Comparative life cycle assessment of various single-use and reuse transport packaging

Analysis of single-use stretch wrap, stretch hood and shrink hood in comparison to single-use paper stretch, single-use and reuse cardboard boxes, reuse sleeves and reuse plastic boxes

final report

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Benedikt Kauertz
Andrea Drescher

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Executive summary

This recent study evaluates and compares various single-use and reuse pallet packaging solutions utilized as transport packaging within the European market. The study aims to offer a transparent contribution to the ongoing discussion about the importance of legal regulations for transport packaging.

This study analyses 5 single-use and 3 reuse transport packaging systems:

- Single-use systems (stretch wrap, stretch hood and shrink hood with 0%, 35% and 65% PCR content; paper stretch and cardboard box)
- Reuse systems (cardboard box, reuse sleeve made mainly from woven PET and reuse plastic box (with and without lid) made from PP)

The purpose of the transport packaging systems examined in this study is to securely hold products in their sales and group packaging on a pallet. Their primary function is to ensure safe transportation over a specified distance. This transport path begins at the production site where the transport packaging is applied and ends at the first economic operator in the logistics chain (typically a central warehouse). The transport packaging examined are considered for various application fields. However, not all transport packaging systems are suitable for every application field. The following figure presents a matrix that illustrates the relationship between different transport packaging solutions and their respective application field.

	Packaging systems							
	Single Use Systems					ReUse Systems		
Fields of application	stretch wrap	stretch hood	shrink hood	paper stretch	carboard box SU	coardbord box Reuse	Sleeve	reuse boxes
cardboard boxes	0% PCR 35% PCR 65% PCR			0% PCR	88% PCR	88% PCR	0% PCR	80% PCR
Water and CSD in PET bottles (Sixpack)	0% PCR 35% PCR 65% PCR			0% PCR	88% PCR	88% PCR	0% PCR	80% PCR
buckets	0% PCR 35% PCR 65% PCR			0% PCR	88% PCR	88% PCR	0% PCR	80% PCR
cement bags		0% PCR 35% PCR 65% PCR		Outside storage : humidity and weather protection avoiding product loss			0% PCR	80% PCR
polymer bags		0% PCR 35% PCR 65% PCR					0% PCR	80% PCR
glass bottles			0% PCR 35% PCR 65% PCR	Pallet stability and hygiene				80% PCR
milk in plastic bottles (HDPE)			0% PCR 35% PCR 65% PCR	Pallet stability, condensation due to cooling and hygiene			0% PCR	80% PCR

For this comparative assessment, the functional unit is the packaging and transportation of 1,000 kg of goods in sales and group packaging between two different or linked economic operators within the same Member State or within the territory of the European Union, in consideration of established logistic chains (e.g. selling channels, distances, means of transport), safety requirements and standardized dynamic testing of loading units.

The study follows an attributive system boundary approach. It considers all stages of the life cycle of the transport packaging from cradle to grave.

The data describing the transport packaging systems (weights and packaging patterns) were determined specifically for each application area as part of a standardised and certified EUMOS test procedure. The data sets essential for the evaluation of the results are taken from peer-reviewed data sets. The study includes a separate discussion of the latest scientific publications in the field to derive the frequency of use of the reuse systems. Overall, all packaging specifications and assumptions made in this study are deliberately conservative with regard to the comparison with reuse systems, ensuring that the results are both highly valid and robust.

The results of this study can be summarised as follows:

- Single-use plastic transport packaging systems, even when PCR material is not utilized, have a lower environmental impact than rigid reuse transport packaging systems (plastic box A and B) across all application fields examined.
- In almost all application fields studied, single-use plastic transport packaging systems also have a lower environmental impact than the flexible reuse transport packaging system under study (reuse sleeve).
- Compared to rigid the single-use transport packaging made from cardboard, single-use plastic transport packaging systems have consistently lower environmental impacts.
- Compared to flexible single-use transport packaging made from paper (paper stretch), single-use plastic transport packaging systems have advantages in most of the application field and environmental impact categories analysed.
- The use of PCR material represents a further path towards sustainability, as the results of this study show that single-use plastic transport packaging with a high PCR share always has the lowest environmental impact of all transport packaging systems under study. However, more studies are needed, as the massive use of PCR materials might significantly alter the overall performance of the industry, potentially reducing the current benefits calculated in this study.

The results are determined by:

- The environmental impact of producing and disposing of the amount of packaging material required to fulfil the functional unit (transport of 1,000 kg of packaged goods).
- The environmental impact of distribution and re-distribution. This life cycle steps are determined by the amount of packaging required to fulfil the functional unit and the transport efficiency of the transport packaging analysed.

Finally, it can be stated that none of the reuse systems analysed in this study have any significant environmental advantages compared to the single-use plastic transport packaging used today.

The findings of this study are only valid for the analysed transport packaging system within the defined application fields under European framework conditions. Moreover, the results are limited to the specified time frame.

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List of abbreviations

I packaging	Sales packaging
II packaging or secondary packaging	Group packaging
III packaging or tertiary packaging	Transport packaging
CSD	Carbonated soft drink
EUPC	European Plastics Converters
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
LLDPE	Linear low density polyethylene
MIR	Maximum Incremental Reactivity
MSWI	Municipal solid waste incineration
NMIR	Nitrogen-Maximum Incremental Reactivity
NMVOC	Non-methane volatile organic compounds
NO_X	Nitrogen oxides
PCR	Post-consumer recycle
PEF	Product Environmental Footprint
PM 2.5	Particulate matter with an aerodynamic diameter of 2.5 µm or smaller

PPWR	Packaging and Packaging Waste Regulation
UBA	Umweltbundesamt (German Federal Environmental Agency)
VOC	Volatile Organic Compounds

1 Goal and Scope

The production and recycling of packaging have increasingly become the focus of environmental debates in Europe in recent years. The consistent implementation of the waste hierarchy, which prioritizes prevention and reuse over material and thermal recycling, is intended by European legislators to significantly reduce the environmental impact of the packaging sector. However, Life Cycle Assessments (LCA) often show, that the calculated environmental impact does not always align with the theoretical waste hierarchy. For an objective and well-founded discussion, it is therefore essential to compile scientific facts and present them in a case-specific manner.

This study compares different single-use and reuse pallet packaging solutions as transport packaging in the European market. Its aim is to provide a transparent and comprehensible contribution to the discussion on the value of legal regulations for transport packaging.

1.1 Background and Objectives

Packaging systems usually consist of several parts. The small sales unit in which retailers offer products to end users is the sales package (e.g. a bottle of water). A defined number of sales units could be grouped together in a grouped package (e.g. a six-pack of 6 bottles of water). Depending on the product, the end users buy not only the sales packaging but also the grouped packaging. However, to transport the product from the manufacturer to the store, a certain amount of pallet wrapping as transport packaging is required in addition to the group and sales packaging. This is never given to the end user but always remains in the store or in the retailer's central warehouse. Transport packaging is primarily used to ensure that the load is transported safely from the manufacturer to the user and that it is handled efficiently within the value chain. In addition, to protecting during transport, the protective function also includes protecting the contents from dust and moisture. Unlike sales and group packaging, it does not have a marketing function as it is usually invisible to the end user.

When considering transport packaging, a distinction must be made between the pallet and the load securing. In most cases, load securing are single-use plastic films, usually made from LLDPE or LDPE. According to current market estimates, the volume of plastic transport packaging in Europe (including Russia) is more than 2 million tonnes of material. At 73%, stretch wrap is the most commonly used form of transport packaging, followed by stretch hood (16%) and shrink hood (11%). In the past, the majority of this packaging was made from primary raw materials, but now secondary materials are also used. The Packaging and Packaging Waste Regulation (PPWR), published in January 2025, defines in Article 7(1) and (2) minimum recycled contents recovered from post-consumer plastic waste. The targets are set per packaging type and format, calculated as an average per manufacturing plant and year. For plastic transport packaging the requirement is 35% PCR from 1/1 2030 and 65% from 1/1 2040. The same percentages apply to any plastic part of the packaging placed on the market as of 2030" (PPWR, Art 7 (1)) and therefore to plastic reuse systems (PET sleeve and boxes).

In the transport packaging market, reuse packaging currently only plays a role for pallets, but not for load securing. PPWR sets re-use targets in Article 29(1)-(3) on economic operators using transport packaging, or sales packaging used for transporting products. Included in the targets are several packaging formats, also “pallet wrappings or straps for stabilization and protection of products put on pallets during transport”, and they must be managed as part of a reuse system to a different extent:

- From 1 January 2030 at least 40% shall be reuse transport packaging and from 1 January 2040 at least 70%, when economic operators trade between two different member states (29(1)). If these packaging formats are used between company sites or sites of affiliated companies in the EU, they must be completely, i.e. 100% reuse from 2030 (Art. 29(2)).
- If these packaging formats are used between companies within a Member State, they must be completely, i.e. 100% reuse from 2030 (Art. 29(3)).

This study compares the life cycle profile of various single-use and reuse transport packaging under the current and future conditions set by the PPWR. LCA profiles are analysed for stretch wrap, stretch hood and shrink hood with respective 0%, 35% and 65% PCR content, used for different applications. The results of this assessment are compared with various single-use and reuse transport packaging solutions to categorise the environmental impact.

The rationale for selecting alternative single-use packaging is, that the systems are common in the market or at least promoted as a marketable alternative to single-use plastic packaging. The selection of possible reuse alternatives is based on what is already described in the literature and what is currently offered at trade fairs. The study focuses only on the environmental impact of the transport packaging, consisting of the handling unit and the load securing system. The environmental impact of the filling material and the sales and outer packaging are not included in the assessment, but they play a crucial role in the assessment of the transport efficiency of the various systems examined and are therefore also included in the data collection.

1.2 Organisation behind the study

The study was initiated and funded by several companies that manufacture, distribute or use single-use plastic transport packaging, or manufacture machinery for the use of single-use plastic transport packaging. These companies have come together under the umbrella of the European Plastics Converters (EUPC). The study was commissioned by EUPC and carried out by ifeu.

1.3 Use of the study, target audience and critical review

The results of this study will be used by the client EUPC and the companies they represent.

EUPC will use the study to provide facts for a constructive dialogue with European legislators on the design of the implementation regulations of the EU-PPWR in the context of the association's work. The intention is to publish the study in its entirety.

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:

- Hélène Cruypenninck (chair), seven-c, France
- Nicolas Cayé, GVM, Germany
- Miguel Brandão, KTH Royal Institute of Technology, Sweden
- Ruben Aldaco Garcia, Cantabria University, Spain

This study is not a study based on the specifications of the Environmental Footprint according to the 'COMMISSION RECOMMENDATION (EU) 2021/2279 of 15 December 2021 on the use of the Environmental Footprint methodology to measure and communicate the life cycle environmental performance of products and organisations', but rather a classical Life Cycle Assessment according to the specifications of ISO 14040 and ISO 14044. The methods used and the specifications made in the study are therefore based on the requirements of the research question and the defined subject of the study as described in the statement of purpose and scope. **They therefore do not necessarily follow the Product Environmental Footprint (PEF) rules. For this reason, the differences at the crucial points of allocation and impact assessment are briefly mentioned and the deviation from the PEF rules is briefly explained.**

1.4 Functional unit

The main goal of this LCA study is to compare the environmental performance of single-use and multiple-use pallet wrapping for stabilization and protection of products put on pallets during transport, as considered in Article 29 paragraph 1 to 3 of the Packaging and Packaging Waste Regulation.

The purpose of the transport packaging examined in this study is to secure products in their sales and group packaging on a pallet, ensuring they can be transported by truck over a specified distance from the production site where the packaging is applicated to the first economic operator in the logistics chain (central warehouse). The following products were assessed in the study as application fields:

- Powdered materials in a cardboard box
- PET water and CSD bottles in shrink packs
- Buckets
- Cement bags
- Polymer bags
- New and empty glass bottles, transported without group packaging from the glass production site to the bottling plant
- HDPE milk bottles in shrink packs

For this comparative assessment, the functional unit is the packaging and transportation of 1,000 kg of goods in sales and group packaging between two different or linked economic operators within the same Member State or within the territory of the European Union, in consideration of established logistic chains (e.g. selling channels, distances, means of transport), safety requirements and standardized dynamic testing of loading units.

The production and disposal of primary and secondary packaging is excluded because it will stay the same for all transport packaging alternatives. Only their weight is accounted to determine the truck load factor. As the packaging systems considered in this study have different stacking patterns, the functional unit has been defined as 1,000 kg of goods. This definition allows comparability between systems as the environmental impact is assessed for the amount of packaging produced, transported and disposed of to transport 1,000 kg of goods.

Transportation between two different or related economic operators within the same Member State or within the territory of the European Union is the long-distance transportation from the factory where the goods to be packaged are produced to the first economic operator in the logistics chain. The stacking plans examined in the study are therefore optimized for transportation and not necessarily for storing or selling the products. Optimisation of capacity utilisation due to partially loaded pallets are not taken into account in the model.

By focusing the functional unit on the amount of goods being transported, systems can be compared across different stacking plans.

1.5 System boundaries

The study is designed as a cradle-to-grave life cycle assessment without the use phase of the packaging, since no relevant differences between the systems studied are expected here or are outside the scope of the study. In other words: it includes the extraction and production of raw materials, processing, all transport and final disposal in incinerators or landfills, as well as recycling of the packaging system.

In general, the study covers the following steps:

- Production of the primary raw materials used in the transport packaging systems and related transports
- Production, recycling and final disposal (incineration) of transport packaging and related transports
- Production and disposal of process chemicals, as far as not excluded by the cut-off criteria (see below) and related transports
- Application processes, which are fully assigned to the transport packaging system
- Transport from the production site where the packaging is applicated to the first economic operator in the logistics chain
- In all manufacturing and application 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.

Another reason for excluding infrastructure from consideration is the study's conservative comparison approach. Since the environmental impact of reusable packaging is largely influenced by the ecological burdens of distribution and redistribution, it is expected that including infrastructure would further worsen the results, particularly in these areas. Consequently, omitting infrastructure means that part of the environmental burden remains unaccounted for—especially the impacts that would further weigh on the results for reusable packaging.

- Production of product (filling good) as no relevant differences between the systems under examination are to be expected.
- Production of sales packaging and group packaging as no relevant differences between the systems under examination are to be expected.
- Distribution of the product (goods), as well as their sales packaging, and group packaging from the filler's production site to the central warehouse of the first economic operator in the logistics chain, as the same quantity of packed and grouped goods is transported for all packaging systems within the same application field.
- Losses due to packaging are expected to be strictly identical because the same EUMOS test is passed and weather conditions (humidity etc…) have been taken into account for the selection of relevant packaging for each use case.
- Floor space consequences are not reflected in the report, although they play a significant role in warehousing, and high floor space usage can lead to increased warehousing floor space and land use. The additional storage space required for the logistics of reuse packaging has not been taken into account. Therefore, there is no change in the storage space required by the systems. This is because (1) the storage space is part of the infrastructure, which is excluded, and (2) the systems are compared to each other, but no compensation is made for any exchange. A positive or negative change in storage space requirements cannot therefore be validly determined.

The following simplified flow chart (Figure 1-1) clearly illustrate the system boundaries considered for the different types of transport packaging in this study.

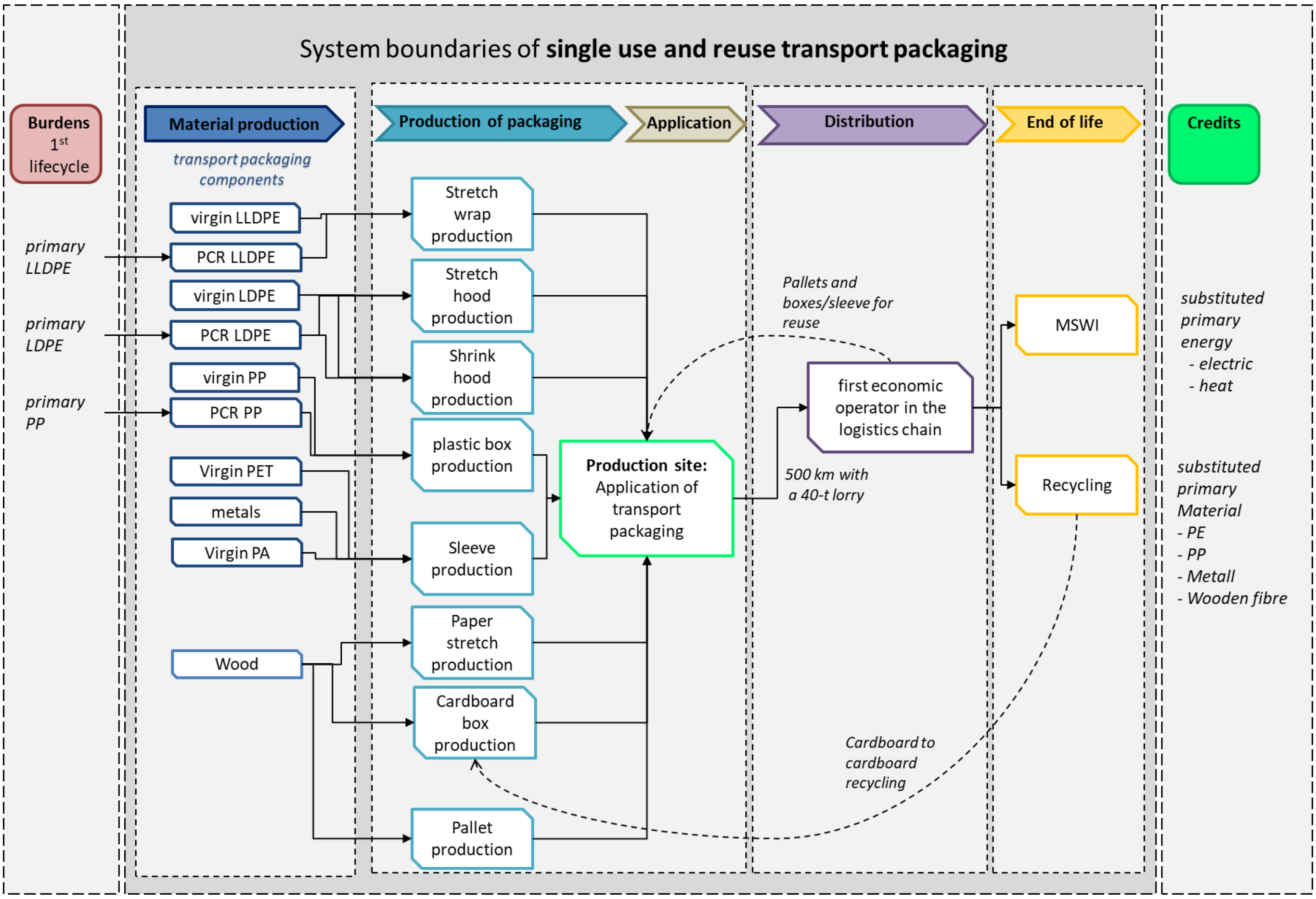

Figure 1-1: system boundaries considered for the different types of transport packaging in this study

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 primary raw 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 a municipal solid waste incineration plant (MSWI).

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 2.3 (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 2010 and 2022. 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 transport packaging in Europe (EU) 27. 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 (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.

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 meets 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 is carried out based on information from phase 1. Based on this, additional relevant data are collected, concerning emissions to air and water, amounts of waste, and transport information. In phase 4, an additional completeness check is carried out, where the LCIA results of the implemented data are cross checked with available LCIA results (e.g., previous data, data from other geographic regions, similar processes).

Missing information on land-use, water use, and toxicity are discussed in section 1.8 (Environmental Impact Assessment) in the respective sections.

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 systems. 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 properlydocumented. If these cases exist at all, then a slight inconsistency in regard to the exclusion of infrastructure may exist.

As part of the results evaluation, a contribution analysis is conducted to determine which life cycle stages have the greatest impact on the outcomes and whether any inconsistencies in the data relevant to the assessment of individual life cycle stages influence the results.

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 and MSWI were taken from the most recent version of it. All data sources are summarised in Table 3-1 and described in section 3. If data from the internal ifeu database are used, the generation of these data is described in detail in Chapter 3. The CR Panel will also have insight into these datasets.

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 2014a).

It should be noted that some of the parameters relevant to the results are subject to a degree of uncertainty. This is partly because they are based on assumptions and partly because the validity of some of the data used in the accounting is known to be limited. In the discussion of the results in Chapter 5, separate sensitivity analyses are therefore carried out to examine the impact of these uncertainties.

However, in order to take possible uncertainties between the compared product systems into account, an estimated significance threshold is often chosen as a pragmatic approach. This means that differences in the results of the impact category indicators between the comparison systems are considered insignificant within a certain range. The German Federal Environment Agency recommends a significance threshold of 10 % as an appropriate value for use in packaging life cycle assessments under the Packaging Ordinance. As part of the evaluation of this study, the authors will discuss whether this pragmatic threshold is appropriate based on the data used for the impact categories considered in this study and whether it can ensure consistency for all impact categories analysed.

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 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 explained further in the subsequent sections.

1.7.1 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 transport packaging and the product in sales and group packing was carried out for the transportation from the production site to the first economic operator. Only the share in environmental burdens related to transport, which is assigned to the transport package, has been accounted for in this study. That means the burdens related directly to the packed good and the sales and group packing is excluded. The allocation between transport package and packed goods is based on mass criterion. This allocation is applied as the functional unit of the study defines a fixed amount of packed goods through all scenarios in the specific fields of application. Impacts related to transporting the packed good itself would be the same in all scenarios. There they don't need to be included in this comparative study of transport packaging systems.

1.7.2 System-related allocation

This study follows the attributional approach and examines the environmental impacts directly associated with the production, use, and disposal of the packaging systems under consideration. Aspects related to the decision for or against a particular system, as well as the resulting consequences, are not the focus of this analysis. Therefore, the system boundary assessment follows a linear logic. Secondary products replace primary materials or energy carriers with largely equivalent properties. This substitution is credited to the system accordingly. For the allocation of these credits, allocation factors are applied to fairly distribute the burdens and benefits of recycling between the supplying and receiving systems. This approach to handling co-products at the system level aligns with the regulations of the Product Environmental Footprint (PEF) as well as the recommendations of the French environmental agency ADEME and the German Environment Agency (UBA).

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.

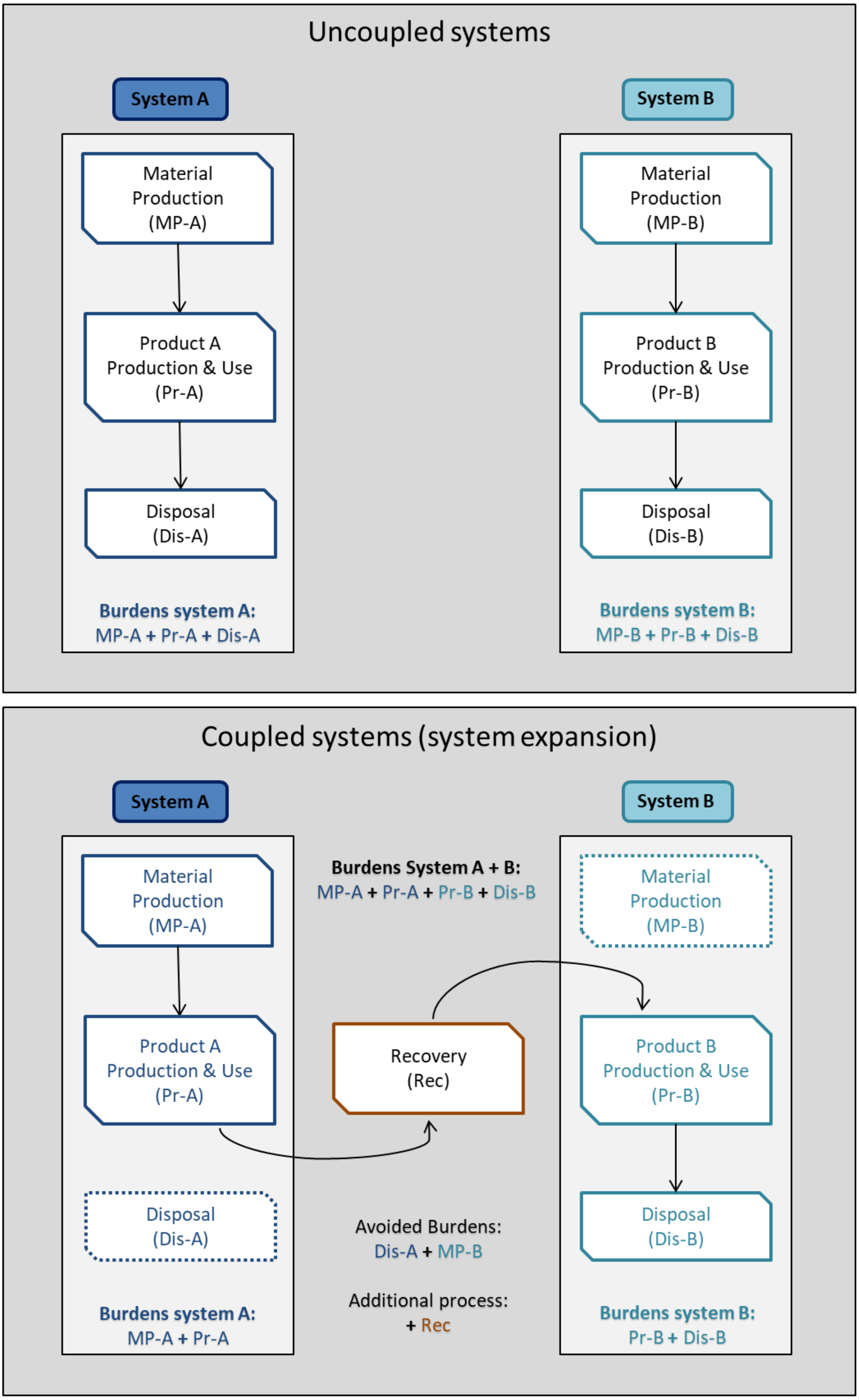

Figure 1-2: Additional system benefit/burden through recycling (schematic flow chart)[1]

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 (base scenarios). The graph shows 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 PCR, the burdens associated with the ultimate disposal of the secondary products produced from the PCR are allocated to the primary system (50% of the burdens of disposal in the 50% allocation).

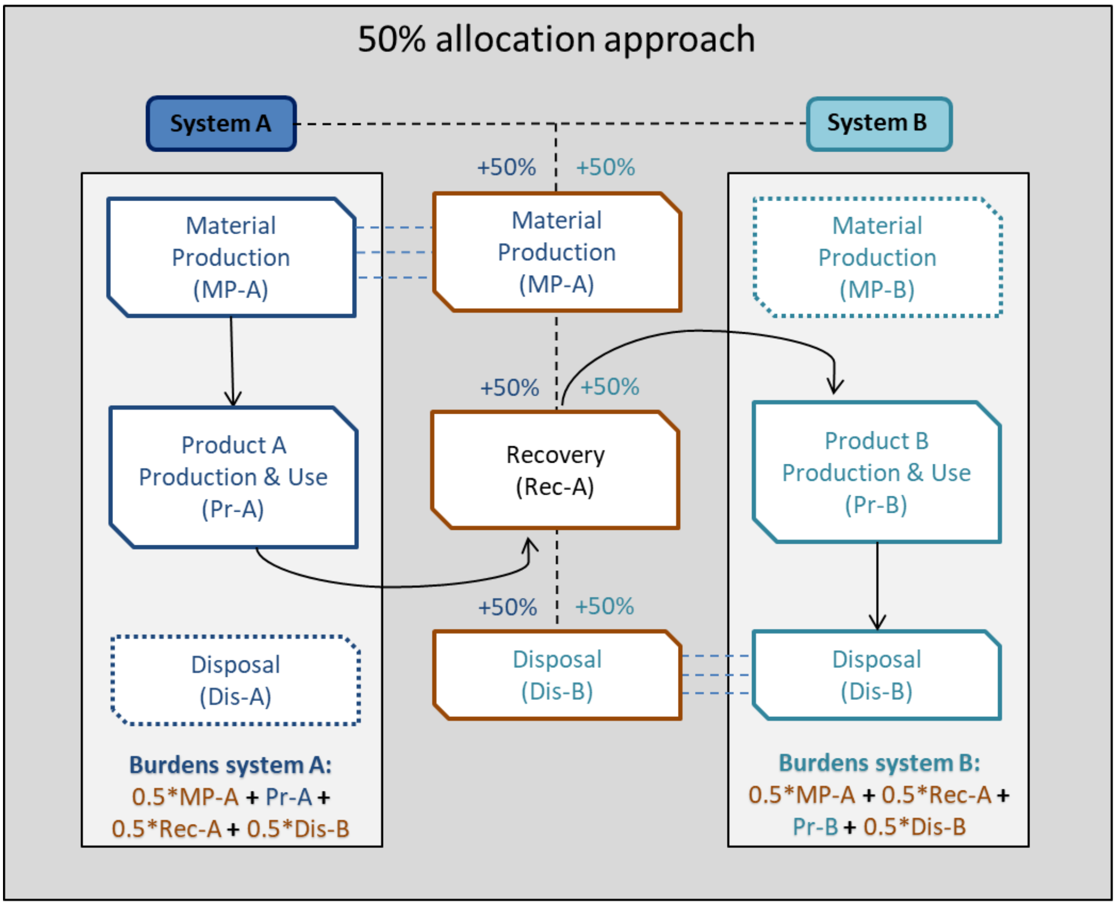

Figure 1-3: Scenario AF 50%: Principles of 50 % allocation (schematic flow chart)[1]

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.

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).

General notes regarding Figure 1-2

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
- 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 considered 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.

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 'downcycling' effects, which describe a recycling process in which waste materials are converted into new materials of lesser quality.

The substitution factors used in this LCA study to calculate the credits for recyclates destined for downstream applications are mainly based on a report by the European Commission (Nessi et al. 2021) and the assessment of the author. For this study, the substitution factors for the balanced secondary materials after the recycling processes (PP, LLDPE and cardboard) are set to 1. Setting the substitution factor to 1 reflects the fact that PCR material is included in many systems in this study. The packaging weights collected in this study show that an increase in the proportion of PCR is generally accompanied by an increase in the packaging material required, so that the effect of material degradation through the recycling process is already reflected in the packaging specifications. Therefore, as a substitution factor of 1 is used in the upstream, it is logical that the same substitution factor is used in the downstream.

Material losses during the recycling process are accounted for in the recycling processes on a material-specific basis.

1.7.3 Discussion of the allocation approach in this study

The allocation approach used in this study is based on an equivalent-material substitution of primary materials and energy carriers with an allocation factor of 50%. This approach follows the recommendation of the German Environment Agency (Umweltbundesamt) for applying system allocation in packaging life cycle assessments.

The PEF approach differs from this method in several aspects. The PEF end-of-life formula (also known as the Circular Footprint Formula (CFF)) integrates allocation, substitution, recycling volumes and yields, and the use of secondary materials into one calculation formula. In addition to the loss of transparency, there are a number of methodological problems that make the use of the CFF in an ISO-compliant LCA at least questionable. In particular, the different allocation factor for different materials should be mentioned, which is 0.5 for plastics, corresponding to the 50% allocation approach in this study. For paper, on the other hand, the factor is 0.2, which makes the use of secondary materials much less attractive. In terms of a conservative comparison between plastic products and paper products with high recycled content, such as packaging paper, the 50% allocation used in this study is the much more conservative approach.

Another difference concerns the substitution factors. In the PEF end-of-life formula, the substitution factors are described by the variable qs/qp. This contains different values for the material fractions relevant to this study:

- Paper fibres from cardboard trays: 0.85
- LDPE from films: 0.75
- PP from rigid packaging: 0.9

These values were determined as part of the PEF pilot phase and are not comparable with the values determined by long-standing experts from the practical waste management sector.

An alternative approach to model material flows between interconnected systems is system expansion. In methodological discussions, this approach is often referred to as "allocation avoidance" and is therefore considered more in line with ISO 14040 ff. However, this approach requires careful evaluation: On the one hand, it includes processes that are external to the system and may need to be considered when defining the functional unit. On the other hand, it implies certain value judgments in the selection of substituted processes. In this study, the use of PCR material is accounted for by linking it to the production of primary material over one life cycle. This means that the PCR material carries half the environmental burden of the primary material and half the burden of reprocessing.

With system expansion, it could be assessed that the material is diverted from thermal recovery with an energy credit through recycling. If thermal recovery is modelled in a way that predominantly generates renewable energy carriers, the PCR material could even result in a negative environmental footprint. In this case, an allocation of 50% would be a significantly more conservative comparison approach.

In summary, system expansion is also not free from value judgments and methodological choices. For this reason, the German Environment Agency (UBA), the French Environment and Energy Management Agency (ADEME), and the Product Environmental Footprint (PEF) recommend applying an allocation approach when assessing short-lived consumer goods such as packaging.

1.7.4 Allocation in distribution

This study analyses the environmental impact of the transport packaging and not the environmental impact of the products in their sales or group packaging. Therefore, in the context of distribution, an allocation of environmental impacts between transport packaging and other transported goods has to be made. The allocation is based on mass. For each packaging system, it is determined how many kg of transport packaging and how many kg of other goods are transported in a transport unit (lorry). The individual load factors play an important role. The following specifications apply:

- A 40-tonne lorry can carry a maximum load of 23 tonnes
- A 40-tonne lorry can carry a maximum of 33 euro pallets
- Pallets are always loaded to the floor space limit or weight limit
  Any optimisation of capacity utilisation that may have occurred in reality due to partially loaded pallets is not taken into account in the model.
- All trucks are fully loaded, overloading is completely eliminated

To determine the emissions from transporting packaging materials, the following parameters are used:

Key Parameters:

- **EF_empty**: Emission factor (kg CO_2 per ton of a full truck per km) for an empty truck.
- **EF_load_max**: Emission factor (kg CO_2 per ton of a full truck per km) for a fully loaded truck.
- **LF (Load Factor)**: The ratio of the actual transported mass to the maximum load capacity.
  $$LF = \frac{M\_load}{M\_load\_max}$$
- **M_LoadedTruck**: Total weight of the truck when loaded.
  $$M\_LoadedTruck = M\_load + M\_Truck$$
- **M_Product**: Total mass of the packaged product.
- **M_Good**: Mass of the product without packaging.
- **M_Truck**: Weight of the empty truck (17,000 kg).
- **M_load_max**: Maximum truck load capacity (23,000 kg).
- **SE_Distance**: Share of empty return distance allocated to the outward journey (20%).

Calculation Steps:

1. Determine the Emission Factor per Ton-Kilometre for the Packaged Product

This step calculates the emissions associated with transporting the packaged product:

$$EF\_product\ with\ packaging = \frac{(EF\_empty \times M\_Truck + EF\_load\_max \times M\_load\_max \times LF) + SE\_Distance \times (EF\_empty \times M\_Truck)}{M\_Good}$$

Explanation:

- The first term accounts for emissions from the empty truck and the loaded truck based on its load factor.
- The second term adjusts for the emissions from the truck's empty return journey, considering the allocated share (**SE_Distance**).
- The total emissions are then divided by the mass of the transported product (**M_Good**) to determine the specific emission factor per ton-kilometre.

2. Allocate Emissions Between the Transported Good and Its Packaging

Since the total emissions include both the product and its transport packaging, this step separates their individual contributions:

$$EF\_transported\ good = EF\_product\ with\ packaging \times \left(\frac{M\_Good}{M\_Product}\right)$$

Explanation:

- This formula assigns a proportion of the total emissions to the transported good based on the mass ratio of the naked product (**M_Good**) to the total packaged product (**M_Product**).

3. Isolate the Emissions of the Transport Packaging

Since the environmental impact of transporting the good itself remains constant across all packaging scenarios, this step isolates the contribution of the packaging:

$$EF\_transported\ packaging = EF\_product\ with\ packaging - MIN(EF\_transported\ good)$$

Explanation:

- The minimum emission factor from all scenarios is subtracted to eliminate the impact of the transported good itself, leaving only the emissions caused by the transport packaging.

4. Calculate the Environmental Impact of Transporting the Packaging

Finally, the total emissions for distributing the transport packaging are determined:

$$LCI\_transported\ packaging = EF\_transported\ packaging \times Distance$$

Explanation:

- The isolated emissions of the transport packaging are multiplied by the transport distance to get the total environmental impact of the distribution of the transport packaging.

Conclusion

This methodology ensures that emissions from transportation are fairly distributed between the product and its packaging. By subtracting the baseline impact of the transported good, the calculation isolates the contribution of transport packaging, allowing for accurate comparisons across different packaging options.

The allocation between packaging and product means that light packaging has a lower environmental impact per kilometre transported than heavy packaging.

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).

In the impact assessment of a life cycle assessment (LCA), a distinction is made between midpoint and endpoint categories:

- Midpoint categories describe the immediate environmental impacts of a product or process:
  - They represent specific environmental issues such as greenhouse gas emissions, acidification, or water consumption.
  - They are closer to the cause of the environmental impact and therefore less uncertain in their calculation.
  - Examples of midpoint categories include climate change (in kg CO_2-equivalents) and terrestrial acidification (in kg SO_2-equivalents).
- Endpoint categories group the environmental impacts into higher-level damage categories:
  - They describe the final effects on protected assets such as human health, ecosystem quality, and resource availability.
  - Endpoint categories are easier to interpret because they are more directly linked to the consequences for people and the environment.
  - Examples of endpoint categories include human health (measured in DALY – disability-adjusted life years) and ecosystem quality (measured in Species*year – species loss over a year).

Midpoint categories have a direct influence on endpoint categories. For instance, climate change as a midpoint category influences the endpoint categories of human health and ecosystem quality.

The choice between midpoint and endpoint indicators depends on the goal of the LCA and the desired level of detail in the analysis. In the present LCA, midpoint categories are used instead of endpoint categories for the following reasons:

- Lower uncertainty: Midpoint indicators are relatively easy to model and have less uncertainty compared to endpoint indicators. Developing robust linear cause-and-effect chains from the inventory data to the tertiary impacts (endpoints) is often not possible or is associated with greater uncertainty in the characterization factors.
- Direct relation to environmental issues: Midpoint categories assess the contribution of the product system to specific environmental issues, while endpoint categories describe the effects on protected assets like human health or ecosystem quality.
- Better differentiation: Midpoint categories allow for a more detailed analysis of specific environmental impacts, such as global warming potential, acidification potential, or eutrophication potential.

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 considered.

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 has to 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.

This study evaluates the GWP fossil, which exclusively considers fossil CO_2e emissions. Biogenic CO_2e emissions are excluded from the assessment due to their classification as CO_2e-neutral.

This approach has proven useful for the carbon footprint of fast-moving consumer goods, as the biogenic C in the products considered here is only bound for a very short time. The system boundaries with the LC2 (see allocation chapter) result in a balanced carbon footprint. Including biogenic C in the calculation would therefore not change the results, but would mean that the results of the sectoral allocation would have to deal with credits and emissions of biogenic C, making them somewhat less transparent. As the focus of the study is also on plastic packaging made from fossil or recycled plastics, biogenic C has not been reported separately.

Ozone depletion

This impact category addresses the anthropogenic impact on the earth's atmosphere, which leads to the decomposition of naturally present ozone molecules, thus disturbing the molecular equilibrium in the stratosphere. The underlying chemical reactions are very slow processes and the actual impact, often referred to in a simplified way as the 'ozone hole', takes place only with considerable delay of several years after emission. The consequence of this disequilibrium is that an increased amount of UV-B radiation reaches the earth's surface, where it can cause damage to certain natural resources or human health. In this study, the Ozone Depletion compiled by the World Meteorological Organisation (WMO 2015) is used as category indicator.

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

Photochemical oxidant formation

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

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

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

- Provision of characterisation factors for more than 1100 individual VOC, VOC mixtures, nitrogen oxides and nitrogen dioxides

- Consistent modelling of potential impacts for VOC and NOx
- Considering of the maximum formation potential by inclusion of most supporting background concentrations of the gas mixture and climatic conditions. This is in accordance with the precautionary principle.

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

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

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, the eutrophication potential according to (Guinée 2002; Heijungs 1992) was chosen as an impact indicator.

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

Particulate matter

The category covers effects of fine particulates with an aerodynamic diameter of less than 2.5 µm (PM 2.5) emitted directly (primary particles) or formed from precursors as NOx and SO_2 (secondary particles). Epidemiological studies have shown a correlation between the exposure to particulate matter and the mortality from respiratory diseases as well as a weakening of the immune system. Following an approach of (de Leeuw 2002), the category indicator aerosol formation potential (AFP) is applied. Within the characterisation model, secondary fine particulates are quantified and aggregated with primary fine particulates as PM2.5 equivalents[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 1-1** summarises some examples of elementary flows and their classification to the impact categories included in the study and described before.

Table 1-1: 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

[2] In previous LCA studies 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.

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

Table 1-2: 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.

1.8.2 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 1-3** gives some examples of mineral and metal resources included in this impact category.

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.

Table 1-3: 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

1.8.3 Additional categories at the inventory level

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

Primary energy

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

Total primary energy (Cumulative Energy Demand, total)

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

The unit for Total Primary Energy is MJ/FU.

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

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

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

Table 1-4: Examples of elementary flows and their classification to inventory level categories

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

Use of nature

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

The 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. Given the limitations of existing methodologies, land use is not assessed in this study.

Another reason for excluding this impact category is that the current models show a high consumption of wood from forestry, but the possible additional demand for storage space for transport packaging is not part of the system boundaries and therefore disturbs the symmetry of the comparison.

Water consumption

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

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

In order to be able to quantify the issue of water and water use in the study, water consumption is analysed – but only on the inventory level.

1.8.4 Differences in impact assessment according to the PEF model

As announced in Chapter 1.3, a comparison of the impact categories considered in this study with the impact categories of the PEF will be made at this point. It should be noted that in the context of a Life Cycle Assessment according to ISO 14040ff, the impact assessment and evaluation must correspond to the objective and object of the study, considering the data sets used in the study. Therefore, the prototypical application of the PEF impact assessment without further reflection is viewed critically by the authors of the study and is not considered appropriate in the sense of ISO 14040ff.

In the authors view, there is therefore no need to justify the use of the impact categories used in this study. The comparison presented is therefore more of an aid to readers from the target group of EU legislation who need to assess the comparability of the results of this study with possible studies based on the narrower PEF regulations.

The following Table 1-5 shows that the differences are marginal. In most cases, the authors use the original sources behind the ReCiPe system, which is often favoured by the PEF, or use more up-to-date sources than the PEF.

Table 1-5: Examples of elementary flows and their classification to resource related impact category.

Impact category	Characterisation model in PEF	Characterisation model used in this study	*Reason for selection/ excluding*
Climate change	IPCC 2013	IPCC 2021	*Use of an updated source*
Ozone depletion	WMO 2014	WMO 2015	*Use of an updated source*
Photochemical oxidant formation	Van Zelm et al, 2008 taken from ReCiPe 2008	Carter 2008	*The model used is more appropriate for the purposes of an LCA.*
Acidification	Seppälä et al., 2006 based on Posch et al., 2008	Posch et al. 2008	*Use of the original source*
Eutrophication	Seppälä et al., 2006, Posch et al., 2008 (terrestrial eutrophication) and Struijs et al., 2009 used in ReCiPe (aquatic eutrophication)	Guinée 2002; Heijungs 1992	*Use of a consistent source for the description of related impact categories*
Particulate matter	Fantke et al., 2016 as used in UNEP 2016	Goedkoop et al. 2013 and JRC 2011	*The used source depicts the PM 2.5 compartment, which is more significant for the environmental impact*
Human and Eco Toxicity (excl. Particulate Matter)	Fantke et al., 2017 adjusted as in Saouter et al., 2018 (USEtox2.1 Modell)	excluded	*The model is classified as not very robust in the PEF. It will be discarded in the evaluation anyway.*
Ionising radiation, human health	Dreicer et al, 1995 and Frischknecht et al., 2000	excluded	*The model is very old and only assesses ionising radiation from nuclear power plants.*
Abiotic resource depletion	CML 2002	CML 2016	*Use of an updated source*
Cumulative Energy Demand, total and non-renewable	Not included	VDI 1997	*Results can provide additional information for the discussion*
Use of nature	De Laurentiis et al., 2019 and Horn und Maier, 2018 (LANCA Modell)	excluded	*The model is classified as not very robust in the PEF. It will be discarded in the evaluation anyway.*
Water scarcity footprint/ water consumption	Boulay et al., 2018; and UNEP 2016 (AWARE Modell)	Only water consumption will be analysed in this study	*The model is classified as not very robust in the PEF. It will be discarded in the evaluation anyway.*

2 Packaging systems and scenarios

2.1 Selection of packaging systems

This study analyses 5 single-use and 3 reuse transport packaging systems:

- Single-use transport packaging systems:
  - Stretch wrap made from LLDPE in combination with a EURO flat pallet
  - Stretch hood made from LDPE in combination with a EURO flat pallet
  - Shrink hood made from LDPE in combination with a EURO flat pallet
  - Paper stretch in combination with a EURO flat pallet
  - Single-use carboard box in combination with an individual wooden pallet
- Reuse transport packaging systems:
  - Reuse cardboard box in combination with an individual wooden pallet
  - Reuse sleeve made mainly from woven PET in combination with a EURO flat pallet
  - Reuse plastic box (with and without lid) made from PP (no additional pallet required)

Figure 2-1: Picture of different transport packaging systems (from the left to the right: single-use stretch wrap, single-use paper stretch, reuse sleeve, single-use and reuse cardboard box, reuse plastic box type A and type B)

In addition, the single-use plastic systems are balanced with three different PCR proportions: 0% PCR, 35% PCR and 65% PCR, resulting in different packaging weights. The study furthermore investigates different applications that pose different challenges for transport packaging. For example, very light but large volume goods (cardboard boxes) or heavy compact goods (cement sacks) are analysed, as well as very fragile goods (new glass bottles). As mentioned in chapter 1.4 the purpose of the transport packaging examined in this study is to secure products in their sales and group packaging on a pallet, ensuring they can be transported by truck over a specified distance from the manufacturer of the packed products to the retailer's central warehouse. But not all types of packaging are suitable for all applications. The following **Figure 2-2** shows a matrix illustrating the relationship between packaging and application.

	Packaging systems							
	Single Use Systems					ReUse Systems		
Fields of application	stretch wrap	stretch hood	shrink hood	paper stretch	carboard box SU	coardbord box Reuse	Sleeve	reuse boxes
cardboard boxes	0% PCR 35% PCR 65% PCR			0% PCR	88% PCR	88% PCR	0% PCR	80% PCR
Water and CSD in PET bottles (Sixpack)	0% PCR 35% PCR 65% PCR			0% PCR	88% PCR	88% PCR	0% PCR	80% PCR
buckets	0% PCR 35% PCR 65% PCR			0% PCR	88% PCR	88% PCR	0% PCR	80% PCR
cement bags		0% PCR 35% PCR 65% PCR		Outside storage : humidity and weather protection avoiding product loss			0% PCR	80% PCR
polymer bags		0% PCR 35% PCR 65% PCR					0% PCR	80% PCR
glass bottles			0% PCR 35% PCR 65% PCR	Pallet stability and hygiene				80% PCR
milk in plastic bottles (HDPE)			0% PCR 35% PCR 65% PCR	Pallet stability, condensation due to cooling and hygiene			0% PCR	80% PCR

Figure 2-2: Overview of packaging systems and fields of application analysed in this study

When considering pallet wrapping**,** single-use transport packaging has been implemented in a variety of product systems, whereas reuse solutions have yet to still be established in the market. reuse. The application areas analysed in the study do not necessarily reflect the market for single-use transport packaging; rather, they were selected to represent a diversity of use cases and to cover the range of possibilities.

The study encompassed both very dense goods with a high weight and low volume, such as sacks, buckets or bottles, and low-density goods, including cardboard boxes and empty bottles, as well as special requirements for load securing, such as easily breakable goods. The selection of application areas is therefore reflective of the divergent requirements that packaged goods place on their transport packaging.

2.2 Description of packaging systems

2.2.1 Single-use transport packaging systems

The flexible single-use packaging systems examined in this study are the current standard to package pallets. Its function is to secure the various products on the pallet for transport. It is usually applied mechanically or semi-automatically. Those transport packaging solutions are intended for single-use and must be disposed of after. Single-use flexible packaging systems made of plastic or paper are delivered to the user either on rolls or in stacks. After the goods that were secured with the transport packaging have arrived at their destination and been unpacked, the transport packaging is disposed of in the designated recycling collection systems. The collection of transport packaging is widespread in the EU as it is an easy way to collect large quantities of plastic and paper. According to industry insiders, the recycling of plastic film from transport packaging is one of the largest sources of secondary plastics.

This type of transport packaging is highly material-efficient. In most cases less than 1 kg of packaging material required per pallet. In addition, this type of transparent transport packaging is very adaptable to the goods to be packaged, so there are no dependencies in packaging design between unit and group packaging and transport packaging.

Paper stretch wrap is another type of flexible single-use transport packaging. Like stretch wrap, it is applied to the pallet by wrapping around the load. Paper stretch wrap is made from 100% virgin kraftpaper and, unlike plastic stretch wrap, is not transparent and is less suitable for an outside storage.

Rigid transport packaging in the form of a cardboard box, which was also examined in this study, is currently used more in an industrial context for the transport of small unit loads (e.g. screws, PET preforms, etc.). However, in this study it is considered as an alternative for packaged products. Like paper, it is not suitable for outdoor or humid indoor storage and therefore cannot be used in all applications.

2.2.2 Reuse transport packaging systems

The operating principles of reuse systems are more complex than those of single-use systems. For the purposes of this study, it is first necessary to distinguish between three basic types of reuse systems.

- managed pool system or closed loop system:
  A managed pool system is characterised by the fact that the recycling of reuse packaging and the maintenance of the pool are controlled by a higher-level organisation. This superordinate organisation is responsible for managing the inventory, purchases and distribution of the reuse packaging to the users within the pool. The system comprises many users and product manufacturers. The best-known example of this type is the reuse bottle system of the *Genossenschaft Deutscher Brunnen eG (GDB)*. B2B reuse systems such as the GS1 reuse box in the drugstore sector can also be categorised as managed pool systems.
- Open pool system or open loop system:
  In contrast to a managed pool, cycle management in an open pool is not managed by a superordinate pool organisation. The administration and pool organisation are the responsibility of individual companies. As a result, several independent administrations exist side by side, with inventory management being decentralised. As with a managed pool system, several users can be involved in the circulation system. Examples of packaging that are organised in an open pool are the so-called Euro pallets.
- Individual systems which are a very strict form of a closed loop system:
  Customised systems are only used by one user. The packaging used has special features compared to standard packaging, for example in the form of a customised shape or labelling. Customized returnable bottles from large breweries are an example of individual systems.

The type of reuse system has an impact on two key aspects of the life cycle assessment of reuse systems. A) the frequency of circulation of the systems and B) the distances for returning the systems after the last and before the next use.

2.2.2.1 Trip rate

An important factor in the accounting of reusable systems is the trip rate. The trip rate is the total number of times a reusable packaging is used. If a packaging is used 50 times (first use and 49 reuses), the trip rate is 50. In the LCA, the impacts of production and disposal of reusable systems are divided by the trip rates. A high trip rate therefore results in lower environmental impacts than a low trip rate. Three different methods have proven themselves in practice for determining the trip rate:

- The purchase calculation as a method for determining the trip rate is based on the quantity of reuse packaging sold in relation to the quantity of newly purchased or returned reuse packaging.
- In the return calculation or loss calculation, the trip rate is determined based on the reuse packaging sold in relation to the quantity of reuse packaging sorted out/lost.
- When calculating the service life, the trip rate is calculated from the determined age of the pool and the annual returnable quota.

In practice, the lifetime calculation is often preferred, as this form of calculation appears to be best suited to levelling out the influence of seasonal fluctuations in reuse use and possible acyclical stock-piling with reuse packaging on the determination of the trip rate.

However, calculating the trip rate using the methods described above generally requires the submission of primary data. In cases where no or insufficient quality-assured data is available, only qualified estimation methods remain to determine the trip rates.

Using data on the maximum technically possible trip rates of reuse packaging generally proves to be of little use, as these maximum values are not achieved in practice. Furthermore, the determination of a break-even value, i.e. a value above which the environmental requirements of a reuse system are identical to those of a disposable system, proves to be of limited use for a life cycle assessment analysis as it says nothing about the trip rates that can actually be achieved.

In [Bick et al 2024] a method of qualified estimation is described, which should also be used here, although adaptations to the model are necessary. Roughly simplified, the following values, which can either be extracted from accessible sources or defined in a well-founded manner, are required for the factual estimation of circulation figures according to Bick et al:

- Age of the reuse system
- Return rate in per cent
- Internal losses in per cent
- Purchase figures per year
- Number of days between two uses

This study analyses hypothetical value-added systems, assuming that the systems are already established on the market. To arrive at a valid and comparable estimate, it is first defined that the systems are already established on the market and that the additional purchase merely compensates for losses, but that there is no further volume growth (steady state is reached).

In this respect, only the parameters of the external and internal losses as well as the days between two utilisations are relevant for determining the circulation figure and the calculation can be carried out using a greatly simplified procedure. The calculation is defined as follows:

- Return rate (external losses):
  The return rate is different for the three reuse systems: it is highest for the pool reuse systems, as the packaging can be reused by many users. A return rate of 99% is assumed for this study. There is no scientific evidence of any significant difference in return behaviour between a managed and an open pool (there is more of a difference in the internal losses). Experiences shows that the return rate is lower for individual systems, as the packaging is more fragmented and it is assumed that the return transport to the distributor is more expensive than the purchase of new packaging, especially for small quantities. A return rate of 95% is assumed for these systems (which corresponds to the maximum value of the SWAP study).
- Internal losses:
  Not all returned reuse packaging is reuse. Heavy soiling and damage mean that returned packaging must be sorted out. This is referred to as internal loss. The losses are lowest in the managed pool (calculated value 2%), as the quality assurance and procurement requirements are specified centrally. In the open pool, the internal losses are higher (calculated value 3%), as the selection decision is made individually by each player. At 5% internal losses, the rejection rates are highest in an individual system. A particularly high-quality standard is generally applied in this system, as marketing and branding aspects usually play a role in addition to the actual function of the packaging.
- Days between uses:
  Another driver for calculating and evaluating the number of days in circulation is the time span between two uses. This time span includes the use of the packaging, the time in the outgoing goods warehouse, the distribution phase, the time in the incoming goods warehouse at the recipient, the unpacking phase, the collection of the emptied reuse packaging, the return transport to the next user, the preparation for reuse and the storage of the prepared packaging until the next use. It is assumed that the number and spatial distribution of the actors influences this period, so that this period is assumed to be relatively short at 80 days for an open pool and 100 days for a closed pool. For customized systems, this period is estimated to be longer at 120 days, as it can be assumed that interim storage takes place during return transport and stockpiling at the distributor increases the storage period before reuse.

The following **Table 2-1** summarises the assumptions made in this study and shows the calculation of the circulation rate.

Table 2-1: calculation of trip rates for different reuse systems

Parameters			Individual system	open pool	Managed pool
Assumptions	*A*	Return rate in per cent	95%	99%	99%
	B	Internal losses in per cent	5%	3%	2%
	C	Number of days between two uses	120	80	100
Calculations	*D*	Maximum possible number of uses per year *D=365/C*	3,04	4,56	3,65
	E	Accumulated loss per year *E=((1-A)+B)*D*	30%	18%	11%
	F	Maximum achievable average age in years *F=(1/E)*	3,29	5,48	9,13
Result	*G*	**Average trip rate** ***G=(D*F)***	**10**	**25**	**33**

All reuse options in this LCA have passed EUMOS test. However, the EUMOS test also showed the forces during transport, which are exerted on all the transport packaging variants analysed. In addition, there are potential losses due to damage caused by e.g. forklifts and/or storage of empty boxes.

2.2.2.2 Discussion of estimated trip rates

For the purposes of this study, it is important to note that the calculation of the number of trips is only an estimate. During the research, only very few valid statements could be found on the subject of circulation numbers for reuse containers. The SWAP report gives the sleeve a circulation number of 50, which must be considered unrealistic based on the figures used in this report. Alternative numbers for the sleeve could not be found in the literature.

Cabka, a manufacturer of reuse transport containers made of virgin plastic and PCR-material, itself gives a range of circulation numbers between 25 and 50 for containers made of recycled plastic. The underlying lifetime of the containers is between 4 and 7 years with a maximum of 7 transports per year. These figures published by a manufacturer are generally in line with the assumptions made in this study. However, the Cabka calculation ignores the importance of cumulative losses. In this respect, the figures obtained here can be considered as valid for circulation[3].

In summary, the trip rates calculated in this study are only estimates and naturally subject to uncertainty. However, unlike other studies (e.g., the SWAP report), this study does not rely solely on technical data but instead provides well-founded estimates.

This approach means that the uncertainty in the actual number of trips is reflected in the assumptions used for the calculations. As a result, the estimated trip numbers are more comprehensible and allow for insights into the key influencing factors. The calculations indicate that increasing the speed between trips would improve the trip rate. Therefore, as part of this study, a sensitivity analysis was conducted, assuming an increase in speed for grazing. In this analysis, a trip rate of 50 was assumed for cage boxes and 15 for the sleeve.

