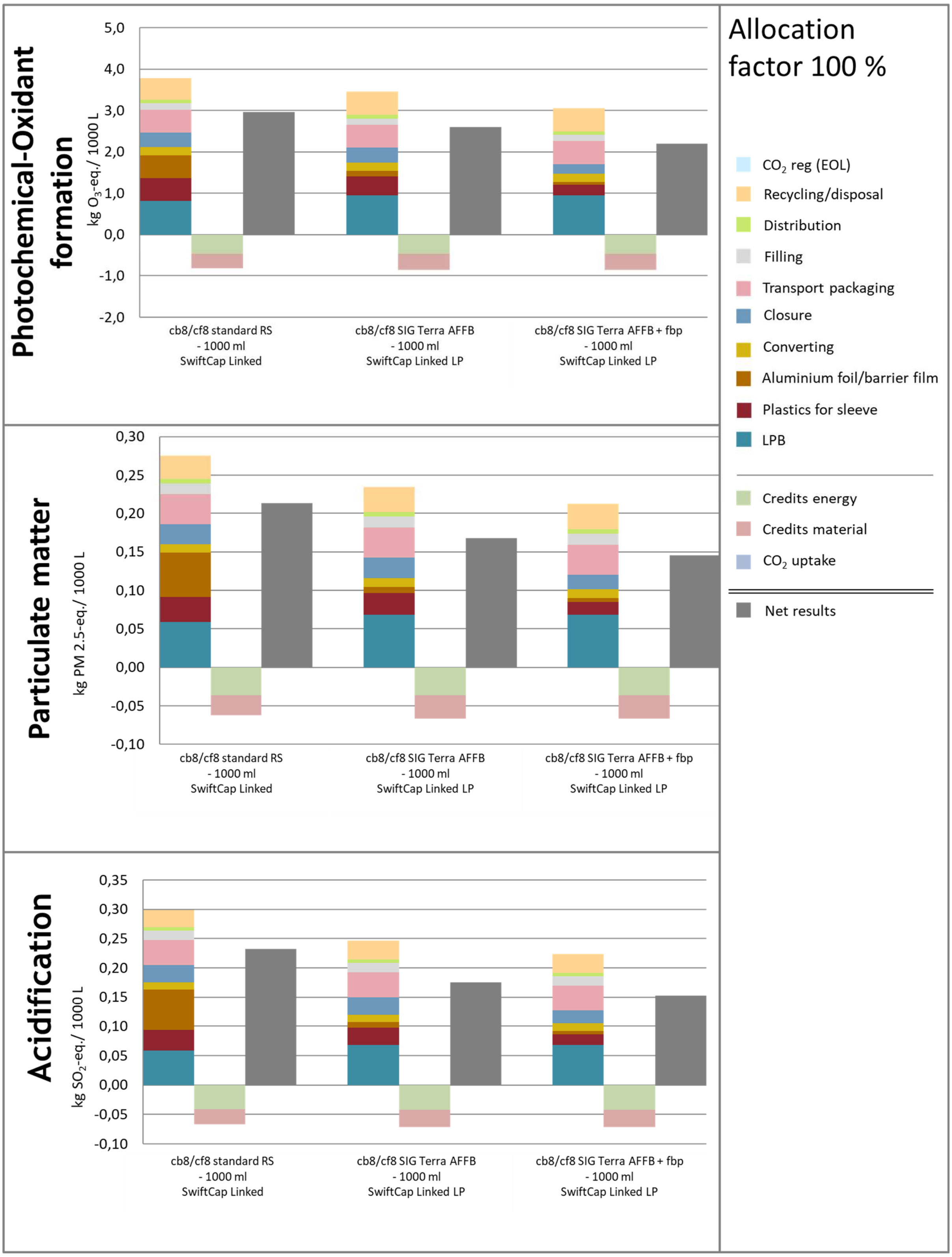

Figure 4-6: Indicator results for base scenarios with allocation factor 100 % (Part 2/4)