Finally, it should be noted that none of the reusable transport packaging systems examined in this study are widely used in practice. As a result, there are inherent limitations in estimating valid calculation values. The authors believe that extrapolating findings to small reusable systems, such as beverage crates and fruit crates—typically used for group packaging—would be of limited value. Among the systems considered, Euro pallets provide the most suitable data. The table above shows that the cumulative annual losses for the pool systems are between 11% and 18%. To put this data into context, the authors try to understand the cumulative annual losses of the EPAL Euro Pallet Pool. Various sources are analysed to show pool size, production figures and repair figures[4]. The calculation is shown in the following **Table 2-2**. The annual losses for the EPAL euro pallets are between 11% and 16%.

This means that the annual losses of the transport packaging analysed in this study are within the range of the Euro pallet, so the figures calculated can be considered robust. Given that the plastic returnable transport packaging analysed is likely to be less robust than the wooden flat pallets, the circulation figures can be regarded as a conservative estimate.

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[3] The circulation figures used in this study are based on theoretical calculations. However, real-world return rates may vary due to logistical constraints and user behaviour

[4] Source for production: EPAL Pallet Production Reaches Record Levels In 2022 EPAL Pallet Production Reaches Record Levels In 2022

Source for 2015 figures: United Nations, page 4 United Nations module 5 of the updated GLEC framework: Smart Freight Centre

Table 2-2: Calculation of the annual loss rates of EPAL euro pallets

Year	Estimated pool size in million pc	Con-firmed produced and re-paired in million pc	Repaired percent-age	Calcu-lated losses in million pc	Loss per-centage	Repaired Percent-age	Total Lost
2014	478.57	67	33%	31.90	6.67%	4.68%	11.35%
2015	**500**	73.6	32%	36.52	7.30%	4.92%	12.23%
2016	521.43	88.00		45.96	8.81%	5.64%	14.46%
2017	543.78	93.00		48.79	8.97%	5.72%	14.69%
2018	567.08	95.00		49.49	8.73%	5.60%	14.33%
2019	591.38	98.00		50.86	8.60%	5.54%	14.14%
2020	616.73	100.00		51.50	8.35%	5.42%	13.77%
2021	643.16	109.00		71.51	11.12%	5.67%	16.78%

2.2.2.3 Reuse systems analysed in this study

The following reuse packaging are analysed in this LCA study:

- Reuse box made of corrugated cardboard
  The reuse box made of corrugated cardboard is firmly attached to a wooden pallet. The entire system weighs 17 kg. In the study, this box is analysed both as a single-use and a reuse system. In view of the mechanical stresses in the distribution process and in reflection of the EUMOS test results, it is assumed that the technically possible number of uses is 5 trips in total. This means that the maximum number of trips is below the bandwidths determined for the systems in chapter 2.2.2.1, so it is irrelevant to the box whether it is managed as an individual or pool reuse system. The figure of 5 rotations also correlates with the information in the French ADEME report.[5]
- Flexible reuse sleeve
  The reuse sleeve is a textile fabric made from PET (56% of total weight) with velcro fasteners made from PA (20% of total weight) and metal D-rings (24% of total weight). The load is fixed to the pallet with the aid of the reuse sleeve. The connection to the pallet is created by two additional straps underneath the floorboards. The sleeve is not a final wrapping but remains open at the top which makes it unfit for outside storage. A well-known supplier of this reuse solution is the US company Cary. According to Cary's web shop, a sleeve with a height of 180 cm weighs 7.26 kg (6' Reuse Pallet Wrap Cover, Heavy Duty w/ Corner Pallet Straps (thecarycompany.com)). The SWAP Report states a weight of 4.88 kg for an identical sleeve. The Chinese-made reuse sleeve tested in this study weighs only 2.46 kg. In this study, only those systems that have undergone the EUMOS test are analysed. Therefore, the reuse sleeve made in China with the lower packaging weight is modelled in this study. As part of the SWAP project, a possible value of 2,500 uses was documented for the sleeve analysed there. This is a technical value that was determined as part of a material test in the laboratory. In

[5] Table 3 in TERRA, ELCIMAÏ, ALTERINNOV, PRAGMATIK, Emmanuelle PAROLA, ADEME (Aurore LAMILHAU-PALOU et Sylvain PASQUIER). 2024. Étude de préfiguration de la filière REP Emballages industriels et commerciaux. 183 pages.

practice, the cuff cannot achieve this value (see also chapter 2.2.2.1).
This study assumes that the sleeve will not be suitable for all applications and will therefore be used primarily as an individual system by specific manufacturers for their products. It is therefore assumed that the flexible reuse sleeve will be used as an individual system.

- Reuse plastic box
  Rigid boxes of a certain size have limited applications as they cannot be adjusted to different product sizes. As part of the study, two foldable reuse plastic boxes were analysed, one of which weighs 48 kg and the other 50 kg. The system does not require pallets, as the forklift mounts are already integrated into the base of the box. As the boxes are foldable, the volume for return transport can be significantly reduced (by up to 75% according to the KTP data sheet).
  The study assumes that the plastic boxes will be managed in a common pool, as the boxes are versatile and suitable for many applications. It is therefore likely that economic synergies can be achieved through a pooling approach. It is assumed that an external refurbishment is involved in the return logistics, which takes over the quality control and, if necessary, the repair of the boxes.
  Returnable plastic boxes can be made of HDPE, PP or a mixture of both materials. Typically, 80% of the system is made of PCR material. For the purposes of this study, it is assumed that the boxes are made of PP and PP-PCR material, as the PP dataset has a more favourable environmental profile than the HDPE dataset.

2.3 Packaging specifications

The packaging specifications contain information on the weight of the transport packaging and the mass of the goods that can be transported in one unit. When defining the packaging specifications, a distinction must be made between flexible single-use transport packaging and rigid single-use and reuse transport packaging:

- In the case of flexible single-use transport packaging, the requirements of the contents determine the need for transport packaging. Therefore, as part of this LCA, the packaging specifications for flexible single-use packaging were developed in a series of tests according to the EUMOS standard. The primary objective of the test series was to develop a loading unit that is both safe and requires a minimum of packaging material. The pallets were tested in accordance with EUMOS standard 40509, using a deceleration test in both longitudinal and transverse directions. In the event of a failure, the test was repeated until a positive result was obtained. During this process, the balance between the stability of the load unit and the amount of packaging material used was constantly optimised. An attempt was also made to find the most efficient packing scheme.
- Rigid single-use transport packaging (here: cardboard) and reuse transport packaging were purchased and weighed. The EUMOS test then determined how much product could be packed in this packaging and still meet the EUMOS safety requirements.

In addition, data on the weights of single-use plastic transport packaging was collected from various companies that manufacture or sell single-use plastic transport packaging. An average value was calculated from the data collected and compared with the packaging weights determined as part of the EUMOS test series as shown in Figure 2-3. It was found that the values obtained in the test series were always in the upper half of the range, which means that the data obtained in the test series can be considered as conservative, as in practice significantly lower weights are sometimes found.

For the purposes of the study, the determination of packaging weights based on the EUMOS test is considered very valid for comparison with reuse systems. Although the primary data collection shows that lower input weights are used in practice, the authors of the study cannot say whether these packaging specifications also meet the requirements of the EUMOS test. Therefore, no sensitivity analysis is carried out with regard to the packaging weight, especially as lower packaging weights would also reduce the environmental impact of single-use packaging. In this respect, the specification made here can be considered conservative by comparison.

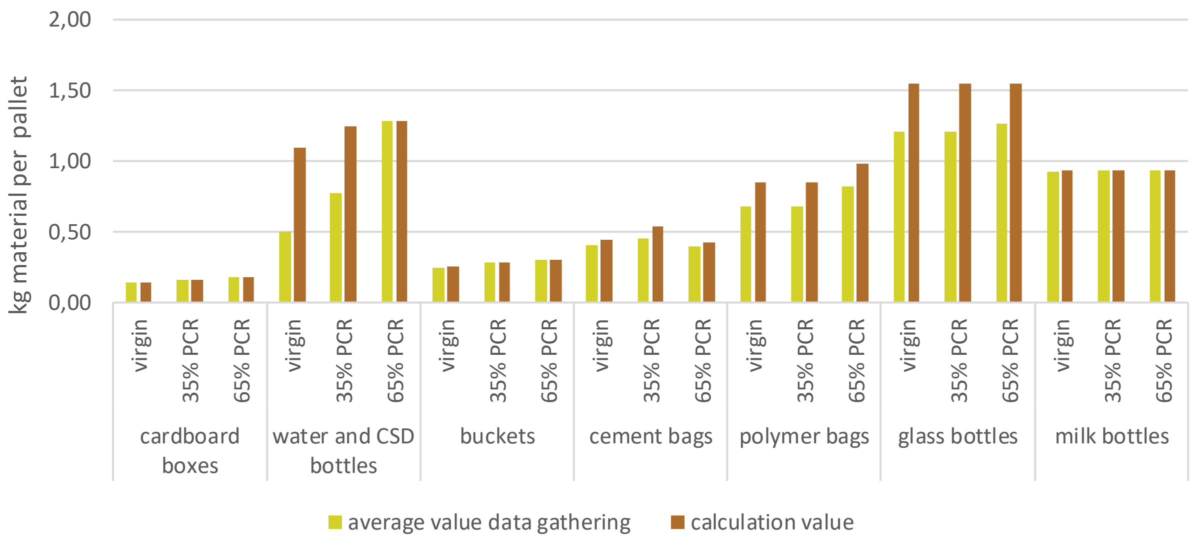

Figure 2-3: Comparison between average packaging weights gathered during the data collection and calculation weights, determined as part of the EUMOS test series

For reasons of confidentiality and because in some cases the number of values averaged is less than 4, the data cannot be documented here in detail. It should be noted that the sample collected in this study is not representative of the whole market.

The following Table 2-3 documents the calculation values used in this study for the quantity of transport packaging per pallet and the mass of the packaged goods on that pallet. These values are used to calculate the mass flow of material used per functional unit of 1,000 kg of packaged goods on a pallet.

The weight limit takes precedence over the volume limit for the flexible single-use transport packaging for cement and polymer bags, water and SCD bottles, glass bottles and milk bottles. This means, that the possible spaces in the trailer must remain empty to avoid overloading. For all reuse transport packaging systems examined and the single-use cardboard box, the volume limit always applies in all applications.

In the base scenarios all transport packaging systems are loaded into the lorry trailers in a single layer only; double or triple stacking is also possible for single-use and returnable boxes. Sensitivity analyses regarding the stacking in lorries are performed to assess the relevance of the results.

At this point, it should be clearly documented once again that, with the exception of the reuse boxes made of PP, the wooden pallet is part of the transport packaging system. All single use plastic transport packaging, as well as the paper stretch and the reusable sleeve, using the typical EURO flat pallet for the purpose of this study. The single use and reuse cardboard packaging are combined with a pallet that is individually tailored to the needs of this packaging system. The distinction between the various disposable and reusable transport packaging examined in this study is based on the load securing systems (stretch film, reusable sleeve, etc.). However, the pallet is always considered, even if it is not always mentioned separately.

Table 2-3: Packaging specifications of all transport packaging analysed in this study

			single use					reuse			
			stretch wrap/ hood + shrink hood			paper stretch	cardboard box	cardboard box	sleeve	plastic box A	plastic box B
			0% PCR	35% PCR	65% PCR						
cardboard boxes	Pallet weight	kg	21.50	21.50	21.50	21.50	11.00	11.00	21.50	48.00	50.00
	Weight of the transport packaging	kg	0.139	0.164	0.176	1.020	6.000	6.000	2.460		
	Weight of packaged goods (product + primary + secondary packaging)	kg	273.36	273.36	273.36	271.48	119.50	119.50	184.04	101.00	101.00
	weight pallet total	kg	295.00	295.02	295.04	294.00	136.50	136.50	208.00	149.00	151.00
	Number of pallet spaces per layer	#	33	33	33	33	33	33	33	33	33
number of packing units to fullfill the FU		#	3.66	3.66	3.66	3.68	8.37	8.37	5.43	9.90	9.90
water and CSD bottles	Pallet weight	kg	21.50	21.50	21.50	21.50	11.00	11.00	21.50	48.00	50.00
	Weight of the transport packaging	kg	1.098	1.243	1.281	3.598	6.000	6.000	2.460		
	Weight of packaged goods (product + primary + secondary packaging)	kg	776.40	776.26	776.22	773.90	295.00	295.00	581.04	295.00	295.00
	weight pallet total	kg	799.00	799.00	799.00	799.00	312.00	312.00	605.00	343.00	345.00
	Number of pallet spaces per layer	#	28	28	28	28	33	33	33	33	33
number of packing units to fullfill the FU		#	1.29	1.29	1.29	1.29	3.39	3.39	1.72	3.39	3.39
buckets	Pallet weight	kg	21.50	21.50	21.50	21.50	11.00	11.00	21.50	48.00	50.00
	Weight of the transport packaging	kg	0.225	0.287	0.305	0.800	6.000	6.000	2.460		
	Weight of packaged goods (product + primary + secondary packaging)	kg	288.75	288.71	288.70	288.20	163.00	163.00	288.04	163.00	163.00
	weight pallet total	kg	310.47	310.50	310.50	310.50	180.00	180.00	312.00	211.00	213.00
	Number of pallet spaces per layer	#	33	33	33	33	33	33	33	33	33
number of packing units to fullfill the FU		#	3.46	3.46	3.46	3.47	6.13	6.13	3.47	6.13	6.13
cement bags	Pallet weight	kg	21.50	21.50	21.50				*21.50*	48.00	50.00
	Weight of the transport packaging	kg	0.445	0.540	0.425				*2.460*		
	Weight of packaged goods (product + primary + secondary packaging)	kg	1050.00	1050.00	1050.00				*625.00*	500.00	700.00
	weight pallet total	kg	1071.95	1072.04	1071.93				*648.96*	548.00	750.00
	Number of pallet spaces per layer	#	21	21	21				*33*	33	30
number of packing units to fullfill the FU		#	0.95	0.95	0.95				1.60	2.00	1.43
polymer bags	Pallet weight	kg	21.50	21.50	21.50				*21.50*	48.00	50.00
	Weight of the transport packaging	kg	0.850	0.850	0.980				*2.460*		
	Weight of packaged goods (product + primary + secondary packaging)	kg	1000.00	1000.00	1000.00				*625.00*	300.00	300.00
	weight pallet total	kg	1022.35	1022.35	1022.48				*648.96*	348.00	350.00
	Number of pallet spaces per layer	#	22	22	22				*33*	33	33
number of packing units to fullfill the FU		#	1.00	1.00	1.00				1.60	3.33	3.33
glass bottles	Pallet weight	kg	21.50	21.50	21.50					48.00	50.00
	Weight of the transport packaging	kg	1.550	1.550	1.550						
	Weight of packaged goods (product + primary + secondary packaging)	kg	718.45	718.45	718.45					148.00	132.00
	weight pallet total	kg	741.50	741.50	741.50					196.00	182.00
	Number of pallet spaces per layer	#	31	31	31					33	33
number of packing units to fullfill the FU		#	1.39	1.39	1.39					6.76	7.58
milk bottles	Pallet weight	kg	21.50	21.50	21.50				21.50	48.00	50.00
	Weight of the transport packaging	kg	0.937	0.937	0.937				2.460		
	Weight of packaged goods (product + primary + secondary packaging)	kg	777.06	777.06	777.06				620.54	406.00	407.00
	weight pallet total	kg	799.50	799.50	799.50				644.50	454.00	457.00
	Number of pallet spaces per layer	#	28	28	28				33	33	33
number of packing units to fullfill the FU		#	1.29	1.29	1.29				1.61	2.46	2.46

Important note: The reuse sleeve was destroyed during the EUMOS test series (see also section 5.2.1). As a result, stacking plans could only be drawn up for the cement bags and polymer bags applications, and it was no longer possible to carry out an EUMOS test. The load capacity is therefore only a best estimate.

2.4 Distribution

In the study, the distribution distance of the entire system is set at 500 km, which corresponds to the average distribution distance of products in a large country such as France, Germany, Poland, Spain, etc. With regard to § 1 and 2 of Art. 29 of the PPWR, a specific distribution distance of 1,000 km between two economic operators or linked company is also considered as a sensitivity analysis to reflect the "within the territory of the European Union" regulatory scope.

The question of the redistribution of reuse transport packaging systems is of crucial importance for the LCA. It is assumed that the customized systems must always be returned to the distributor. Consequently, the return distance corresponds to the distribution distance.

Most LCA studies of reusable systems assume that the return journey is the same as the outward journey. Potential collection and sorting trips that occur in practice are usually not considered. Based on numerous discussions that the authors of this study have had with logistics experts and reuse stakeholders over the last 20 years, this study assumes that the redistribution of reusable transport packaging may operate differently from the redistribution of sales or collection packaging. The working hypothesis is that the return distance can be shorter than the distribution distance because the reuse system can be used by many actors for a wide range of applications.

In the case of open pool systems, the return distance can be significantly shorter with many participants, as the next user may be in the immediate vicinity. A halving of the distance is therefore assumed in the study. This value cannot currently be empirically proven and is therefore purely an estimate based on the assumption that all players in Europe use the returnable system. Based on this assumption, a pick-up and return journey to the processing centre is assumed for the managed pool in addition to the actual return distance. The redistribution distance is therefore 75 % of the distribution.

In principle, all reuse transport packaging systems analysed can be compressed when empty: the cardboard boxes are foldable, the reuse sleeve is flexible and can be rolled up into a compact roll. Different levels of compression are therefore assumed for return transport.

It is assumed that compressed reusable transport packaging is returned in fully loaded trucks. A lorry can accommodate 396 type A or 297 type B reusable boxes, as type B has a larger folded volume. When folded, 396 cardboard boxes also fit in a lorry. The compaction rate assumptions were taken from the data sheets of the returnable boxes. For the cardboard box, the data was taken from the reuse box type A because it has the same folding system. Since no data sheet is available for the sleeves, it is estimated that 825 sleeves can be transported per lorry, utilizing approximately 90% of its capacity.

The redistribution follows the same accounting principles outlined in Section 1.7.4 for distribution, with the key difference that no allocation is made between transport packaging and other contents—only the transport packaging itself is loaded.

As the return of empty reusable transport packaging is expected to have a visible impact on the life cycle assessment of this packaging, a sensitivity analysis is also carried out, assuming that the reusable transport packaging taken back is reused by the first economic operator and therefore no return takes place.

2.5 End of Life

This study only covers transport packaging. Due to the scope of this study, which only covers distribution to the central warehouse, the packaging never reaches private end user, but only ends up in the commercial sector. Used and empty single-use packaging, or destroyed reuse packaging, is placed in the designated collection systems for recyclable materials in the central warehouses or at other points in the value chain. Reuse packaging sorted out for quality reasons is sent for recycling as well.

The publicly available figures for the materials analysed in this study do not accurately reflect this situation, even when they relate to packaging, as this involves collection from the private end user. For example, EUROSTAT publishes a recycling rate of 65.4% for all packaging in 2022. The maximum resolution of the figures is at material level. Here, 83.2% is reported for paper and board, 40.7% for plastics and 34.2% for wood packaging. As always, these figures include collection points at the end user and are also subject to some uncertainty regarding the regional origin of the data[6].

The paper and corrugated board industry publishes its own figures. For example, FEFCO gives a recycling rate of 89%[7] for corrugated board packaging and EPRC gives a rate of 82.5% for paper packaging[8].However, even these figures do not reflect the area analysed in this study. The figure for corrugated board is probably the most meaningful, as a large proportion of it is used for transport packaging.

Given that all the packaging analysed in this study except the reuse sleeve is mono-material packaging with high recyclability, it can be assumed that a high percentage of this packaging is directly compacted and recycled in central warehouses across Europe. The authors of the study assume, that the figures underestimate the situation for corrugated board, paper and plastics. This study therefore assumes a recycling rate of 90% for transport packing made from cardboard and 80% for flexible transport packaging made from paper or plastic. This can be considered as a conservative approach, as it means that the envelope of every 5th pallet is not recycled but burned. The reuse sleeve is made of different materials (PET, PA and metal). The plastics are woven into the textile. As there is still no comprehensive textile recycling in Europe, it is assumed that the PET and PA parts of the reuse sleeve will be incinerated at the end of the product life cycle. Only the metal parts will be recycled.

The wooden pallet is also part of the transport packaging. As this is a reusable system, the issue of disposal is comparatively less relevant. The system calculates that 26% of the sorted pallets are recycled, replacing primary wood, while the remaining 74% are thermally recycled, replacing primary energy.

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[6] https://ec.europa.eu/eurostat/databrowser/view/cei_wm020/default/table
[7] https://www.fefco.org/sites/default/files/FEFCO%20Activity%20Report%202022%20final.pdf
[8] https://www.paperforrecycling.eu/download/1704/?tmstv=1728477607 82,5%

2.6 Scenario overview

The following section provides an overview of the main input parameters for the base scenarios.

Table 2-4: Scenario specifications application field cardboard boxes

type of packaging	packaging weight	packaging material	PCR content	palett weight	distribution distance	redistribution distance/ empty lorry journey	compaction rate for redistribution	trip rate	EOL Split (Rec/ MSWI)
in words	*in kg*	*in words*	*in %*	*in kg*	*in km*	*in km*	*#*	*#*	*in %*
stretch wrap	0.139	LLDPE	0%	21.5	500	100	-	-	80%/20%
stretch wrap	0.164	LLDPE	35%	21.5	500	100	-	-	80%/20%
stretch wrap	0.176	LLDPE	65%	21.5	500	100	-	-	80%/20%
paper wrap	1.020	kraftpaper	0%	21.5	500	100	-	-	80%/20%
cardboard box	6.000	cardboard	88%	11.0	500	100	-	-	90%/10%
cardboard box	6.000	cardboard	88%	11.0	500	250	12	5	90%/10%
sleeve	2.460	PET, PA, steel	0%	21.5	500	500	25	10	PET/PA: 100% MSWI Steel 100% recycling
plastic box A	48.000	PP	80%	0.0	500	375	12	33	90%/10%
plastic box B	50.000	PP	80%	0.0	500	375	9	33	90%/10%

Table 2-5: Scenario specifications application field water and CSD bottles

type of packaging	packaging weight	packaging material	PCR content	palett weight	distribution distance	redistribution distance/ empty lorry journey	compaction rate for redistribution	trip rate	EOL Split (Rec/ MSWI)
in words	*in kg*	*in words*	*in %*	*in kg*	*in km*	*in km*	*#*	*#*	*in %*
stretch wrap	1.098	LLDPE	0%	21.5	500	100	-	-	80%/20%
stretch wrap	1.243	LLDPE	35%	21.5	500	100	-	-	80%/20%
stretch wrap	1.281	LLDPE	65%	21.5	500	100	-	-	80%/20%
paper wrap	3.598	kraftpaper	0%	21.5	500	100	-	-	80%/20%
cardboard box	6.000	cardboard	88%	11.0	500	100	-	-	90%/10%
cardboard box	6.000	cardboard	88%	11.0	500	250	12	5	90%/10%
sleeve	2.460	PET, PA, steel	0%	21.5	500	500	25	10	PET/PA: 100% MSWI Steel 100% recycling
plastic box A	48.000	PP	80%	0.0	500	375	12	33	90%/10%
plastic box B	50.000	PP	80%	0.0	500	375	9	33	90%/10%

Table 2-6: Scenario specifications application field buckets

type of packaging	packaging weight	packaging material	PCR content	palett weight	distribution distance	redistribution distance/ empty lorry journey	compaction rate for redistribution	trip rate	EOL Split (Rec/ MSWI)
in words	*in kg*	*in words*	*in %*	*in kg*	*in km*	*in km*	*#*	*#*	*in %*
stretch wrap	0.225	LLDPE	0%	21.5	500	100	-	-	80%/20%
stretch wrap	0.287	LLDPE	35%	21.5	500	100	-	-	80%/20%
stretch wrap	0.305	LLDPE	65%	21.5	500	100	-	-	80%/20%
paper wrap	0.800	kraftpaper	0%	21.5	500	100	-	-	80%/20%
cardboard box	6.000	cardboard	88%	11.0	500	100	-	-	90%/10%
cardboard box	6.000	cardboard	88%	11.0	500	250	12	5	90%/10%
sleeve	2.460	PET, PA, steel	0%	21.5	500	500	25	10	PET/PA: 100% MSWI Steel 100% recycling
plastic box A	48.000	PP	80%	0.0	500	375	12	33	90%/10%
plastic box B	50.000	PP	80%	0.0	500	375	9	33	90%/10%

Table 2-7: Scenario specifications application field cement bags

type of packaging	packaging weight	packaging material	PCR content	palett weight	distribution distance	redistribution distance/ empty lorry journey	compaction rate for redistribution	trip rate	EOL Split (Rec/ MSWI)
in words	*in kg*	*in words*	*in %*	*in kg*	*in km*	*in km*	*#*	*#*	*in %*
stretch hood	0.445	LLDPE	0%	21.5	500	100	-	-	80%/20%
stretch hood	0.540	LLDPE	35%	21.5	500	100	-	-	80%/20%
stretch hood	0.425	LLDPE	65%	21.5	500	100	-	-	80%/20%
sleeve	2.460	PET, PA, steel	0%	21.5	500	500	25	10	PET/PA: 100% MSWI Steel 100% recycling
plastic box A	48.000	PP	80%	0.0	500	375	12	33	90%/10%
plastic box B	50.000	PP	80%	0.0	500	375	9	33	90%/10%

Table 2-8: Scenario specifications application field polymer bags

type of packaging	packaging weight	packaging material	PCR content	palett weight	distribution distance	redistribution distance/ empty lorry journey	compaction rate for redistribution	trip rate	EOL Split (Rec/ MSWI)
in words	*in kg*	*in words*	*in %*	*in kg*	*in km*	*in km*	*#*	*#*	*in %*
stretch hood	0.850	LLDPE	0%	21.5	500	100	-	-	80%/20%
stretch hood	0.850	LLDPE	35%	21.5	500	100	-	-	80%/20%
stretch hood	0.980	LLDPE	65%	21.5	500	100	-	-	80%/20%
sleeve	2.460	PET, PA, steel	0%	21.5	500	500	25	10	PET/PA: 100% MSWI Steel 100% recycling
plastic box A	48.000	PP	80%	0.0	500	375	12	33	90%/10%
plastic box B	50.000	PP	80%	0.0	500	375	9	33	90%/10%

Table 2-9: Scenario specifications application field glass bottles

type of packaging	packaging weight	packaging material	PCR content	palett weight	distribution distance	redistribution distance/ empty lorry journey	compaction rate for redistribution	trip rate	EOL Split (Rec/ MSWI)
in words	*in kg*	*in words*	*in %*	*in kg*	*in km*	*in km*	*#*	*#*	*in %*
shrink hood	1.550	LLDPE	0%	21.5	500	100	-	-	80%/20%
shrink hood	1.550	LLDPE	35%	21.5	500	100	-	-	80%/20%
shrink hood	1.550	LLDPE	65%	21.5	500	100	-	-	80%/20%
plastic box A	48.000	PP	80%	0.0	500	375	12	33	90%/10%
plastic box B	50.000	PP	80%	0.0	500	375	9	33	90%/10%

Table 2-10: Scenario specifications application field HDPE milk bottles

type of packaging	packaging weight	packaging material	PCR content	palett weight	distribution distance	redistribution distance/ empty lorry journey	compaction rate for redistribution	trip rate	EOL Split (Rec/ MSWI)
in words	*in kg*	*in words*	*in %*	*in kg*	*in km*	*in km*	*#*	*#*	*in %*
shrink hood	0.937	LLDPE	0%	21.5	500	100	-	-	80%/20%
shrink hood	0.937	LLDPE	35%	21.5	500	100	-	-	80%/20%
shrink hood	0.937	LLDPE	65%	21.5	500	100	-	-	80%/20%
sleeve	2.460	PET, PA, steel	0%	21.5	500	500	25	10	PET/PA: 100% MSWI Steel 100% recycling
plastic box A	48.000	PP	80%	0.0	500	375	12	33	90%/10%
plastic box B	50.000	PP	80%	0.0	500	375	9	33	90%/10%

Sensitivity analyses intend to assess the reliability of the final results and conclusions by determining how they are affected by uncertainties in the assumptions made or choice of parameters based on expert judgement. Following the ISO standard's recommendation on subjective choices, the following sensitivity analyses are included:

- Sensitivity to the trip rates of reuse systems
- Sensitivity to distribution distances
- Sensitivity to truck load factors within the distribution chain
- Sensitivity regarding the use of PCR in the reuse sleeve
- Sensitivity regarding the use of EVA in stretch hoods
- Sensitivity regarding the allocation factor

These factors were selected as they may have a significant impact on the environmental performance of transport packaging and are critical variables in real-world logistics operations. A description of the sensitivity analyses performed, and the documentation and discussion of the results is provided in section 5.3.

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 internal ifeu database. The internal ifeu database encompasses a collection of primary data gathered through various industry projects. It also contains data that originates from confidential studies or has been made available to IFEU in some other confidential way. 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 product name	Reference year/ period	Geographic scope
Intermediate goods			
Fossil LLDPE	(Ecoinvent 3.10) / polyethylene, linear low density, granulate	2011-2024	Europe
Fossil LDPE	(Ecoinvent 3.10) / polyethylene, low density, granulate	2011-2024	Europe
Fossil PET	(Ecoinvent 3.10) / polyethylene terephthalate, granulate, bottle grade	2015-2024	Europe
Fossil PP	(Ecoinvent 3.10) / polypropylene, granulate	2011-2024	Europe
Fossil PA	(Ecoinvent 3.10) / nylon 6	1993-2024	Europe
Paper for paper stretch	(Ecoinvent 3.10) / kraft paper production	2011-2024	Europe
Corrugated cardboard	(FEFCO and Cepi Container Board 2022)	2020	Europe
Stainless steel	(Ecoinvent 3.10) / steel, chromium steel 18/8	2011-2024	Europe
Production of transport packaging			
Production of plastic films	Process data of several manufacturers involved in this study	2024	Europe
Production of paper stretch	(Ecoinvent 3.10) / kraft paper production	2021-2024	Europe
Production of cardboard box	(FEFCO and Cepi Container Board 2022)	2020	Europe
Production of reuse sleeve	ifeu database based on primary data from industrial partners	2021-2004	Europe
Production of reuse box	ifeu database based on primary data from manufacturers	2021-2024	Europe
Application of transport packaging			

Material / process	Reference / Reference product name	Reference year/ period	Geographic scope
Shrink tunnel	Primary data obtained in the course of this study	2021-2024	Europe
Stretch wrapper	ifeu database based on primary data from confidential studies	2021-2024	Europe
Stretch hood application	ifeu database based on primary data from European packers	2021-2024	Europe
Recovery and recycling			
Plastic waste recycling	ifeu database, based on data from various European recycling plants	2009-2021	Europe
Paper waste recycling	ifeu database, based on data from various European recycling plants	2020-2024	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
Lorry transport	ifeu database, based on statistics and transport models, emission factors based on HBEFA 4.1 (INFRAS 2019).	2017	Europe

3.1 Manufacture of raw materials

The following raw materials are used within the packaging systems under study:

3.1.1 PP (polypropylene)

PP is produced by catalytic polymerisation of propylene into long-chained polypropylene. The two important processing methods are low pressure precipitation polymerisation and gas phase polymerisation. In a subsequent processing stage, the polymer powder is converted to granulate using an extruder. The present LCA study uses the dataset published in EcoInvent 3.10. The dataset covers the production of PP from cradle to the polymer factory gate. The polymerisation data and subsequent updates refer to the period 2011-2023 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 data set hence represents 76% of PP production in Europe.

3.1.2 LDPE (low density polyethylene)

LDPE is manufactured in a high-pressure process and contains a high number of long side chains. The present LCA study uses the dataset published in EcoInvent 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 and subsequent updates refer to the period 2011-2023. 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 LLDPE (linear low density polyethylene)

LLDPE is either produced in the gas phase process in a fluidised bed reactor or in the solution process. Depending on the kind of co-monomer chosen, the kind of used technology has to be adapted. The present LCA study uses the dataset published in EcoInvent 3.10. The data set covers the production of LLDPE granulates from the extraction of the raw materials from the natural environment, including processes associated with this. The data and subsequent updates refer to the period 2011-2023. Data from a total of 9 participating polymerisation units were collected. The data set represent 86% of LLDPE production in Europe (EU27+2).

3.1.4 PET (polyethylene terephthalate)

Polyethylene terephthalate (PET) is produced by direct esterification and melt polycondensation of purified terephthalic acid (PTA) and ethylene glycol. The model underlying this LCA study uses the dataset published in EcoInvent 3.10 with a reference year of 2015, that represents the production in European PET plants. Data for foreground processes of PTA production are taken from the PTA eco-profile (PlasticsEurope 2017) which is based on primary data from five European PTA producers covering 79% of the PTA production in Europe. The foreground process of ethylene glycol production is taken from the Eco-profile of steam cracker products (PlasticsEurope 2012). For PET production data from 12 production lines at 10 production sites in Belgium, Germany, Lithuania (2 lines), the Netherlands, Portugal, Spain (4 lines) and United Kingdom (2 lines) supplied data with an overall PTA volume of 2.9 million tonnes – this represents 85% of the European production volume (3.4 million tonnes).

3.1.5 PA 6 (polyamide)

Polyamide 6 is manufactured from the precursor's benzene and hydroxylamine. The present LCA study uses the ecoprofile published in EcoInvent 3.10. A more recent dataset is available provided by PlasticsEurope. However, in this dataset ammonium sulphate is seen as a by-product of the PA6 production process of the PA6 pre-product caprolactam. The dataset uses a substitution approach to account for ammonium sulphate. As basically all ammonium sulphate on the market is derived from the PA6 production, in the view of the authors it is not valid to substitute a separate ammonium sulphate production process. Even within the PlasticsEurope methodology this approach is only allowed, "…if there is a dominant, identifiable production path for the displaced product" (PlasticsEurope 2019). Unfortunately, no dataset applying another approach apart from the substitution approach is available. The data set represent the production of 4 European production sites.

3.1.6 Paper for paper stretch

Kraft paper is produced from chemical pulp produced in the kraft process. The present LCA study uses the dataset published in EcoInvent 3.10. The dataset represents average data calculated from several European sack kraft paper mills for the year 2018. The data was collected specifically for sack kraft paper but are representative for all kraft paper production. The data set represent approximately 80% (1,592,115 tonnes) of the total production of sack kraft paper manufactured in Europe (the EU-27 countries plus Norway and Switzerland).

3.1.7 Corrugated cardboard

For the manufacture of corrugated cardboard boxes, the data sets published by FEFCO (FEFCO and Cepi Container Board 2022) were used. The data sets represent weighted average values from European locations recorded in the FEFCO data set. The data refer to the year 2020. All corrugated board is assumed to be sourced from European production. The data set cover approximately 73% of the total annual production in Europe. In order to ensure stability, a fraction of fresh fibres is often used for the corrugated cardboard boxes. According to FEFCO and Cepi Container Board (2022), this fraction on average is 12% in Europe. Due to a lack of more specific information this split was also used for this study. However, the share of fresh fibres may vary across different European countries.

3.1.8 Stainless steel

This LCA study uses the data set for the production of stainless steel (type 304, also known as 18/8) published in EcoInvent 3.10. This dataset represents the average European technology for the production of stainless steel in a two-stage process: Raw materials (chromium, pig iron, carbon steel scrap and ferro-nickel) are fed into an electric arc furnace (EAF) and melted together. The molten metal is then removed from the EAF and transferred to an Argon Oxygen Decarburisation (AOD) refining vessel. The purified molten metal is then continuously cast into stainless steel slabs. Data were taken from plants across Europe and are considered representative for the average situation across Europe.

3.2 Production of transport packaging

Data on plastic films have been provided by several of the companies that have commissioned the study. For each type of plastic film considered, the average values have been calculated from the weights and process data that have been provided. The process data have been coupled with the European energy supply chain. For the paper stretch production the dataset for kraft paper production from Ecoinvent3.10 is applied. . The manufacture of single-use and reuse corrugated cardboard boxes is already included in the data set published by FEFCO (FEFCO and Cepi Container Board 2022).

The dataset for reuse sleeve mainly made from woven PET is based on primary data collected as part of an internal project for a manufacturer of woven PET industrial packaging. The underlying model has been adapted to the packaging specifications of the reuse sleeve. The dataset encompasses the entire production process up to the completion of the finished reuse sleeve, including extrusion, weaving, cutting, and assembly steps. The reuse PP boxes are based on a dataset modelled by internal ifeu experts. Process data was determined using primary data from comparable packaging manufacturing processes. The material input was used as the basis for this derivation. The underlying process data have been coupled with the European energy supply chain. The grammages of those transport packaging systems have been taken from the manufacturer's technical data sheets.

3.3 Application of transport packaging

The different application processes of the plastic single-use transport packaging and the single-use paper stretch wrap have been included in the study. The data were obtained from several companies involved in this study as well as from the ifeu internal database. The ifeu internal application processes are based on confidential studies and on primary data obtained from several European packers. The single-use and reuse corrugated cardboard boxes, the reuse sleeves as well as the reuse PP boxes are applied by hand and not by machine. Therefore, no additional application process was modelled in these cases.

3.4 Transport distances and modes

The following **Table 3-2** provides an overview of the transport settings (distances and modes) applied for packaging materials. Data were obtained from 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 3-2: 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 application (km)
Fossil polymers	500 / road[9]	
Stainless steel	500 / road[9]	
Paper	300 / road[10] 950 / sea[10] 800 / rail[10]	
Corrugated cardboard	primary fibres: 500 / sea, 400 / rail, 250 / road[10] secondary fibres: 300 /road[10]	
Wood for pallets	100 / road[9]	
Transport packaging under examination		500 / road[9]
Pallets		100 / road[9]

In this chapter, only the transport distances and modes for the upstream transport of packaging are presented. Information on the distribution of packaged goods and redistribution of empty reuse transport packaging can be found in section 2.4. Information on the data sets used to calculate the emissions from trucks can be found in section 3.6.1.

3.5 Recovery and recycling

Used transport packaging is either disposed of or sent to a recycling facility. In this study, plastic film and reuse PP box recycling is modeled as follows: The collected and sorted transport packaging is subjected to a regranulation process, which results in the production of secondary raw materials for further use. The data used in the current study is based on ongoing primary data collection from various

[9] ifeu assumption
[10] taken from published LCI reports

European recycling companies. Those data reflect the average state of the art, however country-specific representativeness cannot be assessed.

For reuse sleeves which are collected and sorted it is assumed that the woven sleeve is sent to MSWI (after several uses, the sleeve is damaged to such an extent, that it is no longer suitable for use as secondary material) while the metal D-Rings are recycled.

Paper stretch and corrugated cardboard boxes which are collected and sorted are subsequently sent to a paper recycling facility for fibre recovery. The secondary fibre material is used e.g. as a raw material for cardboard. Chapter 2.5 presents the end-of-life split data for the packaging analysed.

3.6 Background data

3.6.1 Transport processes (lorry)

The dataset used is based on standard emission data that were collected, 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 (for more information please see info box at the end of this chapter)**.** 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 as they have not yet been updated.

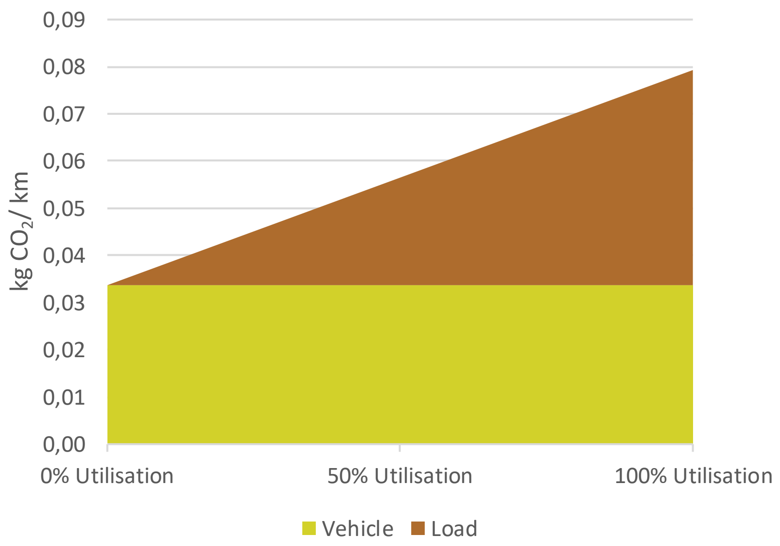


Figure 3-1: Emission factor for the 40t lorry depending on capacity utilisation

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.

In order to map the distribution and redistribution stages of the life cycle, specific utilisation factors are calculated for each packaging system in each application area based on the primary data collected.

These utilisation factors relate to the total load of the lorry, i.e. the transport packaging including the packaged goods. The calculated total transport loads are then allocated using an allocation factor that expresses the ratio between the total load and the mass of the transport packaging.

The table below shows the emissions per truck kilometre as a function of the degree of utilisation for all the environmental impact categories considered.

Table 3-3: Emission factors per 1 km transport done by a 40t lorry

		Emission factors 40t lorry per km		
		0% utilisation	100% utilisation	
Impact and inventory categories	Climate Change	0.0337	0.0793	kg CO2-eq
	Ozone Depletion	0.0000	0.0000	kg R-11-eq
	Photochemical oxidant formation	0.0011	0.0026	kg O_3-eq
	Acidification	0.0001	0.0002	kg SO_2-eq
	Aquatic Eutrophication	0.0000	0.0000	kg PO_4-eq
	Terrestrial Eutrophication	0.0000	0.0000	kg PO_4-eq
	Particulate Matter	0.0001	0.0002	PM 2.5-eq
	Abiotic resource depletion	0.0000	0.0001	kg Sb-eq
	Non-renewable primary energy	446.25	1050	kJ
	Total primary energy	446.25	1050	kJ

The source used to calculate transport emissions (HBEFA) not only uses an average distribution of EURO classes for trucks, but is also based on average driving profile data, which, unlike Ecoinvent's data, also allows for a variation in utilisation rates, which is a prerequisite for application in this study. However, the use of data should be briefly validated. According to a study on behalf of the international road transport union (IRU), a fully loaded 40-tonne truck consumes an average of 39.2 litres of diesel per 100 km[11]. Multiplied by the average CO_2 emission of 2.68 kg per litre of diesel, this gives 105.06 kg of CO_2 per 100 km for a truck at 100% capacity. This is equivalent to 1,050 g per km. This is approximately 30% higher than the value used in the study. It should be noted, however, that these are average values that can vary depending on specific driving conditions, engine type and other factors.

[11] https://www.iru.org/sites/default/files/2016-01/d-co2.pdf source only available in German

For all other transport within the remaining life cycle steps, an average utilisation rate of 50% is assumed. The average capacity utilization of 50% combines load factors and empty trip factors based on (EcoTransIT World 2016) and communication with the logistics sector.

INFOBOX HBEFA
The Handbook of Emission Factors for Road Transport (HBEFA) is a standard data source for emission factors in road traffic. It provides detailed information on greenhouse gas and air pollutant emissions from various vehicle categories. **Key Features of HBEFA** • Contains emission factors for common vehicle types such as passenger cars, vans, heavy-duty vehicles, buses, and motorcycles • Takes into account different traffic situations, technologies, and emission standards • Includes both regulated and unregulated air pollutants as well as greenhouse gas emissions • Provides data for six European countries: Switzerland, Germany, Austria, France, Norway, and Sweden • Covers the period from the 1990s to approximately 2050 (depending on the country) **Applications** • HBEFA is used for various purposes, including: • Climate and air pollutant reporting • Air quality analyses • Environmental impact assessments • Emission inventories • Corporate carbon footprints It also serves as a basis for other emission calculation tools such as COPERT, TREMOD, or EcoTransIT. **Development and Coordination** INFRAS has been developing and coordinating HBEFA since the 1990s in collaboration with various partners, such as the Technical University of Graz and the Institute for Energy and Environmental Research (IFEU) Heidelberg. Funding is provided by the transport or environmental agencies of the participating European countries.

3.6.2 Electricity generation

Modelling of electricity generation is particularly relevant to produce 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 (Fröhlich et al. n.d.), called ELMO. It is based on national electricity mix data for 2021 from the International Energy Agency (IEA)[12] (for more information please see info box at the end of this chapter). The applied shares of energy sources to the related market are given in Fehler! Verweisquelle konnte nicht gefunden werden.The emission factors generated for the European electricity mix used are shown in **Table 3-5** and compared with Ecoinvent 3.10 based on GWP results (**Table 3-6**). It must 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.

Table 3-4: Share of energy source to specific energy mix, reference year 2021.

		Geographic scope
		EU 27+3
Energy source	Hard coal	6.4%
	Brown coal	7.8%
	Fuel oil	1.4%
	Natural gas	20.6%
	Nuclear energy	25.1%
	Hydropower, wind, solar & geothermal	32.4%
	Hydropower	38.6%
	Wind power	42.6%
	Solar energy	18.2%
	Geothermal energy	0.6%
	Biomass energy	4.9%
	Waste	1.4%

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

Table 3-5: Emission factors per 1 kWh of European electricity mix used, reference year 2021.

		Emission factors per kWh electricity	
Impact and inventory categories	Climate Change	3.21E-1	kg CO2-eq
	Ozone Depletion	3.15E-7	kg R-11-eq
	Photochemical oxidant formation	9.50E-3	kg 0_3-eq
	Acidification	1.21E-3	kg SO_2-eq
	Aquatic Eutrophication	1.43E-4	kg PO_4-eq
	Terrestrial Eutrophication	9.05E-5	kg PO_4-eq
	Particulate Matter	9.50E-4	PM 2.5-eq
	Abiotic resource depletion	3.85E-4	kg Sb-eq
	Non-renewable primary energy	7.79	MJ
	Total primary energy	9.87	MJ

Table 3-6: Comparison of GWP results in g CO_2eq/kWh for the European grid electricity production by ifeu ELMO and Ecoinvent 3.10

	Ifeu ELMO model	Ecoinvent 3.10
Climate Change in g CO_2-eq/kWh	0.321	0.324

3.6.3 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 market, reference year 2018.

Geographic Scope	Electrical efficiency	Thermal efficiency	Reference period	Reference
EU	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 (EU 2018).

It is assumed that the electrical energy generated in MSWI plants substitute the market specific grid electricity and that the thermal energy recovered in MSWI plants serves as process heat. The 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%.

INFOBOX ELMO

ELMO (Electricity Model) is a tool developed by ifeu – the Institute for Energy and Environmental Research Heidelberg – for calculating life cycle inventory (LCI) data for electricity supply, as well as district heating and cooling. It enables a detailed analysis and modeling of the environmental impacts associated with the generation and distribution of electricity, district heating, and district cooling.

Functions of ELMO

- Comprehensive Modelling: ELMO covers all energy and material flows related to the supply of electricity, district heating, and district cooling – from raw material extraction and transport to power plant processes and final distribution to end users.
- Flexibility: With a high degree of parameterization, the model can be easily adapted to different study scenarios, including national grids, group-based analyses, or specific cases such as future or marginal mixes.
- Detailed Analysis: ELMO enables the calculation of environmental impacts per kilowatt-hour (kWh) of generated electricity, both at the generation stage (excluding transmission losses) and at the consumption stage (including transmission losses).

Special Features of ELMO

- Diverse Energy Sources: The model considers a wide range of energy sources, including hard coal, lignite, fuel oil, natural gas, biomass (solid and biogas), nuclear energy, municipal waste, photovoltaics, solar thermal energy, hydropower, wind power (onshore and offshore), and geothermal energy.
- Integration of Combined Heat and Power (CHP): ELMO incorporates CHP plants that generate both electricity and heat, allowing for adjustments to the share of district heating as a by-product of electricity generation, depending on the type of power plant.
- Allocation Methods: The model offers different allocation methods (e.g., based on exergy content, energy content, or market price) to distribute environmental impacts between electricity and district heating.

Validity and Representativeness of ELMO's Data

The accuracy and representativeness of the data generated by ELMO depend largely on the quality of the input data and the precision of model parameterization. ELMO utilizes a variety of data sources, including background data (e.g., general statistical data) and foreground data (specific information on individual processes or plants). Its flexibility in adapting to different study scenarios and datasets allows for high accuracy and relevance in the results.

4 Results of base scenarios

This section presents the results of the assessment. A separate sub-section is dedicated to each of the application fields analysed. The results of the base scenarios are presented and described separately from the results of the sensitivity analysis. The presentation of the results differs between the base scenarios and the sensitivity scenarios. The results of the base scenarios are presented in a differentiated way for different life stages, whereby the selection and aggregation of the life stages is based on the system boundaries presented in Chapter 1.4. The following life cycle steps are considered:

- raw material production for transport packaging
- converting of raw material to transport packaging
- shipping of transport packaging to customer + application
- refurbishment of used reuse transport packaging
- production of pallets (material + converting)
- distribution from the production site where the packaging is applicated to the first economic operator in the logistics chain (central warehouse)
- redistribution of empty packaging / empty return journey
- End of life
- credit for energy from incineration
- credit for material from recycling

it is important to note, that LCIA results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins, or risks.

4.1 Results in the application field cardboard boxes

The following **Table 4-1** shows the numerical results for the selected impact category and environmental issues evaluated at the inventory level in the application field cardboard boxes.

Table 4-1: numerical results of all impact categories and environmental issues evaluated at the inventory level in the application field cardboard boxes

impact categories	single use					reuse			
	stretch wrap								
	0% PCR	35% PCR	65% PCR	paper stretch	cardboard box	cardboard box	sleeve	plastic box A	plastic box B
Climate change [kg CO2-equivalents]	5.47E+00	5.46E+00	5.33E+00	7.12E+00	7.58E+01	6.32E+01	3.60E+01	1.14E+02	1.18E+02
Acidification [kg SO2-equivalents]	1.15E-02	1.13E-02	1.09E-02	2.52E-02	2.09E-01	1.37E-01	8.43E-02	2.07E-01	2.13E-01
Summer smog [kg O3-equivalents]	2.00E-01	1.97E-01	1.90E-01	3.80E-01	3.57E+00	2.28E+00	1.24E+00	3.36E+00	3.46E+00
Ozone Depletion [g R-11-equivalents]	4.05E-04	3.85E-04	3.41E-04	4.04E-03	4.92E-02	9.89E-03	5.25E-02	4.19E-03	4.36E-03
Terrestrial eutrophication [g PO4-equivalents]	3.56E-01	3.44E-01	3.14E-01	1.91E+00	1.75E+01	3.51E+00	2.79E+00	2.83E+00	2.94E+00
Aquatic eutrophication [g PO4-equivalents]	-4.46E-02	-5.19E-02	-6.49E-02	2.59E+00	1.05E+01	2.10E+00	1.16E+00	1.14E+00	1.19E+00
Particulate matter [kg PM 2,5- equivalents]	1.23E-02	1.21E-02	1.17E-02	2.52E-02	2.22E-01	1.44E-01	8.85E-02	2.15E-01	2.21E-01
Abiotic resource depletion [kg sb-equivalents]	6.83E-03	6.45E-03	5.91E-03	8.37E-03	9.15E-02	7.79E-02	4.04E-02	1.24E-01	1.27E-01
Non-renewable primary energy [GJ]	7.11E-02	6.71E-02	6.12E-02	9.66E-02	9.30E-01	8.22E-01	4.39E-01	1.35E+00	1.38E+00
Total Primary Energy [GJ]	8.83E-02	8.42E-02	7.83E-02	2.47E-01	1.61E+00	9.58E-01	4.69E-01	1.36E+00	1.40E+00
Fresh Water (Incl. Boiler Feed)	1.85E-03	1.54E-03	1.04E-03	5.16E-02	8.00E-01	1.60E-01	1.34E-02	1.53E-02	1.59E-02

The following **Figure 4-1** shows a relative comparison of the net results of all impact categories and environmental issues evaluated at the inventory level in the application field cardboard boxes

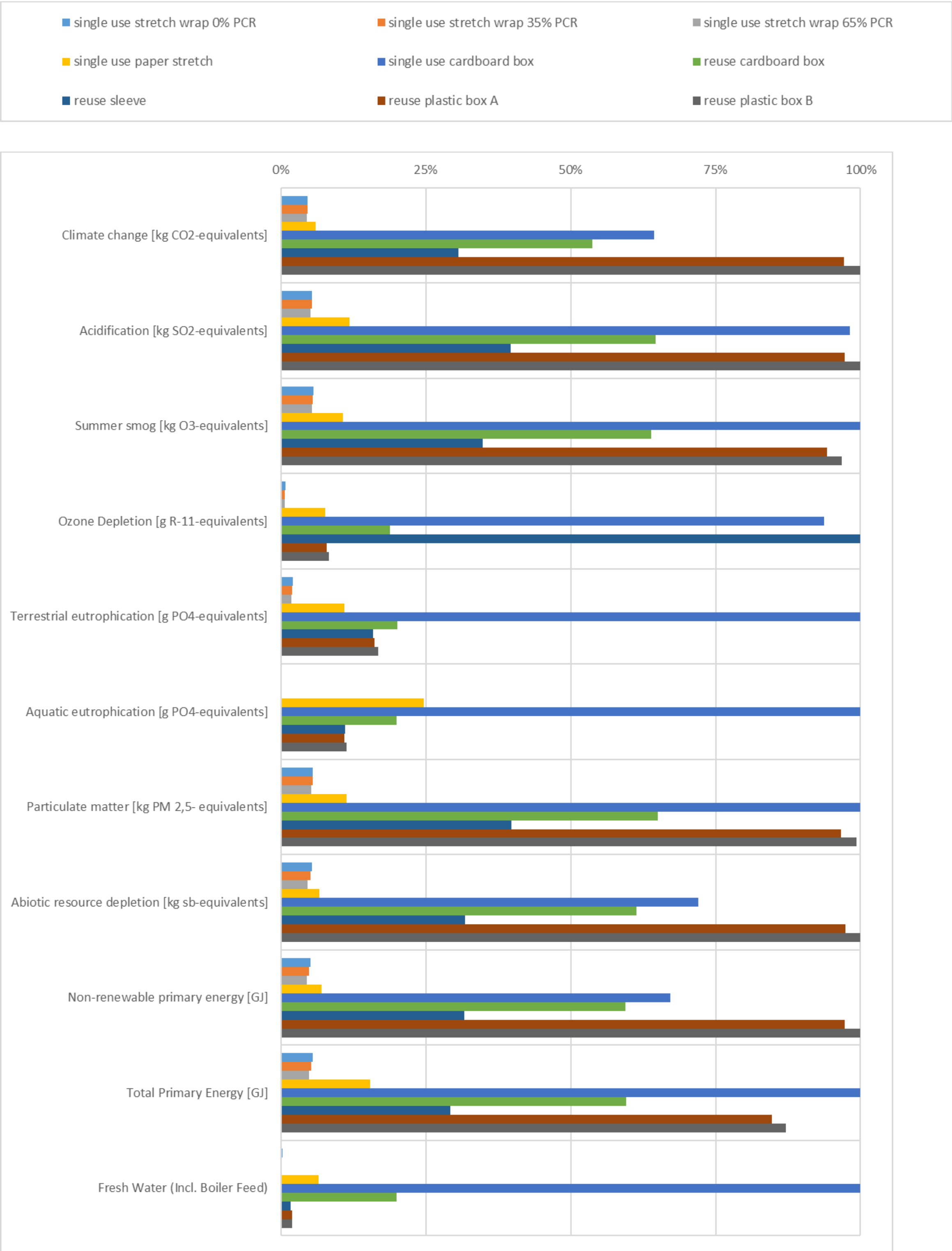
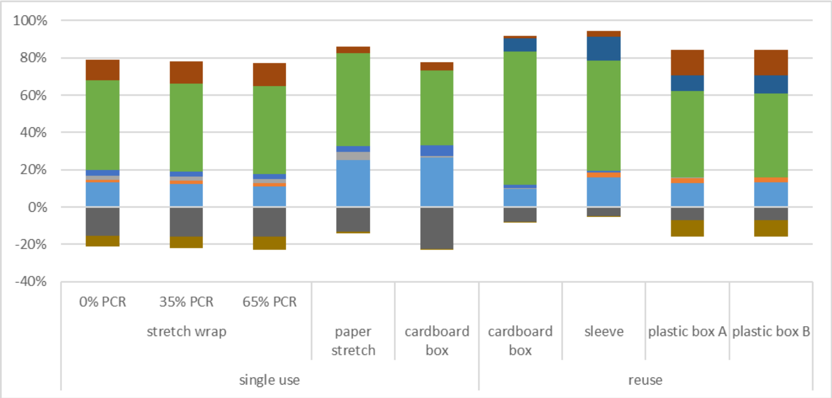


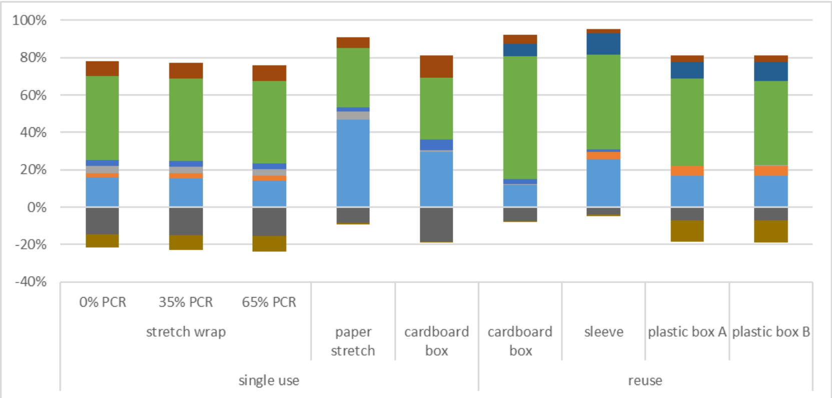
Figure 4-1: relative results of all impact categories and environmental issues evaluated at the inventory level in the application field cardboard boxes

The following **Fehler! Verweisquelle konnte nicht gefunden werden.** to **Figure 4-4** show the relative contribution of lifecycle steps for the eight selected impact categories in the application field cardboard boxes.