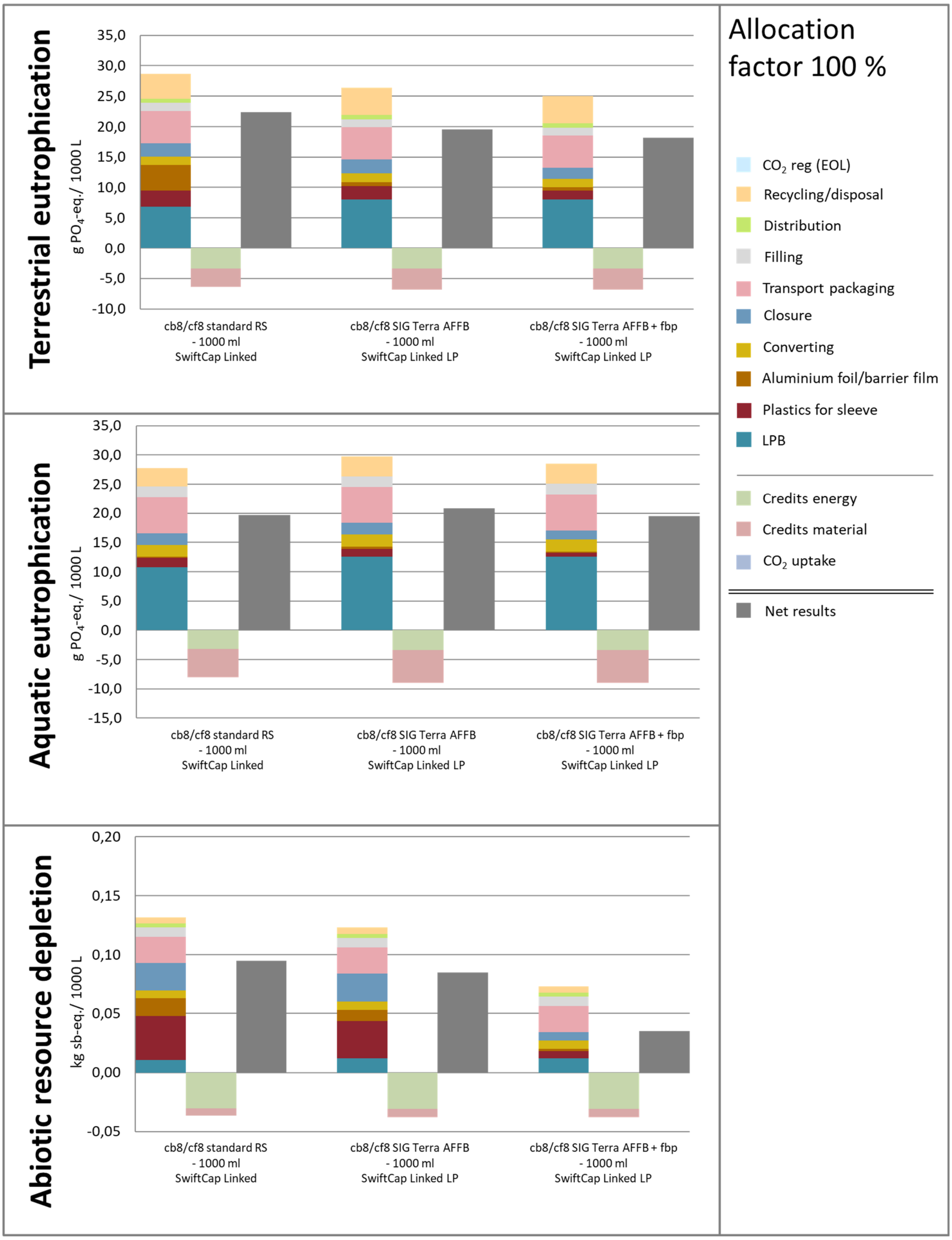

Figure 4-7: Indicator results for base scenarios with allocation factor 100 % (Part 3/4)