Climate change



Acidification



Summer Smog

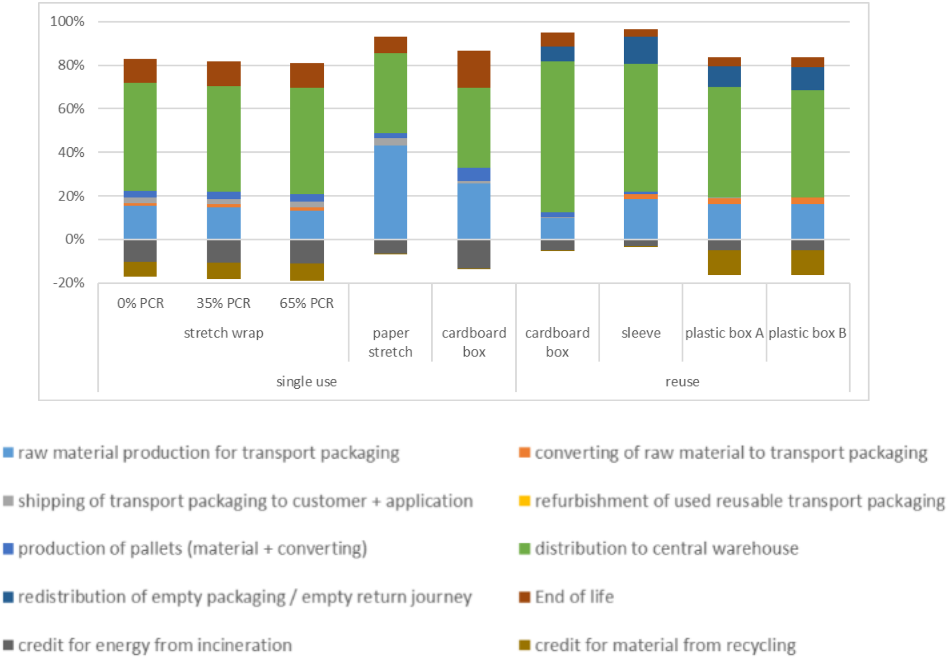


Figure 4-2: relative contribution of lifecycle steps for the impact categories Climate change, Acidification and Summer smog in the application field cardboard boxes

Figure 4-3: relative contribution of lifecycle steps for the impact categories Ozone Depletion Terrestrial and Aquatic eutrophication in the application field cardboard boxes

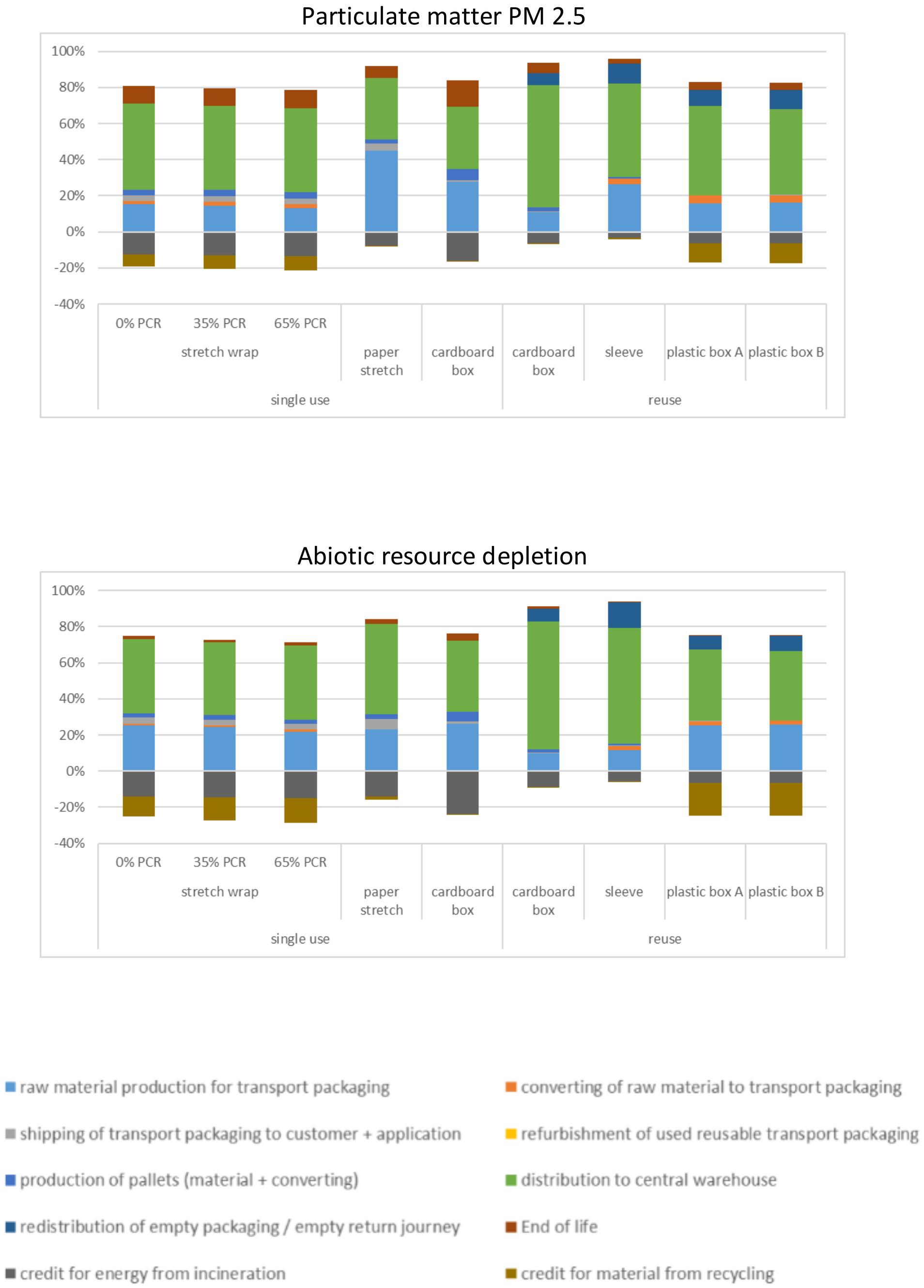


Figure 4-4: relative contribution of lifecycle steps for the impact categories Particulate matter PM 2.5 and Abiotic resource depletion in the application field cardboard boxes

The following **Figure 4-5** shows the relative contribution of lifecycle steps of the environmental issues evaluated at the inventory level in the application field cardboard boxes.

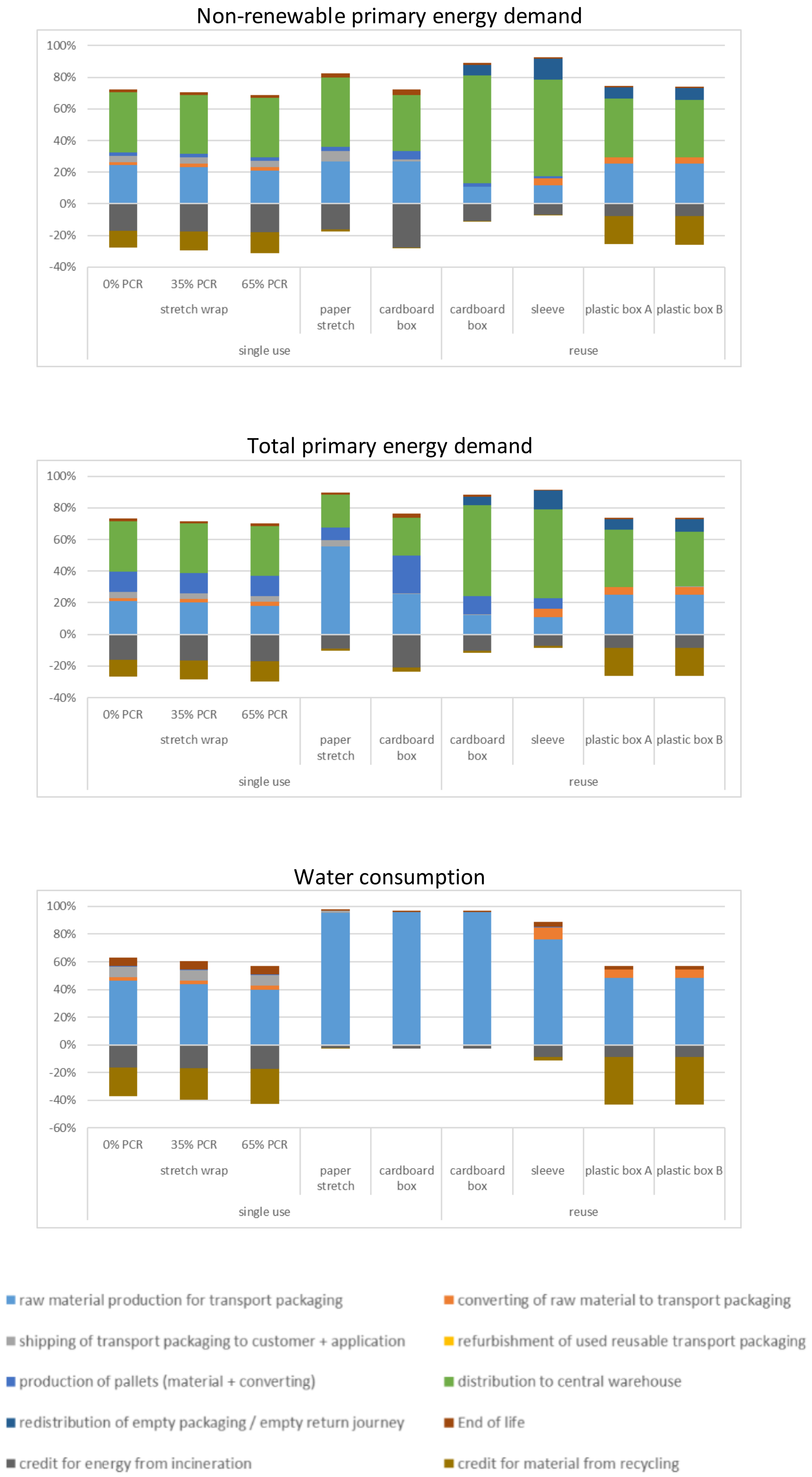


Figure 4-5: relative contribution of lifecycle steps for the categories on inventory level cumulative energy demand Non-renewable and Total and Freshwater consumption in the application field cardboard boxes

4.2 Results in the application field water and CSD bottles

The following **Table 4-2** shows the numerical results for the selected impact category and environmental issues evaluated at the inventory level in the application field water and CSD bottles.

Table 4-2: numerical results of all impact categories and environmental issues evaluated at the inventory level in the application field water and CSD bottles

impact categories	single use					reuse			
	stretch wrap								
	0% PCR	35% PCR	65% PCR	paper stretch	cardboard box	cardboard box	sleeve	plastic box A	plastic box B
Climate change [kg CO2-equivalents]	4.52E+00	4.33E+00	3.89E+00	4.18E+00	2.96E+01	2.45E+01	7.23E+00	3.59E+01	3.70E+01
Acidification [kg SO2-equivalents]	8.06E-03	7.15E-03	5.87E-03	2.07E-02	8.24E-02	5.36E-02	1.84E-02	6.43E-02	6.63E-02
Summer smog [kg O3-equivalents]	1.30E-01	1.17E-01	9.84E-02	2.92E-01	1.41E+00	8.90E-01	2.57E-01	1.04E+00	1.08E+00
Ozone Depletion [g R-11-equivalents]	7.74E-04	6.86E-04	5.52E-04	4.77E-03	1.99E-02	4.00E-03	1.66E-02	1.43E-03	1.49E-03
Terrestrial eutrophication [g PO4-equivalents]	5.81E-01	5.24E-01	4.34E-01	2.19E+00	7.10E+00	1.42E+00	8.82E-01	9.67E-01	1.01E+00
Aquatic eutrophication [g PO4-equivalents]	1.37E-01	1.09E-01	7.12E-02	3.25E+00	4.25E+00	8.50E-01	3.67E-01	3.91E-01	4.08E-01
Particulate matter [kg PM 2,5- equivalents]	8.12E-03	7.28E-03	6.09E-03	2.01E-02	8.78E-02	5.63E-02	1.93E-02	6.67E-02	6.87E-02
Abiotic resource depletion [kg sb-equivalents]	6.14E-03	4.91E-03	3.40E-03	4.78E-03	3.58E-02	3.02E-02	7.63E-03	3.83E-02	3.94E-02
Non-renewable primary energy [GJ]	6.69E-02	5.36E-02	3.72E-02	6.11E-02	3.63E-01	3.19E-01	8.36E-02	4.18E-01	4.30E-01
Total Primary Energy [GJ]	7.39E-02	6.06E-02	4.40E-02	2.31E-01	6.36E-01	3.74E-01	9.33E-02	4.22E-01	4.35E-01
Fresh Water (Incl. Boiler Feed)	5.39E-03	4.30E-03	2.90E-03	6.38E-02	3.24E-01	6.48E-02	4.25E-03	5.24E-03	5.46E-03

The following **Figure 4-6** shows a relative comparison of the net results of all impact categories and environmental issues evaluated at the inventory level in the application field water and CSD bottles.

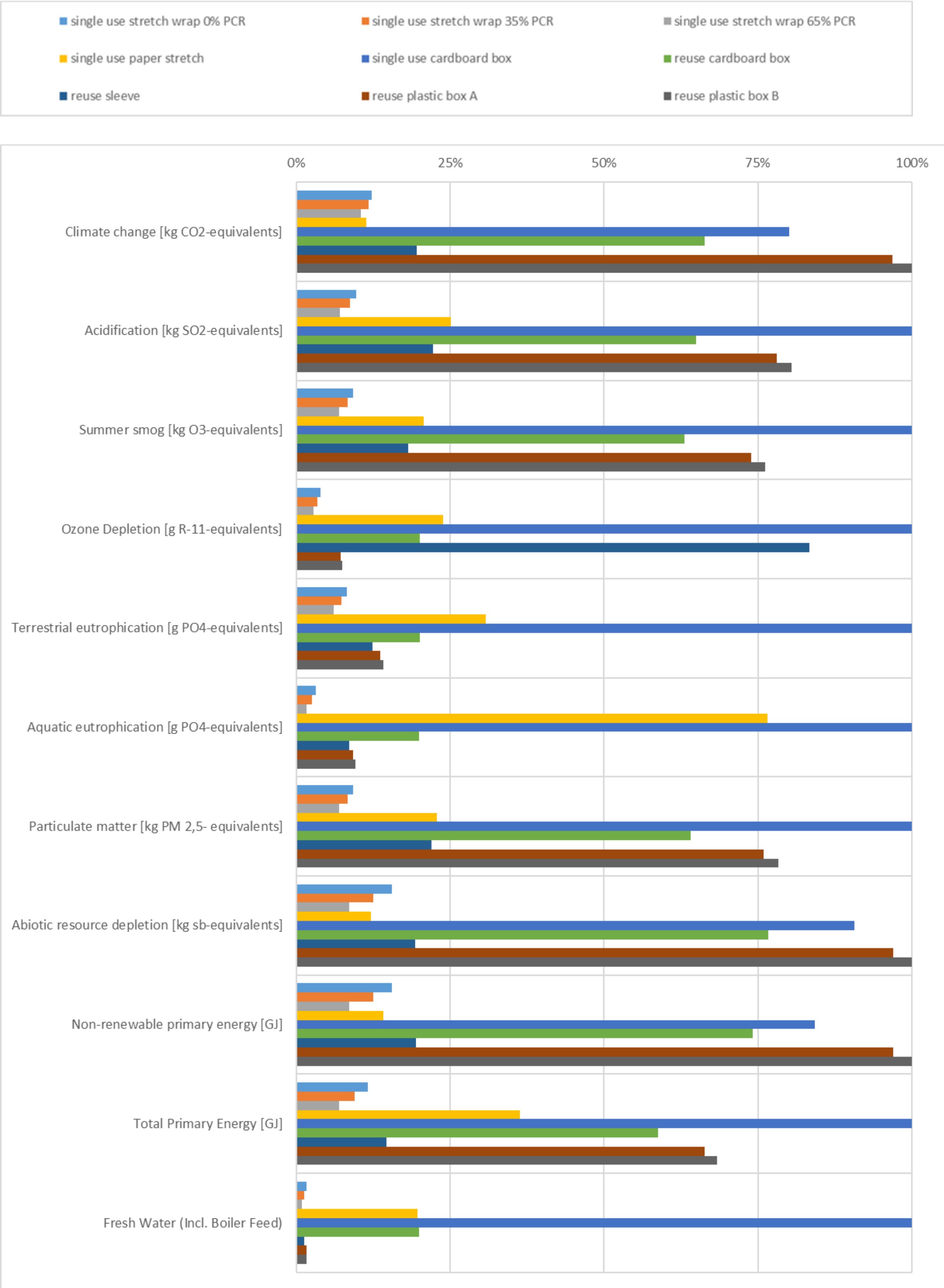


Figure 4-6: relative results of all impact categories and environmental issues evaluated at the inventory level in the application field water and CSD bottles

The following **Figure 4-7** to **Figure 4-9** show the relative contribution of lifecycle steps for the eight selected impact categories in the application field water and CSD bottles.

Figure 4-7: relative contribution of lifecycle steps for the impact categories Climate change, Acidification and Summer smog in the application field water and CSD bottles

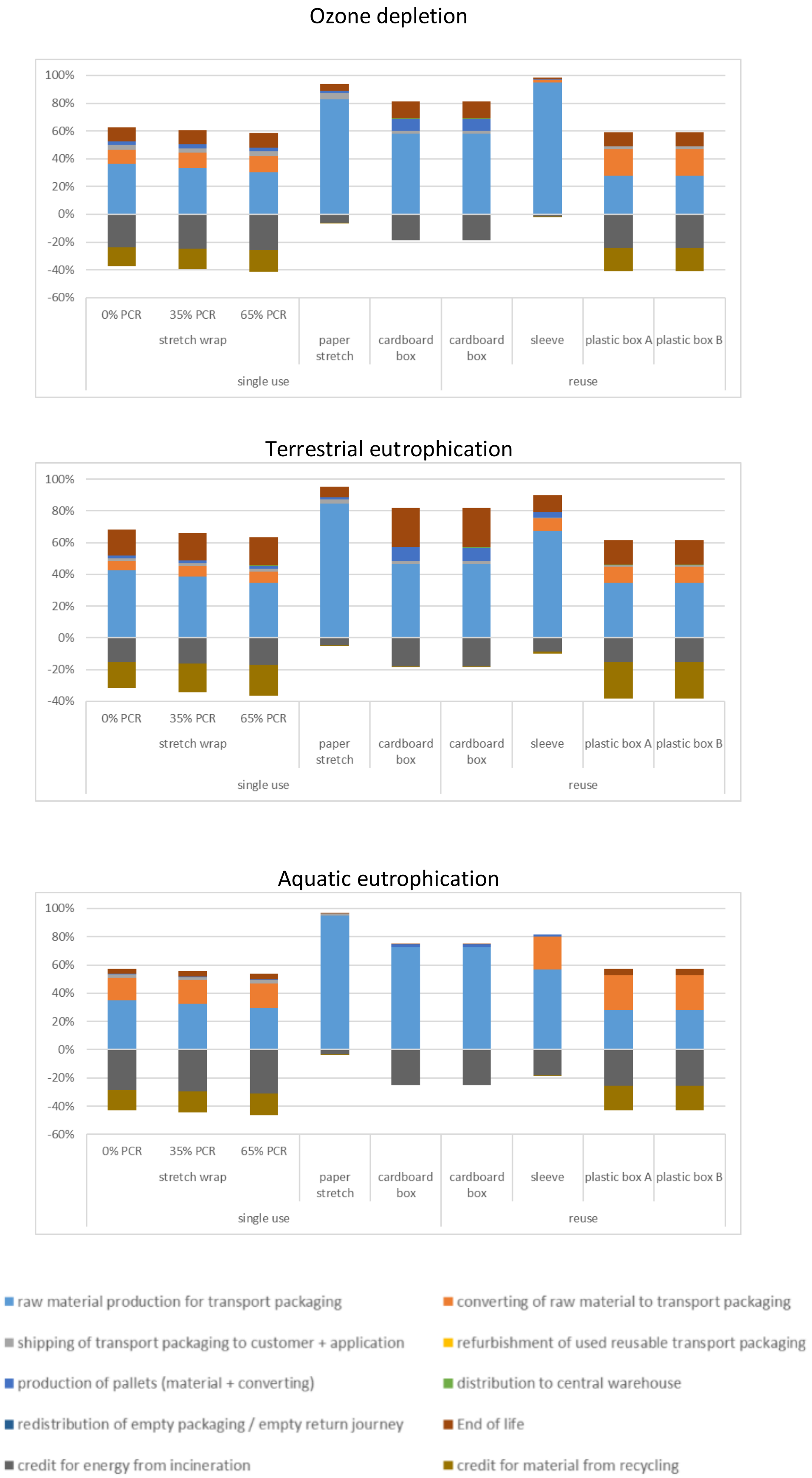


Figure 4-8: relative contribution of lifecycle steps for the impact categories Ozone Depletion Terrestrial and Aquatic eutrophication in the application field water and CSD bottles

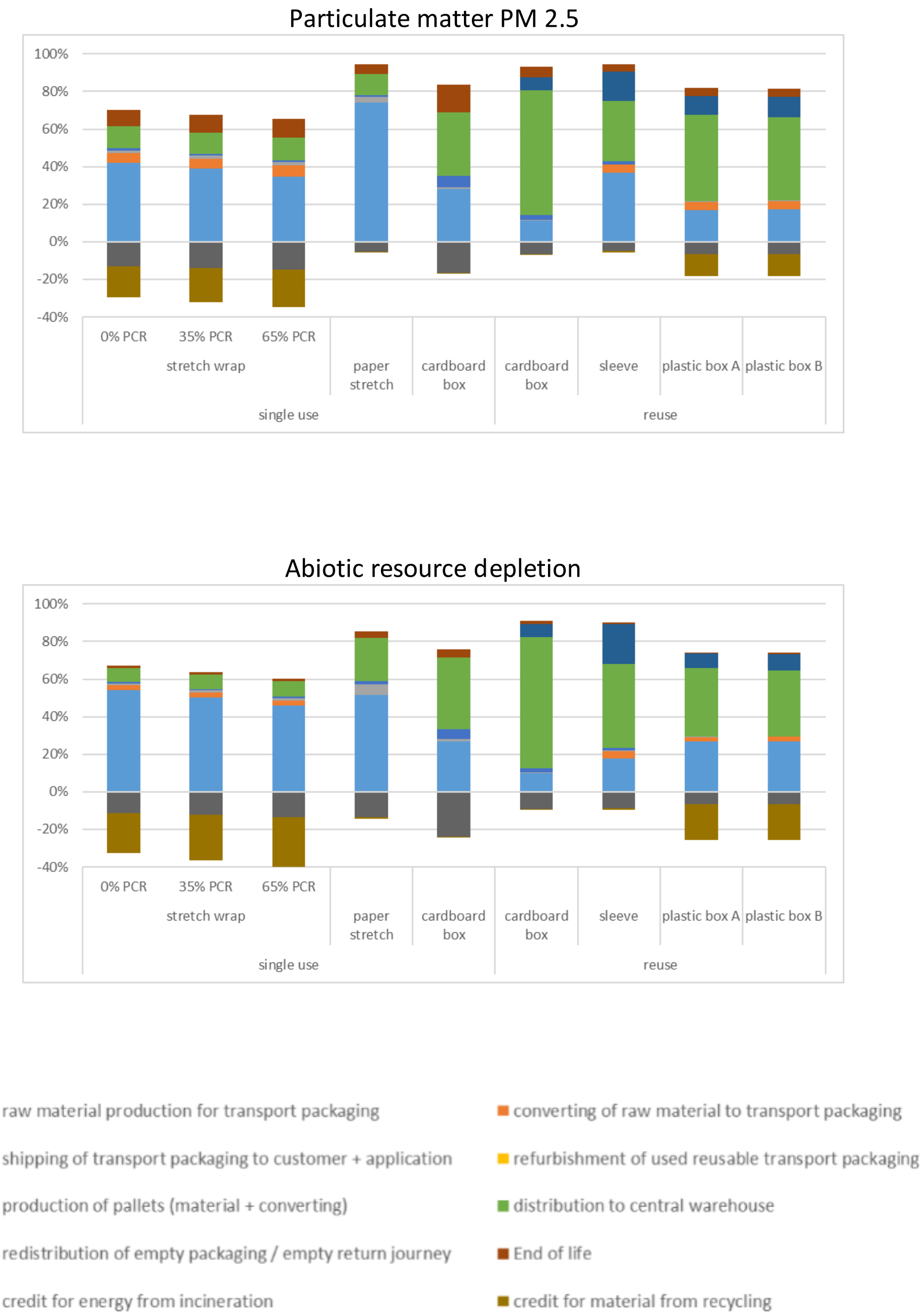


Figure 4-9: relative contribution of lifecycle steps for the impact categories Particulate matter PM 2.5 and Abiotic resource depletion in the application field water and CSD bottles

The following **Figure 4-10** shows the relative contribution of lifecycle steps of the environmental issues evaluated at the inventory level in the application field water and CSD bottles.

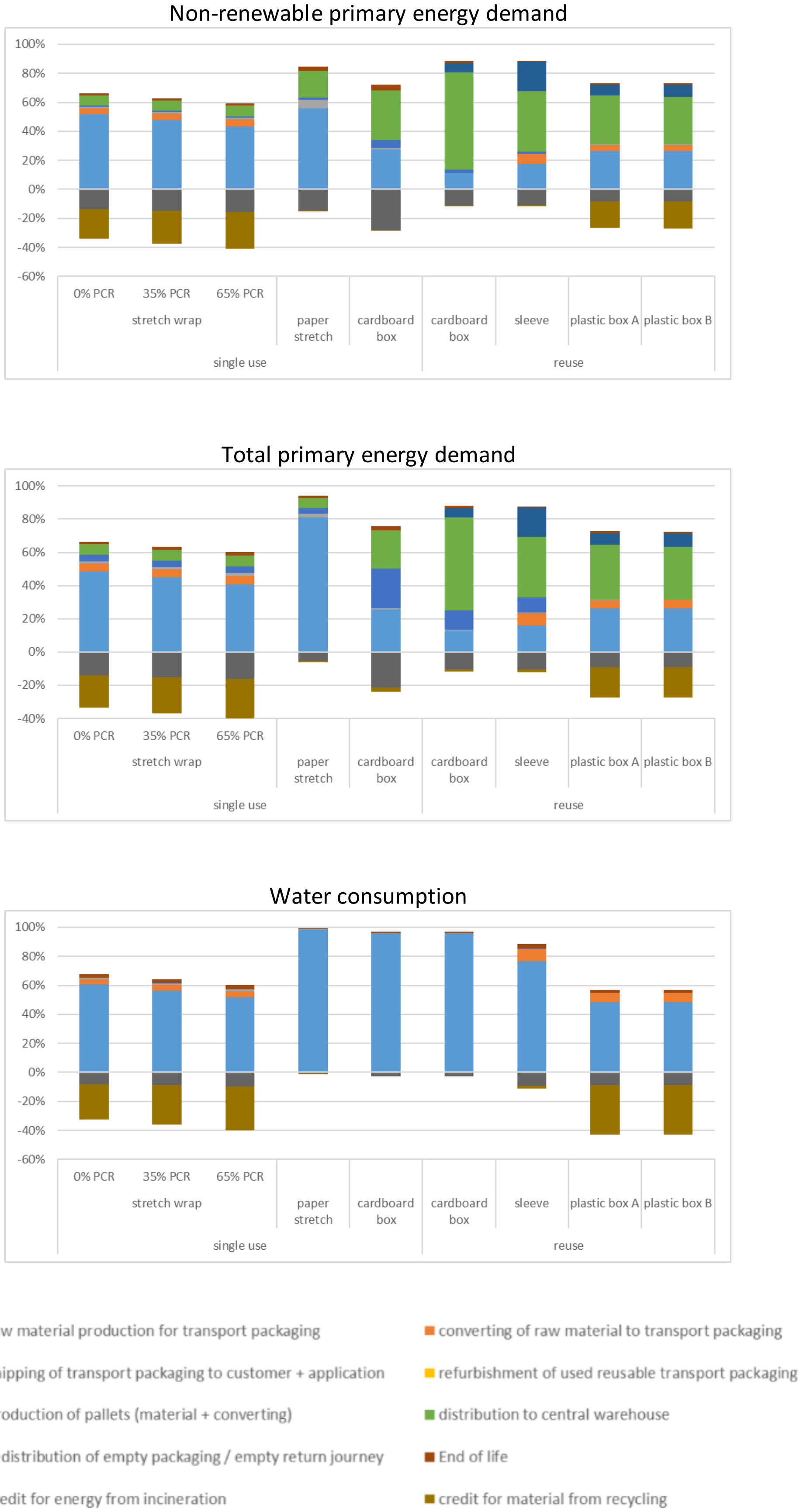


Figure 4-10: relative contribution of lifecycle steps for the categories on inventory level cumulative energy demand Non-renewable and Total and Freshwater consumption in the application field water and CSD bottles

4.3 Results in the application field buckets

The following **Table 4-3** shows the numerical results for the selected impact category and environmental issues evaluated at the inventory level in the application field buckets.

Table 4-3: numerical results of all impact categories and environmental issues evaluated at the inventory level in the application field buckets

impact categories	single use					reuse			
	stretch wrap								
	0% PCR	35% PCR	65% PCR	paper stretch	cardboard box	cardboard box	sleeve	plastic box A	plastic box B
Climate change [kg CO2-equivalents]	6.45E+00	6.34E+00	6.12E+00	6.29E+00	4.83E+01	3.91E+01	1.24E+01	5.96E+01	6.16E+01
Acidification [kg SO2-equivalents]	1.31E-02	1.25E-02	1.18E-02	2.09E-02	1.38E-01	8.63E-02	3.27E-02	1.06E-01	1.09E-01
Summer smog [kg O3-equivalents]	2.23E-01	2.15E-01	2.04E-01	3.21E-01	2.38E+00	1.44E+00	4.47E-01	1.72E+00	1.77E+00
Ozone Depletion [g R-11-equivalents]	5.88E-04	5.34E-04	4.58E-04	3.04E-03	3.61E-02	7.24E-03	3.35E-02	2.58E-03	2.69E-03
Terrestrial eutrophication [g PO4-equivalents]	4.84E-01	4.49E-01	3.98E-01	1.46E+00	1.28E+01	2.57E+00	1.77E+00	1.75E+00	1.82E+00
Aquatic eutrophication [g PO4-equivalents]	7.48E-03	-9.53E-03	-3.17E-02	1.90E+00	7.69E+00	1.54E+00	7.38E-01	7.09E-01	7.38E-01
Particulate matter [kg PM 2,5- equivalents]	1.38E-02	1.33E-02	1.26E-02	2.11E-02	1.48E-01	9.07E-02	3.44E-02	1.10E-01	1.13E-01
Abiotic resource depletion [kg sb-equivalents]	8.21E-03	7.45E-03	6.55E-03	7.42E-03	5.81E-02	4.81E-02	1.27E-02	6.26E-02	6.47E-02
Non-renewable primary energy [GJ]	8.67E-02	7.85E-02	6.86E-02	8.43E-02	5.85E-01	5.07E-01	1.40E-01	6.85E-01	7.08E-01
Total Primary Energy [GJ]	1.03E-01	9.49E-02	8.50E-02	1.99E-01	1.08E+00	6.06E-01	1.59E-01	6.94E-01	7.17E-01
Fresh Water (Incl. Boiler Feed)	3.29E-03	2.61E-03	1.78E-03	3.82E-02	5.87E-01	1.17E-01	8.55E-03	9.48E-03	9.88E-03

The following **Figure 4-11** shows a relative comparison of the net results of all impact categories and environmental issues evaluated at the inventory level in the application field buckets

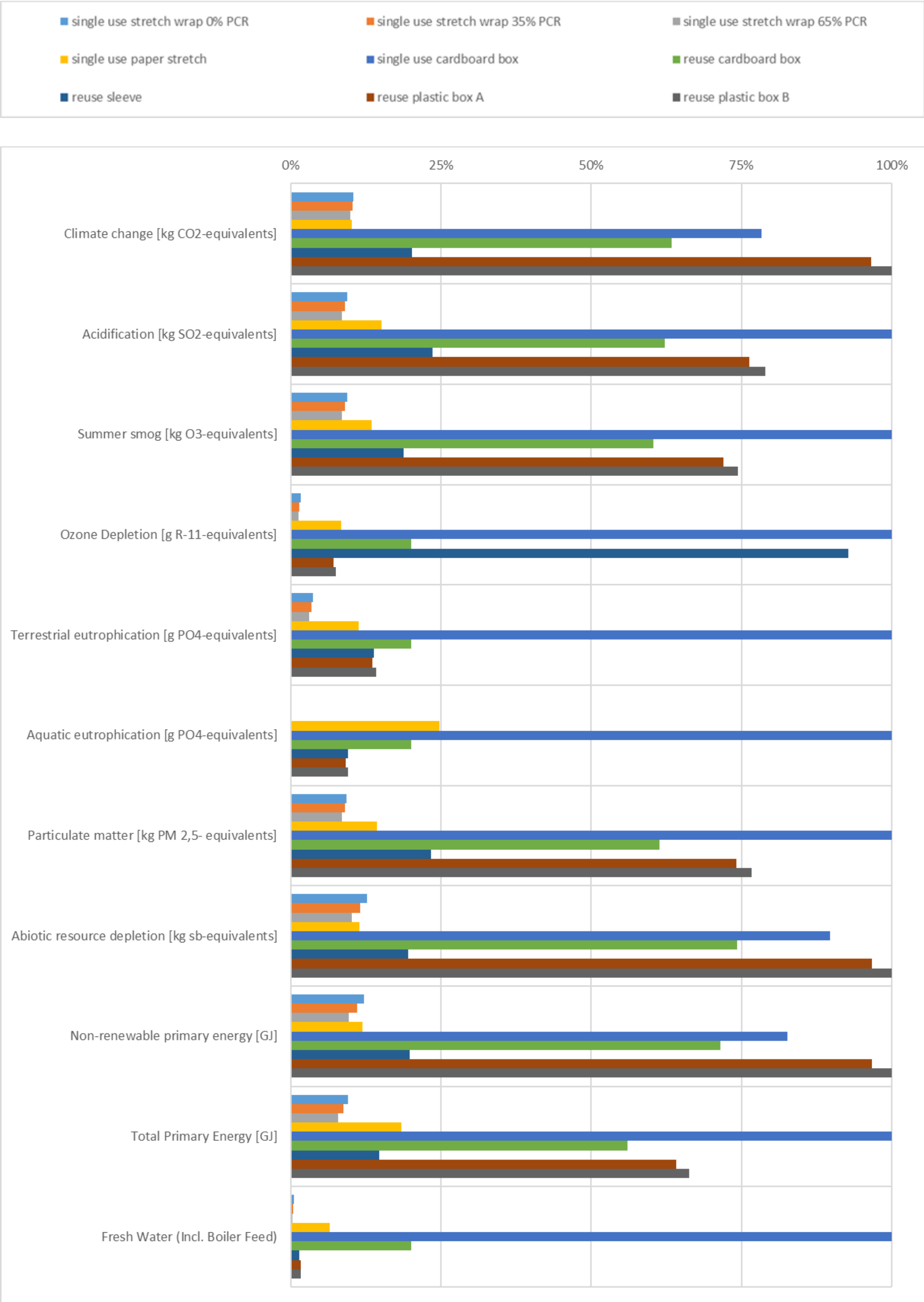


Figure 4-11: relative results of all impact categories and environmental issues evaluated at the inventory level in the application field buckets

The following **Figure 4-12** to **Figure 4-14** show the relative contribution of lifecycle steps for the eight selected impact categories in the application field buckets.

Figure 4-12: relative contribution of lifecycle steps for the impact categories Climate change, Acidification and Summer smog in the application field buckets

Figure 4-13: relative contribution of lifecycle steps for the impact categories Ozone Depletion Terrestrial and Aquatic eutrophication in the application field buckets

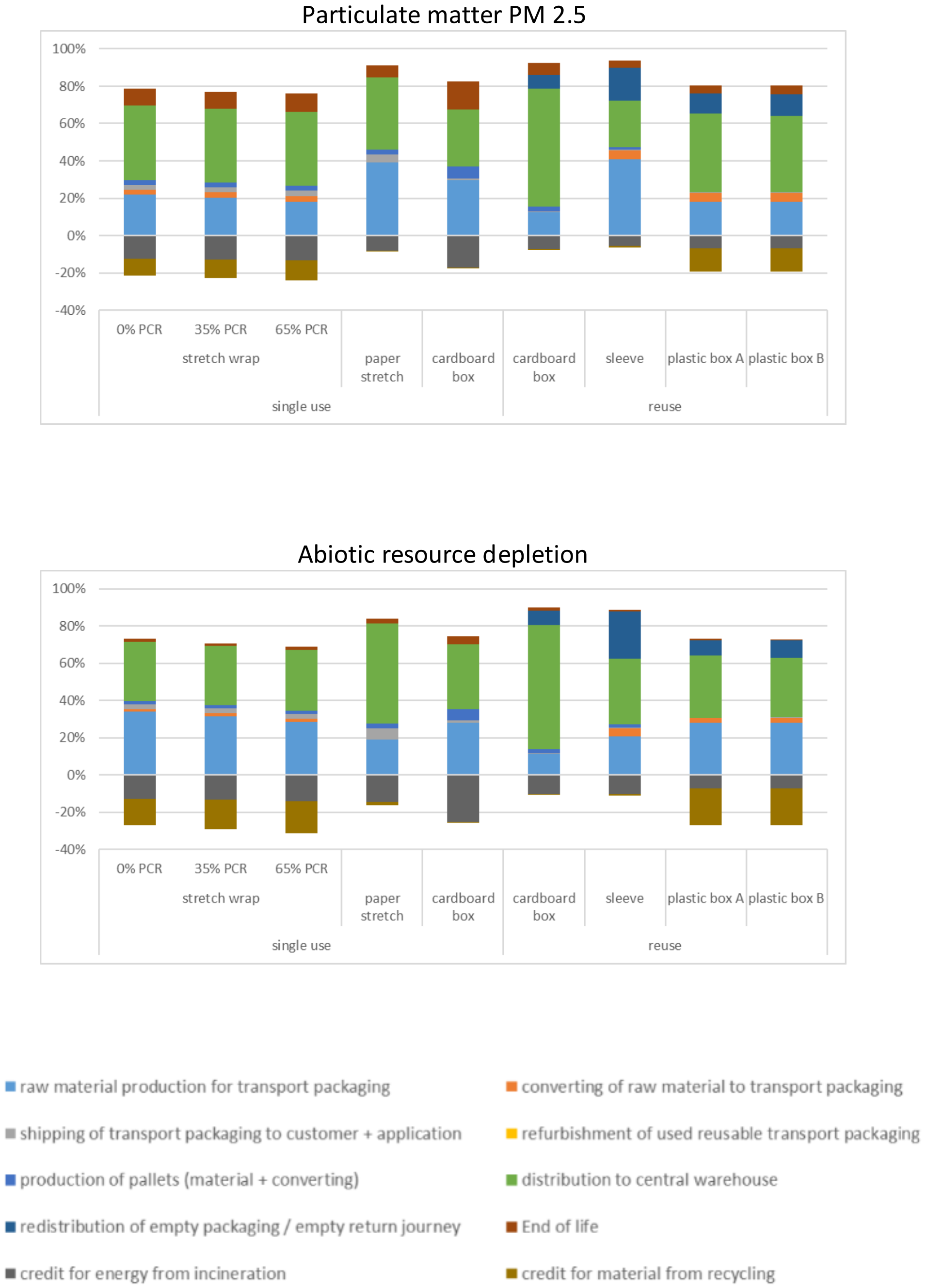
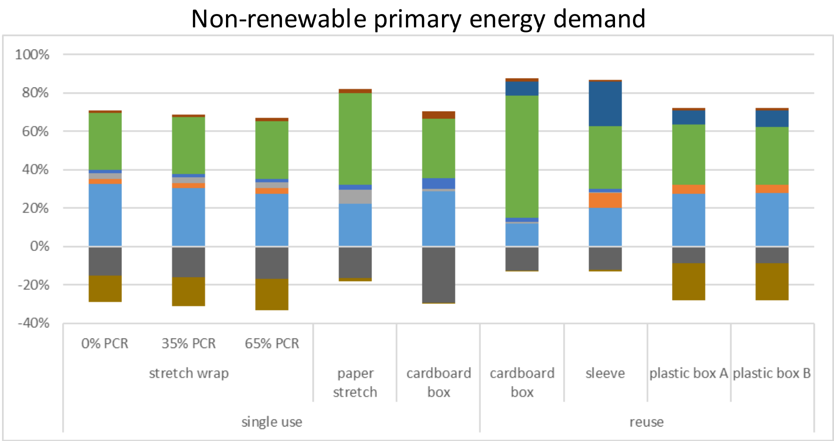
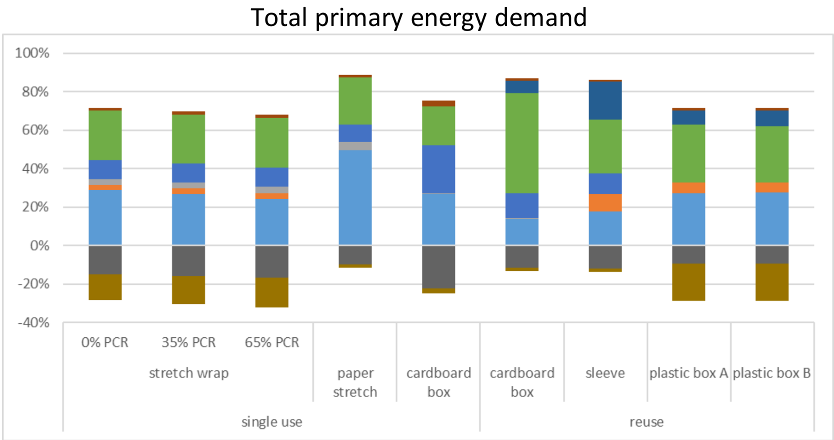


Figure 4-14: relative contribution of lifecycle steps for the impact categories Particulate matter PM 2.5 and Abiotic resource depletion in the application field buckets

The following **Figure 4-15** shows the relative contribution of lifecycle steps of the environmental issues evaluated at the inventory level in the application field buckets.





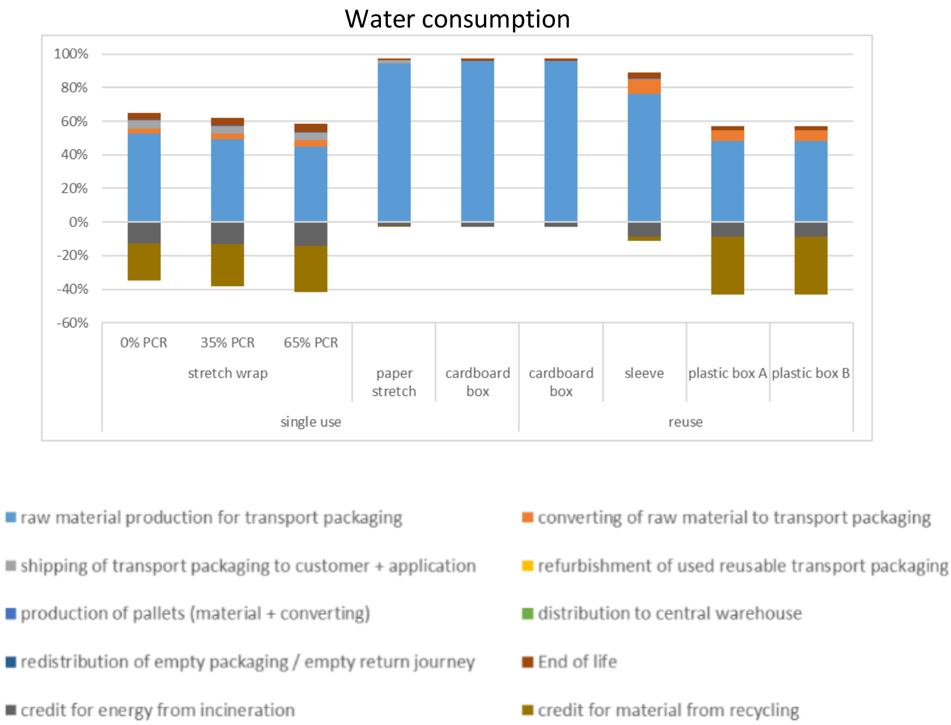


Figure 4-15: relative contribution of lifecycle steps for the categories on inventory level cumulative energy demand Non-renewable and Total and Freshwater consumption in the application field buckets

4.4 Results in the application field cement bags

The following **Table 4-4** shows the numerical results for the selected impact category and environmental issues evaluated at the inventory level in the application field cement bags.

Table 4-4: numerical results of all impact categories and environmental issues evaluated at the inventory level in the application field cement bags

impact categories	single use			reuse		
	stretch hood					
	0% PCR	35% PCR	65% PCR	sleeve	plastic box A	plastic box B
Climate change [kg CO2-equivalents]	1.95E+00	1.96E+00	1.61E+00	5.99E+00	1.53E+01	8.61E+00
Acidification [kg SO2-equivalents]	3.73E-03	3.52E-03	2.86E-03	1.56E-02	2.63E-02	1.41E-02
Summer smog [kg O3-equivalents]	6.64E-02	6.36E-02	5.23E-02	2.15E-01	4.24E-01	2.25E-01
Ozone Depletion [g R-11-equivalents]	1.96E-04	1.76E-04	1.10E-04	1.55E-02	8.95E-04	6.61E-04
Terrestrial eutrophication [g PO4-equivalents]	1.87E-01	1.78E-01	1.23E-01	8.20E-01	5.87E-01	4.36E-01
Aquatic eutrophication [g PO4-equivalents]	1.95E-02	7.77E-03	-1.47E-02	3.41E-01	2.68E-01	1.98E-01
Particulate matter [kg PM 2,5- equivalents]	3.92E-03	3.74E-03	3.10E-03	1.64E-02	2.72E-02	1.44E-02
Abiotic resource depletion [kg sb-equivalents]	2.57E-03	2.28E-03	1.62E-03	6.18E-03	1.53E-02	7.97E-03
Non-renewable primary energy [GJ]	2.74E-02	2.41E-02	1.67E-02	6.79E-02	1.70E-01	8.94E-02
Total Primary Energy [GJ]	3.20E-02	2.86E-02	2.11E-02	7.70E-02	1.73E-01	9.17E-02
Fresh Water (Incl. Boiler Feed)	1.66E-03	1.40E-03	6.80E-04	3.95E-03	4.37E-03	3.22E-03

The following **Figure 4-16** shows a relative comparison of the net results of all impact categories and environmental issues evaluated at the inventory level in the application field cement bags.

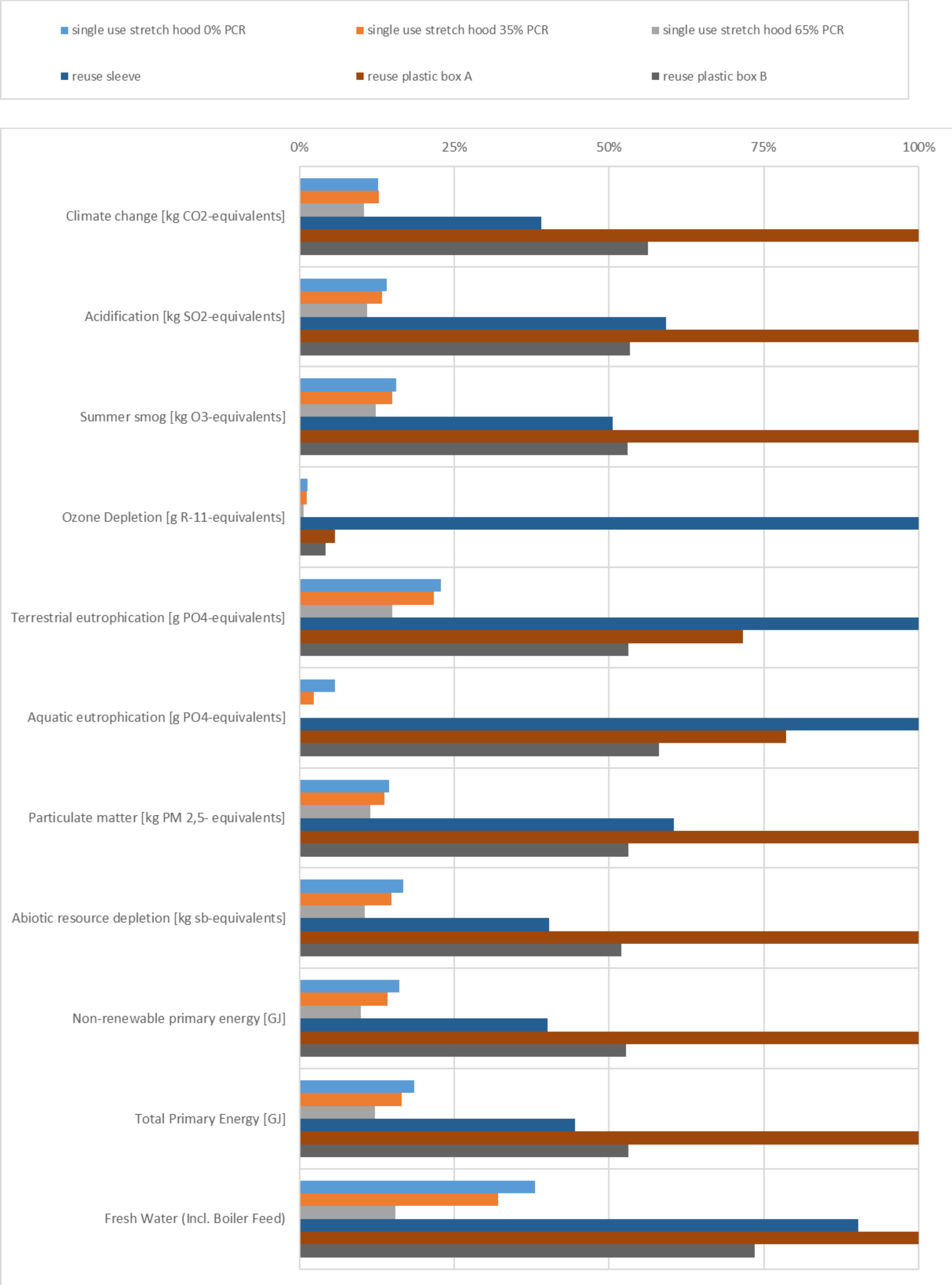


Figure 4-16: relative results of all impact categories and environmental issues evaluated at the inventory level in the application field cement bags

The following **Figure 4-17** to **Figure 4-19** show the relative contribution of lifecycle steps for the eight selected impact categories in the application field cement bags.

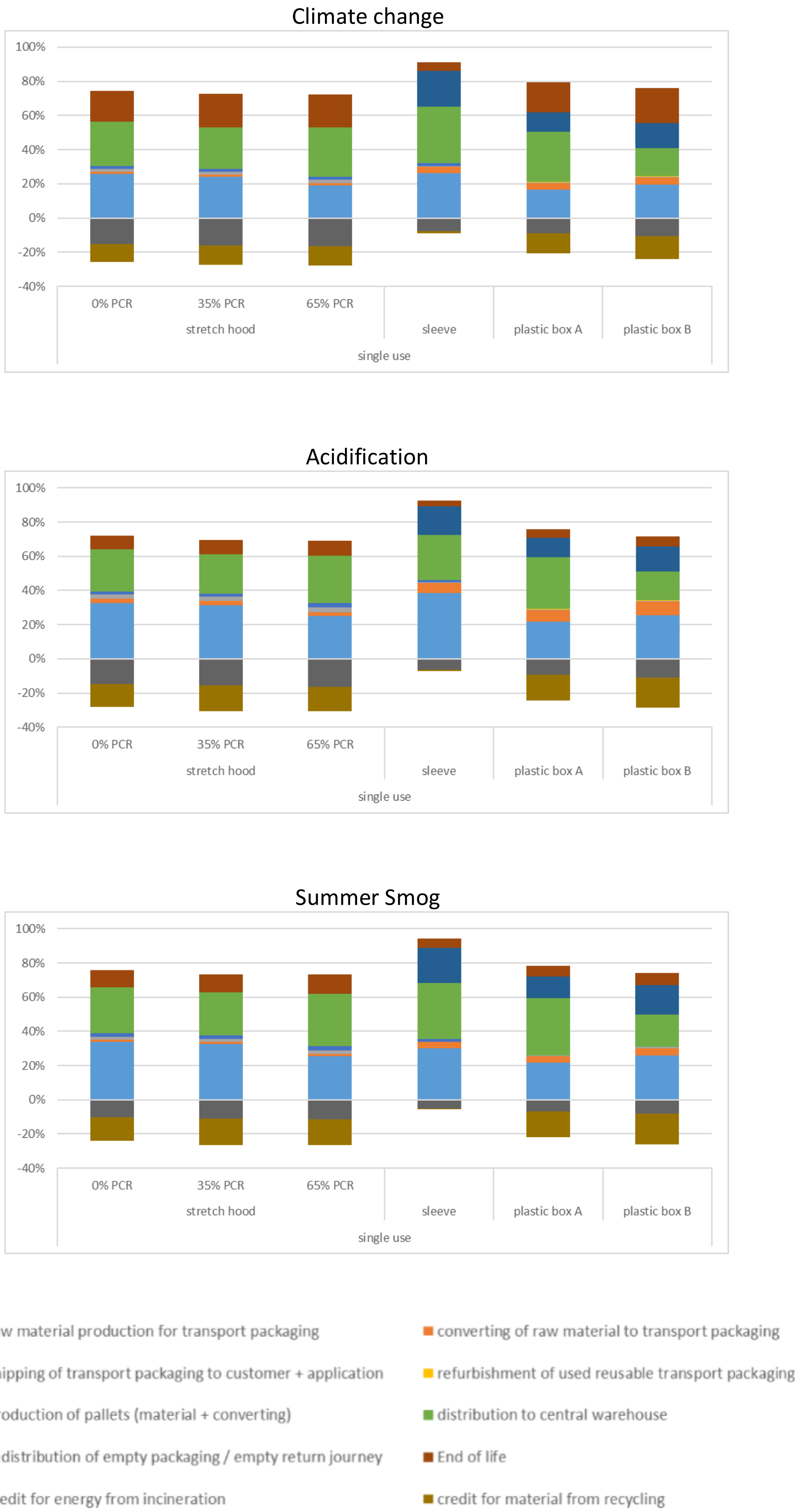


Figure 4-17: relative contribution of lifecycle steps for the impact categories Climate change, Acidification and Summer smog in the application field cement bags

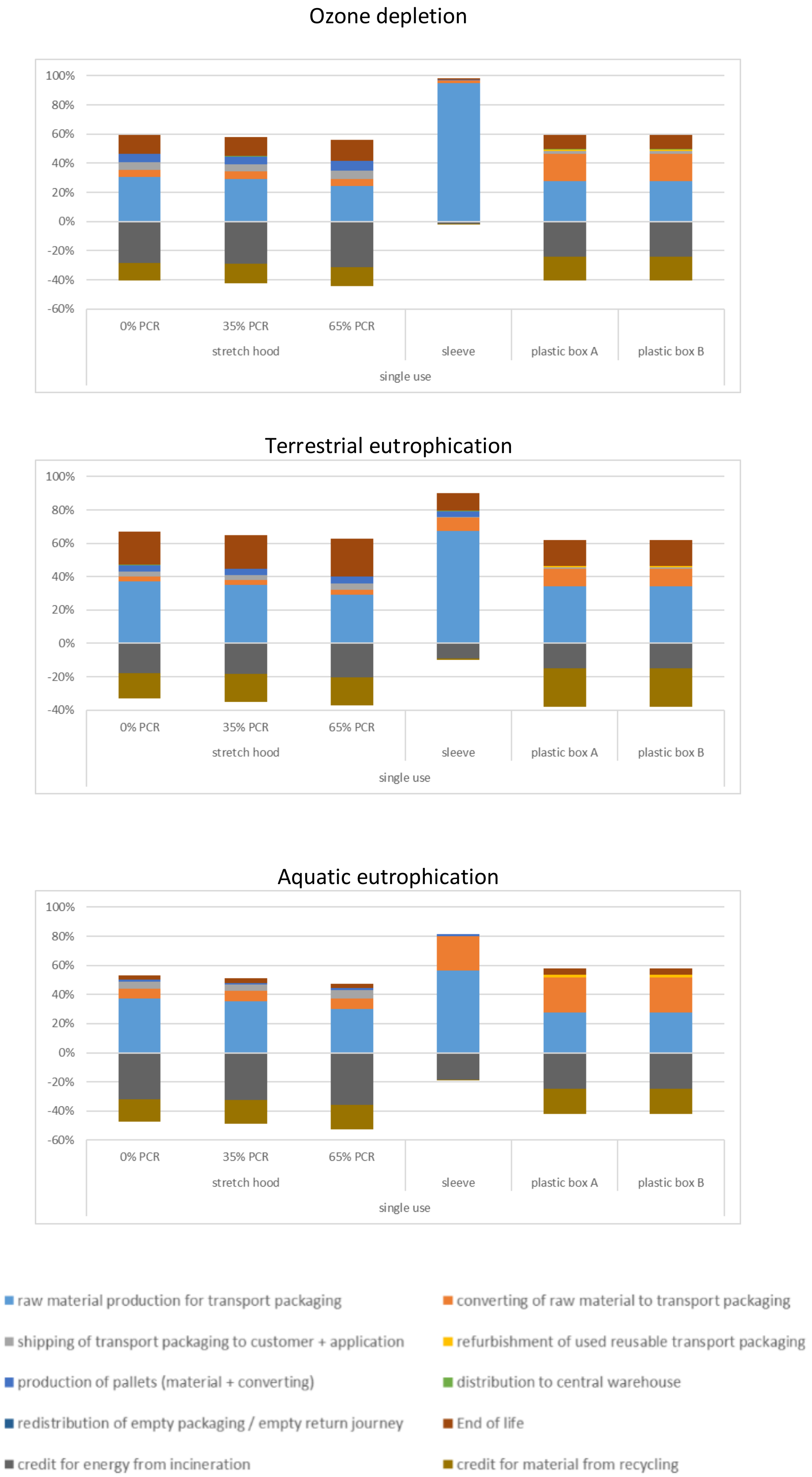


Figure 4-18: relative contribution of lifecycle steps for the impact categories Ozone Depletion Terrestrial and Aquatic eutrophication in the application field cement bags

Figure 4-19: relative contribution of lifecycle steps for the impact categories Particulate matter PM 2.5 and Abiotic resource depletion in the application field cement bags

The following **Figure 4-20** shows the relative contribution of lifecycle steps of the environmental issues evaluated at the inventory level in the application field cement bags.