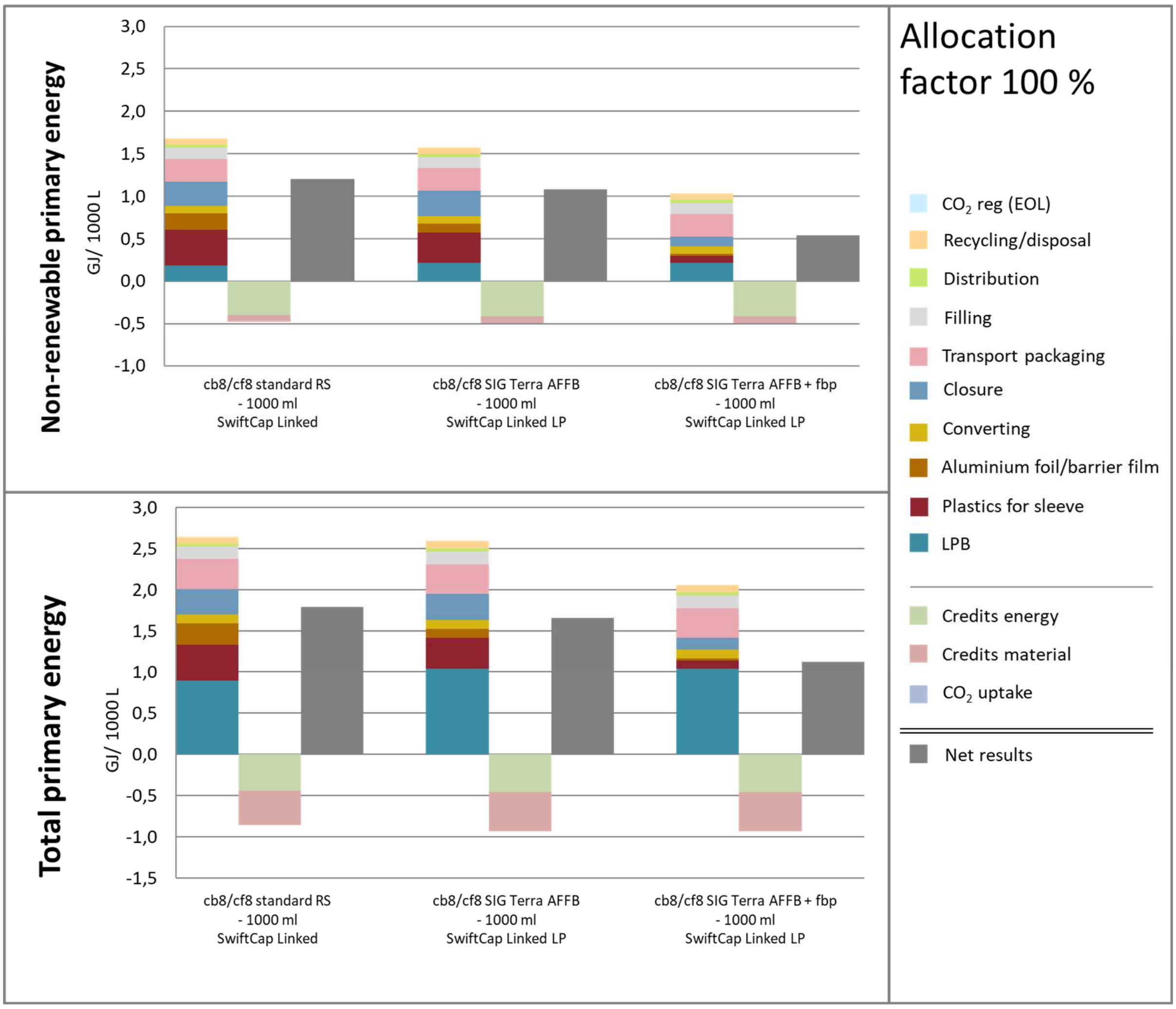

Figure 4-8: Indicator results for base scenarios with allocation factor 100 % (Part 4/4)

Table 4-2: Category indicator results for **base scenarios** with allocation factor 100 %: burdens, credits and net results per functional unit of 1000 L beverage

Base scenarios: allocation factor 100 %		cb8/cf8 standard RS - 1000 ml SwiftCap Linked	cb8/cf8 SIG Terra AFFB - 1000 ml SwiftCap Linked LP	cb8/cf8 SIG Terra AFFB + fbp - 1000 ml SwiftCap Linked LP
Climate Change [kg CO_2-equivalents]	Burdens	124,63	118,13	98,35
	CO2 (reg)	26,66	30,27	46,56
	Credits	-26,46	-27,51	-27,51
	CO_2 uptake	-39,12	-44,58	-70,97
	Net results (∑)	85,71	76,31	46,43
Acidification [kg SO_2-equivalents]	Burdens	0,30	0,25	0,22
	Credits	-0,07	-0,07	-0,07
	Net results (∑)	0,23	0,18	0,15
Photochemical-Oxidant formation [kg O_3-equivalents]	Burdens	3,77	3,46	3,06
	Credits	-0,81	-0,87	-0,87
	Net results (∑)	2,96	2,60	2,20
Ozone Depletion [g R-11-equivalents]	Burdens	0,07	0,08	0,08
	Credits	-0,02	-0,03	-0,03
	Net results (∑)	0,05	0,05	0,05
Terrestrial eutrophication [g PO_4-equivalents]	Burdens	28,70	26,39	25,03
	Credits	-6,37	-6,87	-6,87
	Net results (∑)	22,33	19,52	18,16
Aquatic eutrophication [g PO_4-equivalents]	Burdens	27,72	29,77	28,49
	Credits	-8,02	-8,97	-8,97
	Net results (∑)	19,70	20,80	19,52
Particulate matter [kg PM 2,5- equivalents]	Burdens	0,28	0,23	0,21
	Credits	-0,06	-0,07	-0,07
	Net results (∑)	0,21	0,17	0,15
Abiotic resource depletion [kg sb-equivalents]	Burdens	0,13	0,12	0,07
	Credits	-0,04	-0,04	-0,04
	Net results (∑)	0,09	0,09	0,04
Non-renewable primary energy [GJ]	Burdens	1,68	1,58	1,04
	Credits	-0,48	-0,50	-0,50
	Net results (∑)	1,20	1,08	0,54
Total Primary Energy [GJ]	Burdens	2,65	2,59	2,06
	Credits	-0,86	-0,93	-0,93
	Net results (∑)	1,79	1,66	1,13

4.3 Description and interpretation of base scenario results

The following section describes the results of the life cycle steps the for *cb8/cf8 SIG beverage cartons*. In addition, the effect of the allocation factors is explained.

4.3.1.1 cb8/cf8 SIG beverage cartons

The **LPB** shows the largest contribution in the results of 'Acidification', 'Photochemical-Oxidant Formation', 'Ozone depletion', 'Particulate matter', 'Terrestrial eutrophication', 'Aquatic eutrophication' 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 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. That explains its relatively small influence on Climate change. The contribution of LPB to the results is lower for the *cb8/cf8 standard RS - 1000 ml SwiftCap Linked* as less LPB is used for the sleeve than it is the case for both *cb8/cf8 SIG Terra AFFB beverage cartons.*

For the **plastic for sleeve** and the **closure**, high shares on the environmental burdens can be observed in 'Climate change', 'Photochemical-Oxidant Formation', 'Particulate matter', 'Acidification', 'Terrestrial eutrophication', 'Abiotic resource depletion' as well as in the inventory categories 'Non-renewable primary energy' and 'Total primary energy'.

In all categories examined, the contribution of **plastics for sleeve** and **closure** to the results is lower for the *cb8/cf8 SIG Terra AFFB + fbp - 1000 ml SwiftCap Linked LP* when compared with the examined beverage cartons using fossil-based plastics. This is in contrast to the patterns of previous LCA studies (e.g.(Wellenreuther et al. 2019); (Grünwasser et al. 2022)) comparing conventional SIG beverage cartons using fossil-based polymers with SIGNATURE beverage cartons using forest-based polymers. These LCA studies showed higher climate change impacts for forest-based polymers. The fossil-based polymers were based on LCI datasets from EcoInvent 3.9 and earlier versions. For this LCA study the updated LCI datasets for fossil-based polymers published in EcoInvent 3.10 are used. With the dataset update the climate change results for fossil-based polymers have increased significantly as the methane emissions from the upstream chain are included for the first time. As a result, the climate change impact of forest-based polymers is lower than those of the fossil-based polymers.

The main material for the **plastic for sleeve** and **closure** of the *cb8/cf8 SIG Terra AFFB + fbp - 1000 ml SwiftCap Linked LP is* allocated to bio-based feedstock via applying the mass balance principle. Nevertheless, the same cracking and polymerisation process is needed as for fossil plastics. These production steps play a major role in all impact categories. In addition, energy and hydrogen used by the hydrotreatment process for the production of bio-diesel lead to major contributions to the results of 'Climate change' 'Photochemical-Oxidant Formation', 'Particulate matter', 'Acidification', 'Terrestrial and Aquatic eutrophication', 'Abiotic resource depletion', 'Non-renewable primary energy' and 'Total primary energy'. Nitrogen dioxide and sulphur dioxide emissions related to the acidulation process to produce crude tall oil from BLS play a dominant role in the category 'Acidification'.

The production of **aluminium foil** for the sleeves of the *cb8/cf8 standard RS - 1000 ml SwiftCap Linked* show burdens in most impact categories. High shares of burdens are shown in the impact categories 'Climate change', 'Photochemical-Oxidant Formation', 'Acidification', 'Particulate matter' and 'Terrestrial eutrophication'. These result from SO_2 and NOx emissions from the aluminium production. The contribution of the alternative **barrier film** to the results of both *cb8/cf8 SIG Terra AFFB beverage cartons* is small in all categories examined.

The **filling** and **converting** process contributes to all examined categories. This results from the thermal energy and electricity input. The converting process of both *cb8/cf8 SIG Terra AFFB beverage cartons* show slightly higher emissions than that of the *cb8/cf8 standard RS - 1000 ml SwiftCap Linked beverage cartons* as the weight of those sleeves is slightly higher.

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 the most impact and inventory categories. The pallet and the stretch film production play a minor role. As the amount of secondary and tertiary packaging as well as the number of cartons that can be stacked per pallet is the same for all examined beverage cartons the contribution of transport packaging is similar for all of them.

The life cycle step **distribution** shows similar burdens in all impact categories for both *cb8/cf8 SIG Terra AFFB beverage cartons* and slightly lower emissions for *cb8/cf8 standard RS - 1000 ml SwiftCap Linked beverage cartons* as the weight of its sleeves and closures is slightly lower.

The End of Life phase **recycling/disposal** of the considered beverage cartons is clearly most relevant in the impact category 'Climate change', however the emissions also visibly contribute to 'Photochemical-Oxidant Formation', Particulate matter', 'Acidification', 'Terrestrial eutrophication' and 'Aquatic eutrophication'. 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.

CO_2 reg. (EOL) describes separately all regenerative CO_2 emissions from recycling and disposal processes. These derive mainly from the incineration of paper and mass-balanced plastic components (in case of the *cb8/cf8 SIG Terra AFFB + fbp - 1000 ml SwiftCap Linked LP*) as well as from landfills.

The **energy credits** arise from incineration plants, where energy recovery takes place as well as from the use of the PolyAl fraction as RDF fuel in power plants.

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 and in addition the mass-balanced plastic used in case of the *cb8/cf8 SIG Terra AFFB + fbp - 1000 ml SwiftCap Linked LP beverage carton* 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.

4.3.1.2 Allocation factors

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

In the European market, the benefits from the additional allocation of credits are higher than the additional burdens. That means 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 benefit from receiving more credits does not outweigh the extra burdens obtained. The main reasons for this are the emissions of the waste incineration plants, which are now fully allocated to the examined system. In addition, the allocation factor does not affect the CO_2 uptake, therefore the values for the CO_2 uptake do not increase when applying the 100 % allocation factor. **CO_2 reg. (EOL)** emissions are accounted for 'Climate change' in the same way as fossil CO_2 emissions.

In categories that are driven by thermal energy and electricity generation, credits for energy recovery as well as material credits play an important role. Especially in markets with relatively high electrical and thermal efficiencies of MSWI plants, such as Europe.

4.4 Comparison of packaging systems

The **Table 4-3** to **Table 4-5** show the net result comparison for the base scenarios with allocation factor 50 % and with allocation factor 100 % along all impact categories.

The colors green and blue illustrate the distinction between more (green) and less (blue[16]) favorable net results from the viewpoint of the packaging which is indicated in the respective table at the top and compared to the other packaging systems listed below. Percentages lower than 10 % are considered as insignificant differences and therefore marked by a grey shading of the respective fields.

The percentage is based on the net results of each packaging system. The base scenarios with allocation factor 50 % as well as with allocation factor 100 % are equally used for the comparison between the packaging systems.

[16] Note that this does not apply to any of the categories shown in Table 4-3 to Table 4-5, as the corresponding comparison does not show less favourable results.