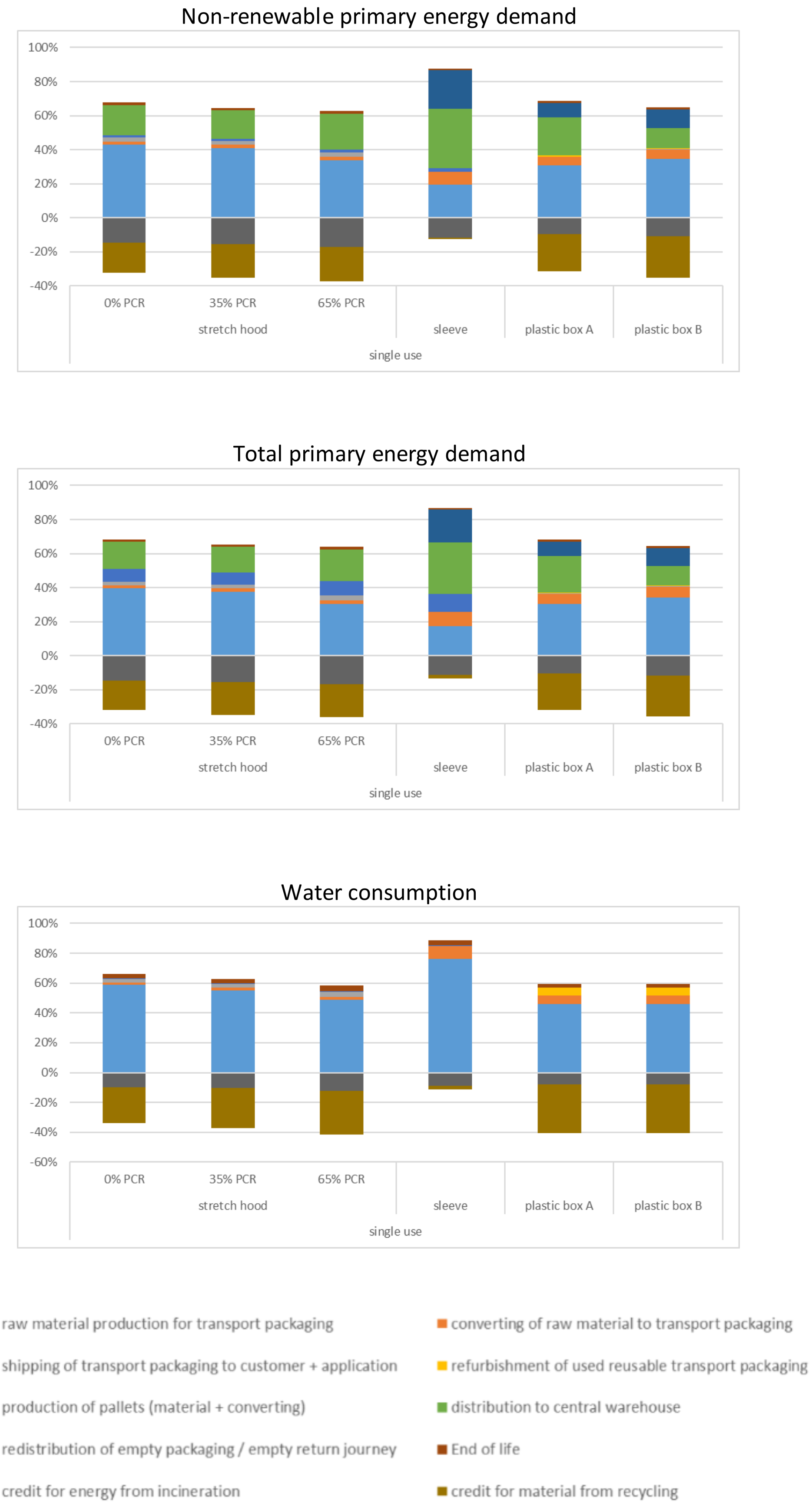


Figure 4-20: relative contribution of lifecycle steps for the categories on inventory level cumulative energy demand Non-renewable and Total and Freshwater consumption in the application field cement bags

4.5 Results in the application field polymer bags

The following **Table 4-5** shows the numerical results for the selected impact category and environmental issues evaluated at the inventory level in the application field polymer bags.

Table 4-5: numerical results of all impact categories and environmental issues evaluated at the inventory level in the application field polymer bags

impact categories	single use			reuse		
	stretch hood					
	0% PCR	35% PCR	65% PCR	sleeve	plastic box A	plastic box B
Climate change [kg CO2-equivalents]	2.77E+00	2.43E+00	2.36E+00	5.73E+00	3.51E+01	3.62E+01
Acidification [kg SO2-equivalents]	4.93E-03	4.03E-03	3.49E-03	1.51E-02	6.29E-02	6.49E-02
Summer smog [kg O3-equivalents]	8.82E-02	7.37E-02	6.56E-02	2.06E-01	1.02E+00	1.05E+00
Ozone Depletion [g R-11-equivalents]	3.57E-04	2.68E-04	2.16E-04	1.55E-02	1.41E-03	1.47E-03
Terrestrial eutrophication [g PO4-equivalents]	3.34E-01	2.69E-01	2.38E-01	8.20E-01	9.51E-01	9.90E-01
Aquatic eutrophication [g PO4-equivalents]	6.61E-02	2.99E-02	3.30E-03	3.41E-01	3.85E-01	4.01E-01
Particulate matter [kg PM 2,5- equivalents]	5.10E-03	4.25E-03	3.77E-03	1.59E-02	6.52E-02	6.72E-02
Abiotic resource depletion [kg sb-equivalents]	3.78E-03	2.78E-03	2.09E-03	5.85E-03	3.74E-02	3.86E-02
Non-renewable primary energy [GJ]	4.09E-02	2.97E-02	2.19E-02	6.45E-02	4.08E-01	4.21E-01
Total Primary Energy [GJ]	4.60E-02	3.45E-02	2.65E-02	7.35E-02	4.13E-01	4.26E-01
Fresh Water (Incl. Boiler Feed)	3.36E-03	2.34E-03	1.69E-03	3.95E-03	5.15E-03	5.37E-03

The following **Figure 4-21** shows a relative comparison of the net results of all impact categories and environmental issues evaluated at the inventory level in the application field polymer bags.

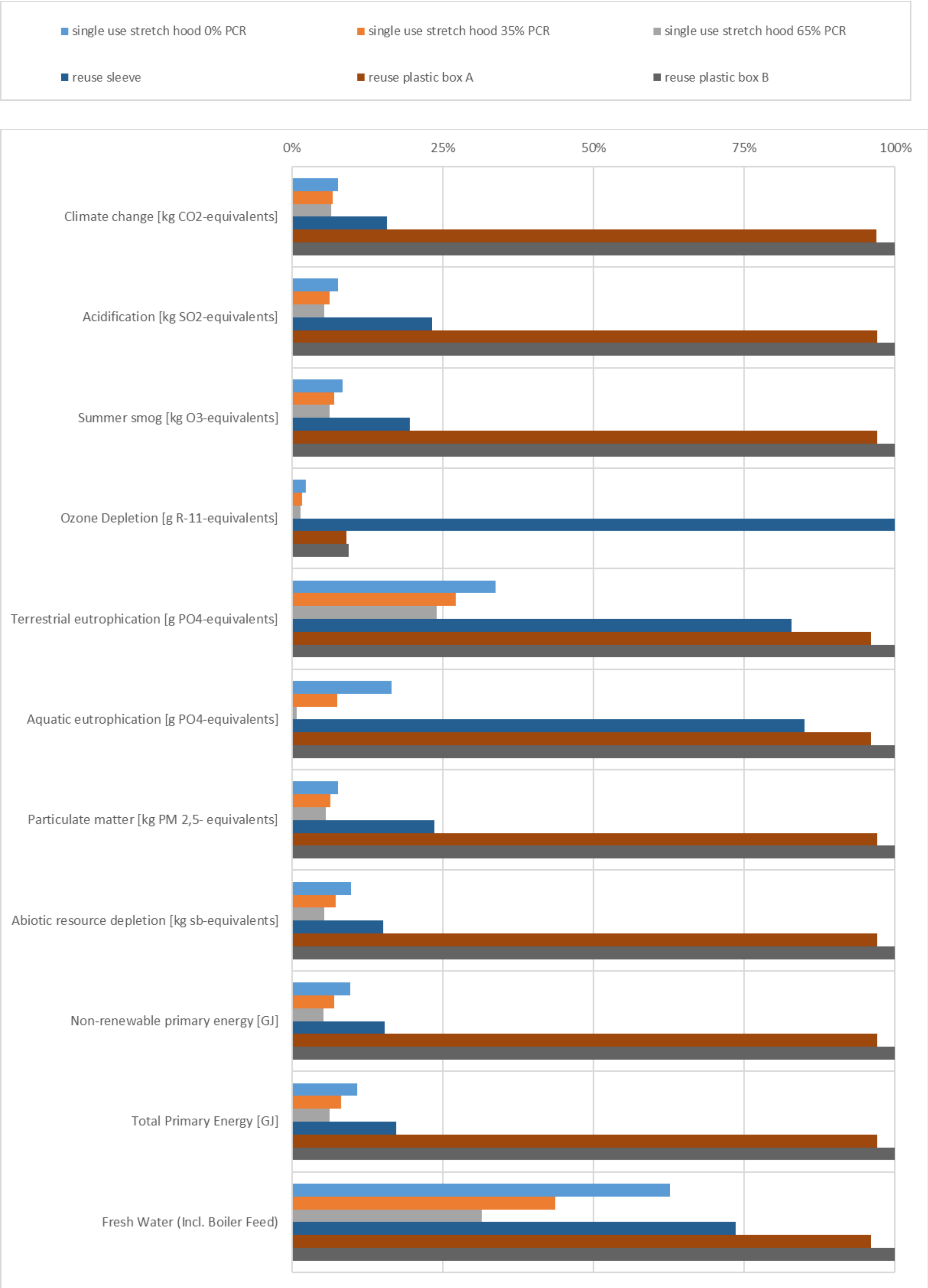


Figure 4-21: relative results of all impact categories and environmental issues evaluated at the inventory level in the application field polymer bags

The following **Figure 4-22** to **Figure 4-24**show the relative contribution of lifecycle steps for the eight selected impact categories in the application field polymer bags.

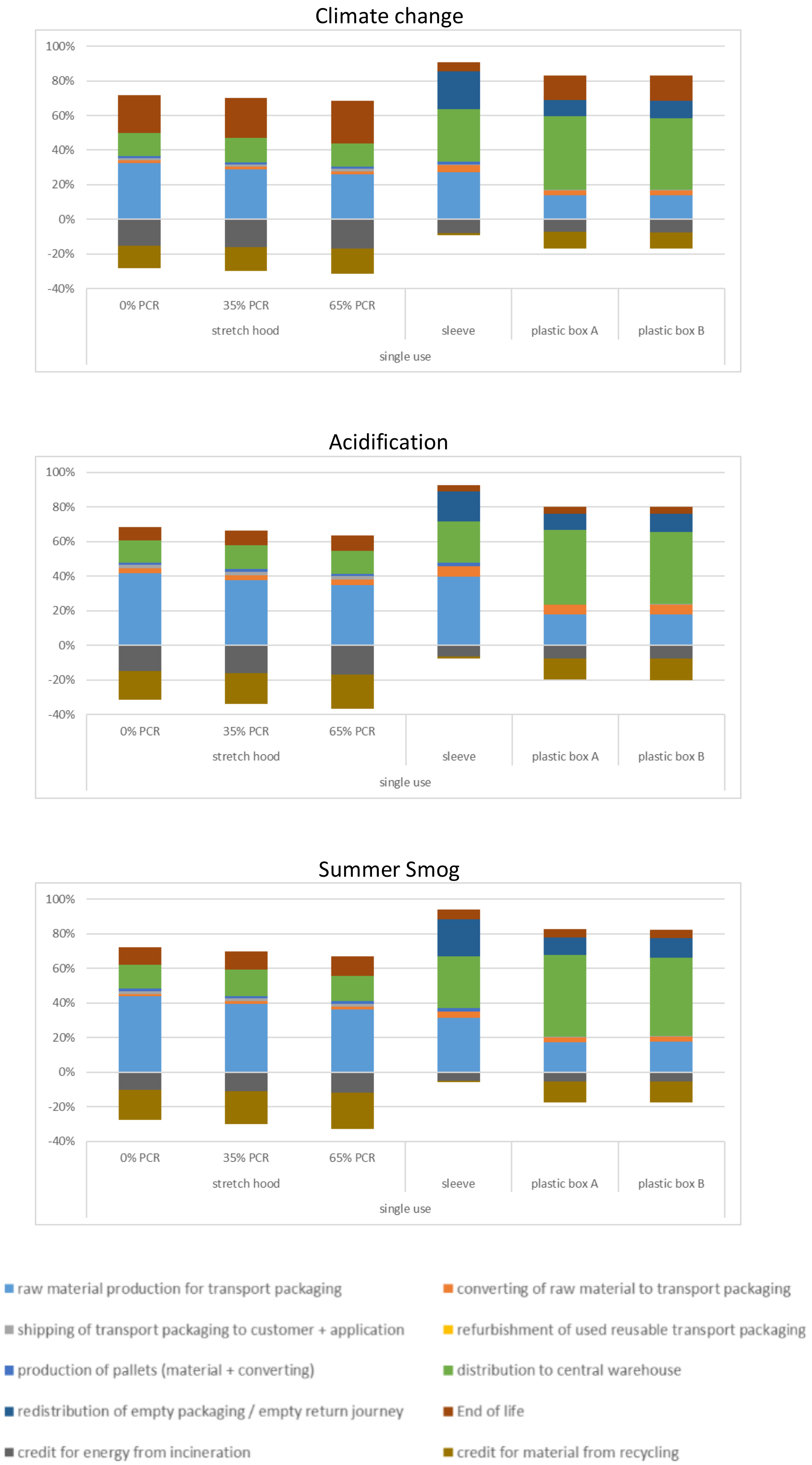


Figure 4-22: relative contribution of lifecycle steps for the impact categories Climate change, Acidification and Summer smog in the application field polymer bags

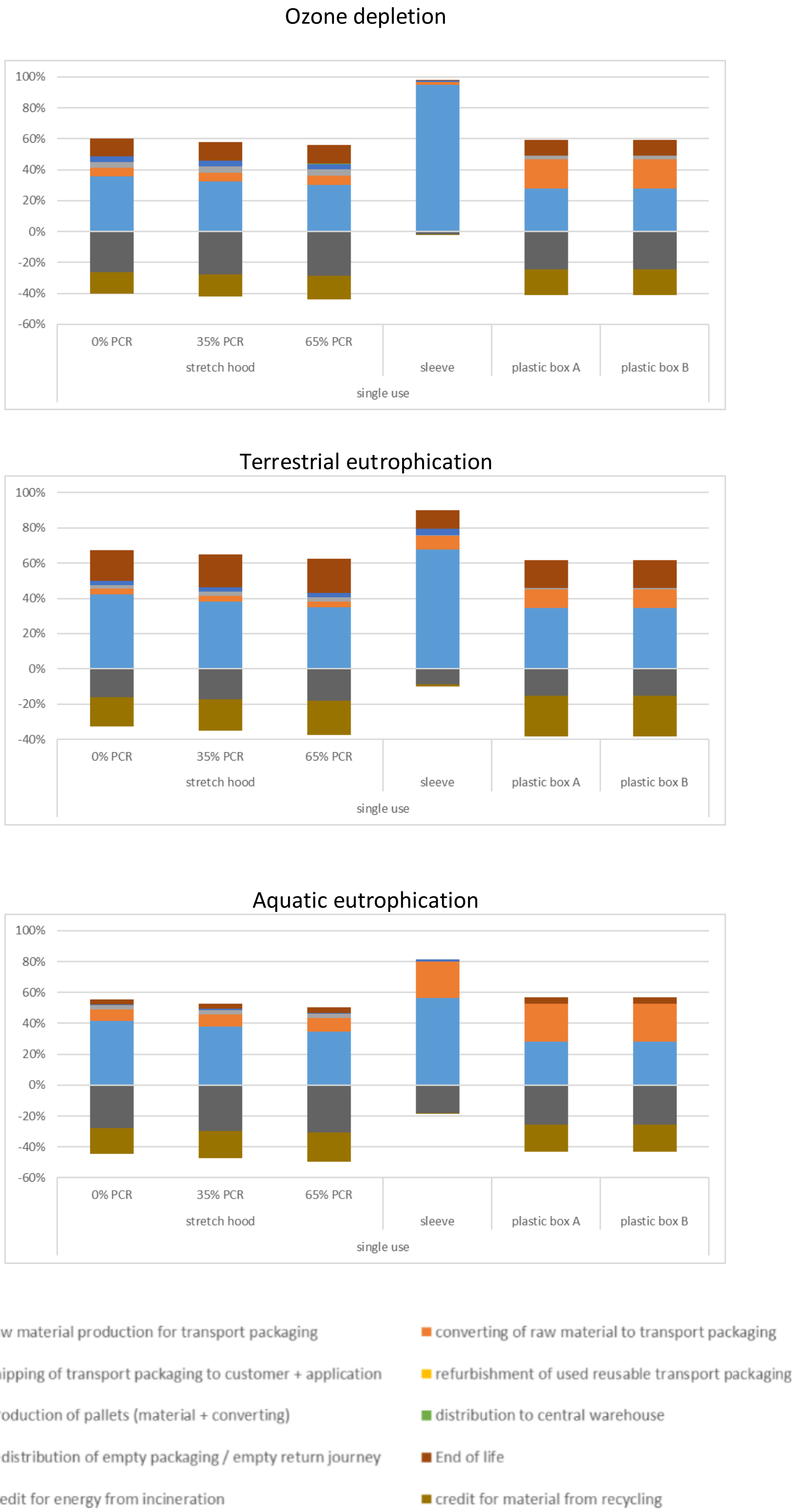


Figure 4-23: relative contribution of lifecycle steps for the impact categories Ozone Depletion Terrestrial and Aquatic eutrophication in the application field polymer bags

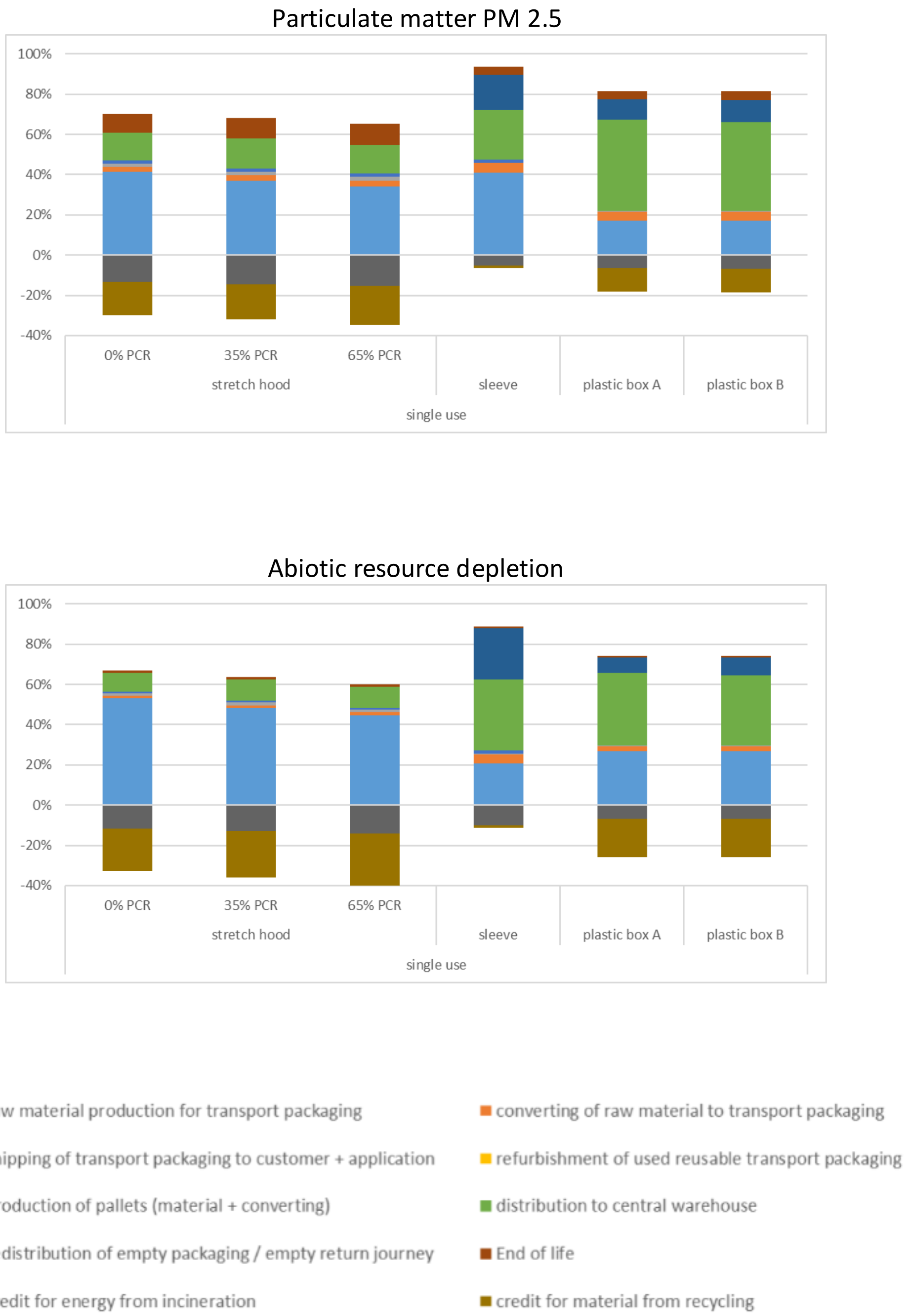


Figure 4-24: relative contribution of lifecycle steps for the impact categories Particulate matter PM 2.5 and Abiotic resource depletion in the application field polymer bags

The following **Figure 4-25** shows the relative contribution of lifecycle steps of the environmental issues evaluated at the inventory level in the application field polymer bags.

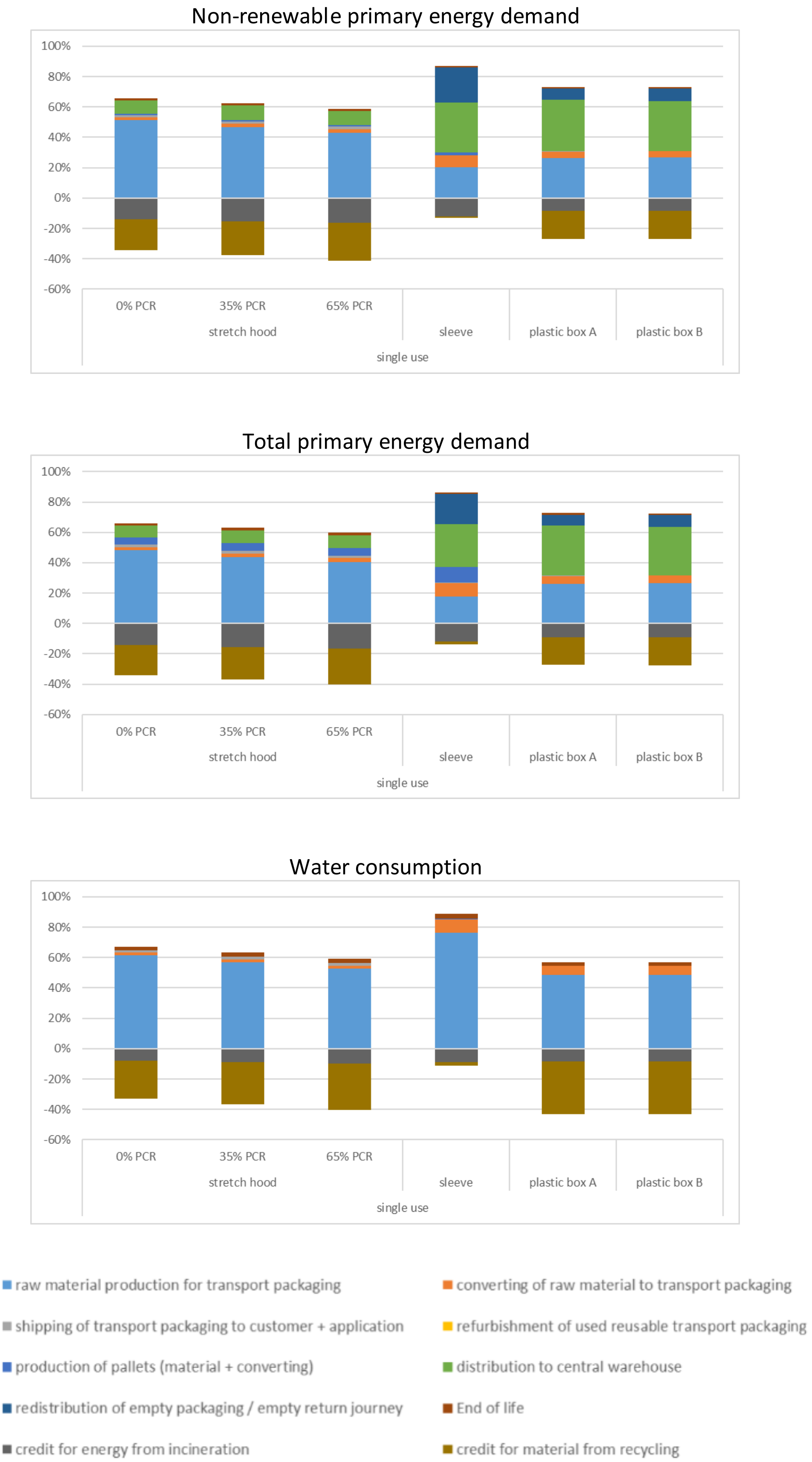


Figure 4-25: relative contribution of lifecycle steps for the categories on inventory level cumulative energy demand Non-renewable and Total and Freshwater consumption in the application field polymer bags

4.6 Results in the application field glass bottles

The following **Table 4-6** shows the numerical results for the selected impact category and environmental issues evaluated at the inventory level in the application field glass bottles.

Table 4-6: numerical results of all impact categories and environmental issues evaluated at the inventory level in the application field glass bottles

impact categories	single use			reuse	
	shrink hood				
	0% PCR	35% PCR	65% PCR	plastic box A	plastic box B
Climate change [kg CO2-equivalents]	7.03E+00	6.18E+00	5.44E+00	8.75E+01	1.02E+02
Acidification [kg SO2-equivalents]	1.14E-02	9.09E-03	7.15E-03	1.60E-01	1.88E-01
Summer smog [kg O3-equivalents]	2.02E-01	1.65E-01	1.33E-01	2.60E+00	3.05E+00
Ozone Depletion [g R-11-equivalents]	1.06E-03	8.38E-04	6.44E-04	3.06E-03	3.56E-03
Terrestrial eutrophication [g PO4-equivalents]	8.83E-01	7.16E-01	5.73E-01	1.99E+00	2.33E+00
Aquatic eutrophication [g PO4-equivalents]	2.43E-01	1.51E-01	7.24E-02	9.04E-01	1.05E+00
Particulate matter [kg PM 2,5- equivalents]	1.16E-02	9.47E-03	7.62E-03	1.66E-01	1.95E-01
Abiotic resource depletion [kg sb-equivalents]	9.88E-03	7.34E-03	5.16E-03	9.62E-02	1.13E-01
Non-renewable primary energy [GJ]	1.08E-01	8.00E-02	5.56E-02	1.05E+00	1.23E+00
Total Primary Energy [GJ]	1.17E-01	8.74E-02	6.25E-02	1.06E+00	1.24E+00
Fresh Water (Incl. Boiler Feed)	9.04E-03	6.44E-03	4.21E-03	1.48E-02	1.71E-02

The following **Figure 4-26** shows a relative comparison of the net results of all impact categories and environmental issues evaluated at the inventory level in the application field glass bottles.

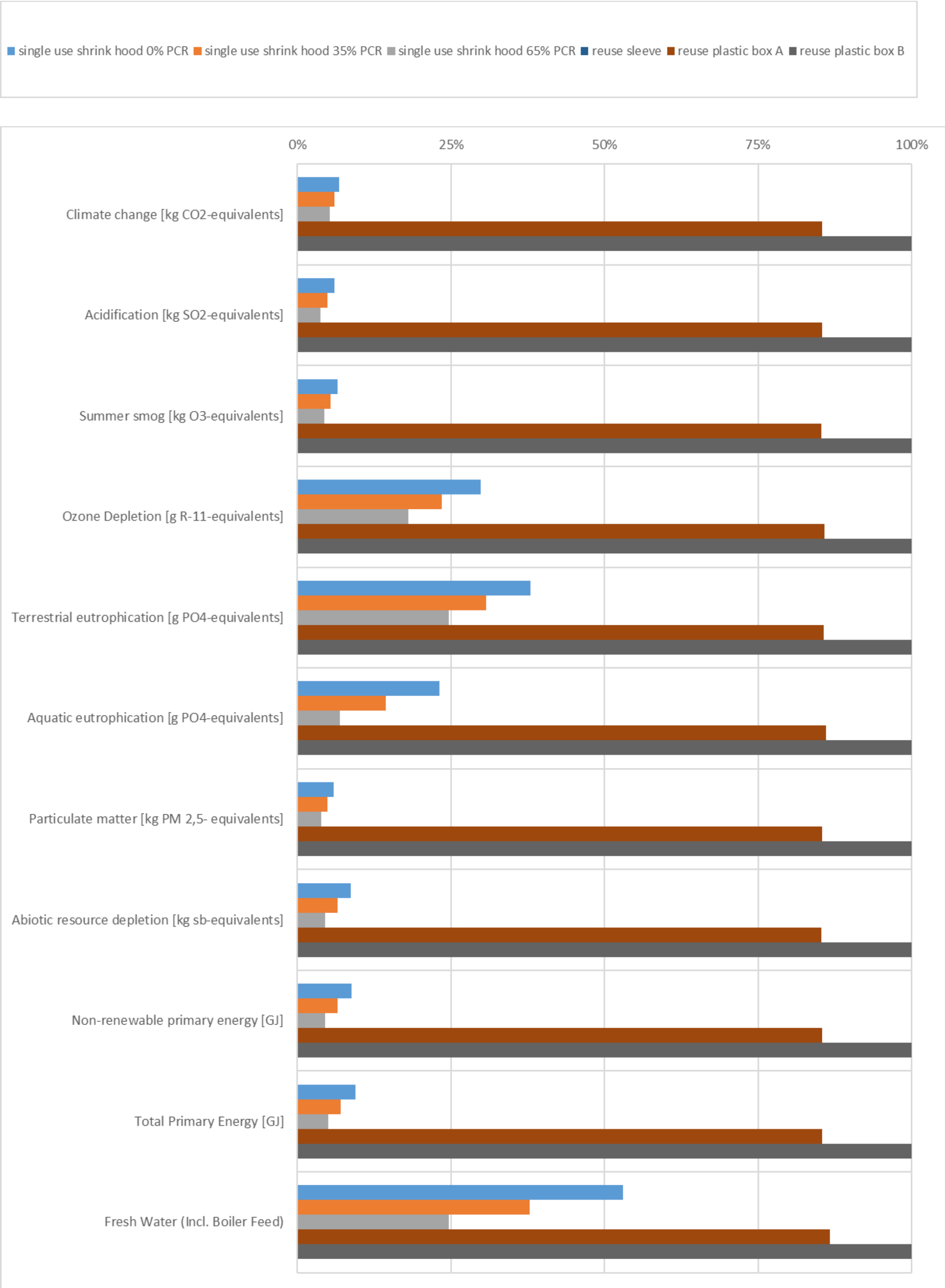


Figure 4-26: relative results of all impact categories and environmental issues evaluated at the inventory level in the application field glass bottles

The following **Figure 4-27** to **Figure 4-29** show the relative contribution of lifecycle steps for the eight selected impact categories in the application field glass bottles.

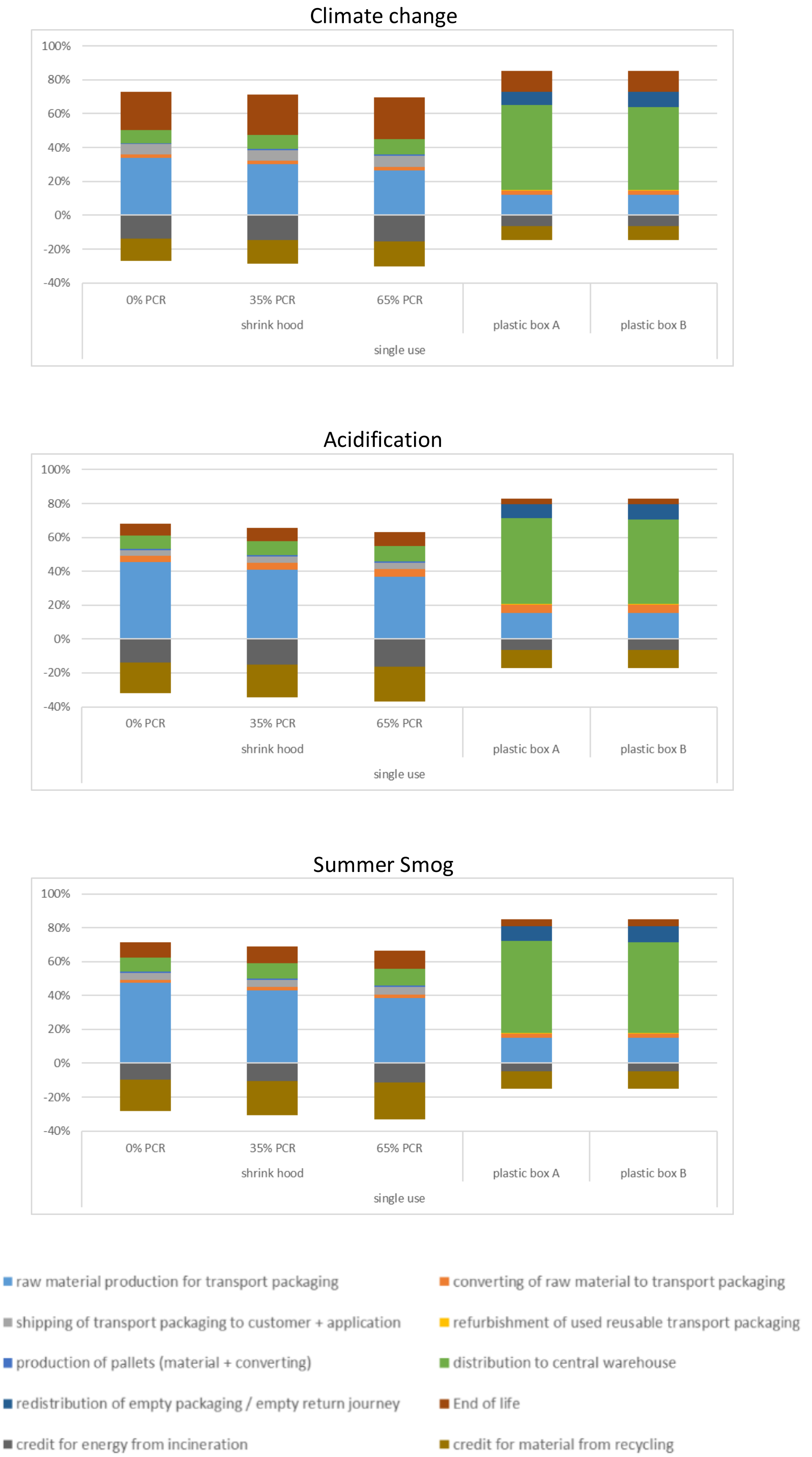


Figure 4-27: relative contribution of lifecycle steps for the impact categories Climate change, Acidification and Summer smog in the application field glass bottles

Figure 4-28: relative contribution of lifecycle steps for the impact categories Ozone Depletion Terrestrial and Aquatic eutrophication in the application field glass bottles

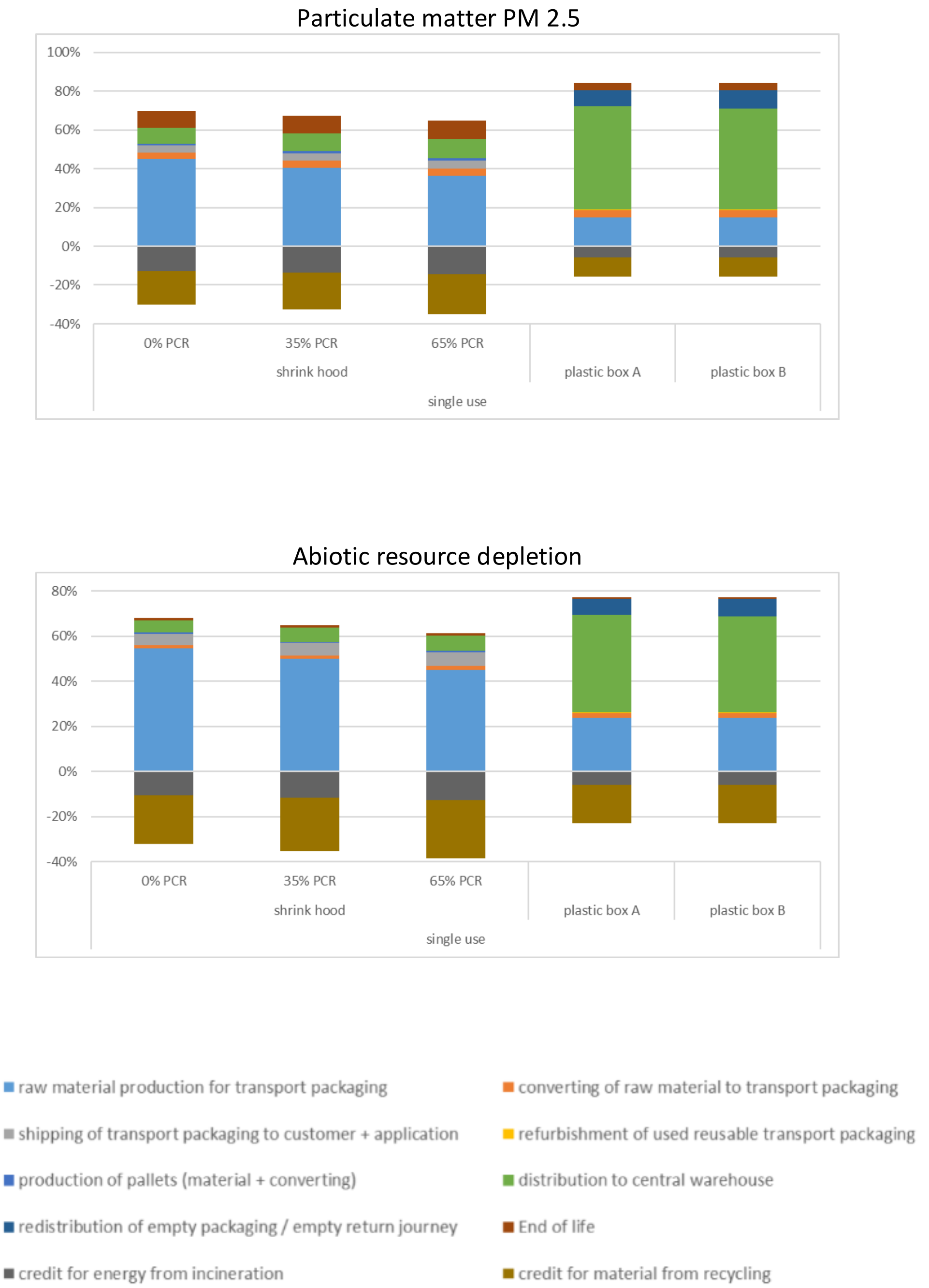


Figure 4-29: relative contribution of lifecycle steps for the impact categories Particulate matter PM 2.5 and Abiotic resource depletion in the application field glass bottles

The following **Figure 4-30** shows the relative contribution of lifecycle steps of the environmental issues evaluated at the inventory level in the application field glass bottles

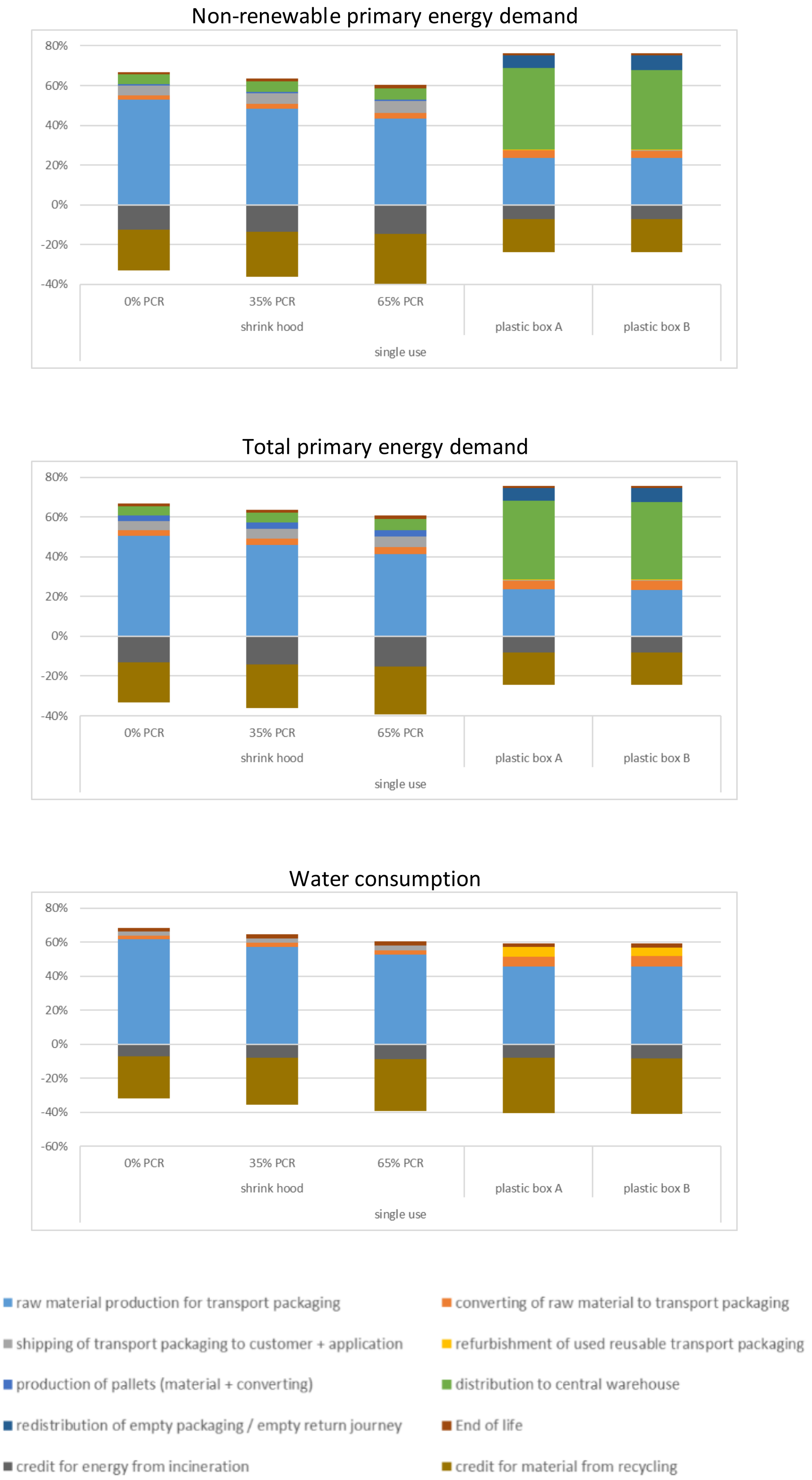


Figure 4-30: relative contribution of lifecycle steps for the categories on inventory level cumulative energy demand Non-renewable and Total and Freshwater consumption in the application field glass bottles

4.7 Results in the application field milk bottles

The following **Table 4-7** shows the numerical results for the selected impact category and environmental issues evaluated at the inventory level in the application field milk bottles.

Table 4-7: numerical results of all impact categories and environmental issues evaluated at the inventory level in the application field milk bottles

impact categories	single use			reuse		
	shrink hood					
	0% PCR	35% PCR	65% PCR	sleeve	plastic box A	plastic box B
Climate change [kg CO2-equivalents]	4.58E+00	4.10E+00	3.69E+00	5.80E+00	2.19E+01	2.26E+01
Acidification [kg SO2-equivalents]	7.47E-03	6.20E-03	5.12E-03	1.53E-02	3.84E-02	3.96E-02
Summer smog [kg O3-equivalents]	1.34E-01	1.13E-01	9.52E-02	2.09E-01	6.22E-01	6.43E-01
Ozone Depletion [g R-11-equivalents]	6.67E-04	5.41E-04	4.33E-04	1.56E-02	1.03E-03	1.08E-03
Terrestrial eutrophication [g PO4-equivalents]	5.42E-01	4.49E-01	3.69E-01	8.26E-01	7.00E-01	7.29E-01
Aquatic eutrophication [g PO4-equivalents]	1.26E-01	7.51E-02	3.11E-02	3.43E-01	2.84E-01	2.96E-01
Particulate matter [kg PM 2,5- equivalents]	7.74E-03	6.54E-03	5.51E-03	1.61E-02	3.97E-02	4.11E-02
Abiotic resource depletion [kg sb-equivalents]	6.38E-03	4.96E-03	3.75E-03	5.94E-03	2.26E-02	2.34E-02
Non-renewable primary energy [GJ]	6.95E-02	5.36E-02	4.00E-02	6.54E-02	2.48E-01	2.56E-01
Total Primary Energy [GJ]	7.64E-02	6.01E-02	4.62E-02	7.45E-02	2.51E-01	2.60E-01
Fresh Water (Incl. Boiler Feed)	5.18E-03	3.72E-03	2.48E-03	3.98E-03	3.80E-03	3.95E-03

The following **Figure 4-31** shows a relative comparison of the net results of all impact categories and environmental issues evaluated at the inventory level in the application field milk bottles.

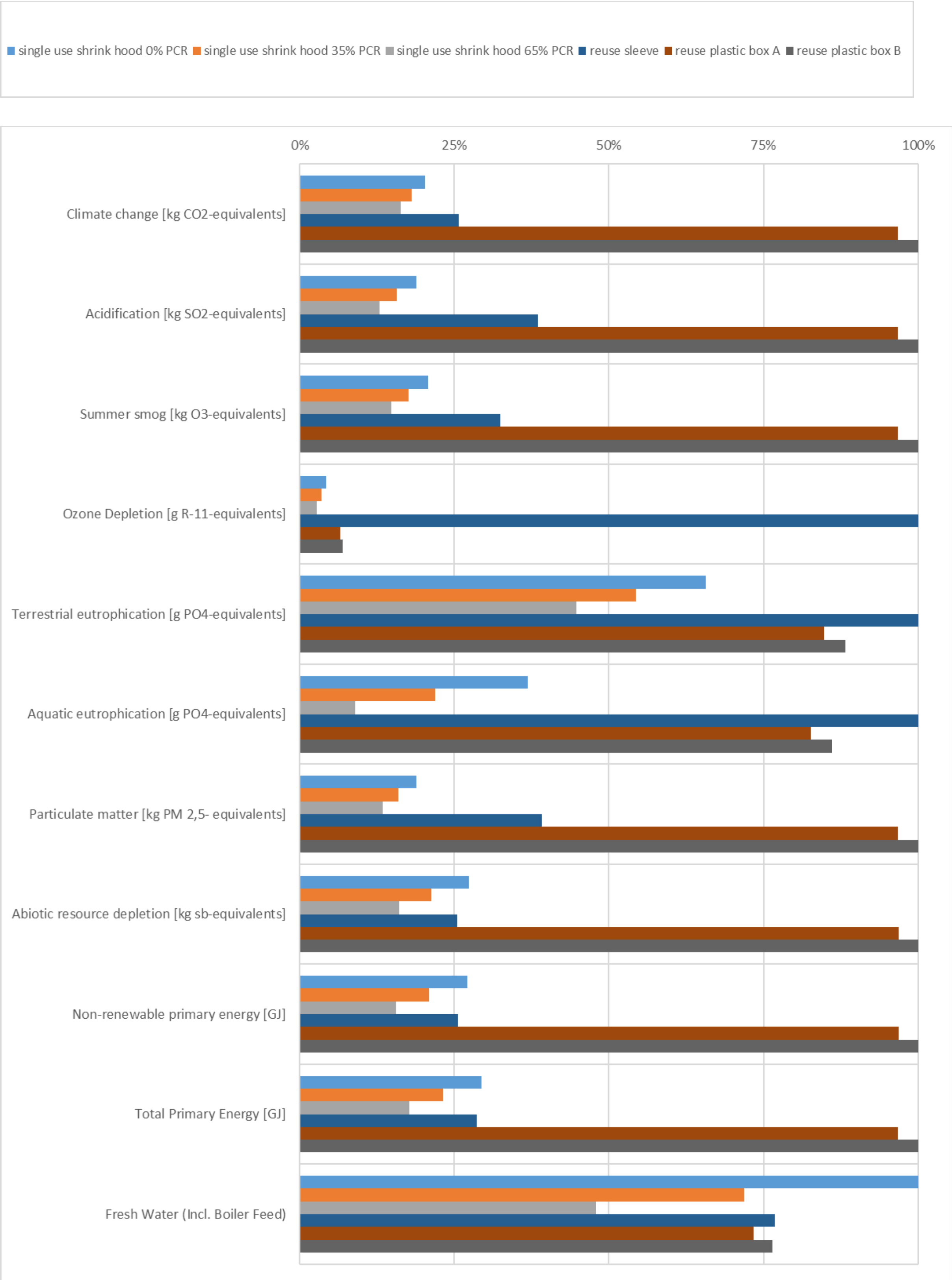


Figure 4-31: relative results of all impact categories and environmental issues evaluated at the inventory level in the application field milk bottles

The following **Figure 4-32** to **Figure 4-34** show the relative contribution of lifecycle steps for the eight selected impact categories in the application field milk bottles.

Figure 4-32: relative contribution of lifecycle steps for the impact categories Climate change, Acidification and Summer smog in the application field milk bottles

Figure 4-33: relative contribution of lifecycle steps for the impact categories Ozone Depletion Terrestrial and Aquatic eutrophication in the application field milk bottles

Figure 4-34: relative contribution of lifecycle steps for the impact categories Particulate matter PM 2.5 and Abiotic resource depletion in the application field milk bottles

The following **Figure 4-35** shows the relative contribution of lifecycle steps of the environmental issues evaluated at the inventory level in the application field milk bottles.

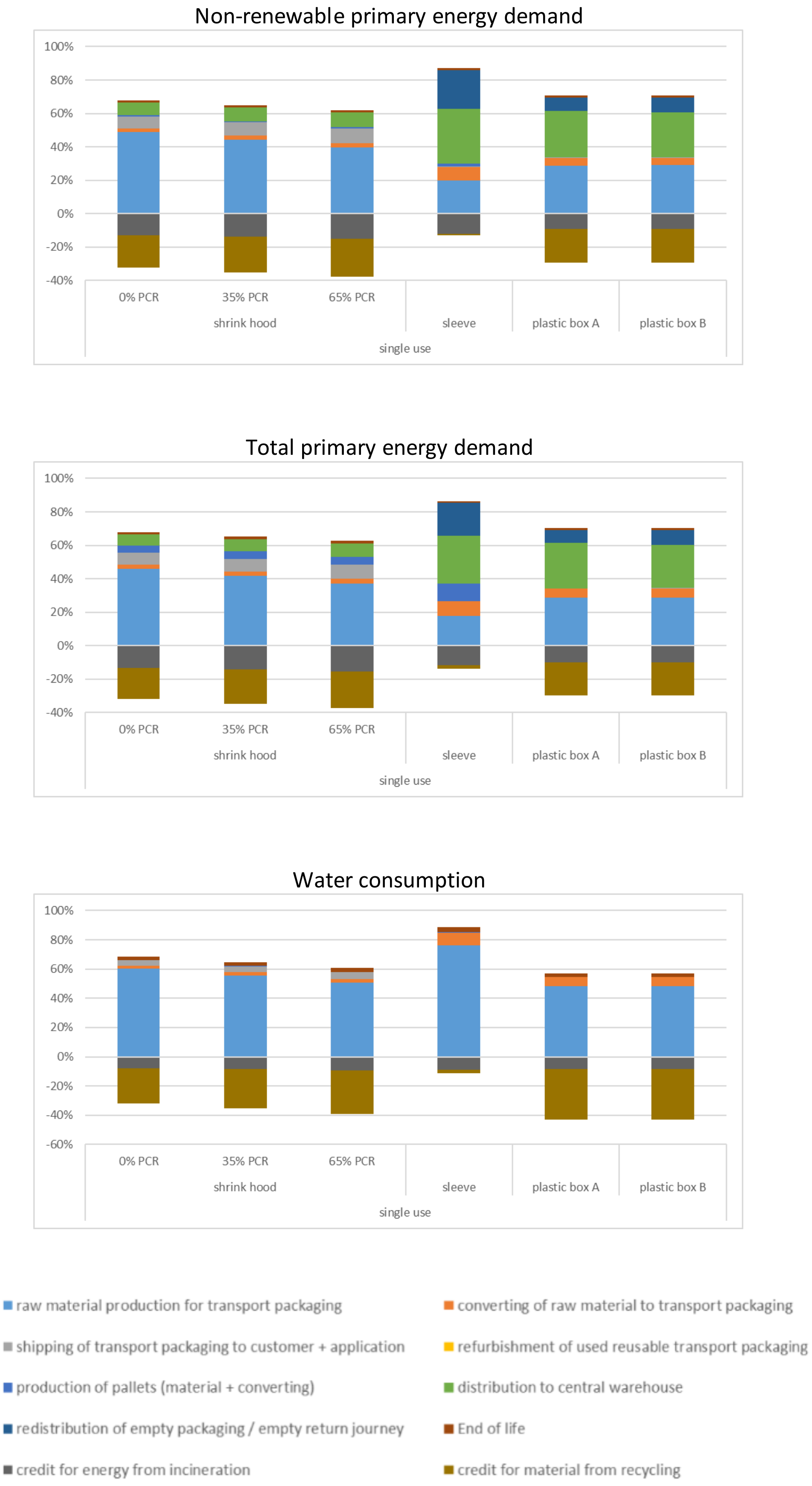


Figure 4-35: relative contribution of lifecycle steps for the categories on inventory level cumulative energy demand Non-renewable and Total and Freshwater consumption in the application field milk bottles

4.8 Summary of the results

Overall, it can be seen, that the results for the transport packaging analysed are very homogeneous. The following comments on the results of the packaging systems therefore apply to all applications fields considered.

In most of the analysed inventory and impact categories, the single-use plastic transport packaging with EURO flat pallet shows the lowest results. Here, the life cycle stages that determine the environmental results of single-use plastic transport packaging in almost all environmental impact categories are as follows

- The production of the plastics - determined by the weight of the packaging in terms of the mass of the packaging per functional unit and the proportion of secondary material used.
- The distribution from the production site where the transport packaging is applicated to the first economic operator in the logistics chain (central warehouse) - determined by the quantity of transport packaging per pallet and the mass of the packaged goods on that pallet per functional unit.
- Credits for the allocation of substituted primary energy sources - determined by the weight of the packaging and the mass of the packaging materials in thermal recovery.

In the following the alternative transport packaging systems examined in this study are briefly summarised:

- The single-use paper stretch shows low results in most of the impact and inventory categories considered. The results are mainly determined by the contribution of raw material production and, in those impact and inventory categories where distribution plays a role, also by this life cycle stage. The paper stretch shows correspondingly higher results in application fields where more material is required to secure the products on the pallet (e.g. water and CSD bottles).
- In the vast majority of the inventory and impact categories considered, the single-use cardboard box shows the highest contributions determined by the production of cardboard and the distribution step.
- In case of the reuse cardboard box, the reuse rate lowers the environmental results compared to the single-use cardboard box. However, the reuse carboard box still shows high results in most of the impact and inventory categories considered. Its results are mainly determined by the distribution and redistribution step.
- Among the reuse transport packaging alternatives, the reuse sleeve achieved the lowest results in most of the impact and inventory categories considered. Its results are mainly determined by the contribution of raw material production and the distribution plus the redistribution step.
- The environmental results of the reuse plastic boxes are considerable high in most of the inventory and impact categories considered. The results are mainly driven by the life cycle steps production of raw material, converting and distribution as well as redistribution.