Table 4-3: Comparison of net results of cb8/cf8 SIG Terra AFFB - 1000 ml SwiftCap Linked LP with cb8/cf8 standard RS - 1000 ml SwiftCap Linked

	The net results of the base scenario of **cb8/cf8 SIG Terra AFFB - 1000 ml SwiftCap Linked LP** are lower (green)/higher (blue*) than those of the base scenario for cb8/cf8 standard RS - 1000 ml SwiftCap Linked	
	AF 50	**AF 100**
Impact categories		
Climate Change	-18%	-11%
Ozone Depletion	1%	-1%
Photochemical-Oxidant Formation	-11%	-12%
Particulate Matter	-19%	-21%
Acidification	-22%	-24%
Terrestrial Eutrophication	-11%	-13%
Aquatic Eutrophication	7%	6%
Abiotic Resource Depletion	-8%	-10%
Non-renewable Primary Energy	-8%	-10%
Total Primary Energy	-4%	-7%

In both base scenarios, the *cb8/cf8 SIG Terra AFFB - 1000 ml SwiftCap Linked LP* shows lower net results than the *cb8/cf8 standard RS - 1000 ml SwiftCap Linked* in the impact categories 'Climate Change', 'Photochemical-Oxidant Formation', 'Particulate Matter', 'Acidification', 'Terrestrial Eutrophication'.

No significant differences are measured between the results of the *cb8/cf8 SIG Terra AFFB - 1000 ml SwiftCap Linked LP* and the *cb8/cf8 standard RS - 1000 ml SwiftCap Linked* in the impact categories 'Ozone depletion', 'Abiotic resource depletion' and 'Aquatic eutrophication' and in the inventory categories 'Non-renewable Primary Energy' and 'Total Primary Energy' with allocation factor 50 %.

For the base scenario of the *cb8/cf8 SIG Terra AFFB - 1000 ml SwiftCap Linked LP* and the *cb8/cf8 standard RS - 1000 ml SwiftCap Linked* with allocation factor 100 %, no significant differences are measured in the impact categories 'Ozone depletion', 'Aquatic eutrophication' and in the inventory category 'Total Primary Energy'.

Table 4-4: Comparison of net results of cb8/cf8 SIG Terra AFFB +fbp - 1000 ml SwiftCap Linked LP with cb8/cf8 standard RS - 1000 ml SwiftCap Linked

	The net results of the base scenario of **cb8/cf8 SIG Terra AFFB + fbp - 1000 ml SwiftCap Linked LP** are lower (green)/higher (blue*) than those of the base scenario for cb8/cf8 standard RS - 1000 ml SwiftCap Linked	
	AF 50	**AF 100**
Impact categories		
Climate Change	-61%	-46%
Ozone Depletion	0%	-3%
Photochemical-Oxidant Formation	-24%	-26%
Particulate Matter	-29%	-32%
Acidification	-31%	-34%
Terrestrial Eutrophication	-17%	-19%
Aquatic Eutrophication	1%	-1%
Abiotic Resource Depletion	-53%	-63%
Non-renewable Primary Energy	-46%	-55%
Total Primary Energy	-29%	-37%

In both base scenarios, the *cb8/cf8 SIG Terra AFFB + fbp - 1000 ml SwiftCap Linked LP* shows lower net results than the *cb8/cf8 standard RS - 1000 ml SwiftCap Linked* in the impact categories 'Climate Change', 'Photochemical-Oxidant Formation', 'Particulate Matter', 'Acidification', 'Terrestrial Eutrophication', 'Abiotic resource depletion' and in the inventory categories 'Non-renewable Primary Energy' and 'Total Primary Energy'.

In the comparison of the *cb8/cf8 SIG Terra AFFB + fbp - 1000 ml SwiftCap Linked LP* with the *cb8/cf8 standard RS - 1000 ml SwiftCap Linked* no significant differences are measured in the impact categories 'Ozone depletion' and 'Aquatic eutrophication' for both allocation factors.

Table 4-5: Comparison of net results of cb8/cf8 SIG Terra AFFB +fbp - 1000 ml SwiftCap Linked LP with cb8/cf8 SIG Terra AFFB - 1000 ml SwiftCap Linked LP

	The net results of the base scenario of **cb8/cf8 SIG Terra AFFB + fbp - 1000 ml SwiftCap Linked LP** are lower (green)/higher (blue*) than those of the base scenario for cb8/cf8 SIG Terra AFFB - 1000 ml SwiftCap Linked LP	
	AF 50	**AF 100**
Impact categories		
Climate Change	-53%	-39%
Ozone Depletion	-1%	-1%
Photochemical-Oxidant Formation	-14%	-15%
Particulate Matter	-12%	-13%
Acidification	-12%	-13%
Terrestrial Eutrophication	-6%	-7%
Aquatic Eutrophication	-5%	-6%
Abiotic Resource Depletion	-49%	-59%
Non-renewable Primary Energy	-41%	-50%
Total Primary Energy	-25%	-32%

In both base scenarios, the *cb8/cf8 SIG Terra AFFB + fbp - 1000 ml SwiftCap Linked LP* shows lower net results than the *cb8/cf8 SIG Terra AFFB - 1000 ml SwiftCap Linked LP* in the impact categories 'Climate change', 'Acidification', 'Photochemical-Oxidant Formation', 'Particulate matter', 'Abiotic resource depletion' and in the inventory categories 'Non-renewable primary energy' and 'Total primary energy'.

No significant differences are measured in the impact categories 'Ozone depletion', 'Aquatic Eutrophication' and ''Terrestrial Eutrophication' for both allocation factors.

5 Data quality evaluation and limitations

5.1 Data quality evaluation

The relevant information and data used for evaluating the examined packaging systems in this study were available. In the authors' opinion no errors affecting the results were found.

The complete life cycle was considered (except the use phase), including the extraction and production of raw materials, converting processes, all transports and the final disposal or recycling of the packaging system, in each case in modeling for the examined packaging systems. Data was acquired along the entire supply chain of packaging production.

Allocation rules, system boundaries and calculations as to impact assessment were applied uniformly and consistently to all examined packaging systems and the scenarios based on them. An exception may be infrastructure which is generally excluded in this study. In case of some aggregated datasets taken from public databases it may be included without being documented.

Following the ISO standard's recommendation on subjective choices, the 50 % and 100 % allocation factors for system allocation are applied equally in this study.

Section 1.6 (Data gathering and data quality) gives an overview of

- The overall completeness check: The relevant information from all life cycle phases are available and complete.
- The consistency evaluation: Data of the same level of detail were used for all considered beverage carton formats**.**
- The overall representative evaluation: The used data can be regarded as representative for the intended purpose of this study.
- Consistency is considered to be sufficient even if data from different data sources are used. Therefore, no serious data asymmetries are to be expected.

However, for potentially occurring uncertainties between the considered beverage carton formats, an estimated significance threshold of 10 % is chosen as approach as it is aimed to apply a consistent approach for all impact categories examined. This means differences in the impact category indicator results between the comparative systems < 10 % are considered as insignificant.

The quality of the data on beverage distribution in the present study is limited due to a lack of data availability. The distribution model is based on assumptions, whereby the same distribution distances were assumed for all systems in order to avoid asymmetries. Since the packaging weights of the beverage cartons studied are however comparable, changes in transport distances do not have a significant impact on the results of the packaging systems.

In summary, in the author's view the quality and symmetry of the data in this LCA is good or very good and is appropriate to the study's objectives.

5.2 Limitations

The results of the scenarios and analysed packaging systems and the respective comparisons between beverage cartons are valid within the framework conditions described in **section 1 (Goal and Scope)** and **section 2 (Packaging systems and scenarios)**. The following limitations must be taken into account, however.

Limitations arising from the selection of market segment

The results are only valid for packaging containing liquid dairy and/or NCSD. Even though carton 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 SIG Combibloc. This selection does not represent the whole European market. It has to be noted, that this study puts the focus on single-use packaging for packed beverages. Refillable packaging systems are not included in this study. Therefore, it is not possible to transfer the results of this study to refillable packages.

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. All packaging specifications of the carton packaging systems were provided by SIG Combibloc. Packaging specifications different from the ones used in this study cannot be compared directly with the results of this study.

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

Limitations concerning distribution data

The quality of the data on beverage distribution in the present study is limited due to a lack of data availability. The distribution model is based on assumptions, whereby the same distribution distances were assumed for all systems in order to avoid asymmetries. The results of the study apply only to the distribution model used in this study and are not easily transferable to other distribution models.

Limitations concerning the chosen environmental impact potentials and applied assessment method

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 impact. 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 categories

The results are valid only for the environmental impact categories, which were examined. The category indicator results represent potential environmental impacts per functional unit. They are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins or risks.

Limitations concerning the significance of the differences

In evaluating the results of the present study, a significance threshold of 10 % was applied for comparative results. The application of other significance thresholds could possibly lead to a different assessment of the systems' comparison. The 10 % threshold applied in this study is an expert judgement intended to rank the results and thus to provide an informative basis.

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 Europe even for the same packaging systems.

This applies particularly for the End of Life settings as the mix of waste treatment routes and specific technologies used within these routes may differ, e.g. in other countries.

Regarding the production of tall oil-based polymers, the results are only valid as long as the tall oil originates from Finland as the tall oil related processes are modelled with Finnish electricity for this study.

Limitations concerning the reference period

The results are valid only for the indicated time scope and cannot be assumed to be valid for (the same) packaging systems at a different point in time.

Limitations concerning system boundaries

The results are valid only for described system boundaries. The listed exclusions are not considered relevant for the comparison, though.

Limitations concerning data quality

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, data from ifeu's internal database and industry data.

There are potential limitations on used data, e.g., regarding inclusion of infrastructure, but they are considered as not sufficient to cast doubt on the results.

The data quality evaluation shows, that no major data asymmetries are to be expected that would influence the overall conclusions and recommendations of this study.

6 Conclusions and Recommendations

The present report provides environmental profiles of different *cb8/cf8 SIG* beverage cartons on the European market. In the following section, the most important significant parameters of *cb8/cf8 SIG* beverage cartons and the comparison between their environmental performances are summarised, and conclusions and recommendations are drawn from the results presented and discussed in the previous sections. Results with the 50 % allocation factor and the 100 % allocation factor are taken into consideration to the same extent. Differences lower than 10 % are considered to be insignificant (please see also **section 1.6** on precision and uncertainty). If the comparison result pattern is quite differentiated, no clear statements can be made about ecological advantages or disadvantages for the respective comparison.

6.1 Significant parameters

For the beverage cartons examined in this study, in most impact categories a considerable part of the environmental burdens is caused by the production of the materials for the components (**sleeve and closure**) of the beverage cartons.

The manufacturing of the **aluminium foil** for the *cb8/cf8 standard RS - 1000 ml SwiftCap Linked beverage carton* is an energy intensive process and is therefore connected to high environmental impacts in most impact categories analysed. In contrast, the contribution of the alternative **barrier film** to the results of both *cb8/cf8 SIG Terra AFFB beverage cartons* is small in all categories examined.

The contribution of the life cycle steps **plastics for sleeve** and **closure** are lower in case of the *cb8/cf8 SIG Terra AFFB + fbp - 1000 ml SwiftCap Linked LP beverage cartons* using tall-oil based polymers when compared with the *cb8/cf8 standard RS - 1000 ml SwiftCap Linked beverage cartons* and the *cb8/cf8 SIG Terra AFFB - 1000 ml SwiftCap Linked LP beverage cartons* using fossil-based plastics.