When interpreting the results for distribution, which is a result-determining life cycle step for many impact categories for all products in all application areas, it must be considered that the burdens of the distribution of the transport packaging incl. pallets are counted here, but not the burdens of the transported goods incl. sales and collective packaging. A glance at the packaging specifications (see Chapter 2.3) shows that the weights of the pallets are generally significantly higher than the weights of the individual transport packaging systems examined (exception: reusable boxes made of PP – no pallets are used here). The impacts of distribution assessed are thus largely determined by the pallet as an integral component of the transport packaging.

5 Discussion of results and limitations

5.1 Development of an evaluation strategy

5.1.1 Identification and assessment of significant parameters

Table 5-1 below summarises the dominance analysis used to derive the significant parameters. The analysis summarises the results of the 7 application areas as well as the results of the individual transport and packaging systems.

Table 5-1: Summary of the dominance analysis

Impact categories	Single use plastic transport packing	Paper stretch	Cardboard box single use	Cardboard box reuse	Sleeve reuse	Plastic box reuse
Climate change	raw material production + Distribution	Distribution + raw material production	Distribution + raw material production	Distribution + Redistribution	Distribution + Redistribution	Distribution + Redistribution
Acidification	raw material production + Distribution	raw material production + Distribution	Distribution + raw material production	Distribution + Redistribution	Distribution + Redistribution	Distribution + Redistribution
Summer smog	raw material production + Distribution	Distribution + raw material production	Distribution + raw material production	Distribution + Redistribution	Distribution + Redistribution	Distribution + Redistribution
Ozone Depletion	raw material production + Energy credits	raw material production	raw material production	raw material production	raw material production	raw material production + converting
Terrestrial eutrophication	Energy credits + raw material production	raw material production	raw material production	raw material production	raw material production + credits	raw material production + credits
Aquatic eutrophication	Energy credits + raw material production	raw material production	raw material production	raw material production	raw material production + converting	raw material production + converting + credits
Particulate matter	raw material production + Energy credits	Distribution + raw material production	Distribution	Distribution + Redistribution	Distribution + Redistribution	Distribution + Redistribution
Abiotic resource depletion	raw material production + Energy credits	Distribution	Distribution	Distribution + Redistribution	Distribution + Redistribution	Distribution + Redistribution + raw material production
Non-renewable primary energy	raw material production + Energy credits	Distribution	Distribution	Distribution + Redistribution	Distribution + Redistribution	Distribution + Redistribution
Total Primary Energy	raw material production + Energy credits	raw material production + Distribution	raw material production + pallet + Distribution	Distribution + Redistribution	Distribution + Redistribution	raw material production + Distribution + Redistribution
Fresh Water (incl. Boiler Feed)	raw material production	raw material production	raw material production	raw material production	raw material production	raw material production

The analysis demonstrates that, for most of the environmental factors and LCA inventory parameters examined, the distribution and production of the raw material is the most significant contributor. For disposable plastic transport packaging, the energy credit is also relevant for certain impact categories.

Knowing that the results of a LCA reflect the input parameters of a LCA, the input parameters of the study that determine the life cycle stages identified as relevant are presented below.

- **Raw material production:** The environmental impact of the raw material stage of the life cycle is determined by the amount of material required to fulfil the function of the functional unit. This material flow is determined by the weight of the packaging and, in the case of reuse packaging, by the trip rate. The proportion of secondary materials also plays a role in the assessment of environmental impacts, as the allocated impacts of the life cycle of the PCR material are also included in the life cycle.
- **Distribution (reuse system: Distribution + Redistribution):** The environmental impact of distribution is determined by the transport distance and the packaging efficiency of the different packaging systems analysed. Since the distribution distance is the same for all systems, the differences in packaging are due to the packaging efficiency, which is determined by the dimensions of the packaging and the resulting loading patterns.
- **Credits (energy credits):** The credits are closely linked to the disposal data of the packaging systems and the mass flow, determined by the packaging weights. Energy credits are not only obtained for the part of the mass flow that goes directly to thermal recovery, but that part of the final thermal recovery of the secondary raw materials verified in the context of material recycling is also returned to the donor system as part of the allocation. It should also be noted that the proportion of pallets in the disposal of flexible one-way transport packaging is significant, as they account for a significant proportion of the mass flow due to their weight, and a high proportion of them are thermally recycled, so that high energy credits are shown here.

It should be noted that the packaging specifications and loading patterns were developed as part of the EUMOS test series and therefore have a high degree of validity and accuracy of fit for the object of investigation.

In the context of evaluating the dominance analysis, two aspects stand out that should be considered in more detail here, as they may affect the validity of the results.

- The results for aquatic eutrophication show negative results for single-use plastic transport packaging with a high PCR content in some application fields (cardboard boxes and cement bags). This is the result of crediting the substituted energy and should not be interpreted as an environmental burden reduction potential. As phosphorus is included in aquatic eutrophication with a high characteristic factor, the result is overlaid by this artefact. The phosphorus emissions come from the electricity mix and are probably due to an overestimated source of phosphorus leaching from coal mining tailings. The results for aquatic eutrophication should therefore be interpreted with caution and are of limited use for comparison.
- A similar case exists for the ODP, where the PET upstream chain is decisive for the emissions of the reuse sleeve system. As the PET dataset is a aggregated dataset from the Ecoinvent database, the plausibility checks carried out by the authors of the study are limited. The comparison with other plastics data sets shows that the ODP values are significantly higher, which means that the results of the ODP should be used for comparison only to a limited extent.

5.1.2 Estimation of the robustness of the impact categories

The robustness of an impact category is determined by two factors:

- How well-developed is the conceptual and computational model of the impact category? In other words, how are the potential environmental impacts described by the impact category, on what basis are the characterization factors derived, etc.?
- How comprehensively do the datasets used cover the elementary flows necessary for calculating the impact category? In other words, are all the required individual results available to accurately calculate the impact category, or do distortions arise because only part of the necessary emissions could be computed?

The following section evaluates the selected impact categories from the perspective of the authors of this study. The classification is divided into three categories: Good, Sufficient, and Inadequate. Additionally, for each impact category considered, the robustness factor according to the PEF guideline is provided. However, it should be noted that the characterization models used in this study differ slightly from those of the PEF. This is explained in more detail in Chapter 1.8.4.

- **Impact category resource consumption (ADP)** is rated as sufficient. The necessary data for assessing this impact category are available, but the derivation of characterization factors is not very transparent and is also incomplete in terms of the described problem (the finiteness of resources), as the consideration of availability is missing. Although this impact category represents an established international standard, it has the reputation of being a stopgap solution. In the PEF, this impact category is classified with the lowest robustness level (III).
- **Impact category climate change** is rated as good. Both the characterization model and the data used for the calculation have high validity, especially since most climate-relevant emissions from processes can be determined and validated in a straightforward manner through stoichiometric calculations. In direct comparison, the climate change impact category demonstrates the highest robustness among all evaluated impact categories. In the PEF, this impact category is classified with the highest robustness level (I).
- **Impact category terrestrial eutrophication** is rated as good. The underlying calculation model adequately represents the environmental impacts, the characterization factors are appropriately derived, and the model can be fully applied in accounting. In the PEF, this impact category is classified with a medium robustness level (II).
- **Impact category aquatic eutrophication** is rated as sufficient. While the underlying calculation model appropriately represents environmental impacts and the characterization factors are properly derived, not all necessary data can be determined in the accounting process. This is because, at the inventory level, reliable data on chemical oxygen demand (COD) and biochemical oxygen demand (BOD) are missing for the majority of wastewater-generating processes. In the PEF, this impact category is classified with a medium robustness level (II).
- **Impact category acidification** is rated as good. The underlying calculation model adequately represents environmental impacts, the characterization factors are properly derived, and the model can be fully applied in accounting. In the PEF, this impact category is classified with a medium robustness level (II).

- **Impact category summer smog** is rated as good. The underlying calculation model adequately represents environmental impacts, the characterization factors are properly derived, and the model can be fully applied in accounting. In the PEF, this impact category is classified with a medium robustness level (II).
- **Impact category ODP (stratospheric ozone depletion)** is rated as sufficient. The impact category of stratospheric ozone depletion (ODP) in the current evaluation of PET packaging (reuse sleeve) is significantly influenced by emissions of methyl bromide (CH_3Br), which arise during the production of terephthalic acid (PTA). The PTA production process is described in the PET dataset using data from an external source (CPME 2016). The validity of CH_3Br emissions within PET production has been confirmed by the authors of the PET dataset. However, as part of the evaluation strategy, the results of this impact category should not be overinterpreted—meaning that they should not lead to a devaluation of the specific contributions of other impact categories. In the PEF, this impact category is classified with the highest robustness level (I).
- **Impact category particulate matter (PM 2.5)** is rated as good. The underlying calculation model adequately represents environmental impacts, the characterization factors are properly derived, and the model can be fully applied in accounting. In the PEF, this impact category is classified with the highest robustness level (I).

No impact categories will be excluded from the evaluation due to insufficient robustness. However, the validity of the results should be considered accordingly when drawing conclusions.

5.1.3 Localisation of potential environmental impacts

All evaluated impact categories fundamentally indicate only impact potentials, meaning they provide information about possible environmental impacts that may occur. Furthermore, when interpreting the results, it is important to consider that certain emissions are accounted for in multiple impact categories (e.g., NOx in terrestrial eutrophication, summer smog, and particulate matter), meaning that some degree of double counting cannot be ruled out.

Although life cycle assessments (LCAs) examine defined geographical areas, they do not localize potential environmental impacts. As a result, LCA results cannot be directly compared with any existing environmental burdens in a specific region.

Nevertheless, statements about the geographical relevance of potential environmental impacts, as expressed through impact category results, can serve as a basis for clustering the findings. It is essential to distinguish whether the potential environmental impacts occur on a global, regional, or local scale. These dimensions are defined as follows:

- **Global dimension**: This refers to potential environmental effects that have global consequences, regardless of where the emission occurs. Impact categories representing global-scale environmental effects include climate change, stratospheric ozone depletion (ODP), and ionizing radiation. The depletion of fossil resources is also classified as a global issue—not because its environmental effects are as widespread, but because its associated protection goal addresses intergenerational equity and long-term resource availability, which are inherently global concerns.

- **Regional dimension**: This concept is broader than "regionality" in other contexts (e.g., distribution). Here, it refers to "world regions" such as Northern or Western Europe, Sub-Saharan Africa, etc. Impact categories influenced by air pollutants belong to this regional dimension, as air pollution tends to spread over large distances and across national borders (hence, this dimension is not referred to as "national"). Even though the potential environmental impacts represented in these impact categories may be relevant worldwide, there is usually a stronger connection between the emission source and its effects compared to globally relevant impact categories. The impact categories classified under the regional dimension include terrestrial eutrophication, acidification, summer smog, particulate matter (PM2.5), and cancer risk potential.
- **Local dimension**: This refers to impact categories where the potential environmental effects are primarily limited to the immediate surroundings of the emission source. These include impact categories that describe resource use with a specific location, such as land use (not assessed in this study) or water consumption. Additionally, some emission-related impact categories can also have a local dimension, such as aquatic eutrophication, which is primarily determined by direct emissions into surface waters. In this case, the potential environmental effects occur near the wastewater discharge point, with increasing dilution as the distance from the source increases. It is worth noting, however, that most surface waters in Europe currently exhibit poor water quality, meaning that aquatic eutrophication is also a regional concern. The primary pathways for aquatic pollution include wastewater discharges and diffuse agricultural emissions into water bodies. However, since agricultural processes are not considered in this study (as no cultivated biomass is included in the system models), aquatic eutrophication is addressed only as a local impact in this study.

As mentioned earlier, assessing the localization of potential environmental impacts primarily serves as a clustering tool to support the evaluation process. No weighting is intended to suggest that global environmental impacts are necessarily more severe than local ones. However, it is important to recognize that local environmental issues must be addressed in a different manner than global environmental problems.

5.1.4 Evaluation strategy - summary

The following **Table 5-2** summarizes the results of the discussed aspects regarding the evaluation of the findings. The table assesses whether a specific individual aspect significantly influences the results of an impact category, thereby reducing the validity of the outcome. It also considers the overall robustness of the values for the impact categories and the discussed localization of potential environmental impacts.

The objective of this evaluation is to identify the key and valid environmental impact categories for assessing the results, thereby condensing the findings. Based on the conducted evaluation, the significance threshold for analysing identified differences is also determined. As described in Section 6, 10% is a default value proposed by the German Environment Agency (UBA) for packaging life cycle assessments. In this study, this threshold applies only to impact categories that achieve PEF robustness score I. A PEF score of 2 results in a significance threshold of 20%, while a score of 3 corresponds to a significance threshold of 30%.

To further condense the findings, results at the inventory category level (energy, waste, and freshwater) will not be pursued further, as their robustness is insufficient (e.g., freshwater) or because the assessed results are identical to an evaluable impact category (as in the case of energy indicators, whose aspects are already fully represented by ADP). However, these results serve to validate the findings of the environmental impact categories and should therefore remain part of the report, even if they are no longer used for the in-depth analysis of results and the derivation of conclusions.

Table 5-2: Summary of the dominance analysis

Impact categories	dominance of particular data?	Robustness	localisation	Considered in study?	recommended significance threshold
Climate change	no	good	global	yes	10%
Acidification	no	good	regional	yes	20%
Summer smog	no	good	regional	yes	20%
Ozone Depletion	yes	sufficient	global	no	-
Terrestrial eutrophication	no	good	regional	yes	20%
Aquatic eutrophication	yes	sufficient	regional	no	-
Particulate matter	no	good	regional	yes	10%
Abiotic resource depletion	no	sufficient	global	yes	30%
Non-renewable primary energy	no	good	global	no	-
Total Primary Energy	no	good	global	no	-
Fresh Water (Incl. Boiler Feed)	no	poor	regional	no	-

Although a further aggregation into a single-score evaluation might seem logical, it will not be carried out, as the loss of information would be too significant. Additionally, this study does not aim to assess whether global environmental issues are more urgent than local ones. Furthermore, aggregated single scores, which inherently imply value judgments, are not necessarily compatible with the ISO 14040ff standards.

The following environmental impact categories are therefore used for the further evaluation of the results:

- Climate change
- Acidification
- Summer smog
- Terrestrial eutrophication
- Particulate matter
- Abiotic resource depletion

5.2 Summarise results and derive of overarching findings

To summarise the results of the base scenarios and to derive overarching patterns in the following section figures (**Figure 5-1** to **Figure 5-7**) with the relative net results of all impact categories selected are presented for each application field. The reference for the relative comparison is the respective packaging system with the highest environmental impact, scaled to 100%. To facilitate the visual reading of the results, a colour code is used. The green colour indicates values up to a threshold of < 20 %. The range between 20% and 80% is displayed in yellow. From 80%, the red colour is used. Differences between the individual results lower than 10 % are considered as insignificant.

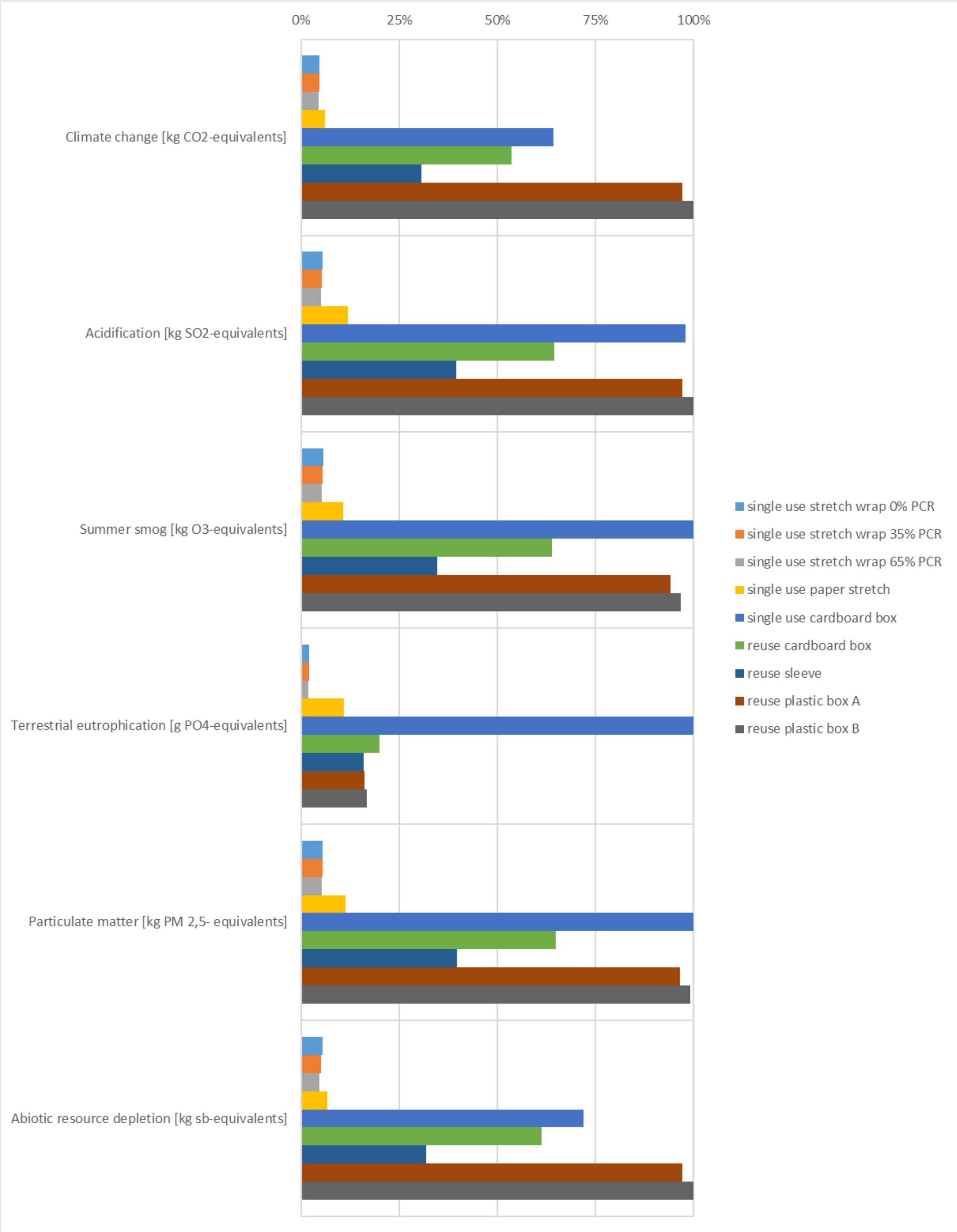


Figure 5-1: relative results in the application field cardboard boxes

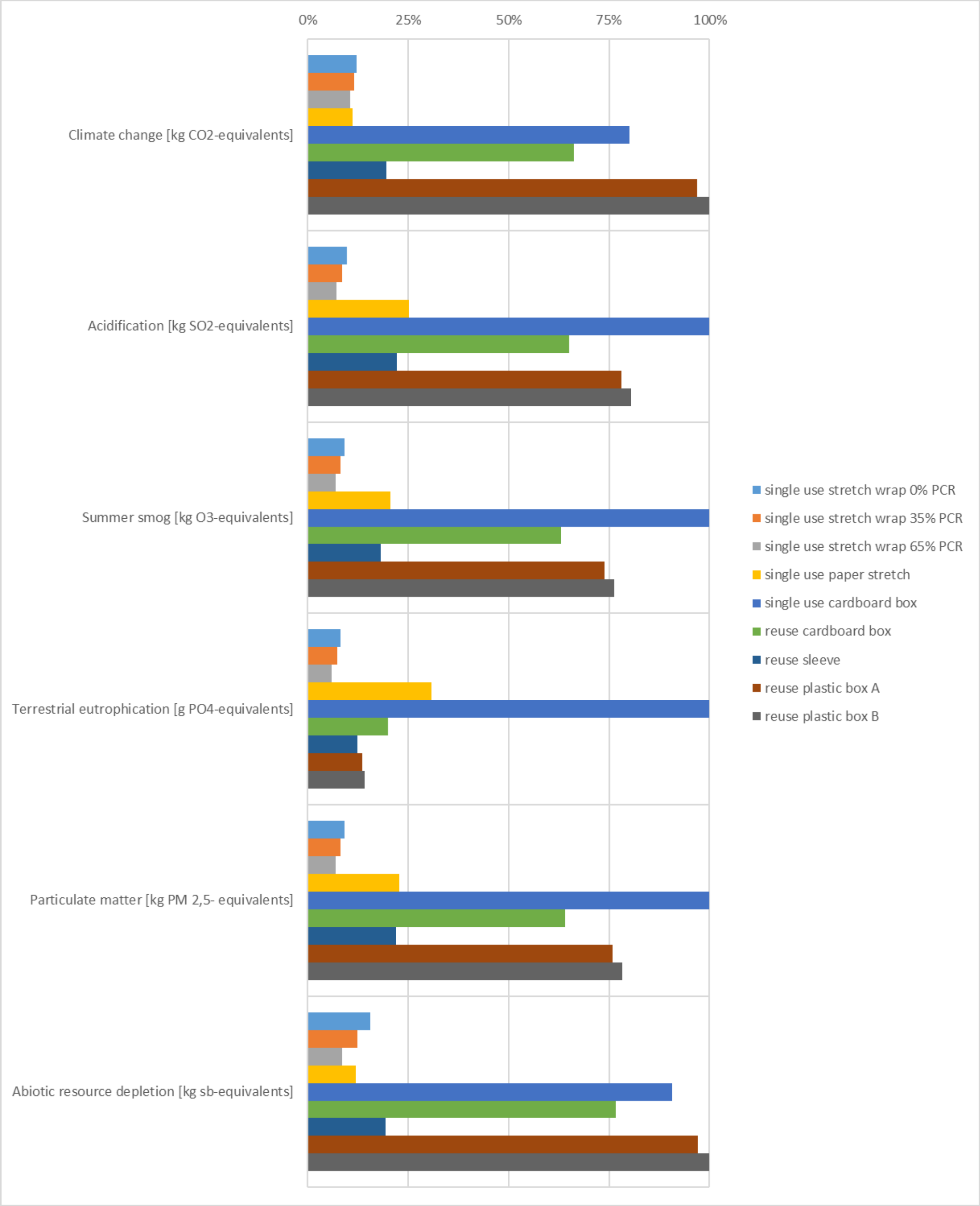


Figure 5-2: relative results in the application field water and CSD bottles

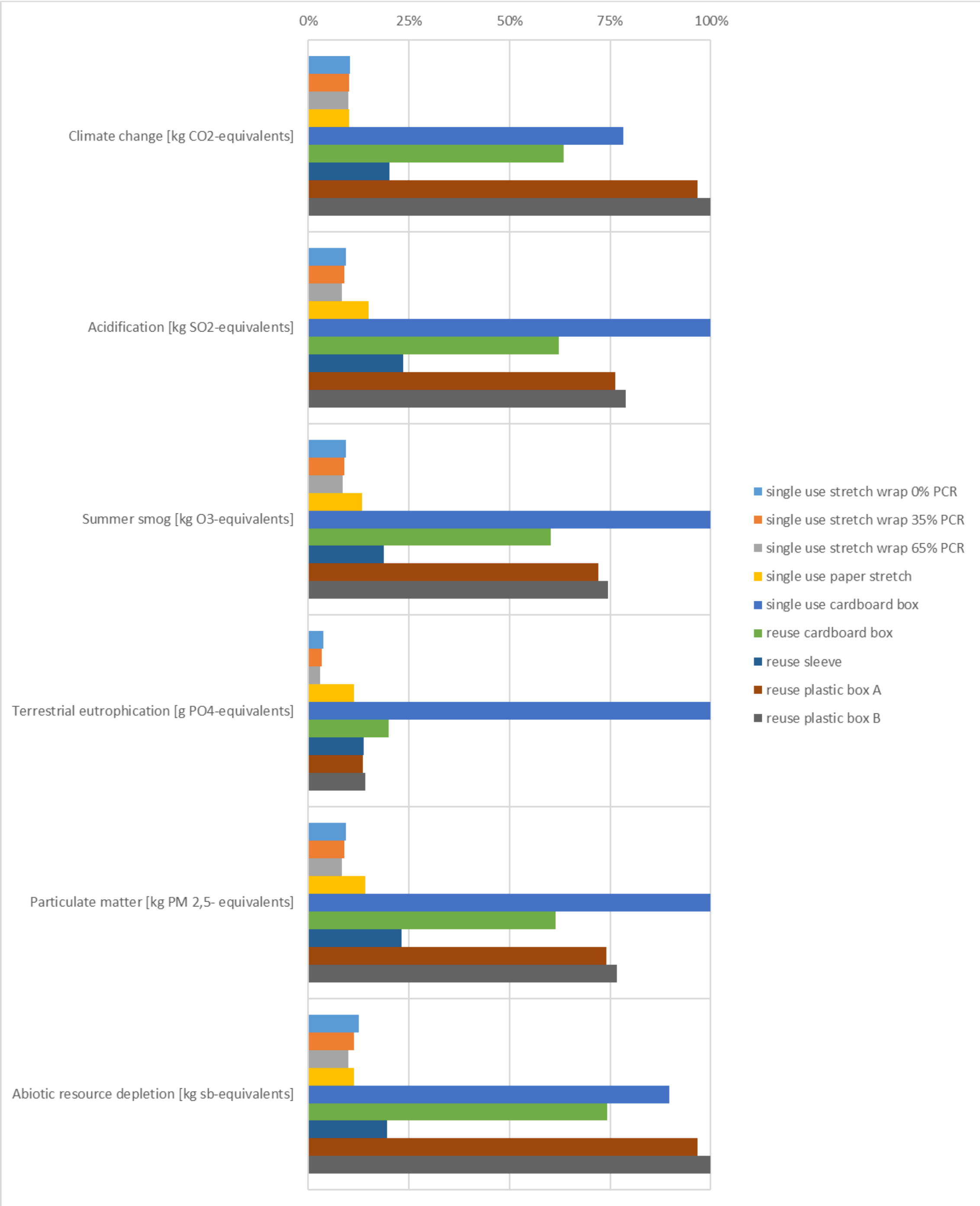


Figure 5-3: relative results in the application field buckets

Figure 5-1 to **Figure 5-3** show that in most of the impact and inventory categories analysed, stretch wrap films have the lowest environmental results and in no case the highest. This is the case for all analysed applications of stretch wrap.

Stretch wrap has significant advantages over the reuse transport packaging systems of rigid plastic and cardboard. When compared to reuse sleeves, the results vary for different applications. While reuse sleeves consistently show higher contributions than stretch wrap for cartons and pails, the results for water and CSD bottles are more difficult to determine. Therefore, a direct comparison of the results obtained using stretch and returnable sleeve packaging in the applications analysed is presented below.

Table 5-3: Direct comparison of the results of the stretch wrap and the reuse sleeve using the significance thresholds

Impact categories	Significance threshold	Stretch wrap with respective PCR share compared to reuse sleeve								
		0% PCR	35% PCR	65% PCR	0% PCR	35% PCR	65% PCR	0% PCR	35% PCR	65% PCR
		In the application field: cardboard boxes			In the application field: water and CSD bottles			In the application field: buckets		
Climate change	10%	-85%	-85%	-85%	-38%	-40%	-46%	-48%	-49%	-51%
Acidification	20%	-86%	-87%	-87%	-56%	-61%	-68%	-60%	-62%	-64%
Summer smog	20%	-84%	-84%	-85%	-49%	-54%	-62%	-50%	-52%	-54%
Terrestrial eutrophication	20%	-87%	-88%	-89%	-34%	-41%	-51%	-73%	-75%	-78%
Particulate matter	10%	-86%	-86%	-87%	-58%	-62%	-69%	-60%	-61%	-63%
Abiotic resource depletion	30%	-83%	-84%	-85%	-20%	-36%	-55%	-35%	-41%	-48%

Benefits above the significance threshold are shown in green, disadvantages in red. Results within the significance threshold are shown in grey.

It can be seen that only in the environmental impact category Abiotic Resource Depletion (ADP) for the stretch wrap systems with 0% PCR content in the application field water and CSD bottles the differences in the results are in a non-significant range. In all other environmental impact categories, the stretch wrap systems show advantages.

The comparison with the other single-use systems (paper stretch and single-use cardboard box) shows that stretch film always has significant advantages over single-use cardboard box. The comparison with paper stretch shows that the results are often at a similar level, except for water and CSD bottles. As much more material is used here to ensure functional equivalence, the contributions of paper stretch are significantly higher, and the advantage of stretch wrap is therefore more significant.

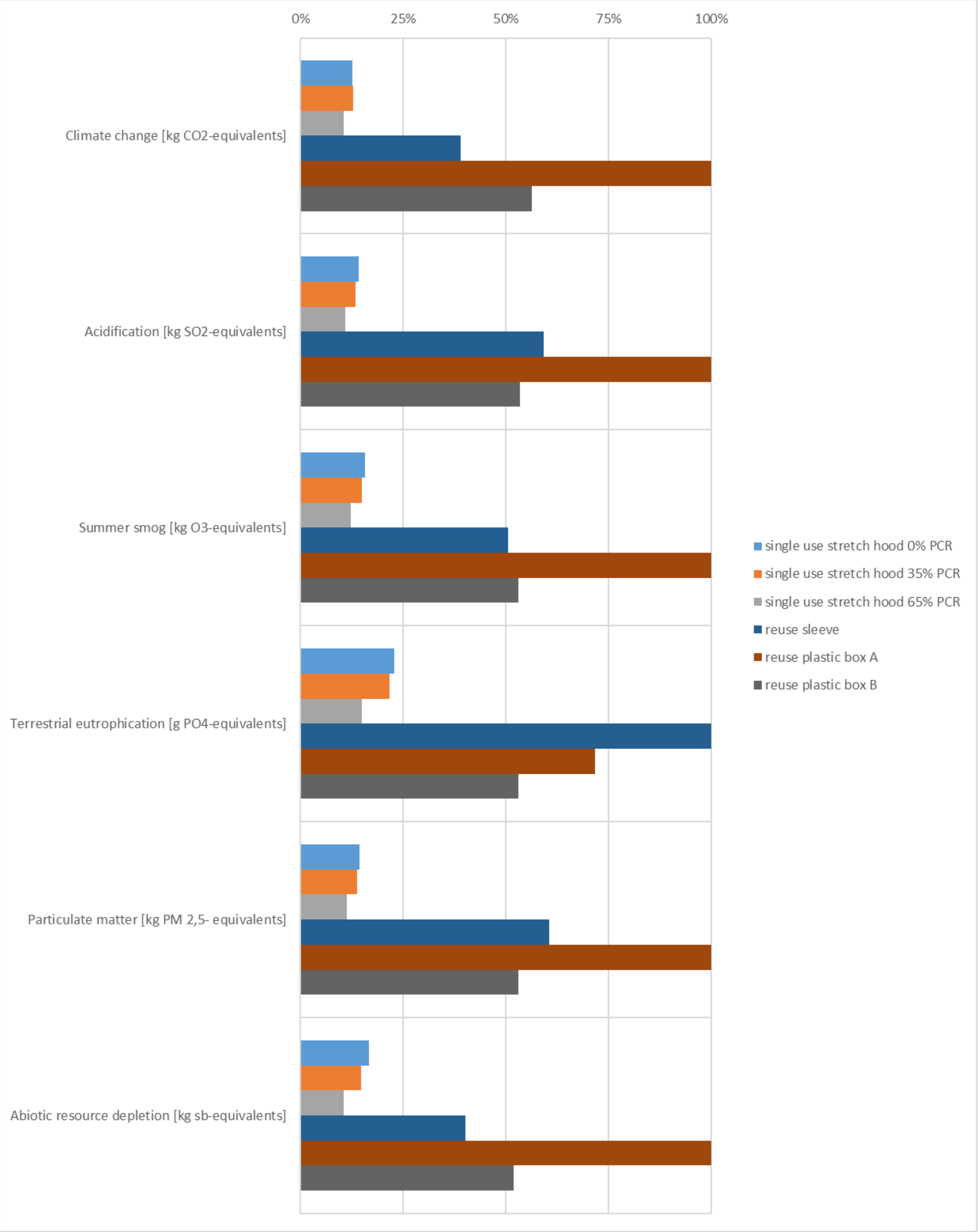


Figure 5-4: relative results in the application field cement bags

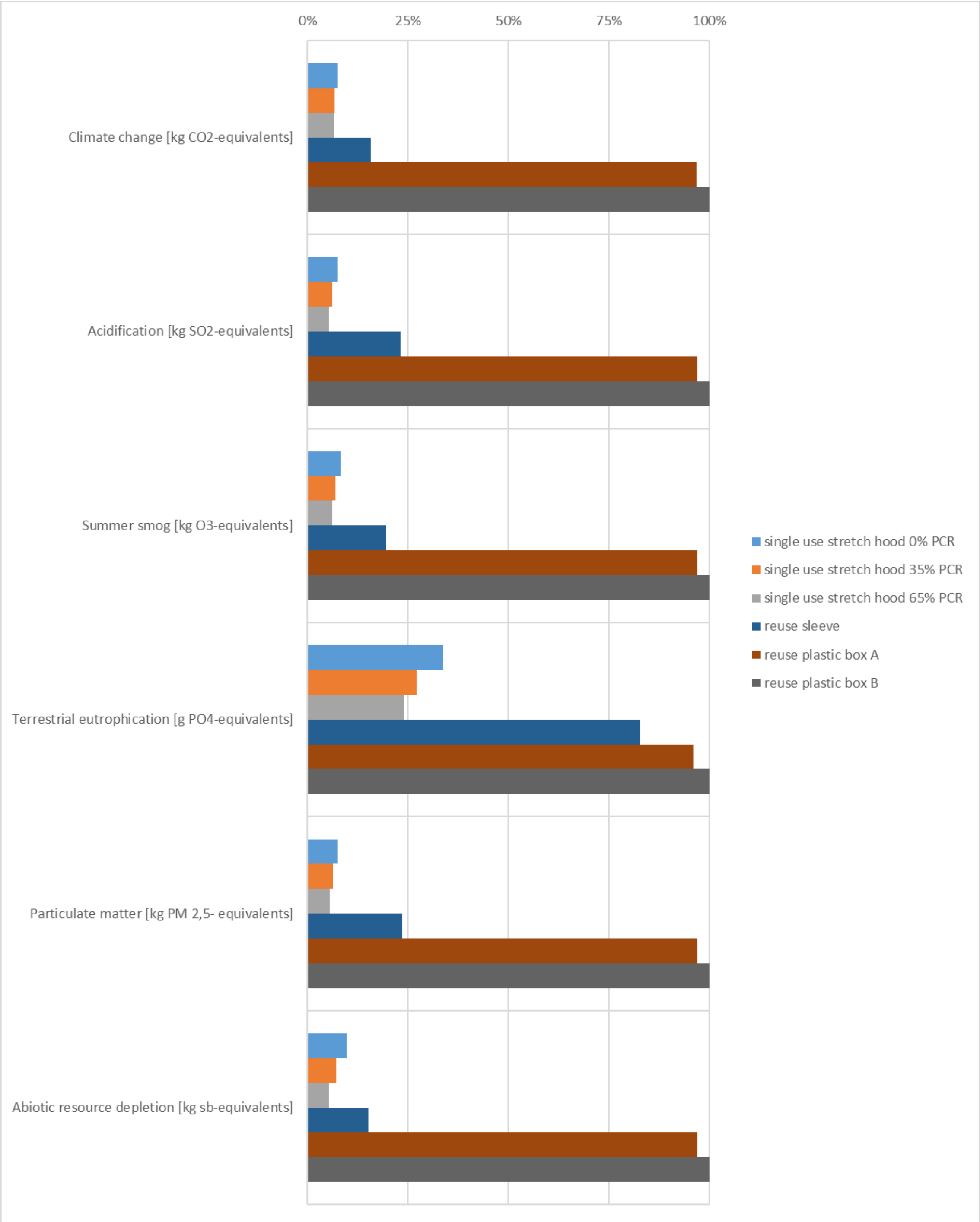


Figure 5-5: relative results in the application field polymer bags

Figure 5-4 to **Figure 5-5** show that in all the impact and inventory categories studied, the stretch hood has the lowest environmental results compared to the reuse packaging systems for both applications studied. The stretch hood with 65% recycled material has the lowest environmental results.

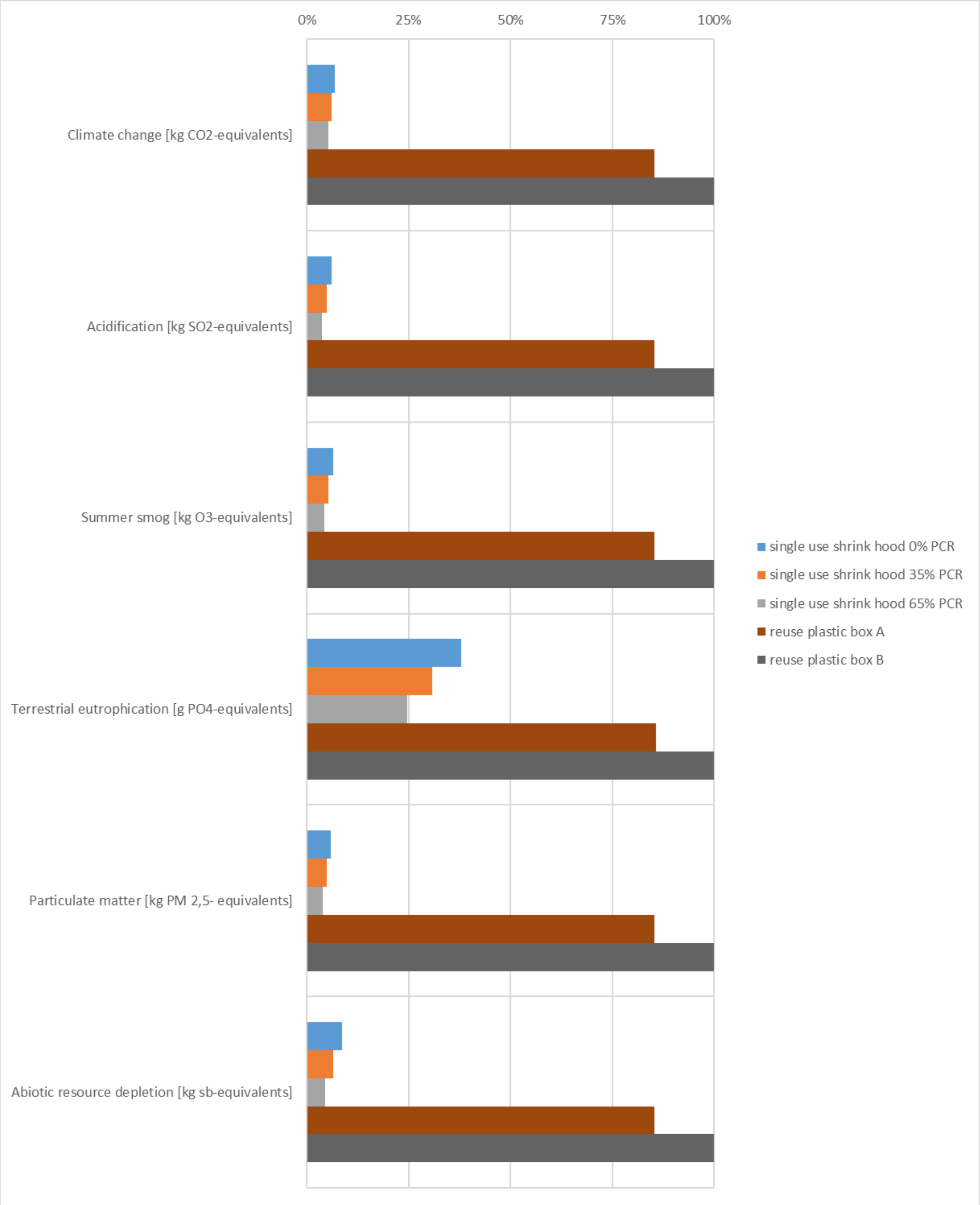


Figure 5-6: relative results in the application field glass bottles

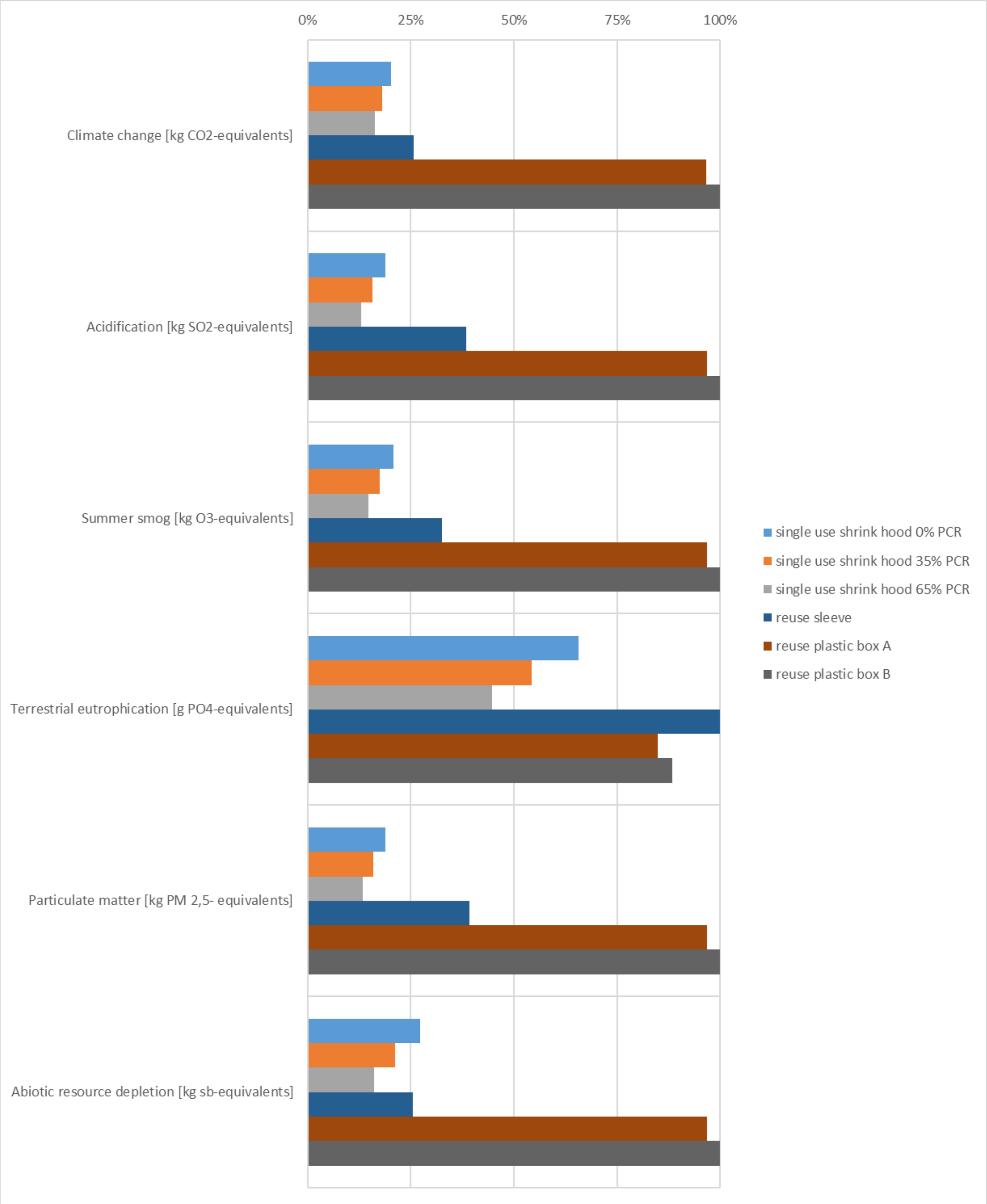


Figure 5-7: relative results in the application field milk bottles

Figure 5-6 shows that for all the impact categories examined, the shrink hoods have the lowest environmental results compared to the reuse plastic boxes for the glass bottle application. The shrink hood with 65% recycled material has the lowest environmental results.

For the HDPE milk bottles application, **Figure 5-7** shows that the single-use shrink hoods have lower environmental results than both types of reuse plastic boxes in all impact categories.

For the majority of the impact and inventory categories examined, the shrink hoods show better environmental results compared to the reuse sleeves. The results for the comparison with the reuse sleeve are inconclusive, so the pairwise comparison should be repeated at this point.

Table 5-4: Direct comparison of the results of the shrink hood and the reuse sleeve using the significance thresholds

Impact categories	Significance threshold	Shrink hood with respective PCR share compared to reuse sleeve		
		0% PCR	35% PCR	65% PCR
		In the application field: milk bottles		
Climate change	10%	-21%	-29%	-36%
Acidification	20%	-51%	-59%	-66%
Summer smog	20%	-36%	-46%	-54%
Terrestrial eutrophication	20%	-34%	-46%	-55%
Particulate matter	10%	-52%	-59%	-66%
Abiotic resource depletion	30%	7%	-16%	-37%

Benefits above the significance threshold are shown in green, disadvantages in red. Results within the significance threshold are shown in grey.

It can be seen that only in the environmental impact category Abiotic Resource Depletion (ADP) for the stretch wrap systems with 0% and 35% PCR content in the application field milk bottles the differences in the results are in a non-significant range. In all other environmental impact categories, the stretch wrap systems show advantages.

In summary, the single-use plastic transport packaging considered in this study has advantages over the other single-use and reuse transport packaging considered in this study in all the environmental impact categories used for the assessment if it has a PCR content of at least 35%. For single-use transport packaging without PCR content, the result described here applies accordingly, with the exception that the single-use plastic transport packaging show no significant difference to the reuse sleeve in the environmental impact category abiotic resource depletion for the particularly heavy HDPE milk bottles.

5.3 Reviewing assumptions (sensitivity analysis)

Sensitivity analysis intend to assess the reliability of the final results and conclusions by determining how they are affected by uncertainties in the data or choice of parameters based on expert judgement.

5.3.1 Assumptions regarding trip rates

The results for the reuse plastic boxes and the reuse sleeve are determined by the trip rate, thus a scenario variant with a higher trip rate (plastic boxes = 50; sleeve= 15) is analysed and presented in the following section. The net results are represented in **Figure 5-8** to **Figure 5-14** including the results of the base scenarios of the other transport packaging systems for comparison.

It is common to analyse the sensitivity of trip rates in an LCA looking at reuse systems, especially when these are more or less hypothetical systems for which no valid data can be collected in practice. In the interest of a conservative approach to the comparison, the high trip rate values could have been included in the base scenarios. However, the thoughts documented in chapter 2.2.2 and the results of the EUMOS test series argue against this. For example, after only five uses, the cuff showed significant defects in the form of a torn seam, making reuse impossible. The EUMOS test showed that the connection between the side walls and the loading floor of the type A reuse box did not function reliably, which could minimise the service life of the box in the long term.

The results of the sensitivity analysis are presented below in the form of relative results graphs to allow direct comparison with the results of the base scenarios, which are documented in identical form in chapter 5.2.

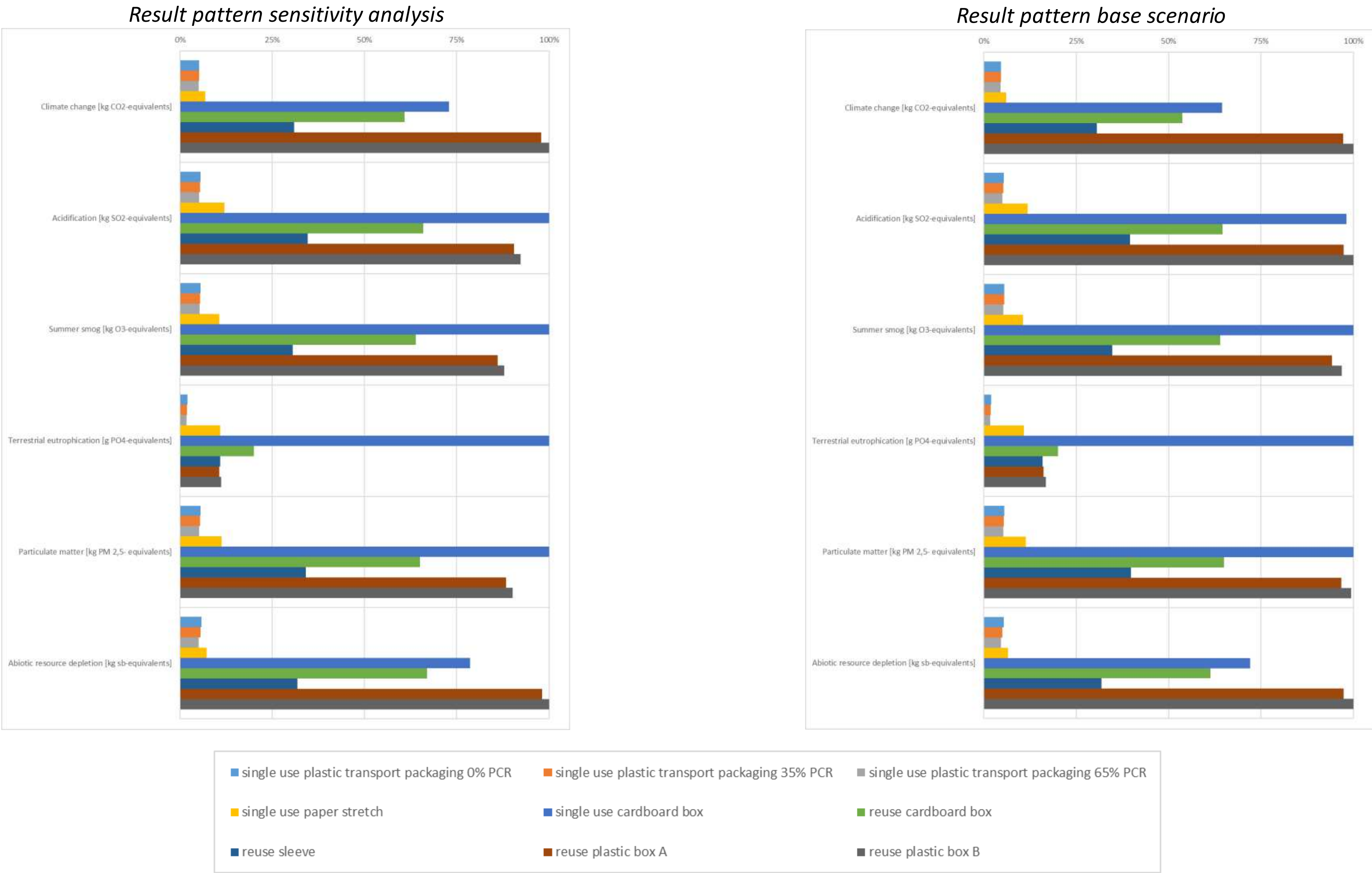
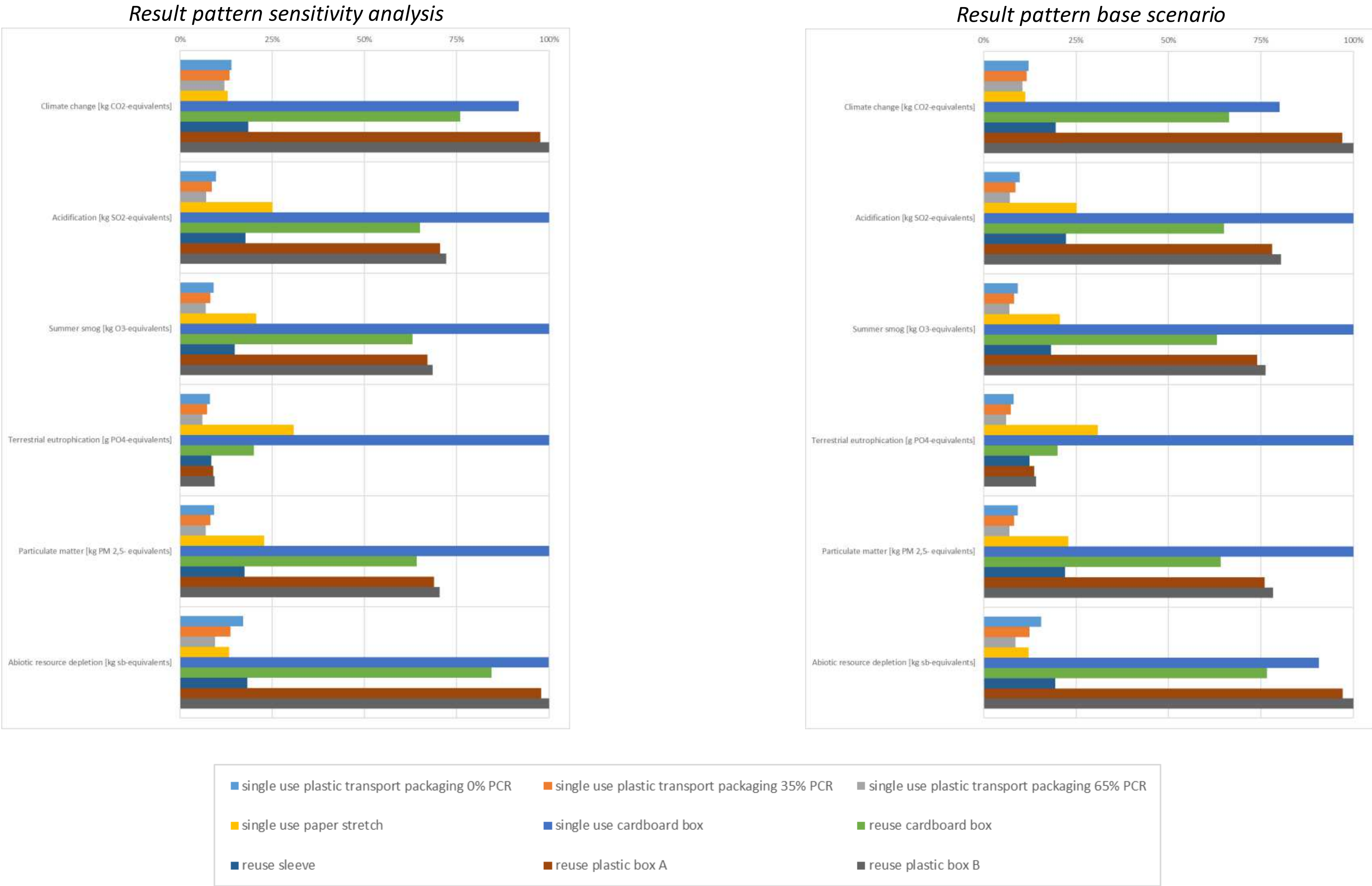


Figure 5-8: relative results in the application field cardboard boxes – sensitivity analyses trip rates



0 **Figure 5-9:** relative results in the application field PET water and CSD bottles – sensitivity analyses trip rates