The contribution of **transport packaging** to the net results comes from the production of corrugated cardboard for secondary and tertiary packaging and plays an important role in almost all impact categories analysed.

The **recycling and disposal processes** of the beverage cartons considered are particularly relevant for the 'Climate change'.

6.2 Comparison between packaging systems

With an allocation factor 50 %, the *cb8/cf8 SIG Terra AFFB - 1000 ml SwiftCap Linked LP* shows either lower net results or non-significant differences in net results ('Aquatic eutrophication', 'Ozone depletion', 'Abiotic resource depletion', 'Non-renewable Primary Energy', 'Total Primary Energy') in the impact categories analysed, when compared with *cb8/cf8 standard RS - 1000 ml SwiftCap Linked.*

With allocation factor 100 %, the *cb8/cf8 SIG Terra AFFB - 1000 ml SwiftCap Linked LP* shows either lower net results or non-significant differences in net results (‘Aquatic eutrophication’, ‘Ozone depletion’, ‘Total Primary Energy’) in the impact categories analysed, when compared with the *cb8/cf8 standard RS - 1000 ml SwiftCap Linked.*

In comparison with the *cb8/cf8 standard RS - 1000 ml SwiftCap Linked*, the *cb8/cf8 SIG Terra AFFB + fbp - 1000 ml SwiftCap Linked LP* shows predominantly lower net results, with only two impact categories (‘Aquatic eutrophication’, ‘Ozone depletion’) showing no significant difference in net results for both allocation factors.

In the impact categories analysed, the *cb8/cf8 SIG Terra AFFB + fbp - 1000 ml SwiftCap Linked LP* shows either lower net results or non-significant differences in net results (‘Terrestrial eutrophication’, ‘Aquatic eutrophication’, ‘Ozone depletion’) when compared with the *cb8/cf8 SIG Terra AFFB - 1000 ml SwiftCap Linked LP carton* regardless of the applied allocation factor*.*

6.3 Recommendations

Based on the results of the base scenario (**section 4**), the limitations listed in **section 5.2** and the methodological choices including the selection of impact categories the authors developed the following recommendations:

- Since the environmental result of the examined *cb8/cf8 SIG beverage carton format* is significantly influenced by the production of its main components, the sleeve and closure, measures to use less material are recommended as long as the same functionality is ensured.
- It is further shown, that the alternative barrier film used for the *cb8/cf8 SIG Terra AFFB + fbp - 1000 ml SwiftCap Linked LP* and the *cb8/cf8 SIG Terra AFFB - 1000 ml SwiftCap Linked LP* has lower impacts in most of the analysed impact categories than the aluminium foil used in the *cb8/cf8 standard RS - 1000 ml SwiftCap Linked beverage cartons.* In view of this and the fact that the use of the alternative barrier film has no negative influence on the recyclability of the beverage cartons after use, it is recommended, that aluminium foils are substituted by alternative barrier films.
- Transport packaging contributes significantly to most impact and inventory categories and can be attributed to the use of cardboard boxes and slip sheets. It is recommended that measures are taken to use less secondary and tertiary packaging as long as the same level of transport safety is ensured.
- The comparative results do not show that any beverage carton system has lower results in all impact and inventory categories compared to another beverage carton examined in this study. However, the beverage carton *cb8/cf8 SIG Terra AFFB + fbp - 1000 ml SwiftCap Linked LP* shows lower environmental impacts in several impact categories and no higher impacts in any other category when compared to the *cb8/cf8 standard RS -1000 ml SwiftCap Linked* and the *cb8/cf8 SIG Terra AFFB - 1000 ml SwiftCap Linked LP*. Therefore, from an environmental viewpoint it is recommended to prefer the *cb8/cf8 SIG Terra AFFB + fbp - 1000 ml SwiftCap Linked LP* beverage carton over the *cb8/cf8 standard RS - 1000 ml SwiftCap Linked* and the *cb8/cf8 SIG Terra AFFB - 1000 ml SwiftCap Linked LP* beverage carton examined in this study on the European market.
- The *cb8/cf8 SIG Terra AFFB + fbp - 1000 ml SwiftCap Linked LP* having lower impacts than *cb8/cf8 SIG Terra AFFB - 1000 ml SwiftCap Linked LP* (which has the same specifications apart from the choice of polymers) shows that environmental advantages can be reached by the use of mass-balanced

renewable material. Consequently, the use of mass-balanced renewable material is recommended from an environmental point of view. In the authors' view, showing the benefits of using renewable materials by the application of the mass-balanced approach in the production of polymers, is an important driver to facilitate an increasing substitution of fossil resources by biogenic resources for the production of polymers.

- It is also recommended to actually achieve a more significant physical share of tall oil-based input materials for the production of polymers, as the by-product of the pulp industry is currently mainly dedicated to direct thermal use. The utilisation and demand of mass-balanced polymers by SIG Combibloc might be a driver to do so.

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Critical review statement

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Analysis of cb8/cf8 SIG beverage cartons on the European, French, Germany, Italian and Spanish markets

This document forms the critical review statement for the study "Analysis of cb8/cf8 SIG beverage cartons on the European market; Comparative life cycle assessment of cb8/cf8 SIG beverage cartons for liquid dairy and NCSD on the European market" as reported by ifeu in their report for Study Number CB- 100740, dated January 2025, and the subsequent market extension reports covering the more specific markets of France, Germany, Italy and Spain.