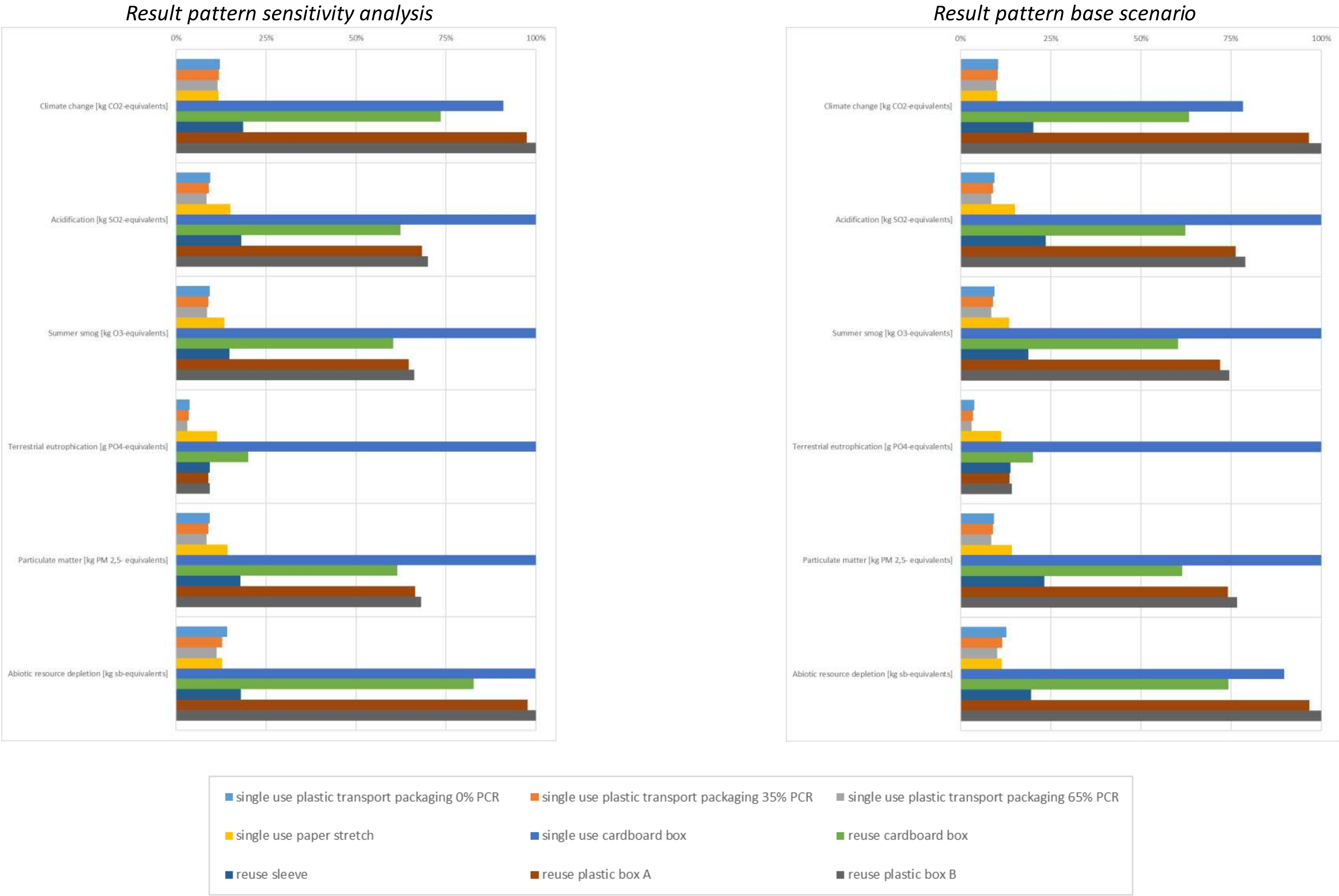
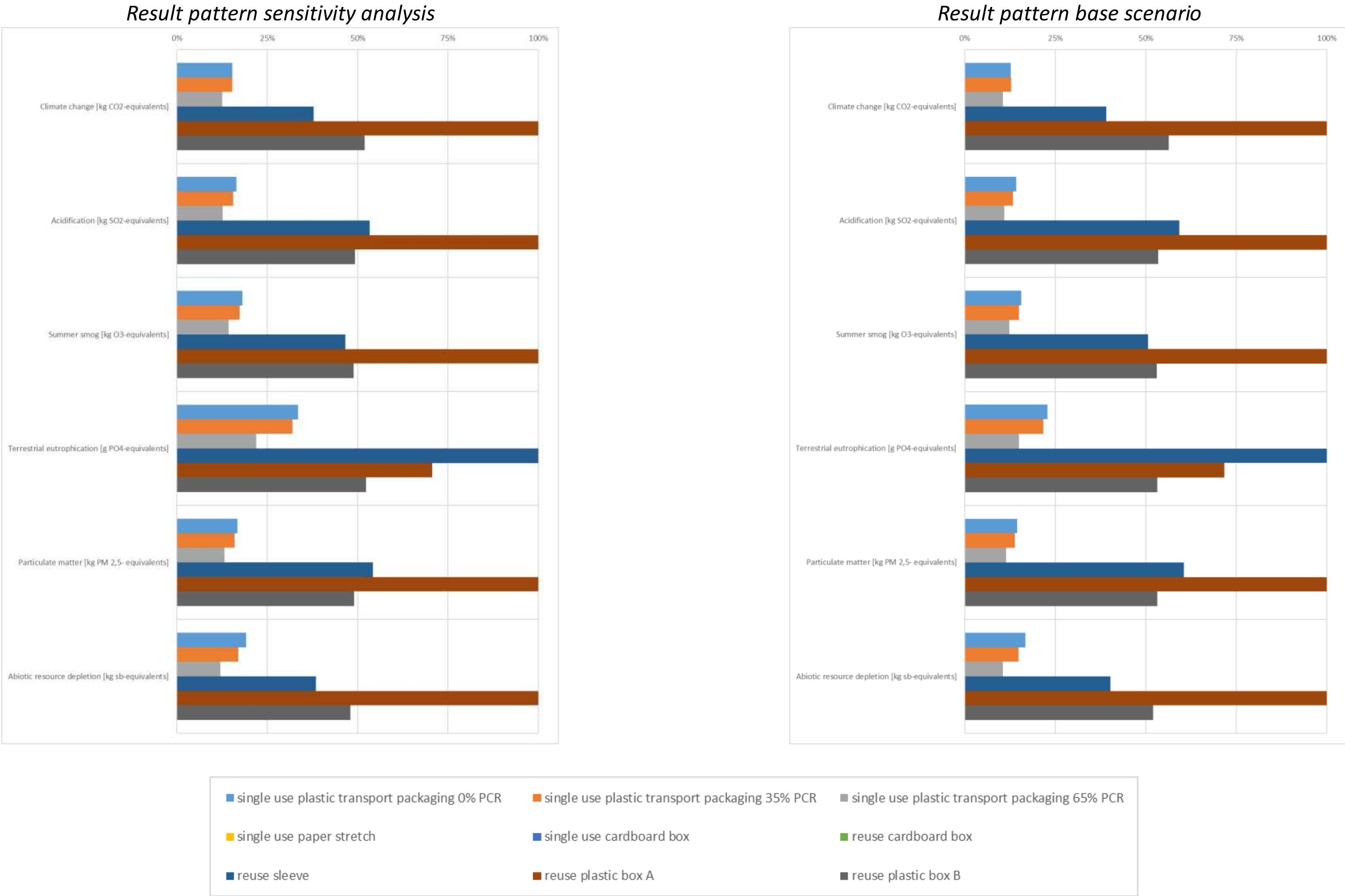
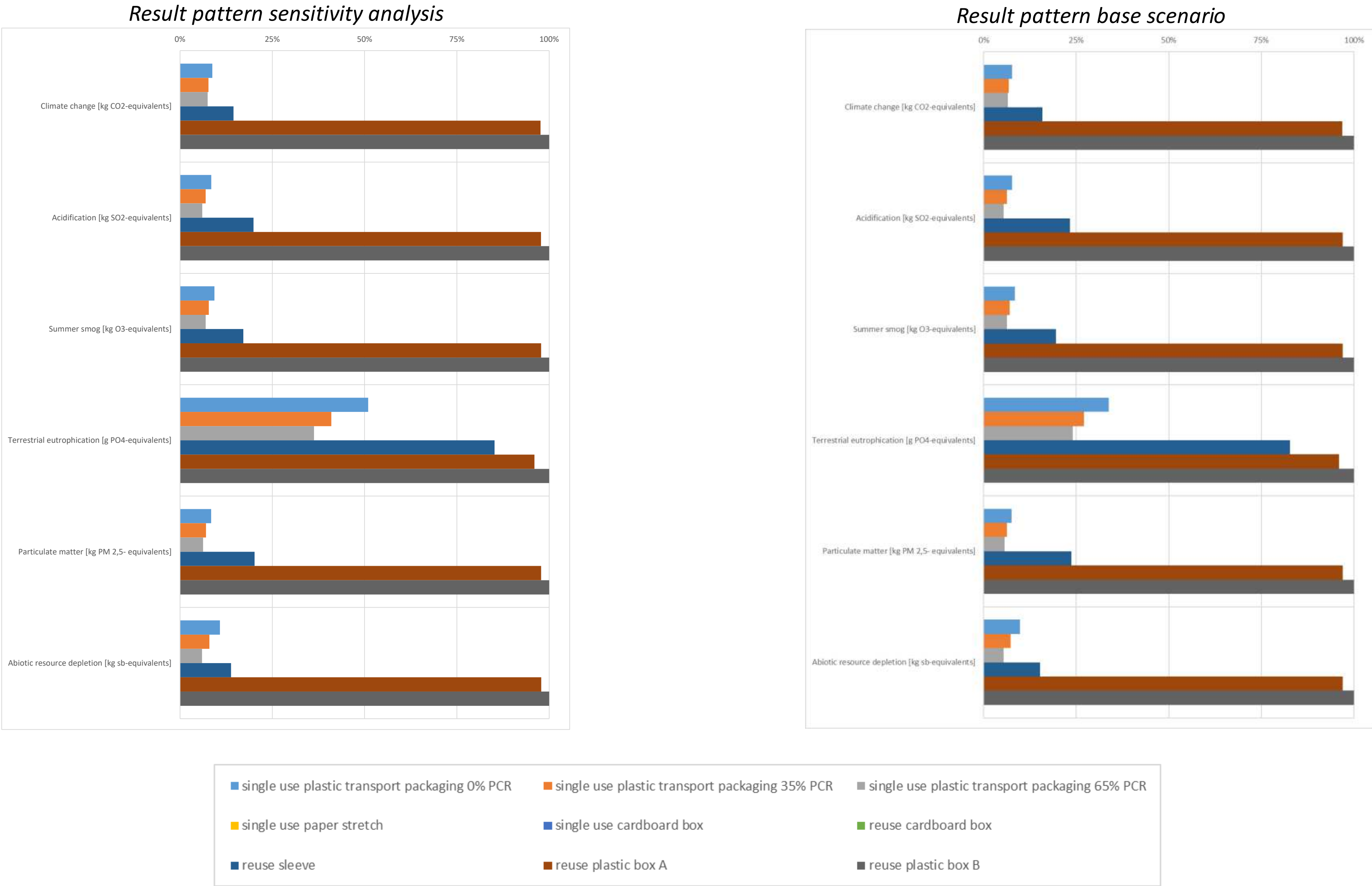


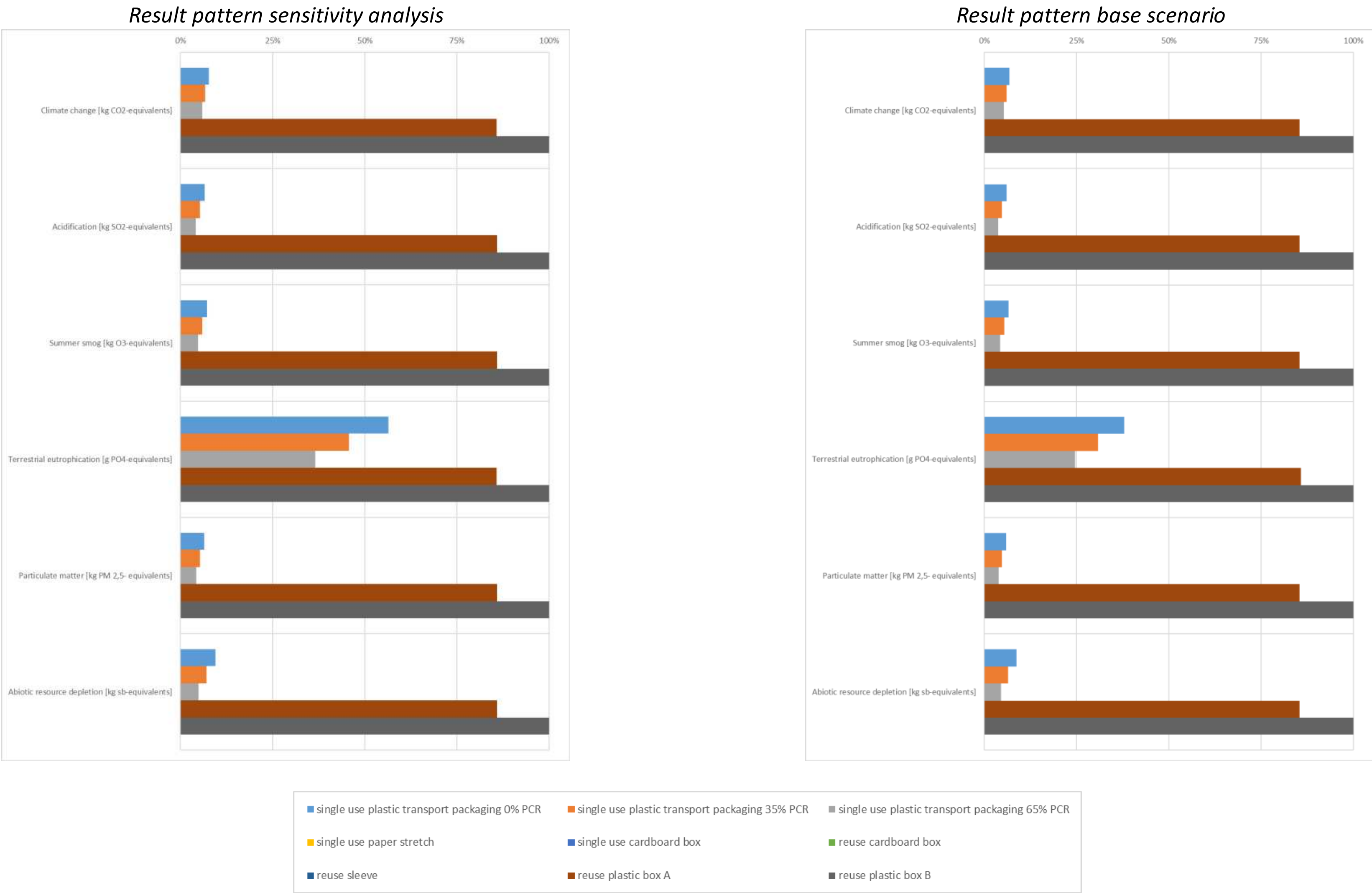
Figure 5-10: relative results in the application field buckets – sensitivity analyses trip rates



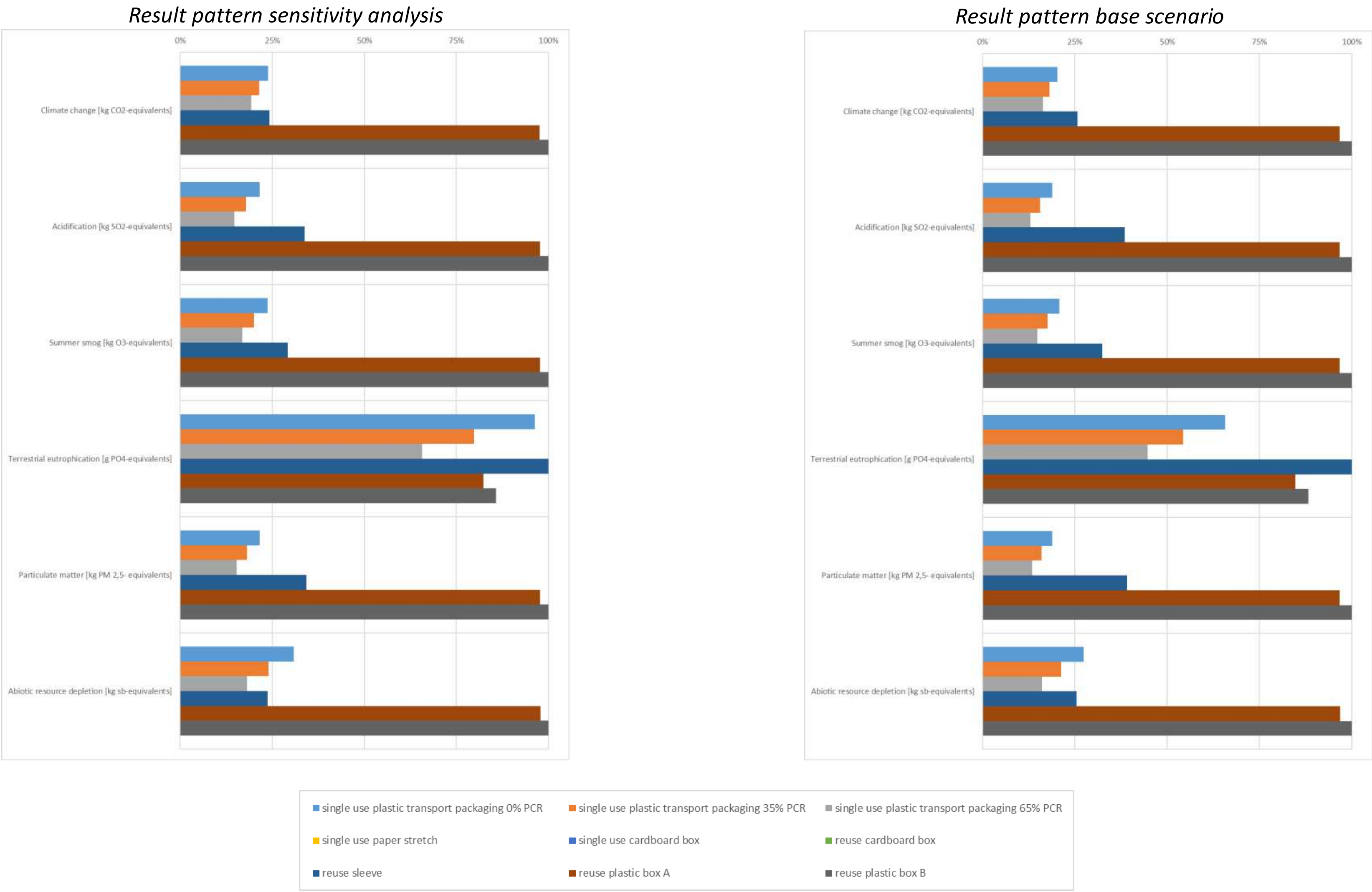
2 **Figure 5-11:** relative results in the application field cement bags – sensitivity analyses trip rates



3 **Figure 5-12:** relative results in the application field polymer bags – sensitivity analyses trip rates



4 **Figure 5-13:** relative results in the application field glass bottles – sensitivity analyses trip rates



5 **Figure 5-14:** relative results in the application field milk bottles – sensitivity analyses trip rates

The results of the sensitivity analysis 'trip rate' show slight shifts in the pattern of results. The results of the reuse alternatives improve and the differences to the single-use plastic transport packaging become smaller. However, there is no reversal of the result pattern at any point. The results are therefore robust to the assumptions made for the trip rates.

In many impact categories a breakeven point is not reached as the distribution burdens in the reuse systems are higher than the net results of the single-use plastic transport packaging.

5.3.2 Assumptions regarding distribution distance

The distribution is a decisive stage in the life cycle of the transport packaging systems. As a distance of 500 km is estimated to be rather low in the base scenarios for the European context, the net results with a higher distribution distance (= 1,000 km) are presented in the following section.

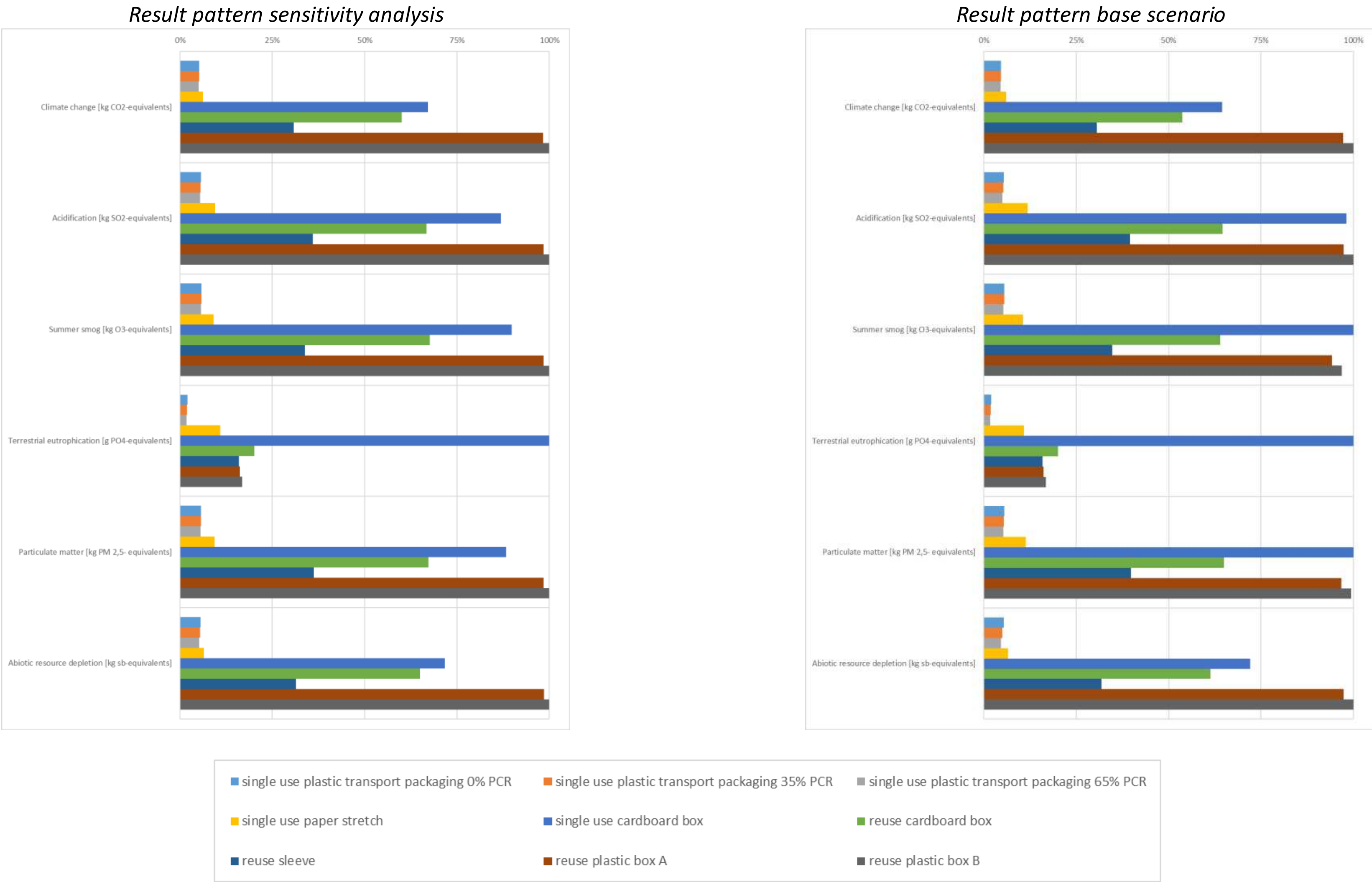


Figure 5-15: relative results in the application field cardboard boxes – sensitivity analyses distribution distance

Result pattern sensitivity analysis *Result pattern base scenario*

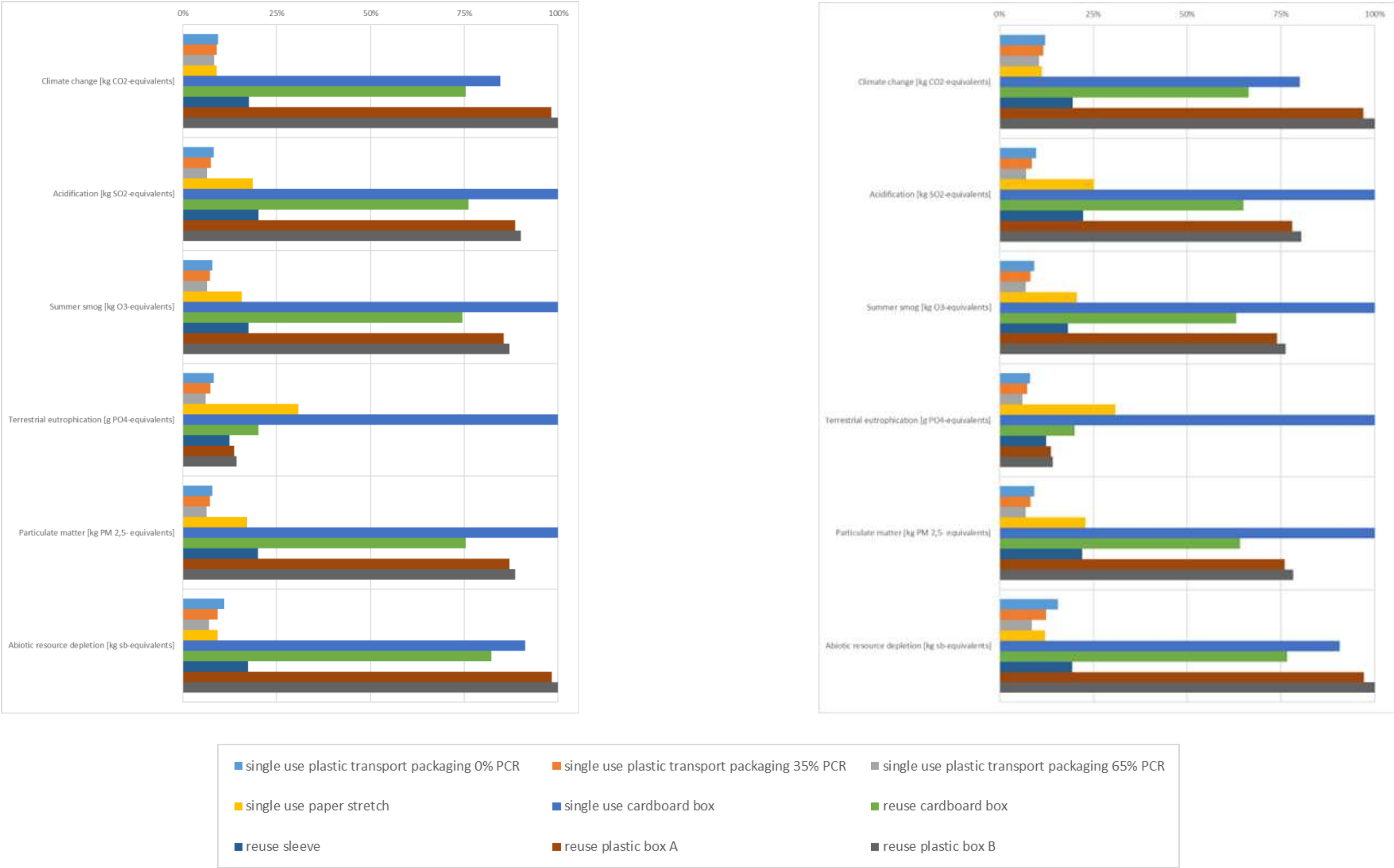


Figure 5-16: relative results in the application field PET water and CSD bottles – sensitivity analyses distribution distance

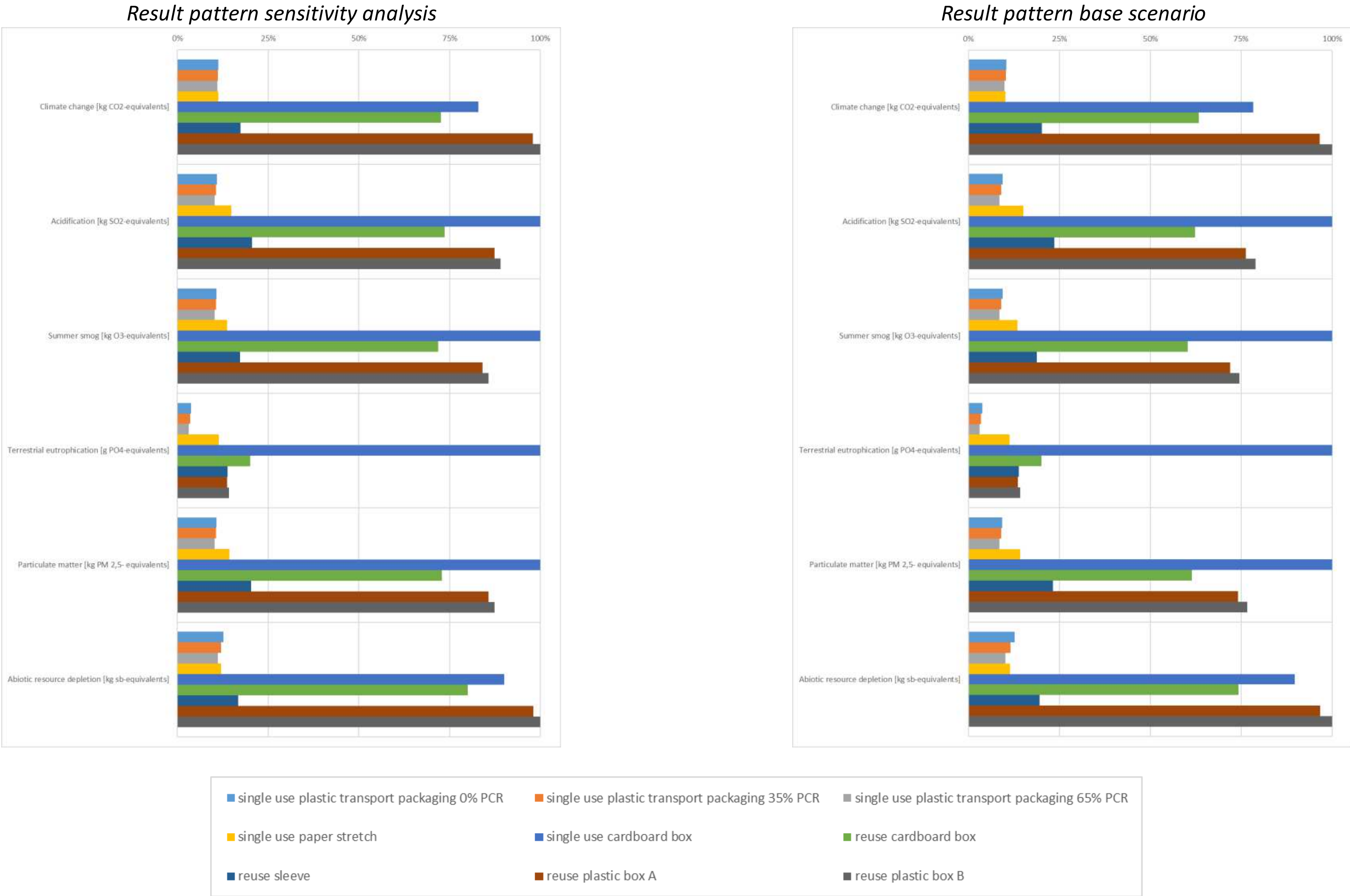
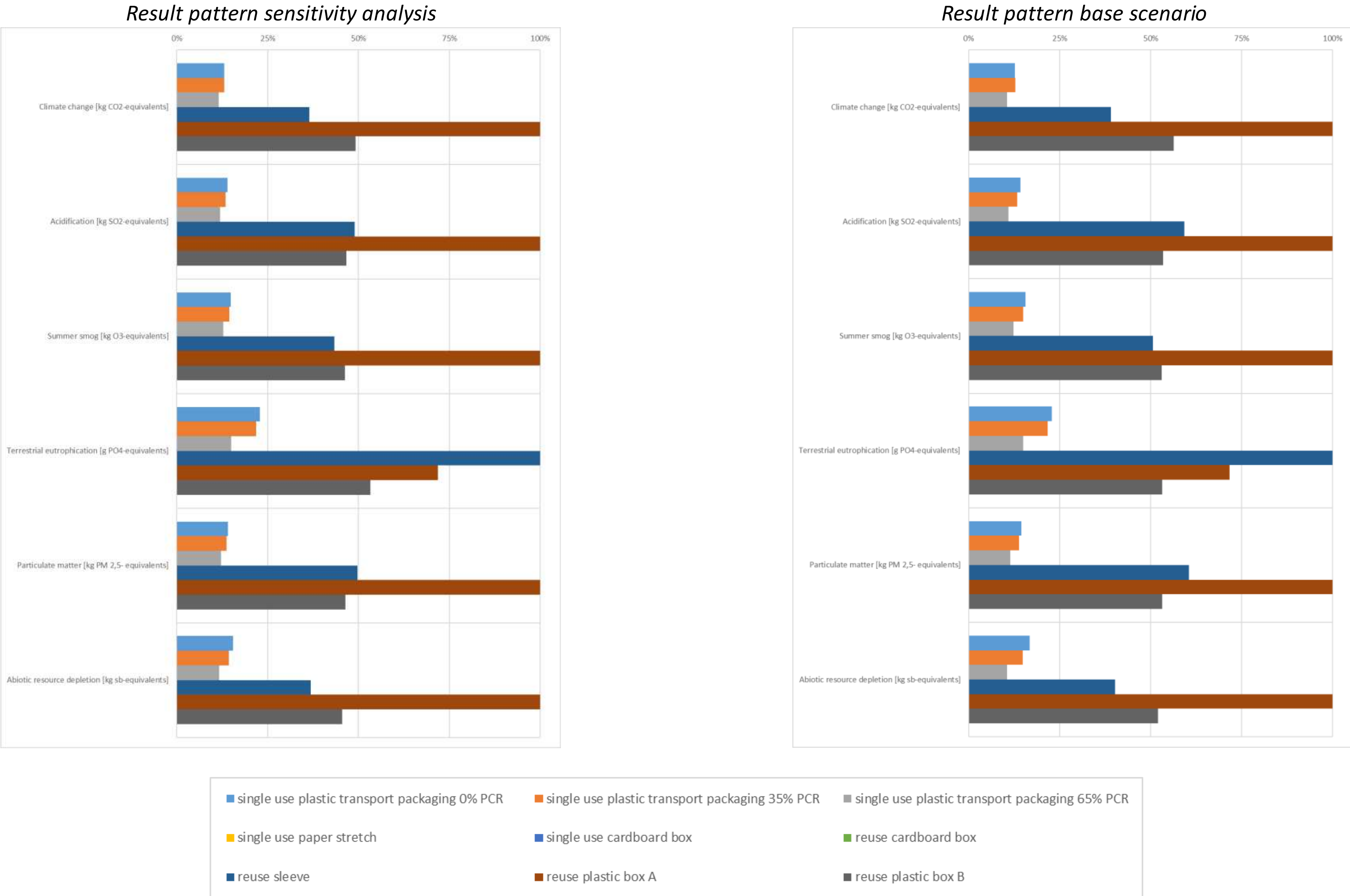
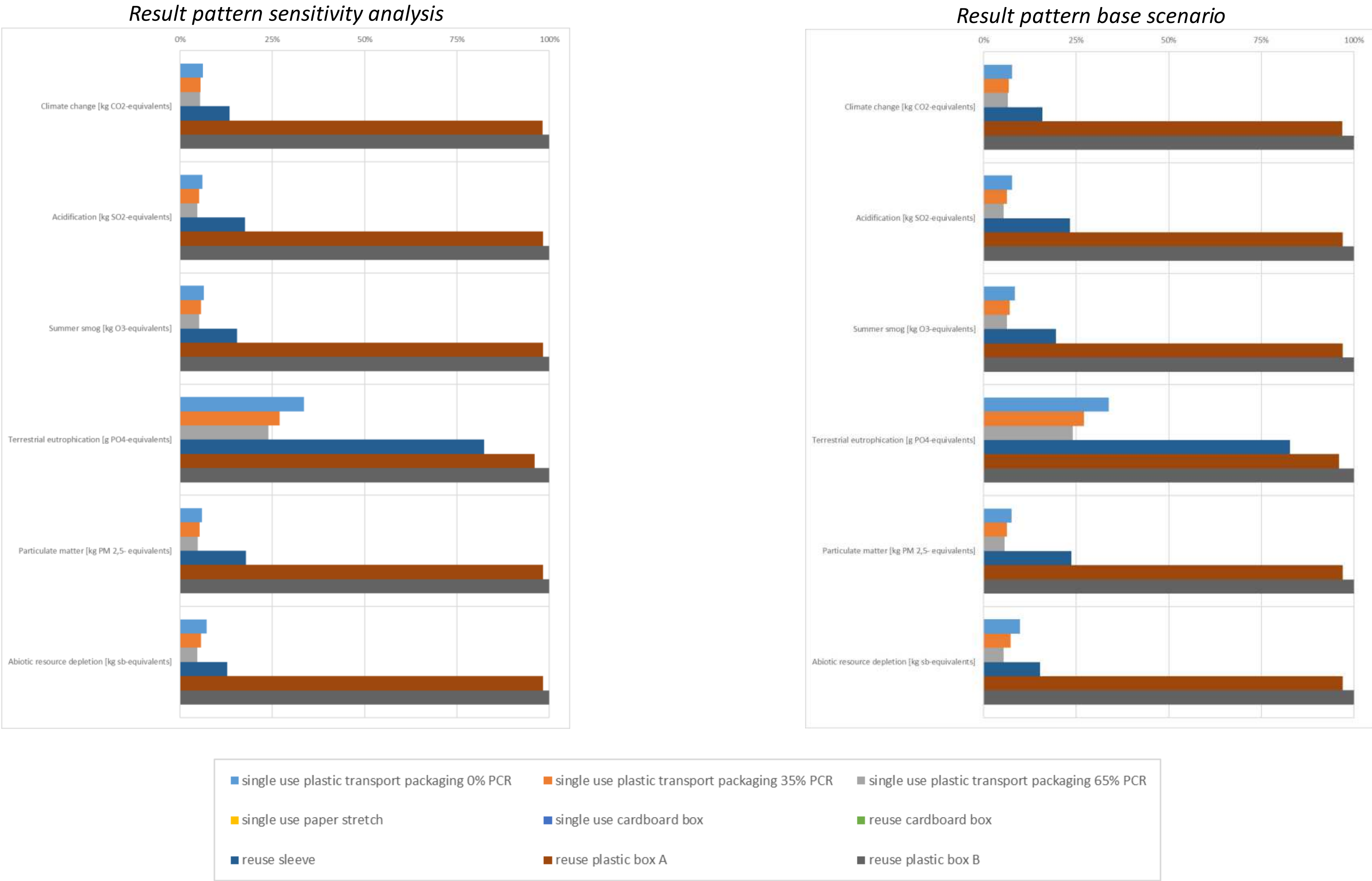


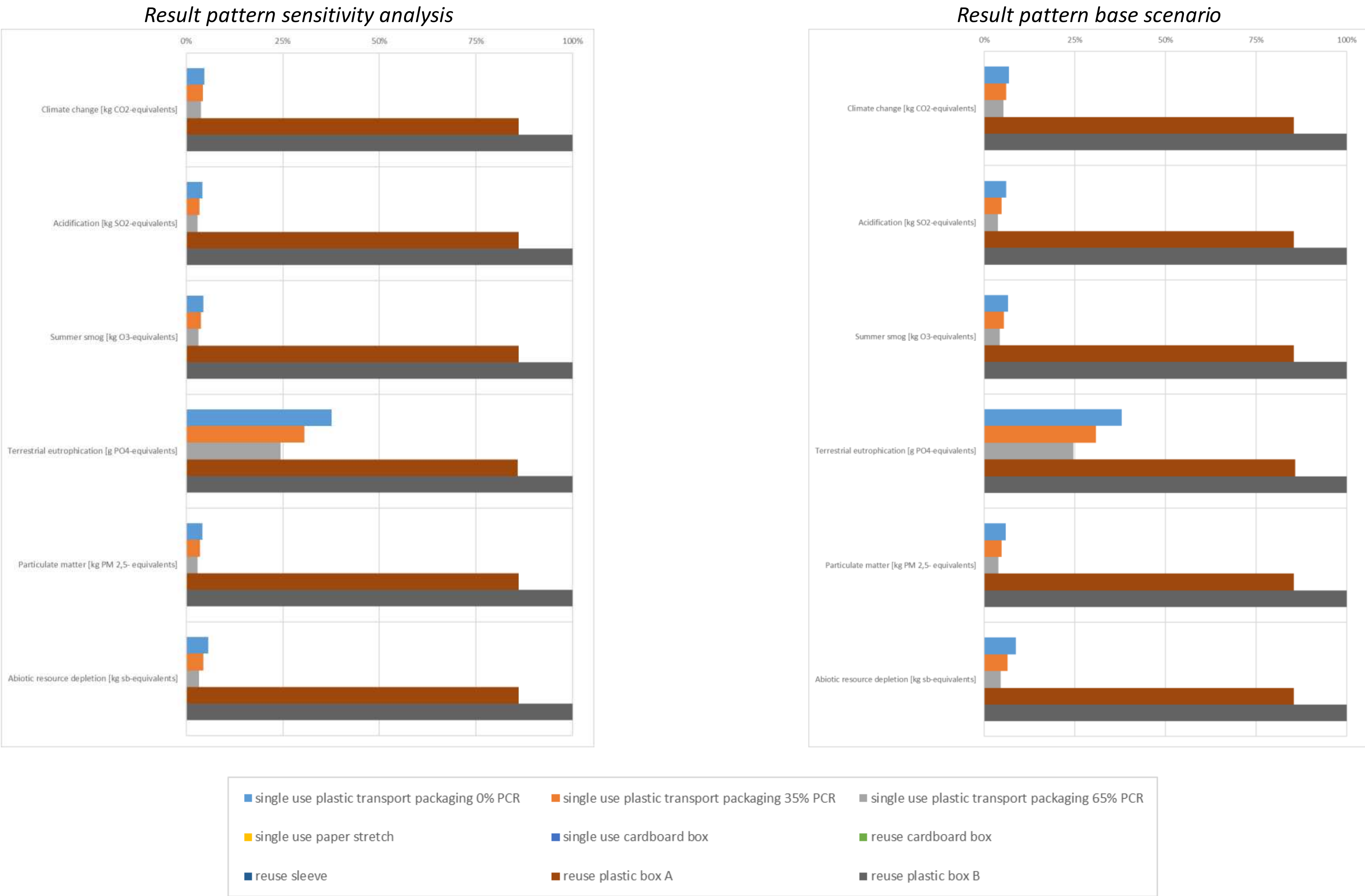
Figure 5-17: relative results in the application field buckets – sensitivity analyses distribution distance



22 **Figure 5-18:** relative results in the application field cement bags – sensitivity analyses distribution distance



23 **Figure 5-19:** relative results in the application field polymer bags – sensitivity analyses distribution distance



24 **Figure 5-20:** relative results in the application field glass bottles – sensitivity analyses distribution distance

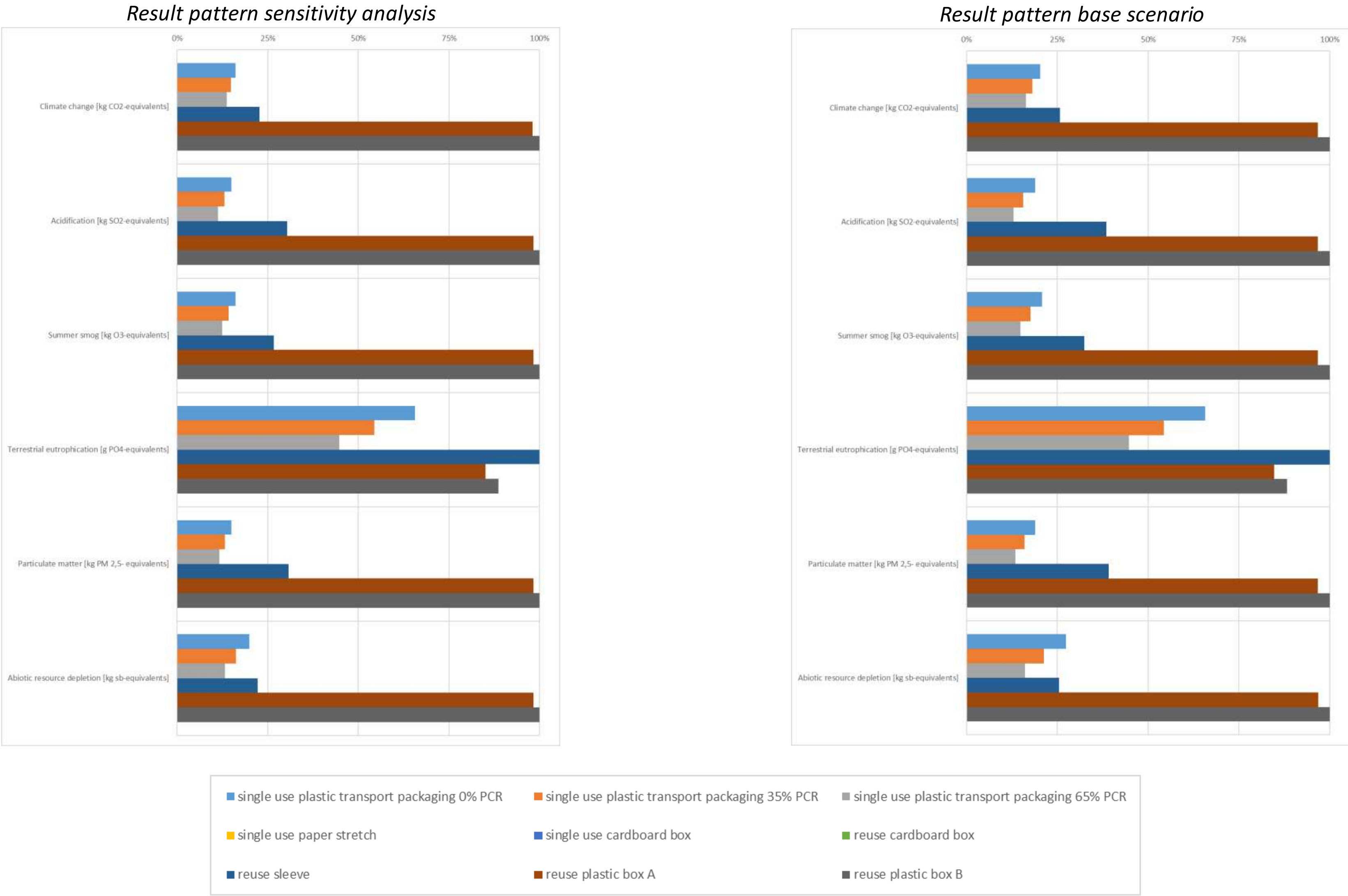


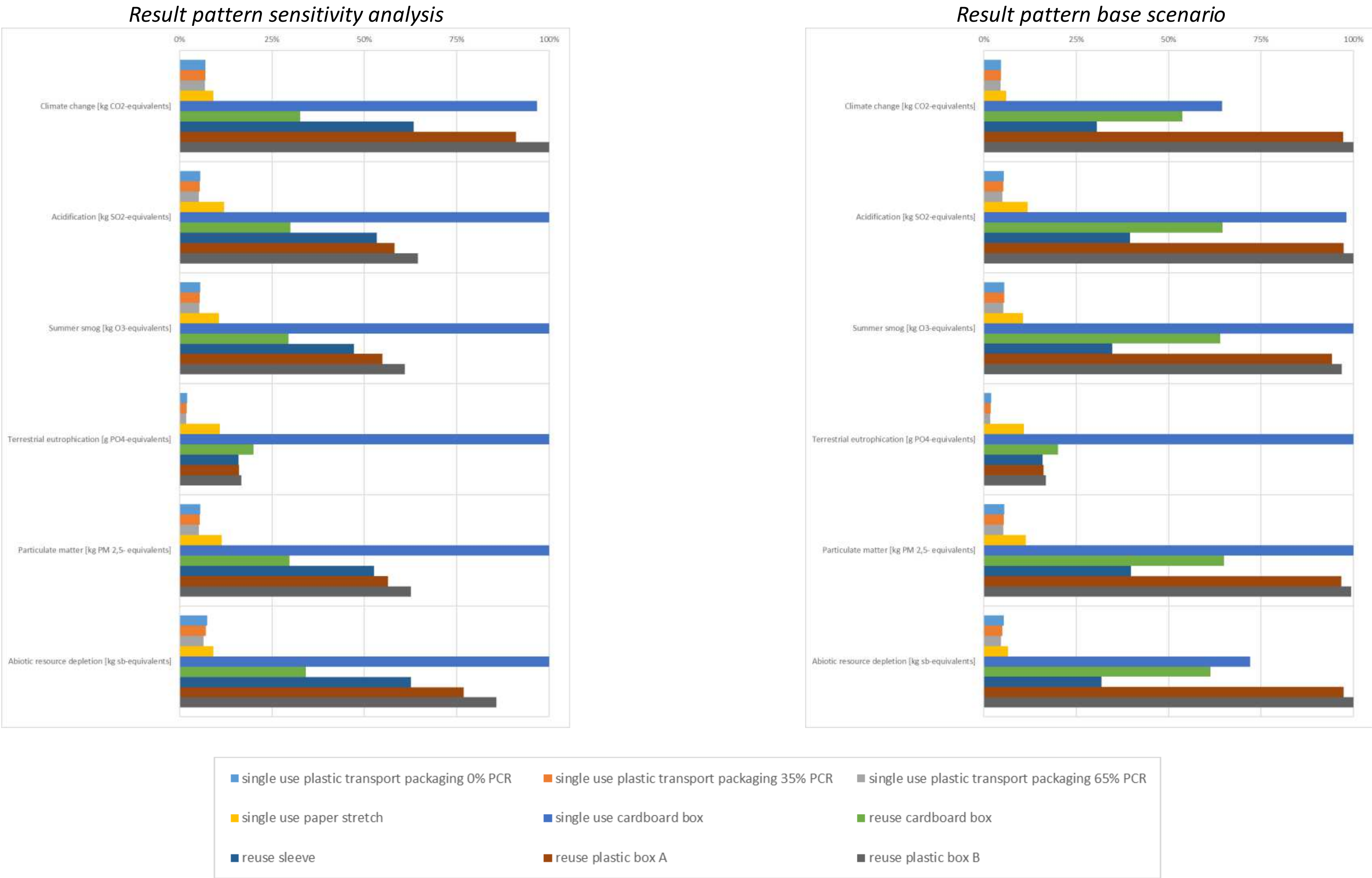
Figure 5-21: relative results in the application field milk bottles – sensitivity analyses distribution distance

The basic pattern of results is changing in that the gap between single-use plastic transport packaging and reuse alternatives is widening, as distribution tend to play a greater role in reuse systems.

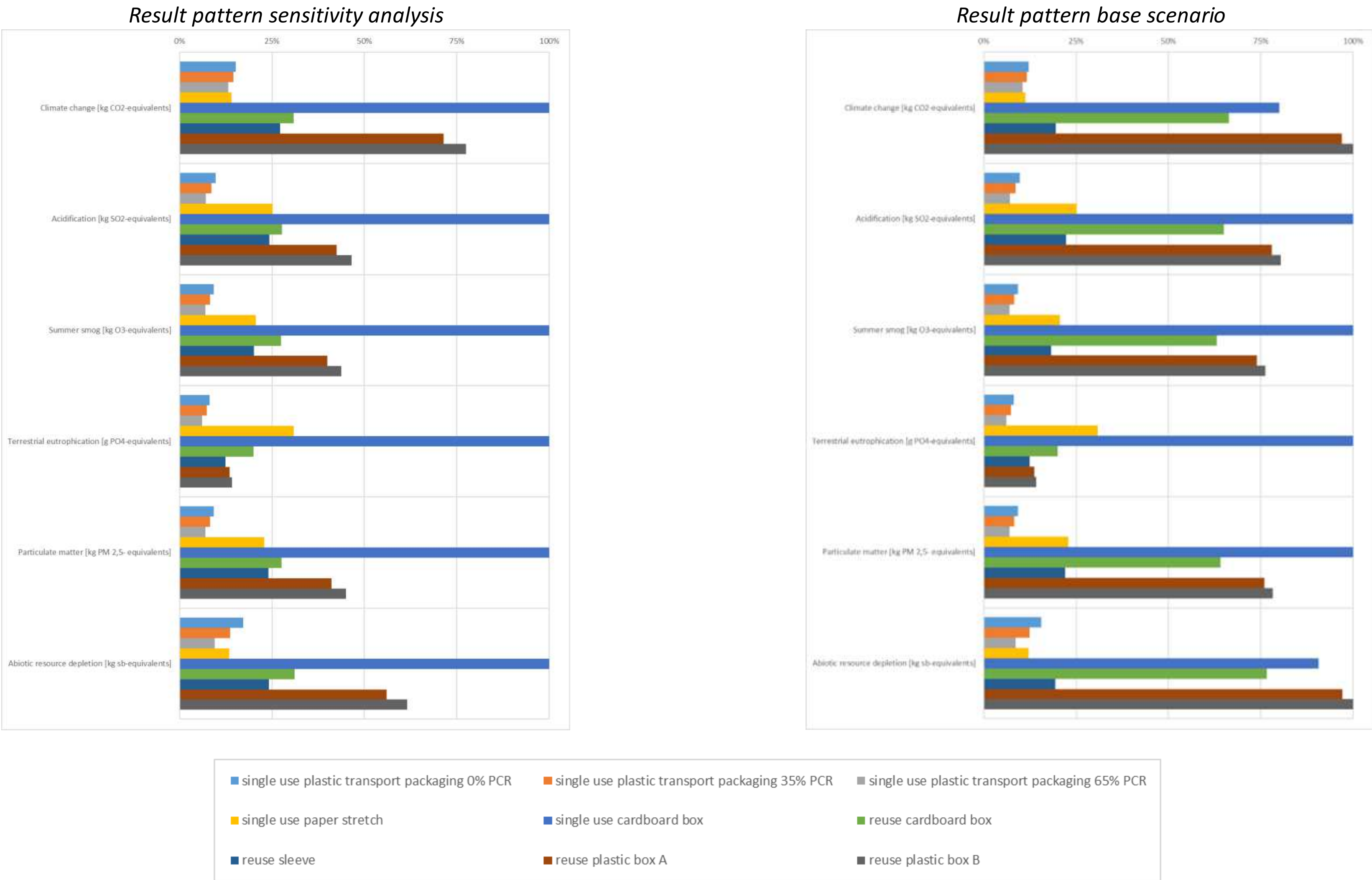
5.3.3 Assumptions regarding utilisation rate in distribution

It turns out, that capacity utilisation is a more important determinant of transport emissions than the distribution distance. In the base scenarios, the capacity utilisation of the reuse systems is relatively low as the EUMOS test series assumes that the boxes are only single-stacked. This leads to a low utilisation and therefore to higher emissions per tonne of goods transported (as the basic load of the truck must be distributed over fewer goods). A sensitivity analysis is therefore carried out by increasing the capacity utilisation in the lorries until either the weight or volume limit is reached. To do this, double or triple stacking of packaging systems (single-use and reuse) is included in the balance wherever possible.

In the base scenarios with single layer truck loading, the payload is already more than 50% exhausted for the cement bags, polymer bags and milk bottles. Double stacking would therefore lead to the permissible payload being exceeded, so no sensitivity analysis can be carried out for these three application fields.