The study was prepared by ifeu, Institut fur Energie und Umweltforschung Heidelberg, and was commissioned and funded by SIG, a leading provider of packaging solutions including cartons, pouches and bag-in-box.

The critical review has been performed by an independent panel consisting of:

- Michael Sturges (panel chair) - RISE Research Institutes of Sweden – a life cycle (LCA) assessment practitioner with specific experience of environmental studies relating to packaging and forest industry value chains
- Nicolas Caye – GVM – a project manager with specific expertise in packaging markets
- Dr Alex Hetherington – Head of Climate Nature and Resources at sustainability consultancy 3Keel Group Ltd– an experienced sustainability professional with a multi-sector background in the process and FMCG industries, and over 15 years experience of LCA, including those involving packaging systems.

All reviewers were contracted directly by SIG and were independent of the LCA study.

Critical review process

The review was performed based on the requirements of ISO14044:2006 Section 6.3, i.e., critical review by panel of relevant experts.

The critical review began with consideration of the goal and scope and draft final report. These were presented to the critical review panel during a video conference and delivered as MS Word documents for detailed consideration. One of the critical review panel members (Dr Alex Hetherington) was also guided through the Umberto LCA models.

The critical review panel provided written feedback on the draft documents which was also discussed during a follow up video conference with the LCA practitioners and the project sponsors.

The LCA practitioners responded to the comments, providing amendments or further explanations as appropriate. This was an iterative process until the critical review panel were satisfied that all points raised had been sufficiently addressed.

For each round, comments were provided using a MS Excel feedback template. The LCA team then responded to the comments and provided its feedback, also describing subsequent changes to the data, models and report, by using the appropriate section of the feedback template. This approach provided a clear audit trail of the critical review panel's comments and the LCA practitioners' subsequent actions and responses.

The reviewers have considered these responses and changes and are satisfied that appropriate clarifications and actions have been provided.

Result of the critical review

The critical review panel found that the study was performed in conformance with ISO 14040 and ISO 14044.

Opinion of the reviewers

The reviewers conclude that the study's level of quality, detail and transparency is appropriate considering the goal and scope.

As with all LCA studies, there are methodological choices and modelling limitations that need to be understood when interpreting the results. All methodological choices are transparently documented in Sections 1.7 & 1.8 of the main report; it is of course important that users of LCA reports take account of such aspects.

In this particular study, as with all LCA studies including systems for forest industry products, the treatment of biogenic carbon requires consideration. In the baseline systems the practitioners have chosen an impact assessment methodology which accounts for biogenic removals and emissions of carbon dioxide. However, for bio-based materials with potential for recycling at end-of-life, allocation between the first life cycle of virgin fibres and subsequent life cycles of secondary or recovered fibres is required. In the approach adopted and documented in this study, uptake of biogenic carbon dioxide is allocated to the primary product, whereas a significant proportion of the biogenic emissions are allocated to the subsequent life cycle, thereby apparently reducing the overall climate change impact of the virgin product. The methodological choice regarding treatment of biogenic carbon dioxide emissions and removals is entirely valid and transparently documented.

The detailed sensitivity analysis provides transparency of the uncertainties and confidence in the overall robustness of the results achieved and conclusions drawn.

Subsequently, the reviewers consider the results and conclusions to be a sound and fair reflection of the potential comparative environmental impacts of the studied systems representing the SIG packaging solutions and the compared solutions.

In conclusion, it is the opinion of the review panel that the report provides useful and realistic information for stakeholders interested in this topic.

Critical review sign-off

The reviewers certify that the statement provided is a fair reflection of their assessment and views of the study "Analysis of cb8/cf8 SIG beverage cartons on the European market;

Comparative life cycle assessment of cb8/cf8 SIG beverage cartons for liquid dairy and NCSD on the European market" (CB- 100740) and the subsequent extension reports:

a. "Extension: Life Cycle Assessment of cb8/cf8 SIG beverage cartons and alternative packaging systems on the French market; Comparative life cycle assessment of cb8/cf8 SIG beverage cartons for liquid dairy and NCSD on the French market" (CB-100742),

b. "Extension: Life Cycle Assessment of cb8/cf8 SIG beverage cartons and alternative packaging systems on the German market; Comparative life cycle assessment of cb8/cf8 SIG beverage cartons for liquid dairy and NCSD on the German market" (CB-100741);

c. "Extension: Life Cycle Assessment of cb8/cf8 SIG beverage cartons and alternative packaging systems on the Italian market; Comparative life cycle assessment of cb8/cf8 SIG beverage cartons for liquid dairy and NCSD on the Italian market" (CB-100744); and

d. "Extension: Life Cycle Assessment of cb8/cf8 SIG beverage cartons and alternative packaging systems on the Spanish market; Comparative life cycle assessment of cb8/cf8 SIG beverage cartons for liquid dairy and NCSD on the Spanish market" (CB-100743).

Signed………………………. **Dated:** 14th April 2025

Michael Sturges, RISE Research Institutes of Sweden (lead panelist)

Signed………………………. **Dated:** 14th April 2025

Nicolas Caye, GVM Gesellschaft für Verpackungsmarktforschung mbH

Signed……………………….. **Dated:** 22nd April 2025

Dr Alex Hetherington, 3Keel Group Ltd