43 **Figure 5-22:** relative results in the application field cardboard boxes - sensitivity analyses utilisation rate



44 **Figure 5-23:** relative results in the application field PET water and CSD bottles - sensitivity analyses utilisation rate

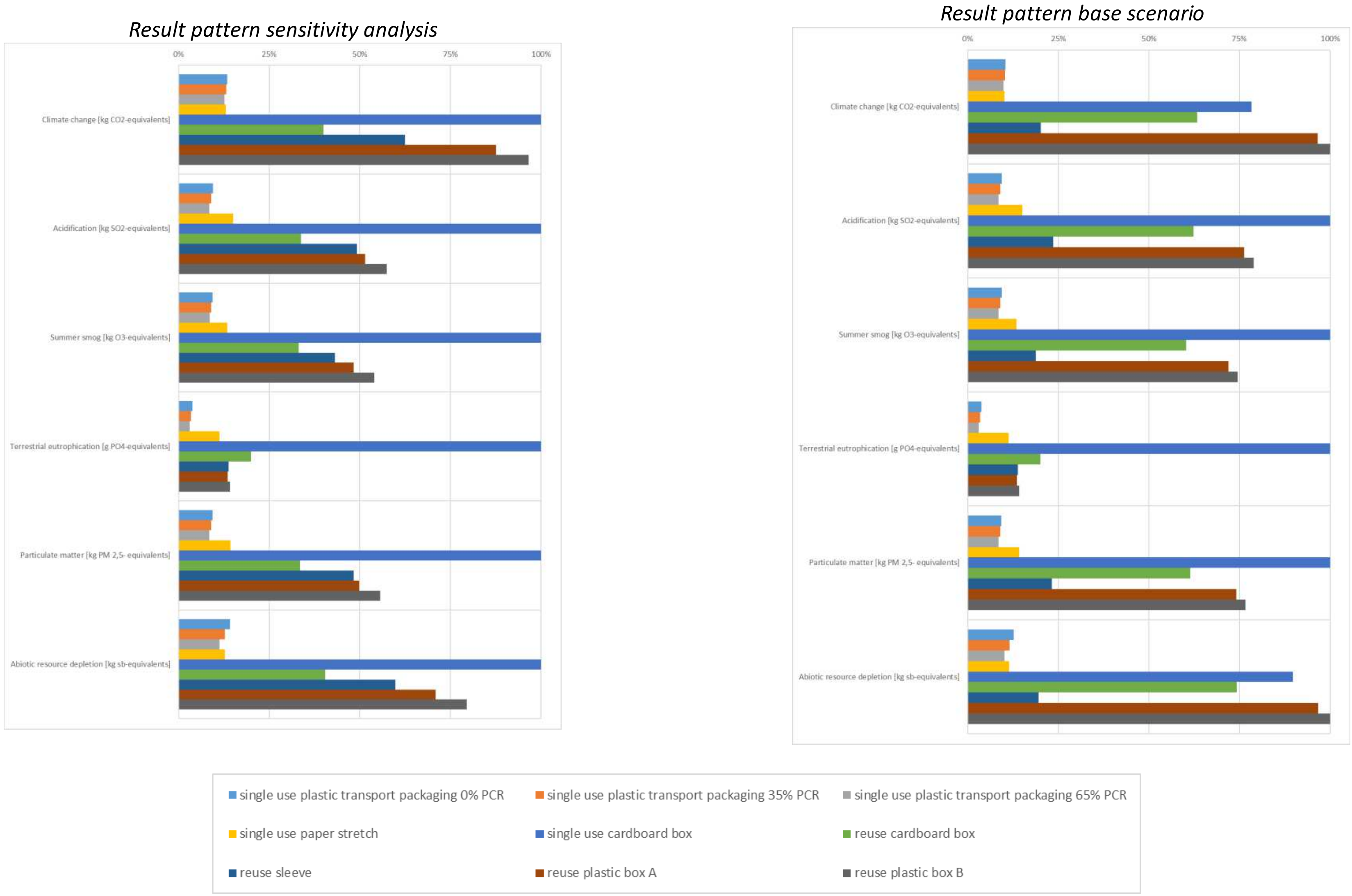
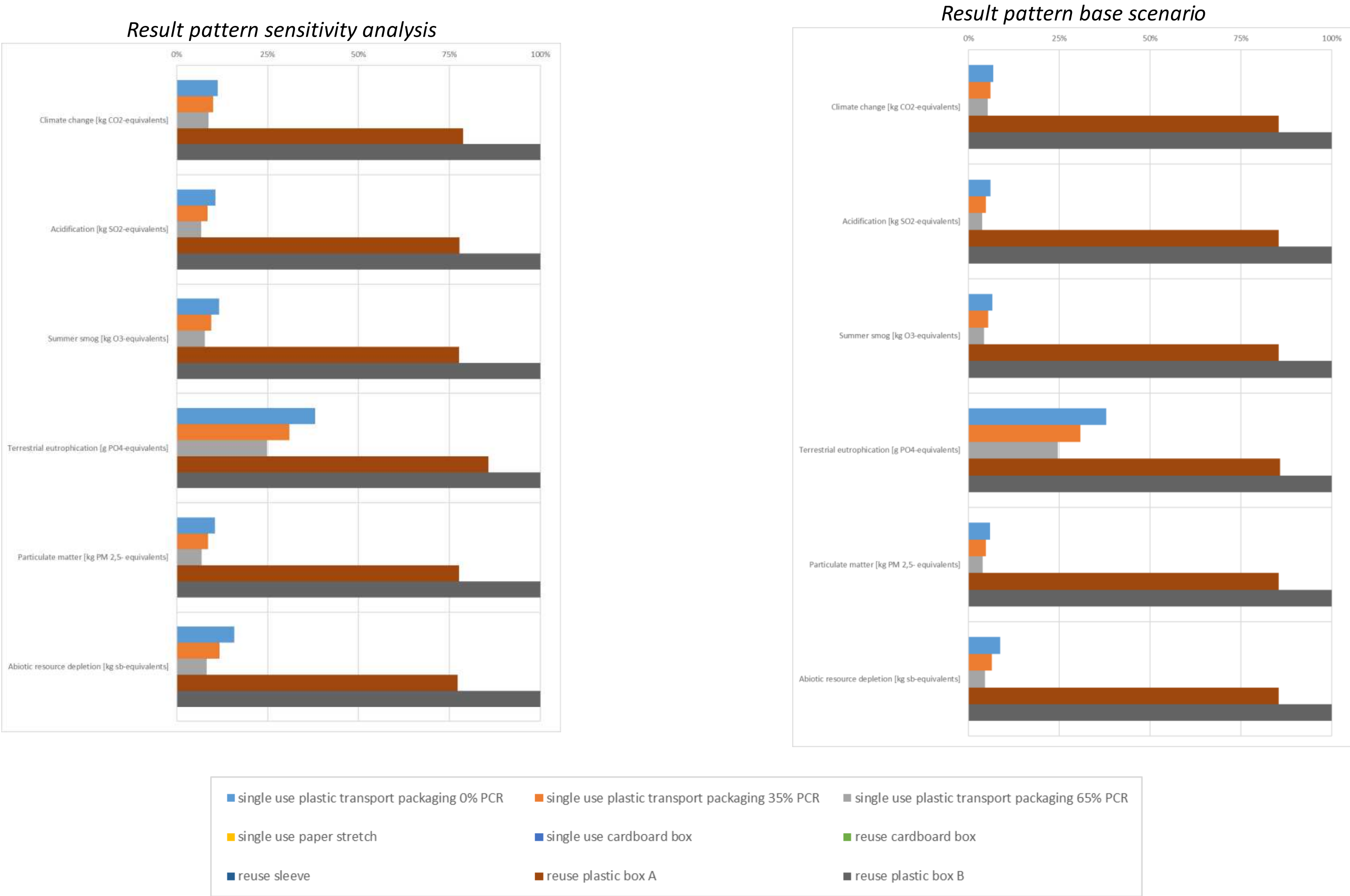


Figure 5-24: relative results in the application field buckets - sensitivity analyses utilisation rate



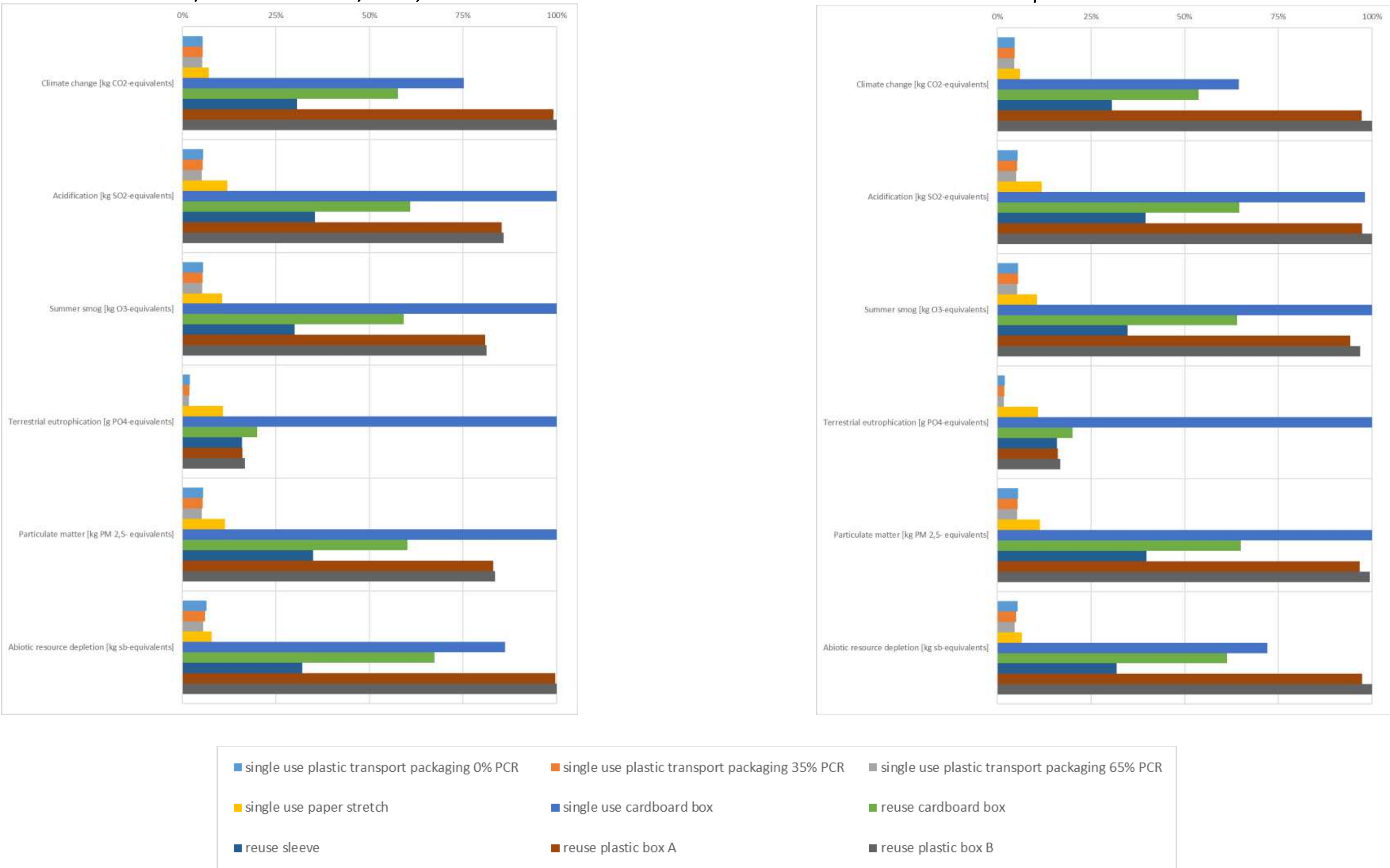
46 **Figure 5-25:** relative results in the application field glass bottles - sensitivity analyses utilisation rate

The results show that the differences between single-use plastic transport packaging and format-specific reuse solutions are diminishing, but without reversing the base scenario results. For most of the environmental aspects studied, the single-use cardboard box remains the solution with the highest environmental impact. The results of the study are therefore robust to the assumption of double or triple stacking of reuse and single-use packaging.

5.3.4 Assumptions regarding redistribution distance

As described in chapter 2.4 various positive assumptions regarding the redistribution of empty reuse transport packaging are made. The result of these assumptions show that redistribution is not a relevant life cycle stage in the LCA of reuse packaging. Nevertheless, a sensitivity analysis is carried out at this point where the environmental impacts of redistribution are completely excluded from the systems. This sensitivity assumes that the reuse transport packaging can be reused directly.

Result pattern sensitivity analysis *Result pattern base scenario*



59 **Figure 5-26:** relative results in the application field cardboard boxes – sensitivity analyses redistribution distance

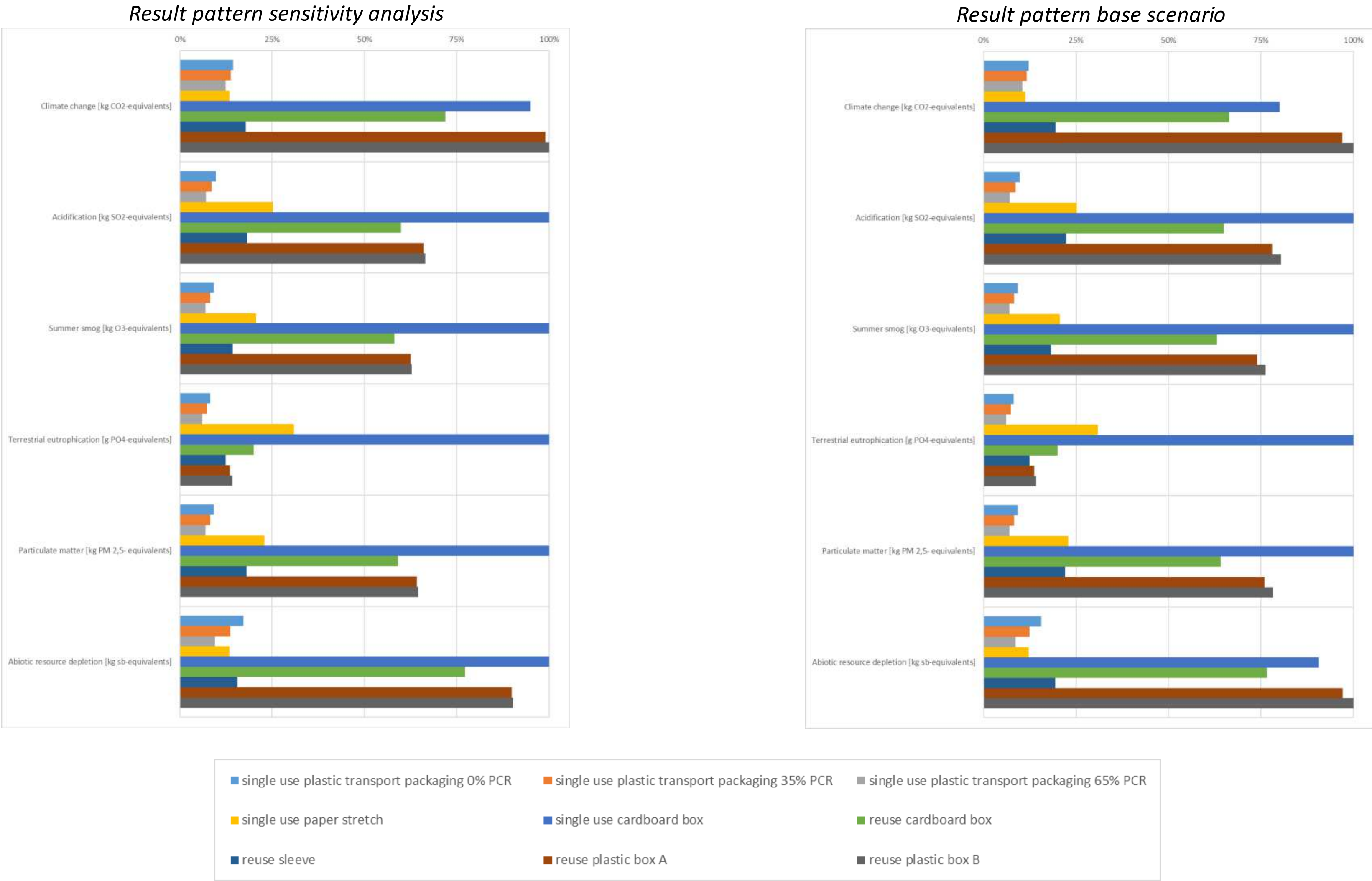
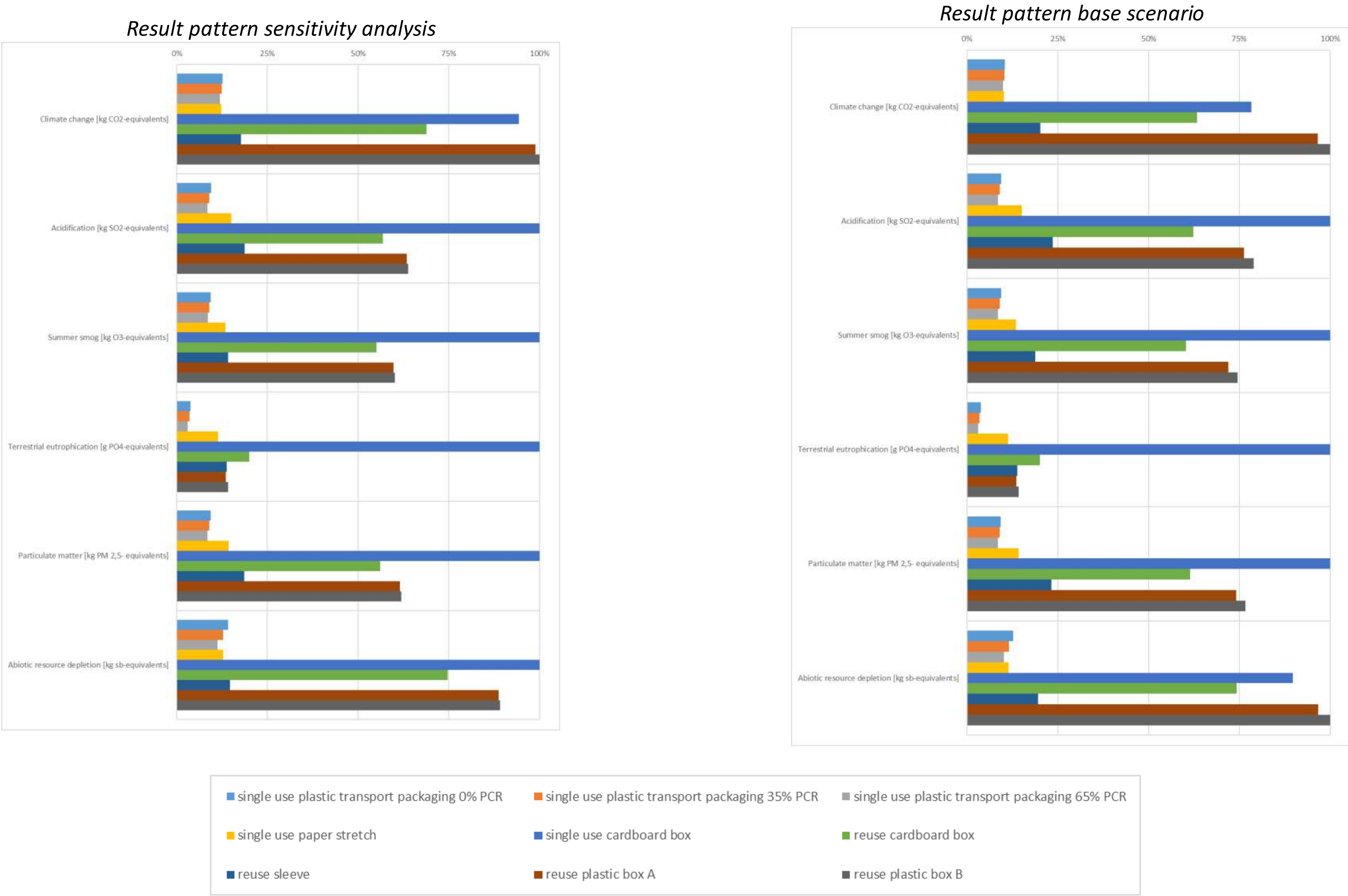
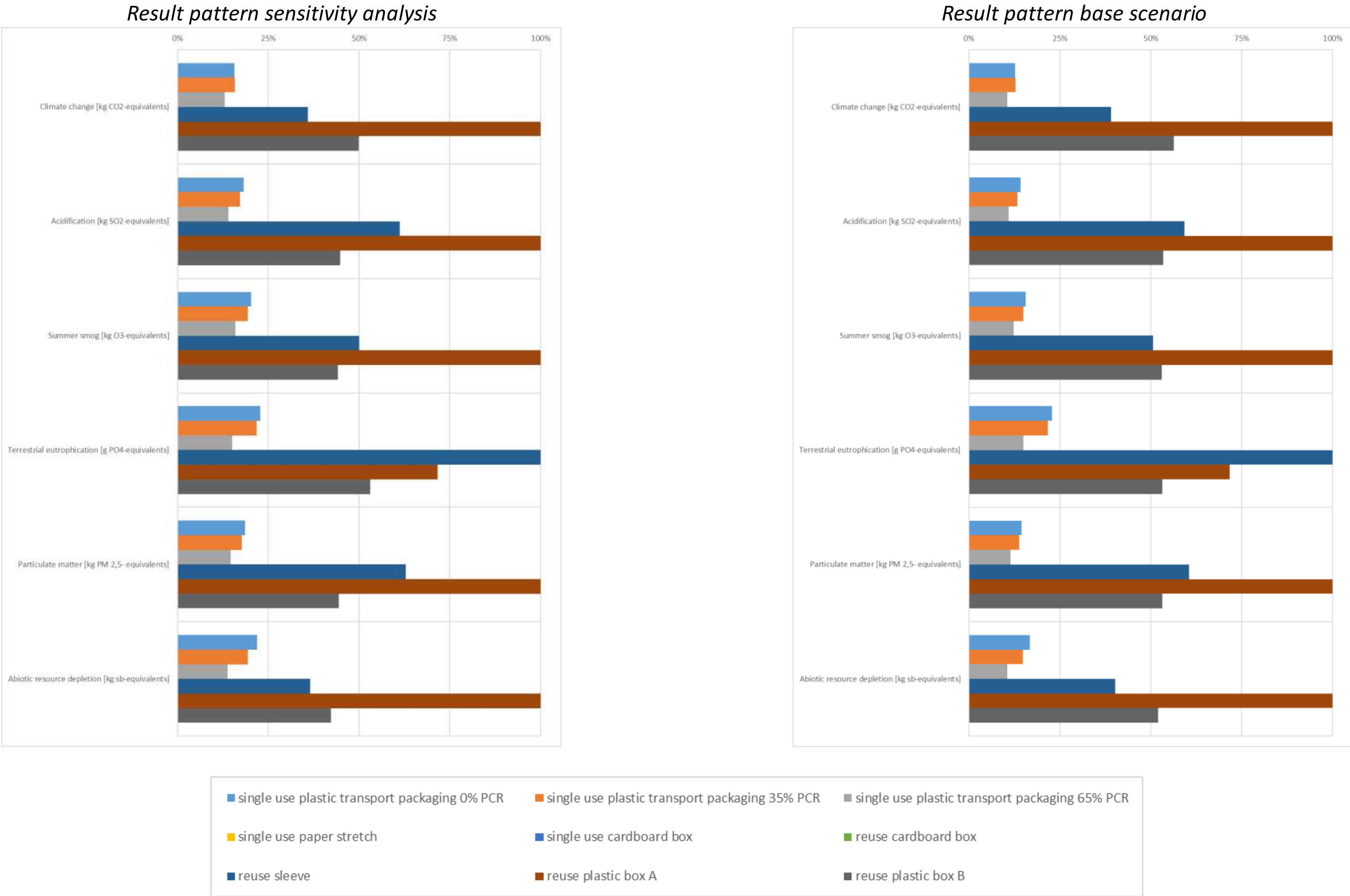


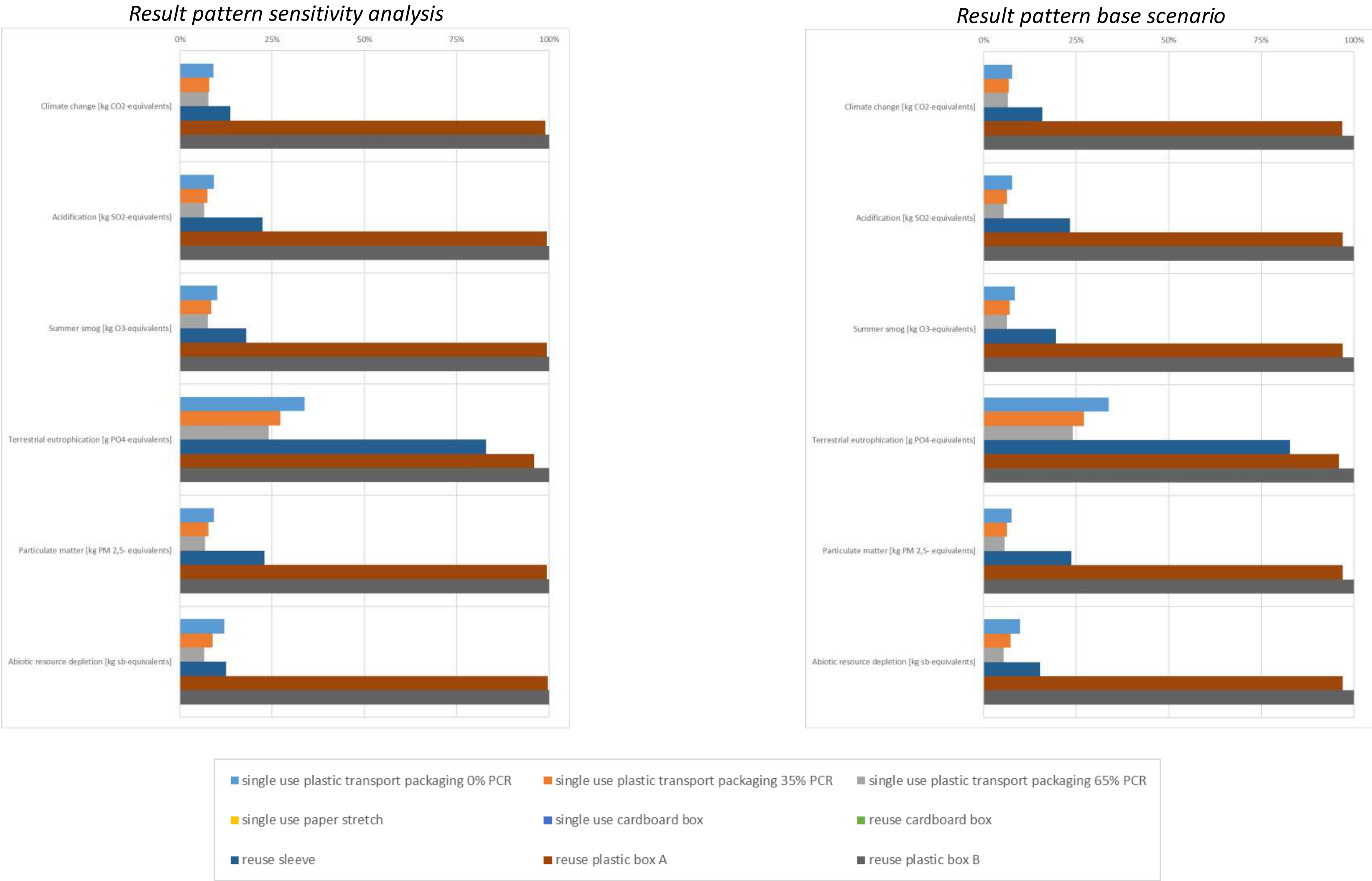
 Figure 5-27: relative results in the application field PET water and CSD bottles – sensitivity analyses redistribution distance



61 **Figure 5-28:** relative results in the application field buckets – sensitivity analyses redistribution distance



62 **Figure 5-29:** relative results in the application field cement bags – sensitivity analyses redistribution distance



63 **Figure 5-30:** relative results in the application field polymer bags – sensitivity analyses redistribution distance

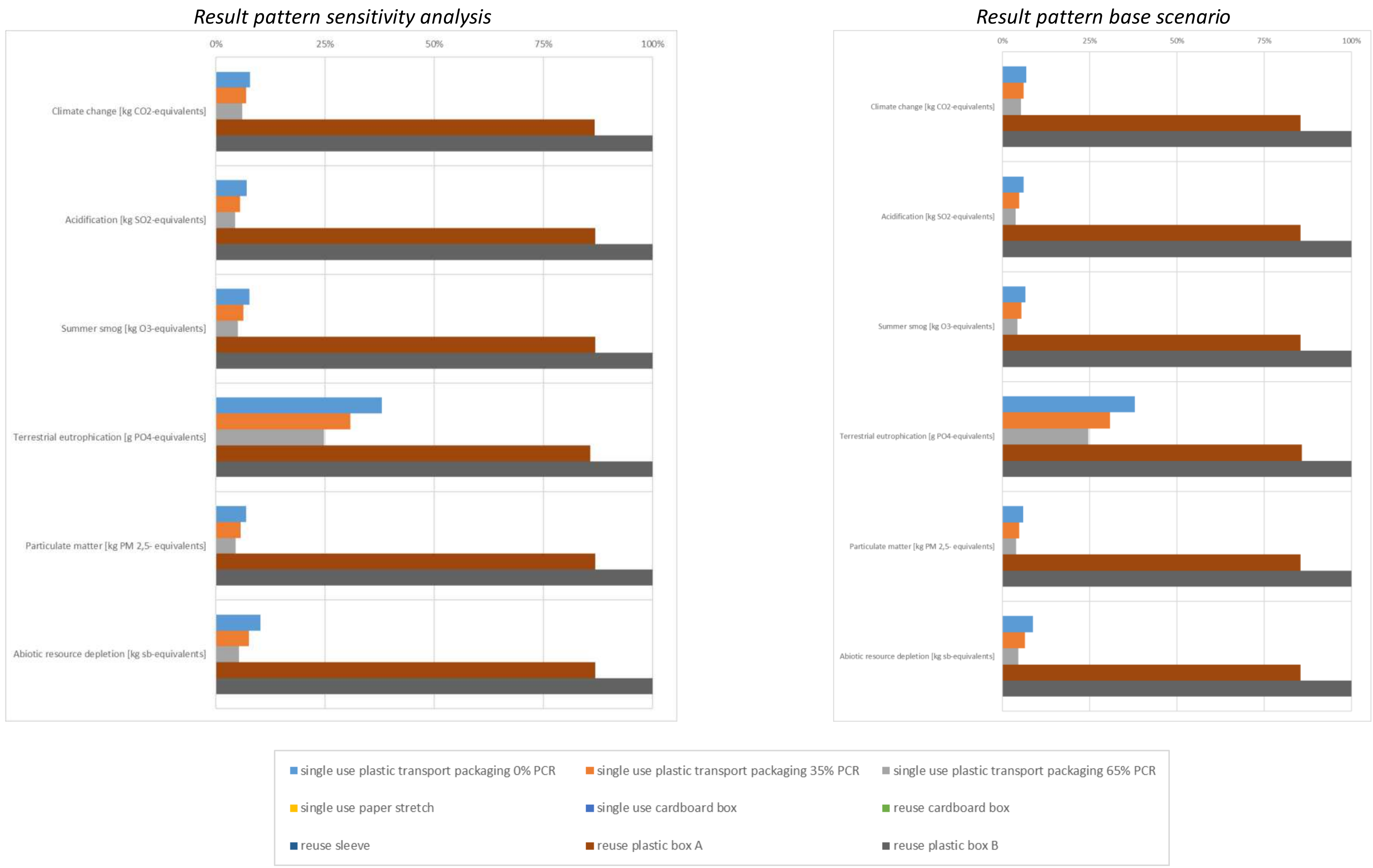
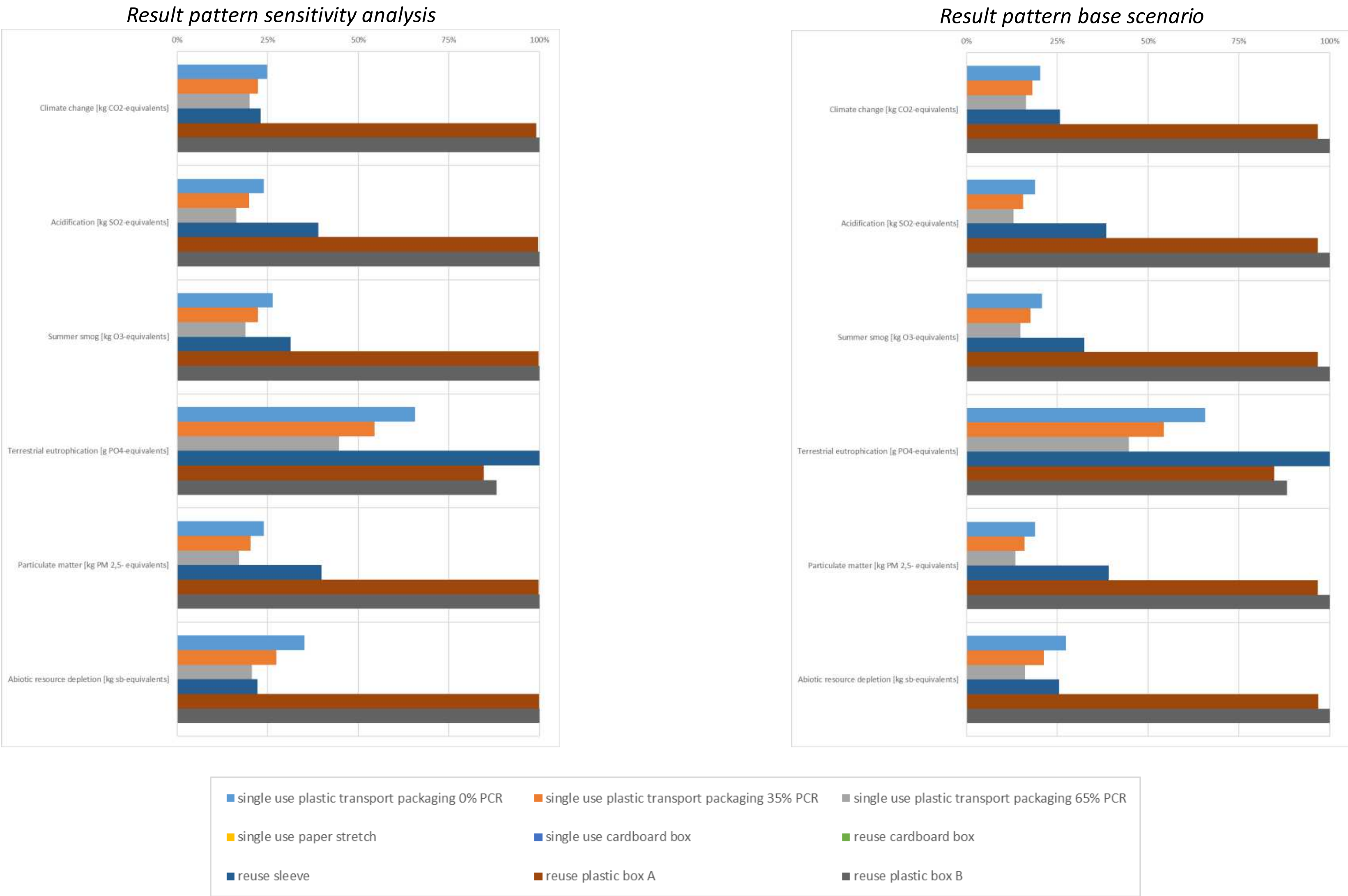


Figure 5-31: relative results in the application field glass bottles – sensitivity analyses redistribution distance



65 **Figure 5-32:** relative results in the application field milk bottles – sensitivity analyses redistribution distance

The patterns of results change only slightly, as redistribution does not make a significant contribution to the overall environmental impact of the reuse systems in the baseline scenarios either.

5.3.5 Assumptions regarding the PCR content in the reuse sleeve

In the base scenarios, the reuse sleeve is analysed without the use of PCR, as the product purchased for testing purposes does not claim to contain PCR material and the odour of the product suggests that it is made from 100% new material.

However, as reuse products will also have to provide evidence of PCR content from 2030, a variant of the reusable sleeve with 65% PCR content in the plastic is analysed in the form of a sensitivity scenario. For this, the PCR content in the PET fabric is increased to 88.2% as part of the assessment in order to achieve the 65% quota. It is assumed that the PA hook and loop fastener is still made from primary material.

Amorphous PET from the reprocessing of rigid and semi-rigid PET packaging is used as PCR material, as the reprocessing loads for amorphous PET are significantly lower than for PET bottle grade. However, as the PCR material is used in the form of a fabric, it can be assumed that bottle grade quality is not required.

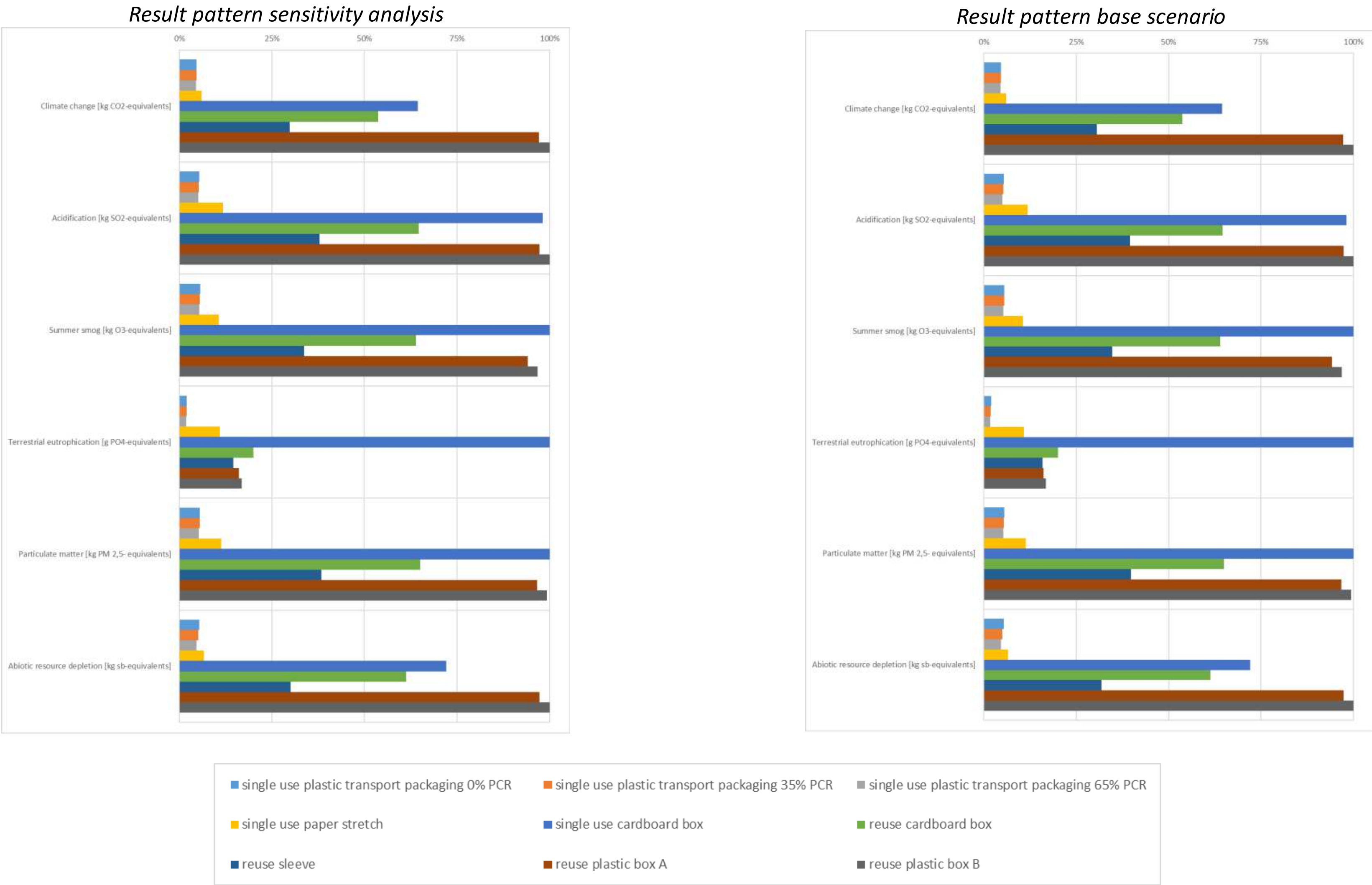


Figure 5-33: relative results in the application field cardboard boxes – sensitivity analysis PCR content in reuse sleeve

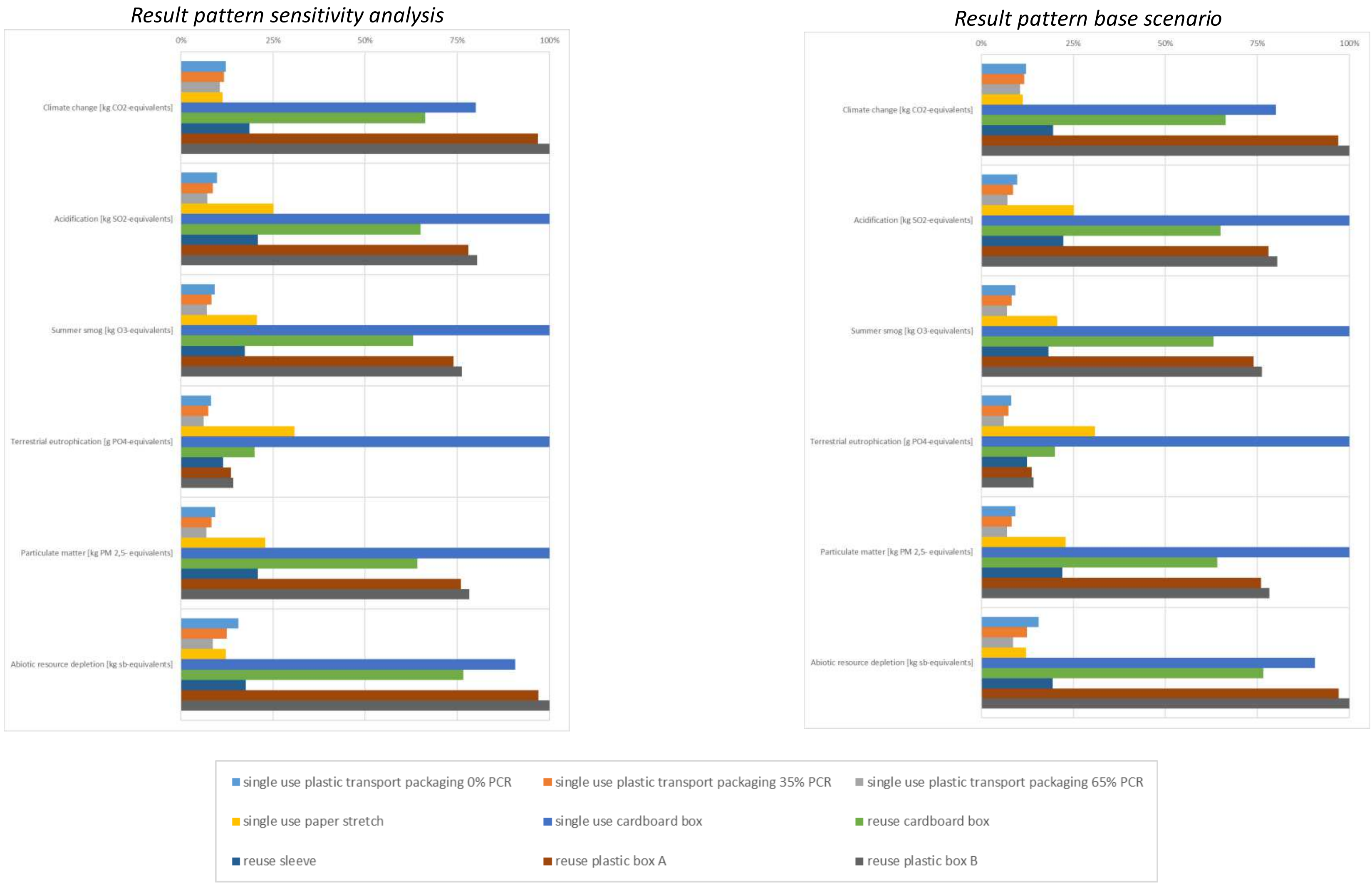
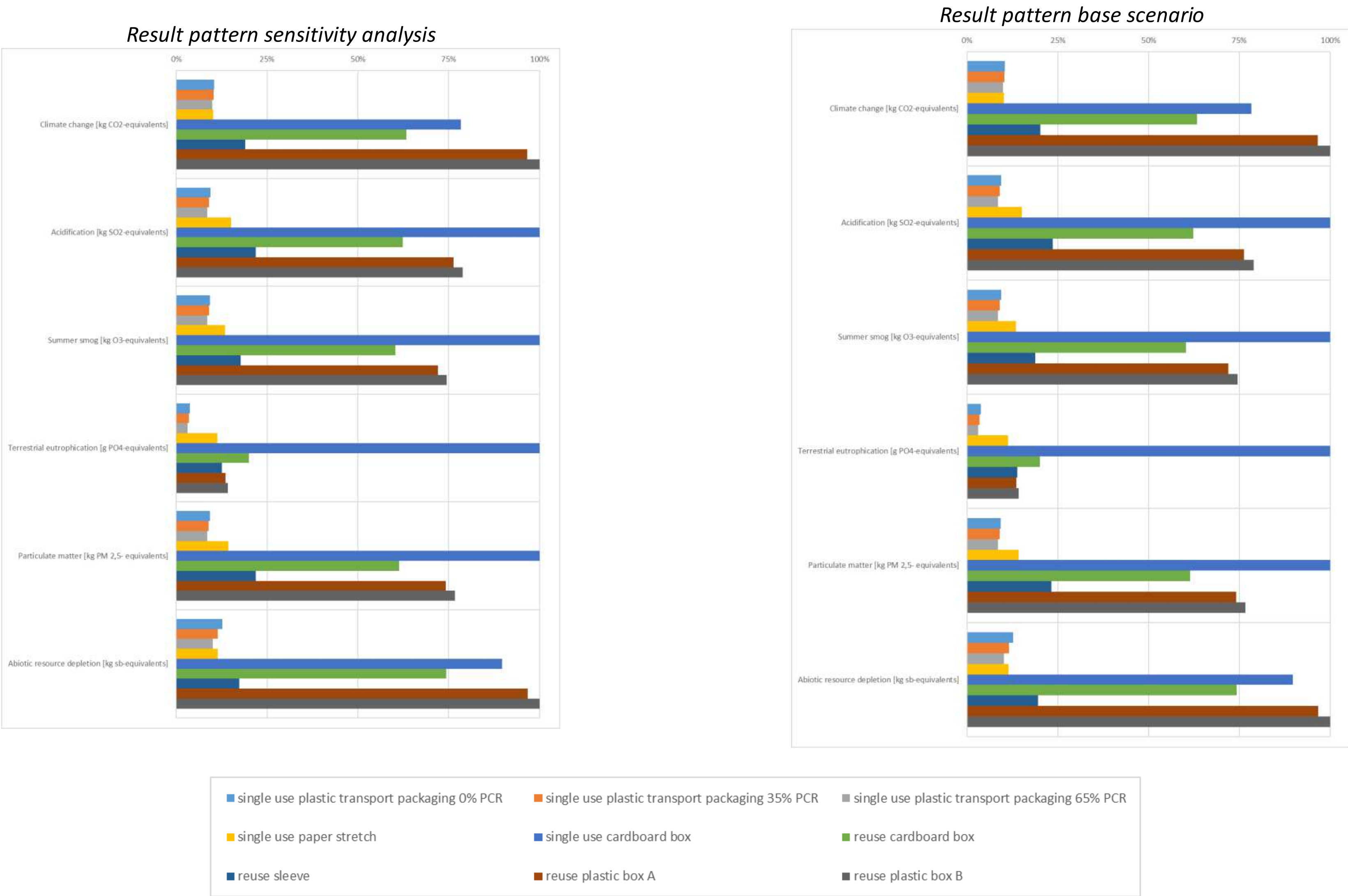


Figure 5-34: relative results in the application field PET water and CSD bottles – sensitivity analysis PCR content in reuse sleeve



85 **Figure 5-35:** relative results in the application field buckets – sensitivity analysis PCR content in reuse sleeve

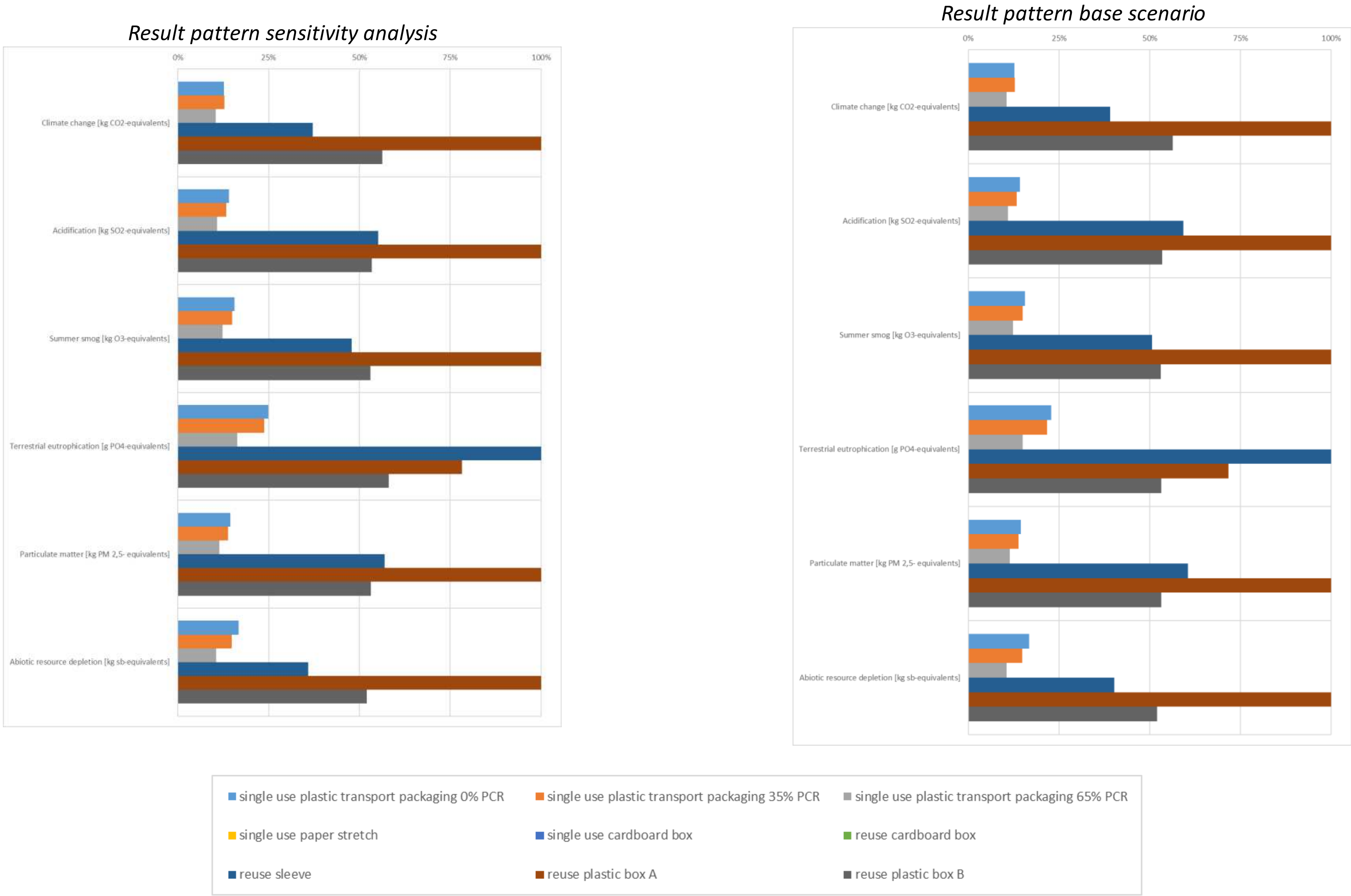
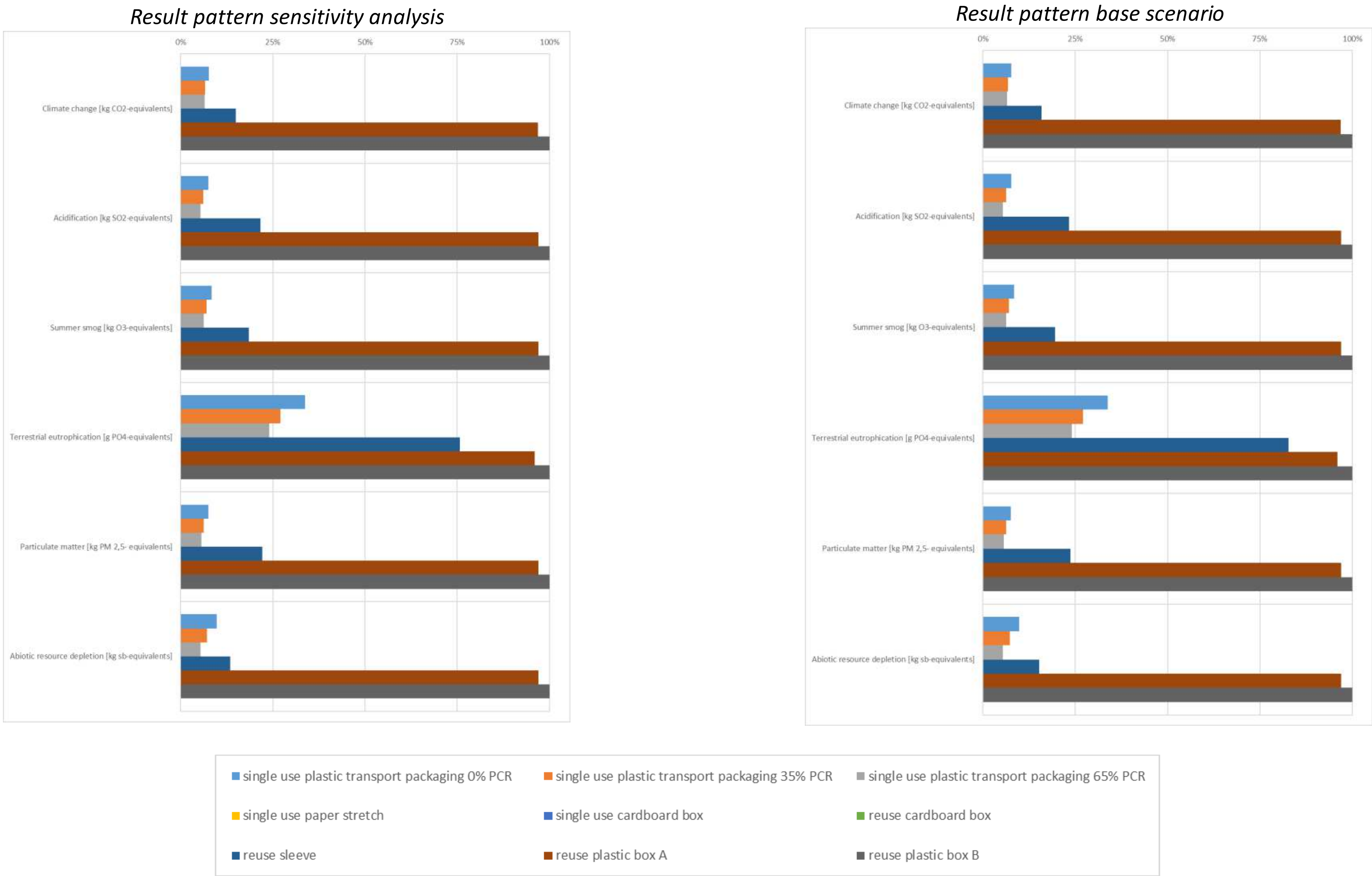


Figure 5-36: relative results in the application field cement bags – sensitivity analysis PCR content in reuse sleeve



87 **Figure 5-37:** relative results in the application field polymer bags – sensitivity analysis PCR content in reuse sleeve

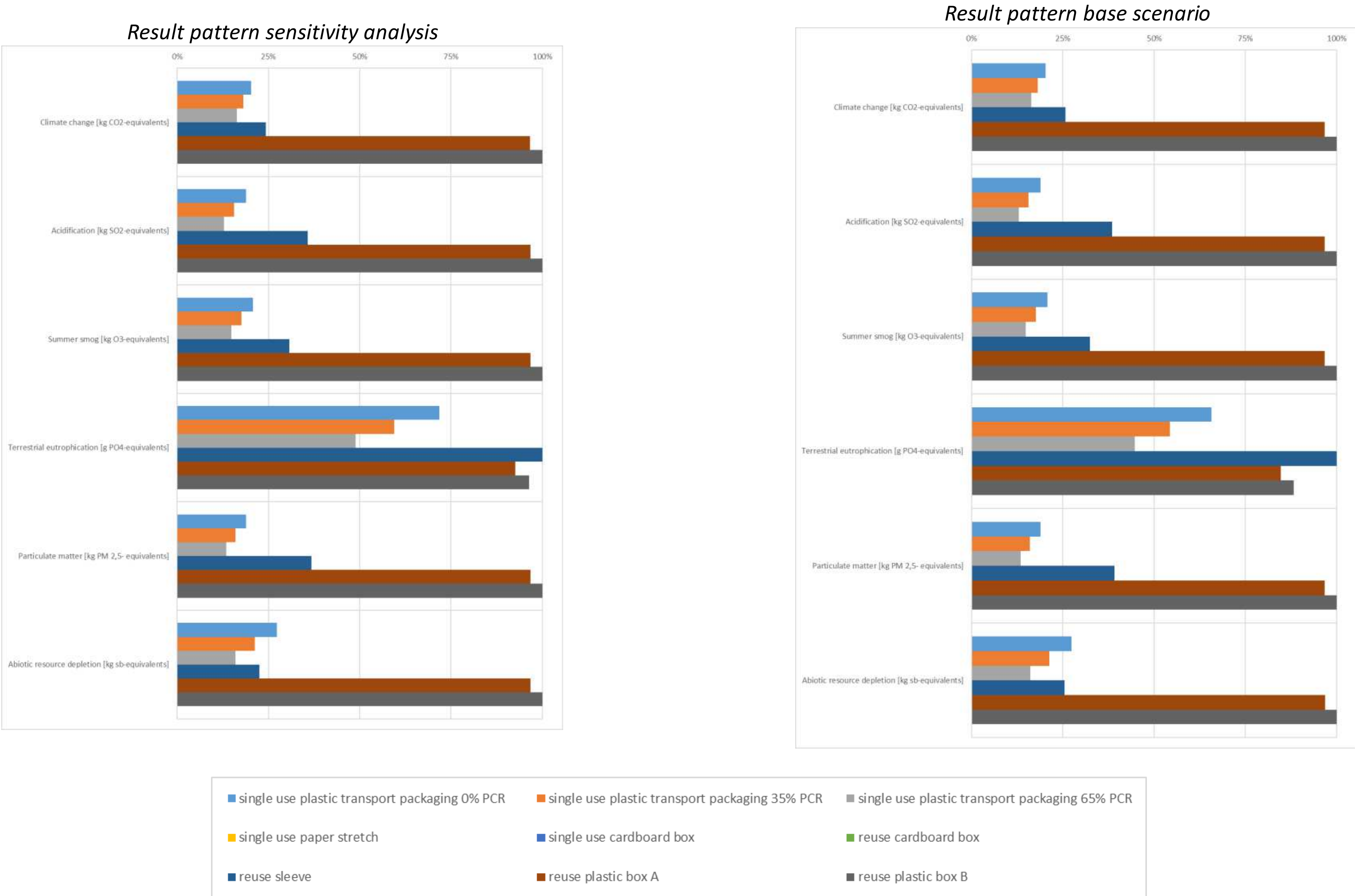


Figure 5-38: relative results in the application field milk bottles – sensitivity analysis PCR content in reuse sleeve

The results show that the environmental impact of the reuse sleeve is reduced when PCR is used. However, there is no significant change in the pattern of results already known from the base scenarios. In the application areas of water and CSD bottles and milk bottles, where the results of the reuse sleeve are already close to the results of the single-use transport packaging in the base scenarios, there is a change in the direct positioning in certain impact categories. The differences in the numerical results remain well below the defined significance threshold.

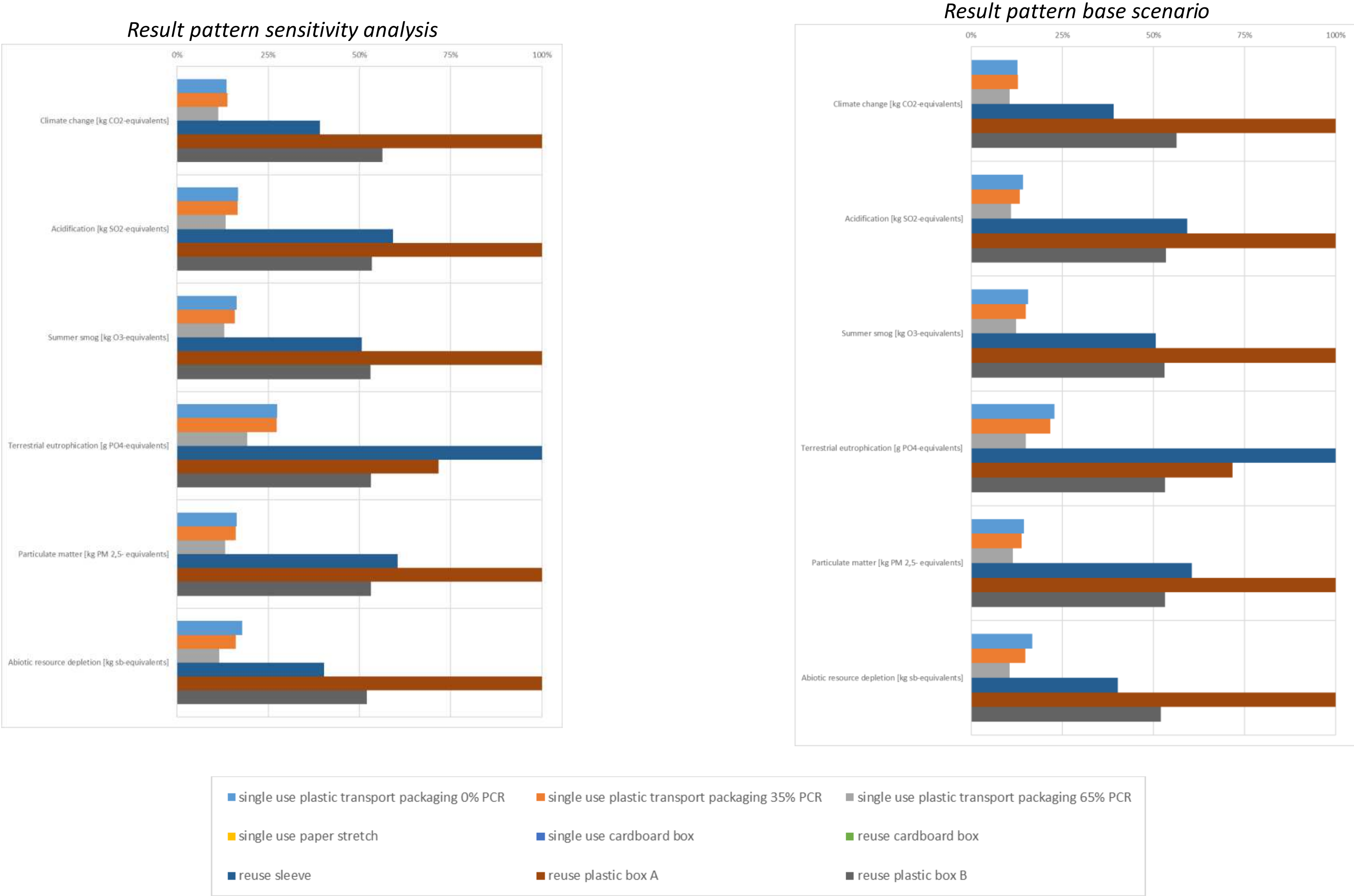
In all other areas of application, the advantages of the single-use transport packaging system known from the base scenarios are maintained. The inclusion of the mandatory PCR proportion in the reuse systems from 2040 therefore has no impact on the conclusions of the system comparison.

5.3.6 Assumptions regarding the EVA content in stretch hood

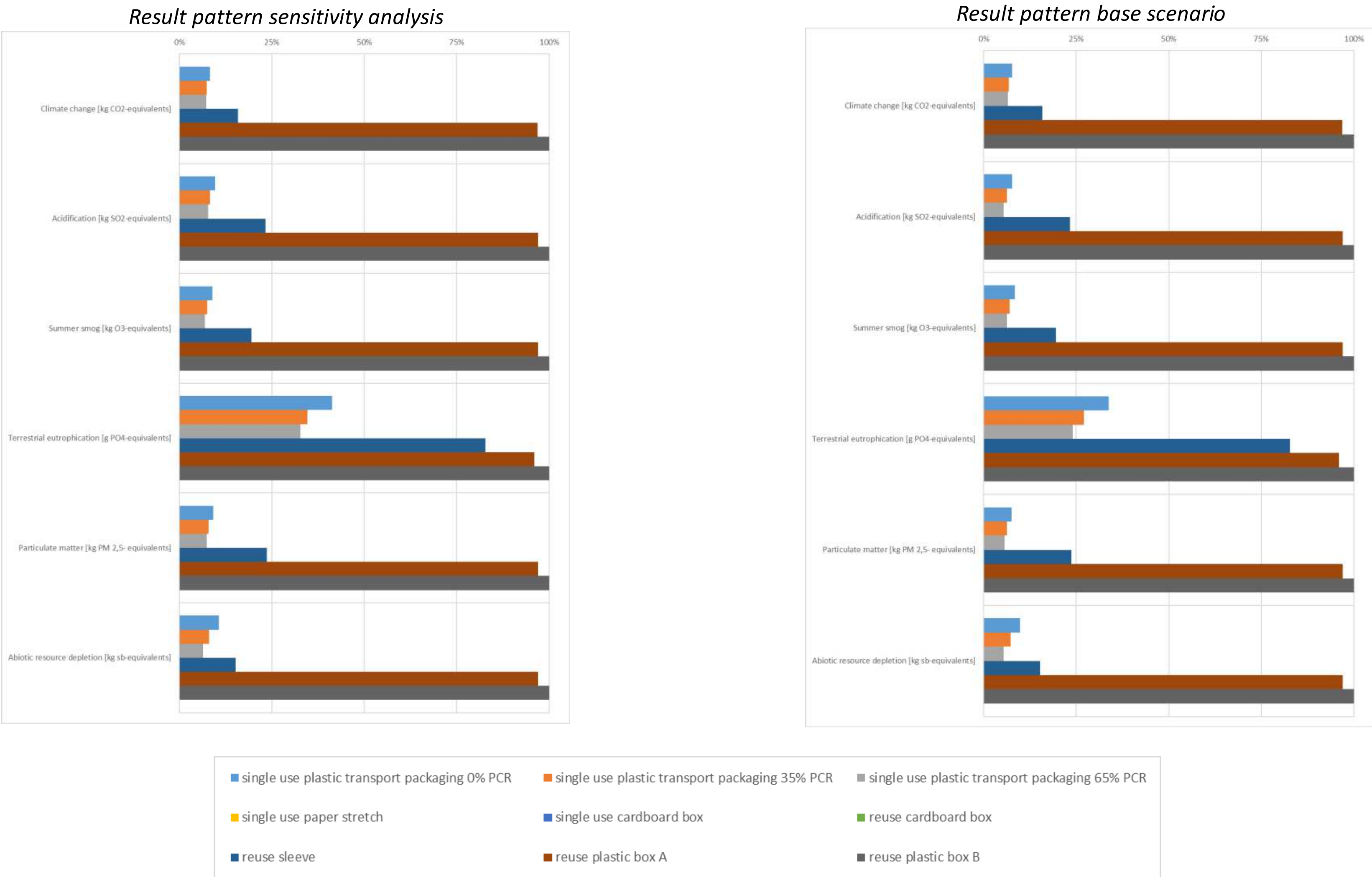
The survey of packaging specifications revealed that some manufacturers of stretch hood packaging use EVA in their specific material composition. According to the unanimous opinion of the companies involved in this project, around 50% of all stretch hoods on the European market have an EVA content of up to 30%. EVA consists of 83% PE and 17% vinyl acetate (VA).

The pure VA content in stretch hoods is therefore 2.55% and the mass input into the stretch hood and pallet system (only new material to compensate for losses) is less than 1%. This means that the EVA content in the base scenarios is below the cut-off threshold.

In order to critically review the assumptions, a sensitivity analysis is performed at this point to determine the relevance of this finding to the results. For this purpose, the stretch hood scenarios with an EVA share of 30% are considered. It should be noted, that the EcoInvent EVA data set is not very robust, partly because it is old and partly because it is not representative.



111 **Figure 5-39:** relative results in the application field cement bags– sensitivity analysis EVA content in stretch hood



112 **Figure 5-40:** relative results in the application field polymer bags– EVA content in stretch hood

The pattern of results of the sensitivity analysis is not different from the base scenarios. The impact of the assumptions on the EVA share of the stretch hood is therefore small.

5.3.7 Assumptions regarding system allocation

For each of the studied packaging systems a base scenario for the European market is defined, which is intended to reflect the most realistic situation under the described scope. These base scenarios are clustered into groups within the same application field. Following the ISO standard's recommendation, a variation of the allocation procedure shall be conducted. Therefore, sensitivity scenarios with an allocation factor of 0% (cut-off) are calculated for each packaging system.

As the end-of-life impact and the crediting of the recycled products play an important role in the results of the base scenarios, a cut-off model or 0% allocation is considered as part of the sensitivity analysis. This means, that all PCR in the regarded system are credited, which benefits not only the single-use plastic transport packaging but also, to a large extent, the reuse plastic boxes, which consist of 80% secondary raw materials. The results for cardboard boxes do not change, as these are already considered as a closed loop (cardboard loop) in the base scenarios.

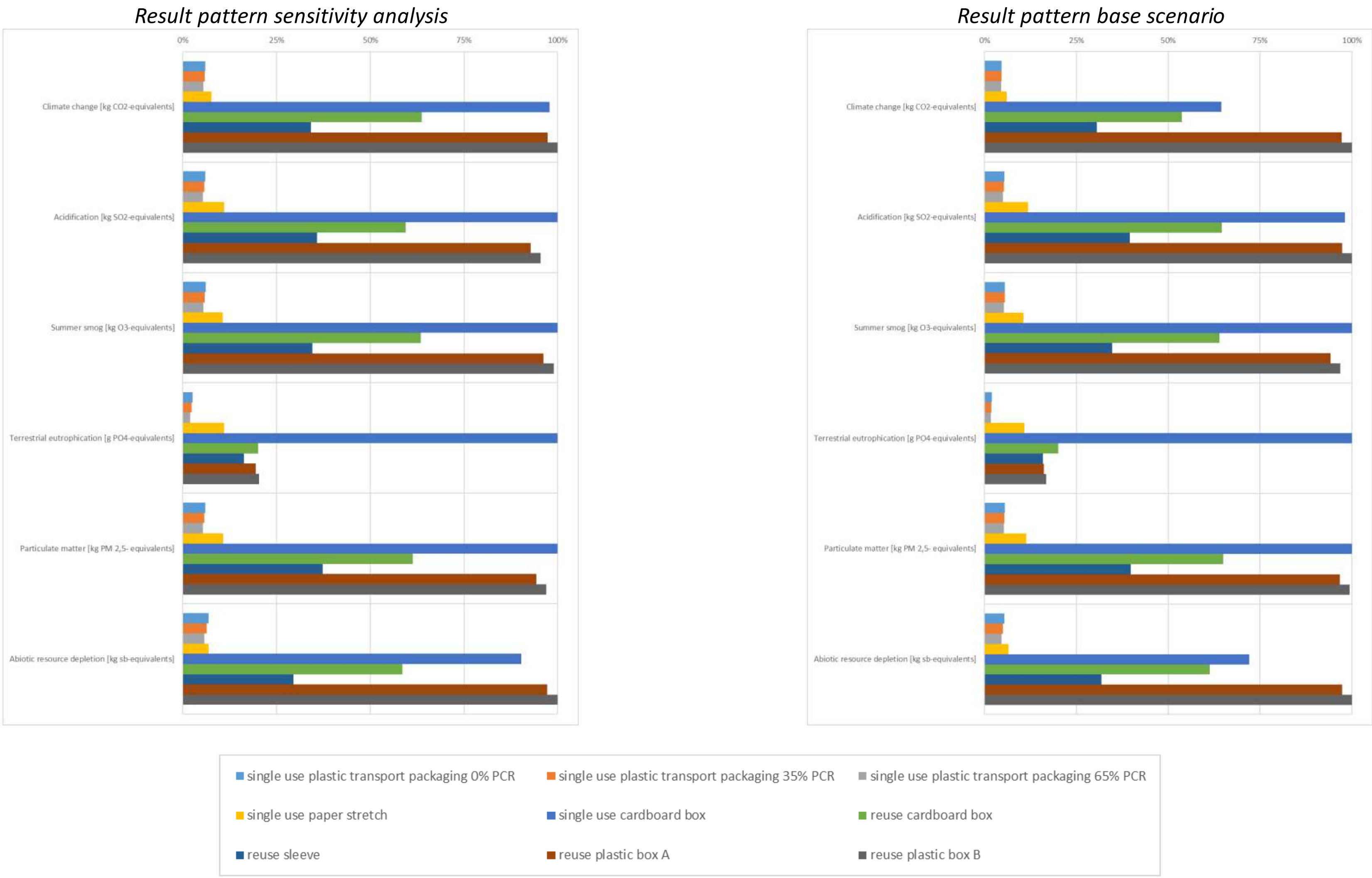


Figure 5-41: relative results in the application field cardboard boxes – sensitivity analysis AF 0%

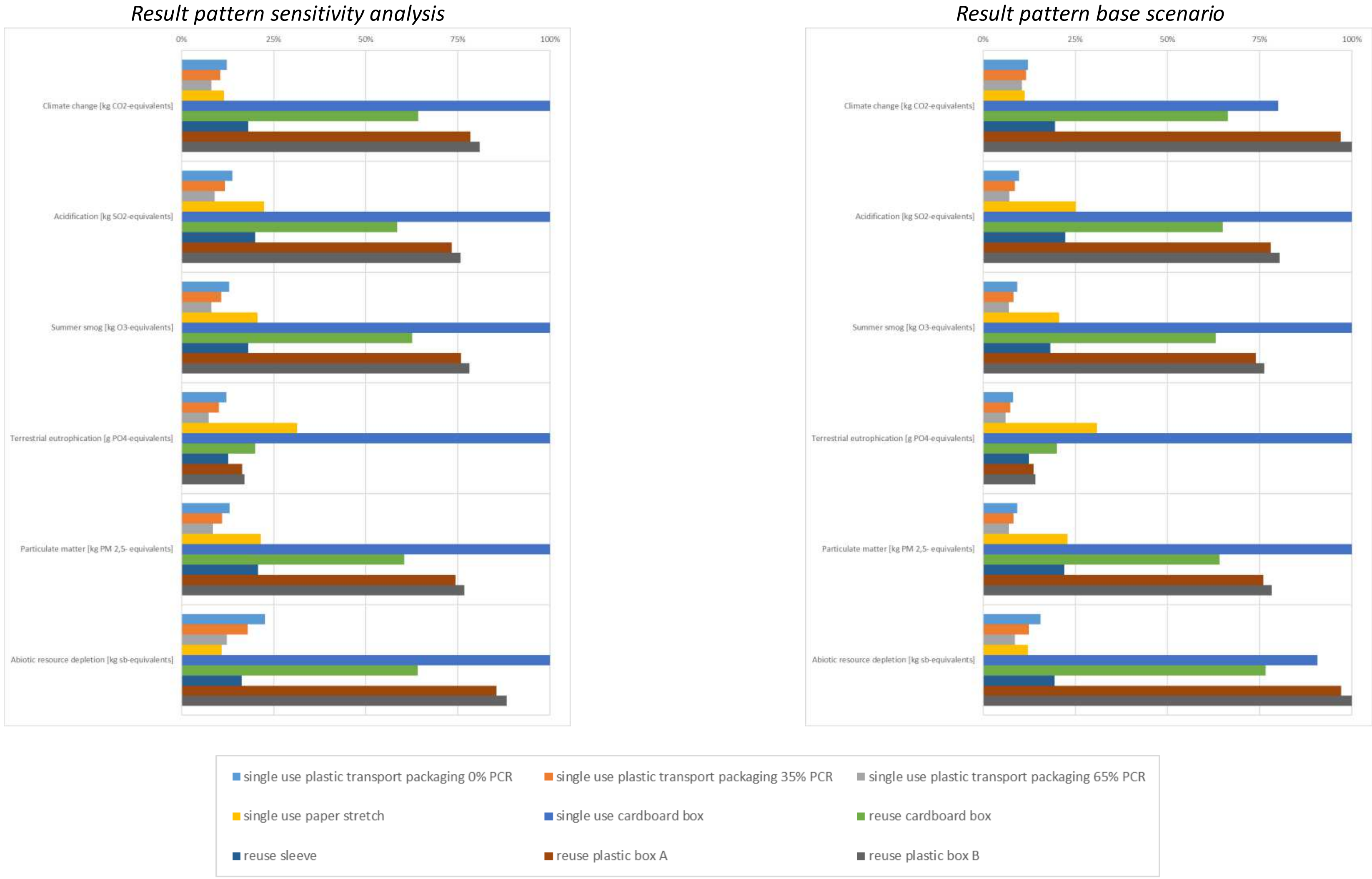
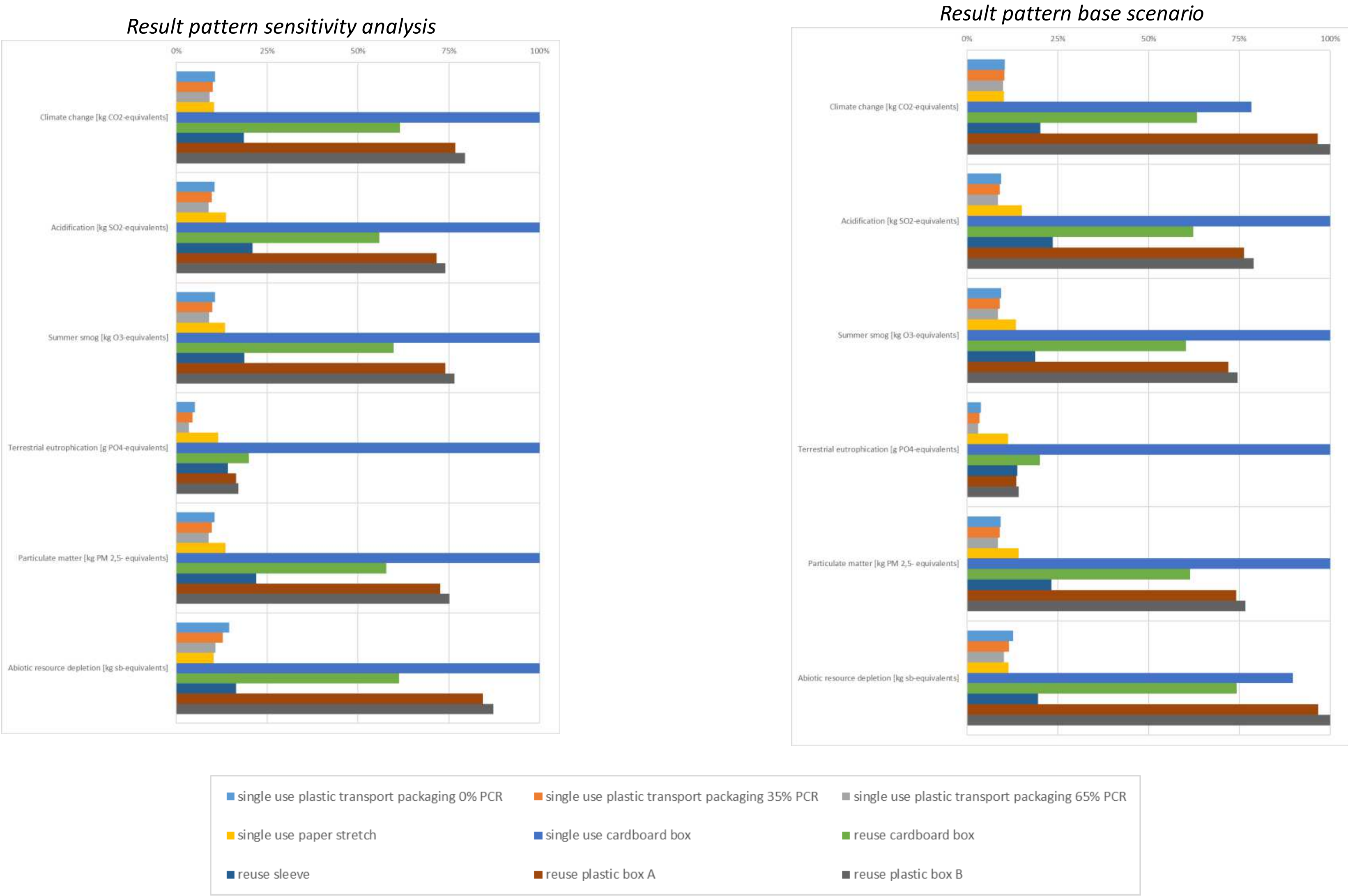


Figure 5-42: relative results in the application field PET water and CSD bottles – sensitivity analysis AF 0%



131 **Figure 5-43:** relative results in the application field buckets– sensitivity analysis AF 0%

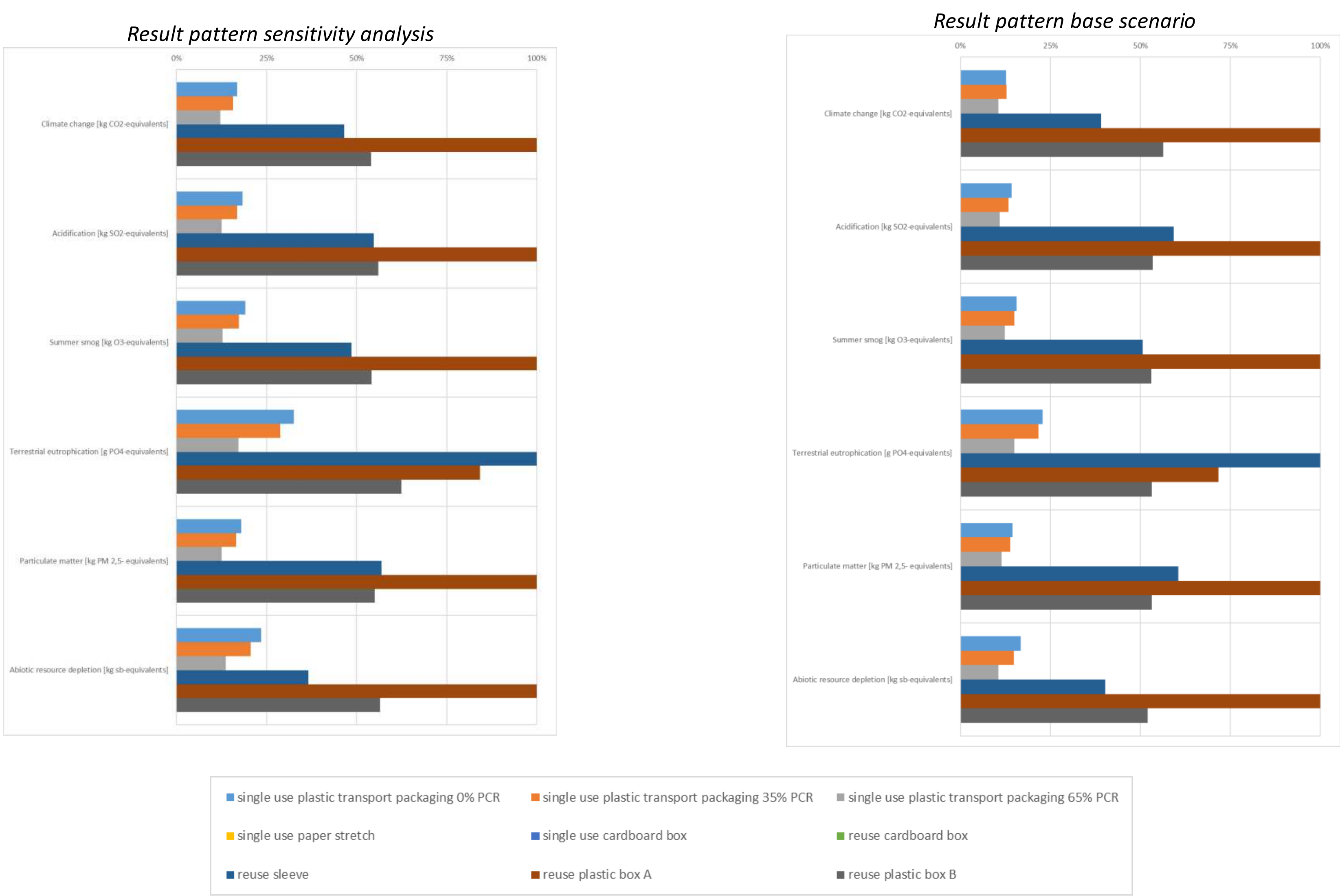
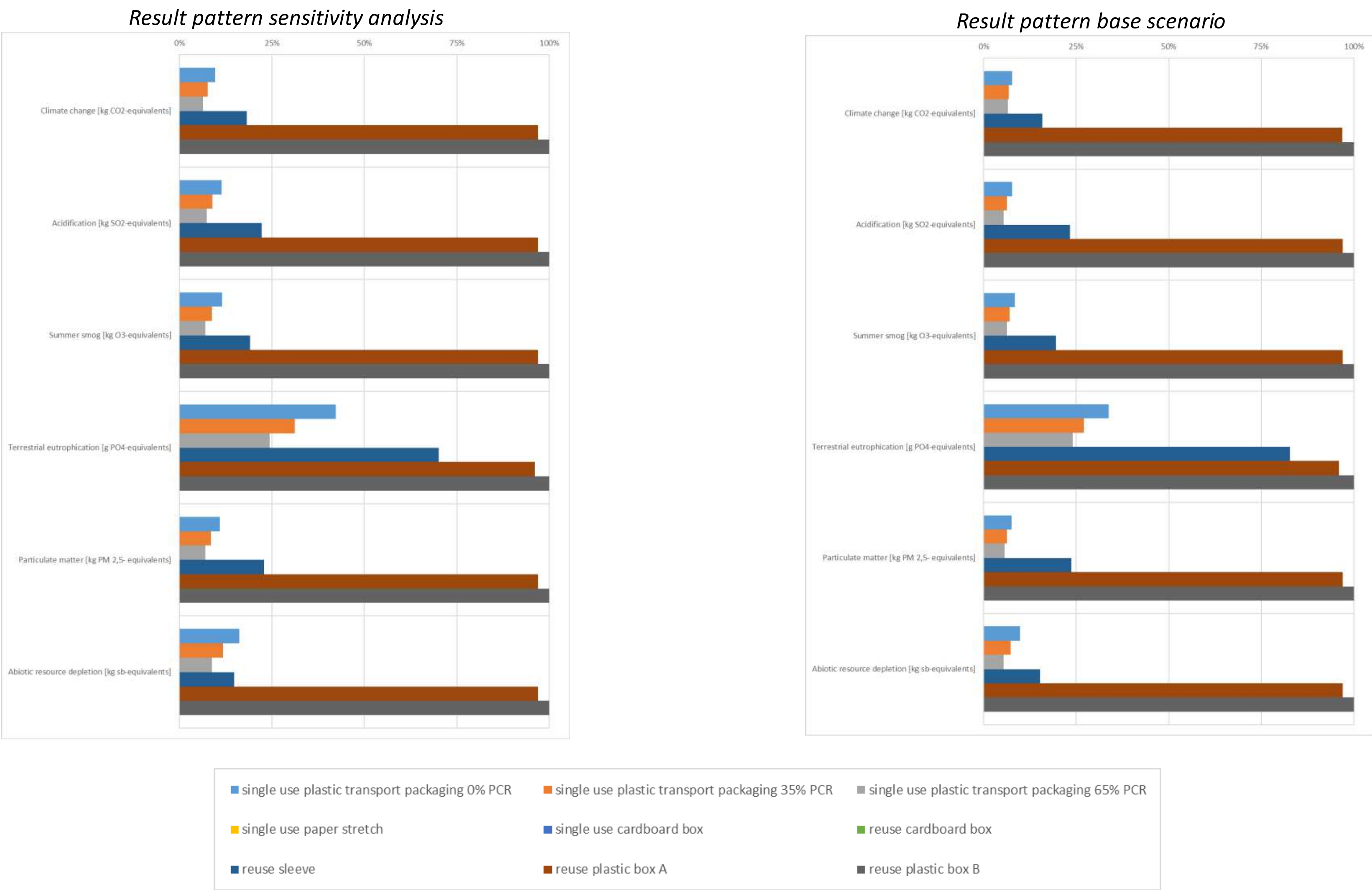


 Figure 5-44: relative results in the application field cement bags– sensitivity analysis AF 0%



133 **Figure 5-45:** relative results in the application field polymer bags– sensitivity analysis AF 0%

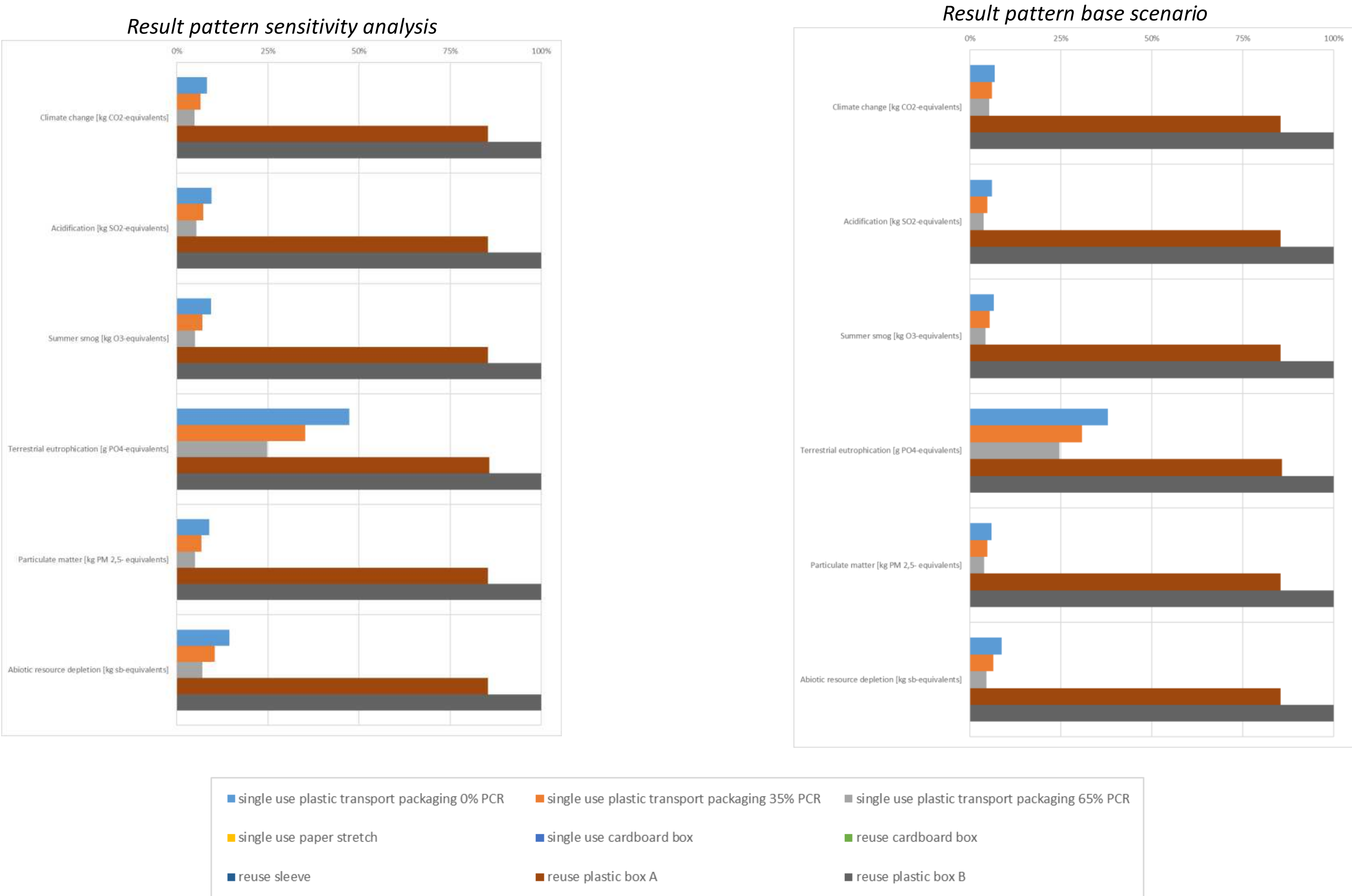


Figure 5-46: relative results in the application field glass bottles– sensitivity analysis AF 0%

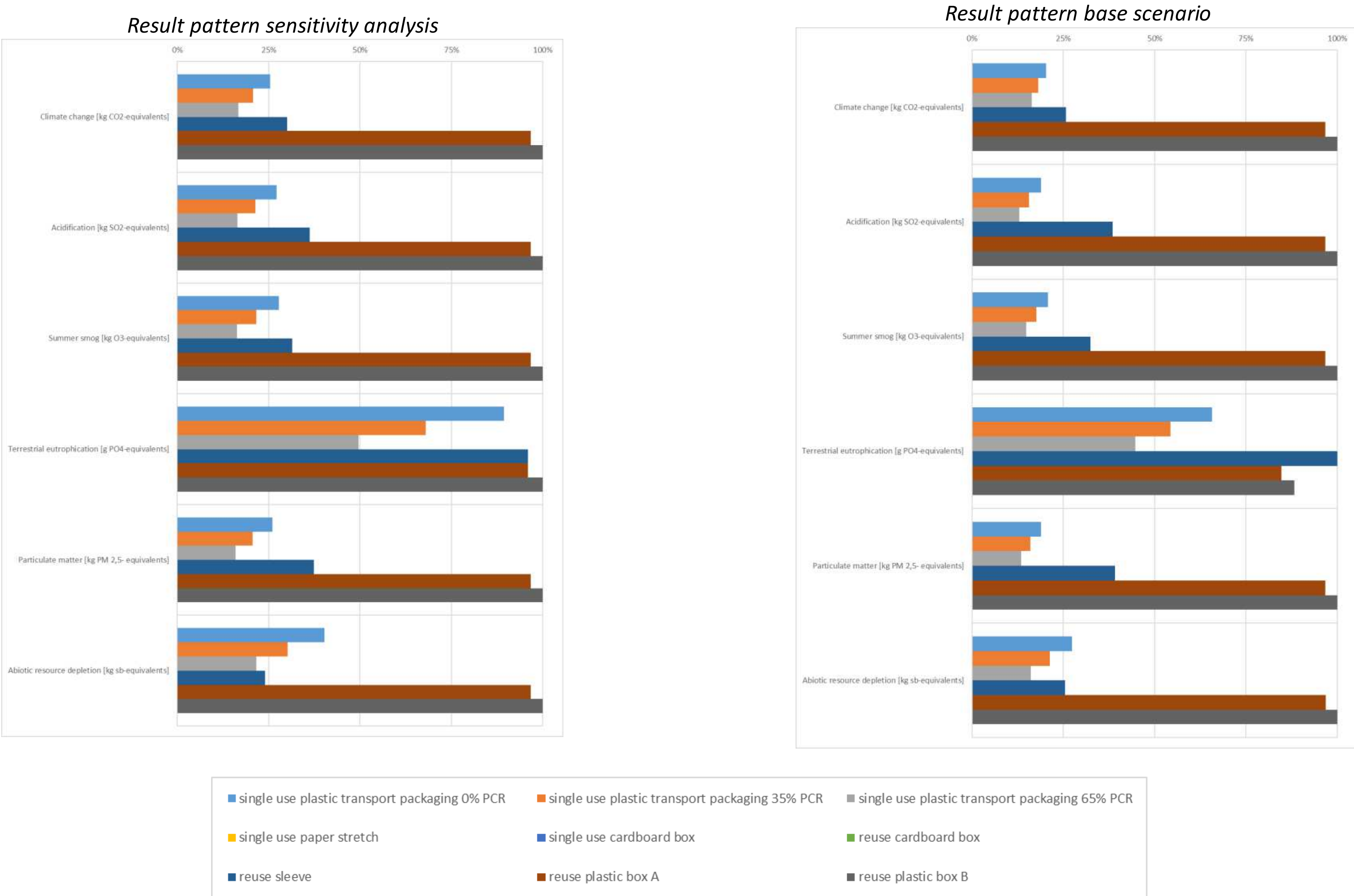


Figure 5-47: relative results in the application field milk bottles– sensitivity analysis AF 0%

The results of the sensitivity analysis broadly reflect the results of the base scenarios, although the differences between single-use plastic transport packaging and the reuse alternatives are reduced. Overall, the differences between the various transport packaging systems remain significant for most of the environmental impact categories analysed.

The results for the reuse sleeve are only slightly affected by the allocation factor as firstly, no PCR is used for the reuse sleeve in the base scenarios and secondly, the end-of-life burdens and achieved credits are roughly balanced in the base scenarios.

The results for paper stretch and cardboard packaging are also very robust to the choice of system allocation, as the secondary material is recycled anyway and does not exceed the system limit.

In summary, the results are very robust to the choice of allocation factor. As the choice of allocation factor is generally based on value judgements, this finding is very important for the validity of the results and shows that the authors' value judgements do not bias the results in any direction.

5.3.8 Discussion of sensitivity analysis results

None of the sensitivity analyses carried out in section 5.3.1 to 5.3.7 are suitable to call into question the results of the base scenarios described in section 4; on the contrary, the results show the fundamental robustness of the results with respect to the assumptions made in the study.

Nevertheless, the relevance of individual parameters to the results should be highlighted here as a brief summary:

- Trip rates are a neuralgic point in the balance of reuse systems as they directly influence the material flow within the system. In the context of this study, trip rates could only be estimated as the reuse systems examined are so far only hypothetical systems that are not currently used on a large scale in practice. A qualified estimate - even if it is based on a comparison with other existing systems such as the EPLA pallet - is always subject to uncertainties. Trip rates for the reuse sleeve and reuse boxes have been increased significantly for the sensitivity scenarios. This reduces the gap with the single-use systems but does not change the basic direction of the results, as the distribution remains the determining factor in many environmental impact categories for the reuse systems.
- Transport distance is also a topic of discussion. This study assumes, that there are no fundamental differences in the delivery distance of products depending on the chosen transport packaging. In the base scenarios, 500 km is therefore assumed for all transport packaging systems. As the study is conducted for the European context, it seems useful to also analyse longer distribution distances. This transport distance of the base scenarios has therefore been doubled for the sensitivity scenarios. This is because the distribution is much more important for reuse systems due to their weight and capacity utilisation. The choice of 500 km is therefore a conservative assumption for comparison purposes.
- As already mentioned, the degree of utilisation has a major influence on the results. The EUMOS test did not consider the stacking of boxes. Thus, stacking was not considered by the developing of the packaging specifications, this was done in the form of a sensitivity analysis. It was found, that increasing the degree of utilisation in the lorry improves the results of the reuse systems but does not change the basic direction of the comparative results.

- In the present study, positive assumptions have already been made regarding return distances and compaction of empty reuse transport packaging. However, a sensitivity is calculated in which the return distance is completely excluded. This assumption has no further impact on the comparative results.
- In the current discussion, the use of PCR material is seen as the key to optimising plastic packaging. The results of the base scenarios reflect this only to a limited extent; the difference between 0% PCR and 65% PCR is clear, but not very large. This is due to the chosen way of allocating the burdens and credits for secondary material use and generation (50% allocation factor in the base scenarios). In the sensitivity analysis regarding the allocation factor (0% allocation or cut-off), burdens for primary material production is transferred to upstream system. Thus, the systems benefit significantly more from the use of PCR. This is true for both, single-use and reuse plastic systems.
- The use of PCR material also improves the life cycle assessment of the reuse sleeve. The assumption, that the reuse sleeve contains PCR material or not does not affect the basic direction of the results.
- The calculation of shrink hoods with an EVA of 30% as part of the sensitivity analysis has no impact on the derivation of the comparative results. If the allocation of burdens for primary material production is transferred to upstream system (0% allocation or cut-off), a different picture emerges. In this form of sensitivity analysis, the systems benefit significantly more from the use of PCR. This is true for both single-use and reuse plastic systems. As the reuse systems require more primary material per functional unit than the single-use systems with a high proportion of PCR, the result changes only slightly compared to the base scenarios. This shows that the balance is robust to purely value-based assumptions.

In summary, the sensitivity analyses support the results of this study and provide a clear outlook on the optimisation potential of the individual systems. Single-use transport packaging benefits from the inclusion of PCR material. Reuse transport packaging benefits from high trip rates and an optimised truck utilisation.

5.4 Limitations

The results of the scenarios and analysed packaging systems 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 considered.

Limitations arising from the selection of application fields

The results are only valid for the examined application fields. Even though these transport packaging systems examined are commonly used to pack other products on a pallet, other products create different requirements towards their transport packaging and thus certain characteristics may differ strongly, e.g., stability and safety requirements.

Limitations concerning selection of transport packaging systems

The results are valid only for the exact transport packaging systems which have been chosen by the involved companies and EUPC. This selection does not represent the whole European market. It has to be noted, that this study puts the focus on single-use and reuse transport packaging systems for specific application fields. It is not possible to transfer the results of this study to other single-use and reuse transport packaging solutions in the same or another application field.

Limitations concerning transport packaging specifications

The results are valid only for the examined transport 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 examined transport packaging systems were provided by the involved companies and EUPC. 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 packed product can vary considerably for all product types that were studied. It is not possible to transfer the results of this study to products with other filling volumes or weight specifications.

Limitations concerning distribution data

The quality of the data on 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 trip rate of reuse systems

The quality of the data on the trip rate of reuse systems in the present study is limited due to a lack of data availability. The circulation rates are based on assumptions and extrapolations in accordance with [Bick et al 2024]. The results are valid only for the trip rates as defined in section 2.2.2 since any alternation of the latter may potentially change the overall environmental profile. It is not possible to transfer the results of this study to systems with other trip rates.

Limitations concerning the application process

For some of the transport packaging considered, there is no automated application of products so far. In these cases, the product has to be packed by hand. This process is not included in the model as there are high uncertainties in deriving the environmental impact of manual activities in terms of calorie consumption and nutritional form.

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 transport 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 % - 30% was applied for comparative results. The application of other significance thresholds could possibly lead to a different assessment of the systems' comparison. The 10 % - 30% 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 transport packaging systems.

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) transport 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 assessment, 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.

5.5 Discussion of uncertainties

According to ISO 14044 4.2.4.2 a discussion of uncertainties should be an integral part of an LCA. Throughout the study, this discussion takes place in different places, where it makes sense thematically. For example, Chapter 2 takes a critical look at the main approaches used to describe the packaging systems analysed and the scenarios considered, while Chapter 3 discusses the Life Cycle Inventory data. At the beginning of Chapter 5, the robustness of the environmental impact categories used is examined in detail and the interaction between data, assumptions and impact categories is discussed. Finally, all relevant life cycle stages are analysed in terms of the parameters that determine them. these critical parameters are then tested for their relevance to the results using different sensitivities. finally, the limitations of the conclusions of the study are clearly stated.

It is therefore not the intention of this chapter to provide a further numerical estimate of uncertainty, but simply to make transparent which parameters and assumptions of the balance sheet are of particular importance and how valid they are. The dominance analysis shows that for all the packaging analysed in all the application areas and for all the environmental impact categories considered in the assessment, raw material production and distribution are the dominant life cycle stages.

- The environmental impact balanced in the **raw material production** life cycle stage is determined by the amount of packaging material that must be newly produced to fulfil the functional unit. The parameters that determine the results are therefore the packaging weights, the load patterns and the trip rates. The datasets that drive the results are the raw material production datasets.
    - The package weights and load patterns have been developed specifically for the applications considered in this study: Primary data obtained through a standardised and certified procedure (EUMOS test).
      It can be stated that this data point is valid and has only a minor uncertainty.
    - It was not possible to use primary data to determine the circulation figures. it was also not possible to use data sets from the literature, as no information is yet available for the systems analysed here. therefore, assumptions had to be made as part of the investigation. these assumptions were made and discussed as transparently as possible, but the assumptions are still subject to uncertainty. for this reason, the circulation figures were checked using a sensitivity analysis. however, the impact on the result is small. It should also be mentioned that the circulation figures in the basic scenarios are already high, e.g. the reuse sleeve was not able to demonstrate the assumed 12 trips during the EUMOS test series; it was destroyed after only 5 applications.
      It can be stated that this data point has a high level of uncertainty - but this has been checked in the form of a sensitivity analysis and is not highly relevant to the results.
    - The datasets used to analyse this life cycle stage are all published and peer reviewed. The reference years and geographical scope correspond to those of the study. There are only few minor uncertainties in their use.
      It can be stated that this data is valid and has only a minor uncertainty.
- The calculation of transport emissions is primarily based on the assumed distances, the weights of the packaging considered, the specific utilisation of the trucks (depending on the load pattern) and, of course, the dataset used to calculate transport emissions.
    - As stated before, the package weights and load patterns have been developed specifically for the applications considered in this study: Primary data obtained through a standardised and certified procedure (EUMOS test).
      It can be stated that this data point is valid and has only a minor uncertainty.
    - The distribution distance is a best estimate that is assumed to be the same for all systems. The value of 500 km for the geographical scope of Europe is generally low, so the assumption can be considered conservative for the purposes of comparison. However, the assumption is subject to a high degree of uncertainty. The sensitivity of the distribution distance carried out as part of the study shows that this data point is not highly relevant to the results.

It can be stated that this data point has a high level of uncertainty - but this has been checked in the form of a sensitivity analysis and is not highly relevant to the results.

- The emission factors used for distribution are based on the Manual of Emission Factors for Road Transport (HBEFA). This standard work provides comprehensive data on the greenhouse gas and air pollutant emissions of various vehicle categories. The HBEFA has been developed and coordinated by INFRAS since the 1990s in cooperation with partners such as the Graz University of Technology and the Institute for Energy and Environmental Research (IFEU) in Heidelberg. It is funded by the transport and environment ministries of the participating European countries.
  It can be stated that this data is valid and has only a minor uncertainty.

Based on this analysis, it can be concluded that both the foreground data (packaging specifications and loading patterns) and the background data (raw parameters and transport measurements) that determine the results have high validity and low uncertainty. In summary, the data quality of the study can be considered as good and the uncertainty as low.

6 Conclusions and Recommendations

The aim of this study is to compare the life cycle profile of different types of single-use plastic transport packaging (stretch wrap, stretch hood and shrink hood in combination with a EURO flat pallet) under the current and future conditions set by the PPWR with the environmental profile of other single-use and reuse transport packaging solutions (reuse boxes made from PP without wooden pallet) in seven different application fields.

The results, which are presented in section 4 and discussed in section 5, can be summarised as follows:

- Single-use plastic transport packaging, even without the use of PCR material, has a lower environmental impact than rigid reuse transport packaging (plastic box A and B) in all application fields examined.
- In almost all application fields studied, single-use plastic transport packaging also has a lower environmental impact than the flexible reuse transport packaging under study (reuse sleeve).
- Compared to rigid single-use transport packaging made from cardboard, single-use plastic transport packaging has consistently lower environmental impacts. Compared to flexible single-use transport packaging made from paper (paper stretch), single-use plastic transport packaging has advantages in most of the application field and environmental impact categories analysed.
- The use of PCR content represents a further path towards sustainability, as the results of the study show that single-use plastic packaging transport with a high PCR content always has the lowest environmental impact of all transport packaging systems under study. However, more studies are needed, as the massive use of PCR materials might significantly alter the overall performance of the industry, potentially reducing the current benefits calculated in this study.

The results are determined by:

- The environmental impact of producing and disposing of the amount of packaging material required to fulfil the functional unit (transport of 1,000 kg of packaged goods).
  The amount of packaging material required is derived from the weight of the packaging, the trip rate of reuse packing systems and the different transport efficiencies of the systems. The results show, that single-use plastic transport packaging require less material in all application fields.
- The environmental impact of distribution and re-distribution which is determined by the amount of packaging required to fulfil the functional unit and the transport efficiency of the transport packaging analysed.
  The main questions are: How much product can be transported in a lorry and whether the choice of transport packaging leads to under-utilisation. This study shows a repeatedly under-utilisation in the case of rigid reuse systems as they are not adaptable to the dimensions of the packaged goods in their sales and group packaging. It is therefore noticeable, that the differences are smaller for application fields with very dense packaged goods (water, CSD and milk bottles), because the transport loads are more balanced by the contents.

None of the reuse systems analysed in this study have any significant environmental advantages compared to the single-use plastic transport packaging used today. The reuse sleeve still appears to be the most viable alternative (in terms of least additional emissions). However, this system currently still requires manual use, the environmental impact of which could not be included in the LCA for methodological reasons (see section 5.4). In addition, the reuse sleeve showed weaknesses in the EUMOS test, suggesting that this solution was analysed with overly positive parameters (trip rate) in this LCA while it is less adaptable to all kinds of products to be transported on a pallet than the current single-use plastic packaging.

When disseminating the results, it should be noted that they apply only to the application areas considered in this study. Transferability to other application areas is strictly excluded, although the application areas have been selected to reflect a wide range of possible product specifications and case groups. Furthermore, when disseminating the results, it should be noted that all key factors (parameters and data sets) used to analyse the results are highly valid and reliable. The conclusions drawn in this study are therefore based on a very solid foundation.

It is therefore recommended, that the commissioners of the study communicate the findings of this study to the political process in an appropriate, differentiated and transparent manner. Together with partners from industry and trade, measures should be developed to implement the PCR rates of the PPWR in a sustainable and feasible manner, taking care to verify that the assumed benefits are maintained in the industrial practice.

It is also recommended, that the results of this independent and peer-reviewed study are taken up and processed by policy makers, who are the addressees of the client's communication. The authors hope, that the results will be used not only for the preparation of delegated acts, but also directly for the necessary awareness-raising to allow for an appropriate evaluation and adaptation of the PPWR in 2030.

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Appendix – Critical Review Statement

Date
15th April 2025

Critical Review Statement of the report and study "Comparative life cycle assessment of various single-use and reuse transport packaging”

- **LCA study for review**

  Comparative life cycle assessment of various single-use and reuse transport packaging

  Analysis of single-use stretch wrap, stretch hood and shrink hood in comparison to single-use paper stretch, single-use and reuse cardboard boxes, reuse sleeves and reuse plastic boxes
- **Date of the study**

  April 14th 2025
- **Authors**

  The study was carried out by Benedikt Kauertz and Andrea Drescher from ifeu.
- **Commissioners**

  The study was commissioned by EUPC (European Plastics Converters).
- **Critical reviewers**

  Due to the requirements specified for Life Cycle Assessment (LCA) in the ISO standard, ISO 14044:2006, a Critical Review panel has been used for the critical review of the present LCA study. The review panel consisted of the following four independent members:
  - Hélène Cruypenninck (chair), seven-c, France
  - Nicolas Cayé, GVM, Germany
  - Miguel Brandão, KTH Royal Institute of Technology, Sweden
  - Ruben Aldaco Garcia, Cantabria University, Spain

INTRODUCTION

The comparative life cycle assessment of various single-use and reuse transport packaging was commissioned by European Plastics Converters (EUPC) and carried out by ifeu in 2024-2025.

The primary objectives are to compare the life cycle profile of various single-use and reuse transport packaging for several good transport cases in order to inform current and future debates about packaging transport regulation at the European level.

As the study is comparative, and independent peer review of the study was carried out, according to ISO 14 044:2006 chapter 6.3 requirements.

The review panel consisted of:

Name of the reviewer	Company	Field of expertise / main focus during the review process
Hélène Cruypenninck	Seven-C	President of the review panel, LCA expert. Focused on packaging data and transport modelling.
Nicolas Cayé	GVM	Packaging expert. Focused on packaging specifications, recycling rates, use of recycled content, number of trips for reusable packaging, transport systems and distance.
Miguel Brandão	KTH Royal Institute of Technology	LCA expert. Focused on ensuring compliance with the ISO standards.
Ruben Aldaco Garcia	Cantabria University	LCA expert. Focused on compliance with ISO 14040 and 14044 Standards, specifically on framework and methodological requirements for conducting a LCA.

In accordance with ISO 14 044:2006 chapter 6.1, the review panel verified if:

- the methods used to perform the LCA are consistent with this International Standard;
- the methods used to carry out the LCA are valid from a scientific and technical point of view;
- the data used are appropriate and reasonable in relation to the objectives of the study;
- the interpretations reflect the limitations identified and the objectives of the study; and
- the study report is transparent and coherent.

SCOPE OF THE STUDY

The task of the review panel was to review the LCA report, underlying data, and methods for the calculations in the study "Comparative life cycle assessment of various single-use and reuse transport packaging". The study covers the market situation in Europe (27), based on 2024 packaging specification.

The study covers a broad range of transport packaging solutions, single-use or reuse, that are compared based on their applicability for real use cases. The selection of packaging options was based on packaging transport resistance test, to ensure the use cases reflect real transport practices.

REVIEW PROCESS

- **Key dates**

Date	Type	Topic	Participants
09th December 2024	Online meeting	Virtual kick-off	ifeu team Commissioners Panel members
14th January 2025	Online meeting	EUMOS test presentation	ifeu team Commissioners Panel members
17th January 2025	Online meeting	Presentation of the draft report	ifeu team Commissioners Panel members
28th February 2025	Online meeting	Panel meeting	Panel members
05th march 2025	Online meeting	Discussion on comments	ifeu team Panel members
05th march 2025	Comments	Panel members sent 1st round of comments via excel	
21st march 2025	Report	ifeu shared updated report	
04th April 2025	Online meeting	Panel meeting	Panel members
04th April 2025	Comments	Panel members sent 2nd round of comments via email	
10th April 2025	Report	ifeu shared updated report	
11th April 2025	Online meeting	Transport calculation	Ifeu + head of panel
14 April 2025	Report	ifeu shared final report	

- **General comments about the review process**

The panel made 95 comments via an Excel file that is meant to facilitate tracking.

Most important comments were related to:

- A study summary was missing
- Functional unit description with suggestion to improve the wording
- System boundaries description with suggestion to improve graphs and wording as well as consistency across the report
- Data sources and justification that needed improvement for transparency
- Transport modelling correction and improvement
- Results analysis and discussion that needed to be expanded.

All comments were proactively and correctly implemented by ifeu in a very short time. The report significantly improved over iterations.

REVIEW OF THE VALIDITY OF THE METHODS USED

- **Reference framework**

The objective of the study is to compare transport packaging alternatives in the European context, using Life Cycle Assessment as a tool.

ifeu chose to follow ISO 14 044 and to move away from PEFCR on some specify points such as end-of-life modelling and environmental impact indicators selection.

Justification for these choice are reflected in the report.

- **Scope and boundaries**

Scope and boundaries are clearly defined and the report and consistent with the study's objective.

- **Transport modelling**

The reviewers requested to access transport modelling. Transport model was shared in an Excel file for the panel to review it. The panel detected some implementation and calculation errors and made some suggestions for improvement. All comments were taken into account by ifeu.

Transport modelling significantly improved during the review panel, in order to better reflect the contribution of packaging to transport optimization/deoptimization.

The panel appreciates the intense discussion around this topic and ifeu's implementation of transport modelling.

- **End-of-life allocation**

Although the PEF "circular footprint formula" is not used, the allocation method for end-of-life and recycling impact is clearly described and transparent.

REVIEW OF THE DATA

Some key data are sourced from ifeu's internal database built over time. This database is not public. A selection of lifecycle profiles coming from this database were made available to the panel members.

Packaging data description are based on real use cases and crossed-checked with EUMOS test. in several instances, ifeu chose a conservative approach for single use plastic packaging.

The panel appreciate that ifeu and EUPC made EUMOS test results accessible to panel members and validate the conservative approach for single use plastique packaging.

REVIEW OF THE INTERPRETATION OF THE RESULTS

The indicators used in the study are scientifically based and are relevant for packaging application.

As per panel suggestion, robustness and inherent uncertainty of indicators was better reflected in the results analysis.

The panel outlines the great work to present the significant amount of use cases in results in an efficient manner.

REVIEW OF THE TRANSPARENCY AND CONSISTENCY OF THE REPORT

Data sources and justification were initially not sufficiently described to ensure transparency and to allow for the reviewers to validate the robustness. Data sourcing and description improved over iterations.

Data, methods, assumptions and limitations are presented in sufficient detail to allow the reader to comprehend the complexities and trade-offs inherent in the LCA.

CONCLUSION OF THE REVIEW PROCESS

Considering that all comments and suggestions were taken into account in the final report, the panel confirms that this LCA study followed the guidance of and is consistent with the international standards for Life Cycle Assessment (ISO 14040:2006 and 14044:2006) as follows:

- The methods used are scientifically and technically valid as far as possible given the goal of the study and the assumptions.
- The data used are appropriate and reasonable in relation to the goal of the study.
- The interpretation of the results and the conclusions of the study reflect the goal and the findings of the study.
- The study report is largely transparent and consistent.

In summary, the reviewers conclude that the methods, models, and principles on which the LCA is based are consistent with the ISO 14040 and 14044 standards. Furthermore, **the LCA study ensures consistency, credibility, and comparability, making the results reliable for decision-making and potential public communication.**

This critical review statement is only valid for the final LCA report as presented to the review panel.

The panel would like to stress the great quality of the study and the quality of the discussions that took place during the review process.

RECOMMENDATION ON COMMUNICATION BASED ON THE STUDY

The report including its executive summary is the only material submitted to the panel. Panel members disclaim all liability for any other communication that would be made based on the study. Nonetheless, the panel suggest that any communication based on the study should :

- Recall the functional unit and the use case
- Recall the geographic and temporal representativeness
- Recall that the results and findings are restricted to the transport leg between the production site where the packaging is applicated to the first economic operator in the logistics chain (e.g. central warehouse) and no generalisation for other transport leg should be made.
- Recall assumptions on reuse rates and return distances assumption for reusable packaging.

SIGNATURE

Hélène Cruypenninck

Nicolas Cayé

Miguel Brandão

Ruben Aldaco Garcia