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Life cycle assessment study on the treatment of plastic and aluminum packaging for beverages

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Summary

The study used the Life Cycle Assessment (LCA) method in accordance with ČSN ISO 14040 to carry out an assessment of the possible environmental impacts of two applied treatment systems for used beverage PET, aluminum and steel bottles. The two systems examined were a deposit-refund scheme and a non-deposit-refund scheme. The environmental impacts of both assessed systems were determined based on a life cycle inventory analysis, followed by description using the ReCiPe methodology. The conclusiveness of the differences between results was tested using the stochastic Monte Carlo method, whereupon it was demonstrated that the differences between the systems are statistically significant, with the exception of the impact category "human toxicity".

Based on the data obtained, it may be concluded that the implementation of a deposit-refund system would result in a decrease of environmental impacts related to beverage packaging by up to approx. 28%. Compared to the non-deposit-refund system, the deposit-refund system shows lower environmental impacts in the following impact categories: climate changes/global warming, fossil fuel depletion, ionizing radiation, metal depletion, particulate matter formation, photochemical oxidant formation, terrestrial acidification, terrestrial ecotoxicity and water depletion.

The largest influence on the total environmental impacts of non-deposit-refund and deposit-refund systems comes from the following impact categories: climate changes (global warming) both on ecosystem and human health levels; loss of fossil fuel raw materials; loss of metals and particulate matter formation. The implementation of a deposit-refund system would result in a statistically significant decrease in the indicator result values of all assessed impact categories, with the exception of the impact category "human toxicity", where both systems are assessed as comparable.

The main limitation of this study is represented by the fact that multi-colored PET bottles have limited recyclability and secondary use potential, which has not been taken into consideration in the study due to the lack of relevant data (the usability of PET bottles as a secondary raw material would increase if colorless PET bottles were used.). The repeated use of PET bottles has not been considered in this study. The model is based upon processing PET bottles as a secondary raw material that substitutes the primary raw material.

Contents

1 Introduction

The goal of this study is to compare, using the Life Cycle Assessment (LCA) method and within the Czech context, the possible environmental impacts of the current treatment system for used beverage bottles made of PET, aluminum and sheet steel with an alternative scenario for such bottles involving a deposit-refund system. This study is part of a project awarded by Karlovarské minerální vody, a.s. in 2018 and performed in cooperation with INCIEN, Institut cirkulární ekonomiky, z.ú. and the company Eunomia, and must be regarded in the context of the project as a whole.

The Life Cycle Assessment (LCA) method is an analytic tool based on measuring the technological, operational and environmental parameters of particular organizations or industrial enterprises which are involved in the production, transport, operation or disposal of any material, equipment, fuel or energy carrier entering at any stage of a product life cycle. The LCA method is performed in accordance with ČSN EN ISO 14040[1] and ČSN EN ISO 14044[2], and represents a robust and transparent tool for quantifying the possible environmental impacts associated with particular input and output materials and energy. LCA is an internationally used method that is promoted by UNEP[3] and is being currently discussed in connection with the transition to the circular economy. The basis of the LCA method lies in determining material and energy flows inwards towards and outwards from the assessed system, where their quantity, composition, character and importance for the environment are monitored. From the identified volume of material and energy flows we derive their causes and effects, and these are then used for determining the resulting possible changes in the environment.

The selected functional unit of the study, i.e. the quantified expression of the magnitude of the function of the assessed system, was the treated quantity of bottles made of PET, aluminum and sheet steel that represented the annual placement onto the market in the Czech Republic in 2017. All data for the beverage packaging flow in 2017 come from the official data of the company EKO-KOM a.s. The basic assessment scenario is the current method used for treating used bottles at landfill sites, in waste-to-energy facilities, cement plants and recycling lines. This basic scenario is denoted as "*Baseline*" in the study. The scenario considering a deposit-refund for bottles is denoted as "*DRS*" (Deposit Refund System).

The LCA study is designed to be attributional, it aims to assess the possible environmental impacts of the scenarios being assessed. The outcomes that would result from the implementation of the

[1] ČSN EN ISO 14040 Environmental management – Life Cycle Assessment – Principles and Framework, ČNI 2006.
[2] ČSN EN ISO 14044 Environmental management – Life Cycle Assessment – Requirements and Guidelines, ČNI 2006.
[3] http://www.uneptie.org/pc/sustain/lcinitiative/

deposit-refund system, for example on the system for waste management or for recycled plastics within the current waste management system, have not been included into the study because of the unavailability of verifiable data and with respect to the planned scope of the work. To process such a LCA, it would have been necessary to acquire additional data the acquisition of which was beyond the scope of this study.

2 Description of the assessed systems – system boundary

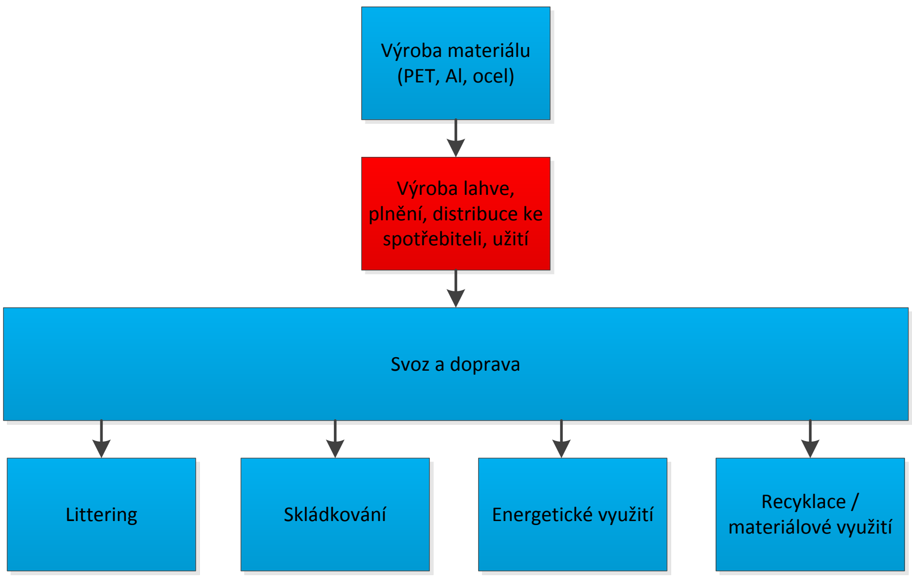
Two systems for the treatment of used beverage packaging made of PET, aluminum and steel sheet are the subject this assessment of their potential impact.

a) The current system (*Baseline*), where a bottle used in a non-deposit-refund system is the subject of waste management and is disposed of either in landfill or used in waste-to-energy facilities, or recycled and used as waste-to-material. A proportion of bottles enter the environment in the form of littering.

b) A deposit-refund system (*DRS*), where a refundable deposit is applied to beverage packaging and the deposit is refunded upon the return of the packaging. A smaller part of bottles (than in the Baseline system) is disposed of by landfill, is used in waste-to-energy facilities or enters the environment in the form of littering.

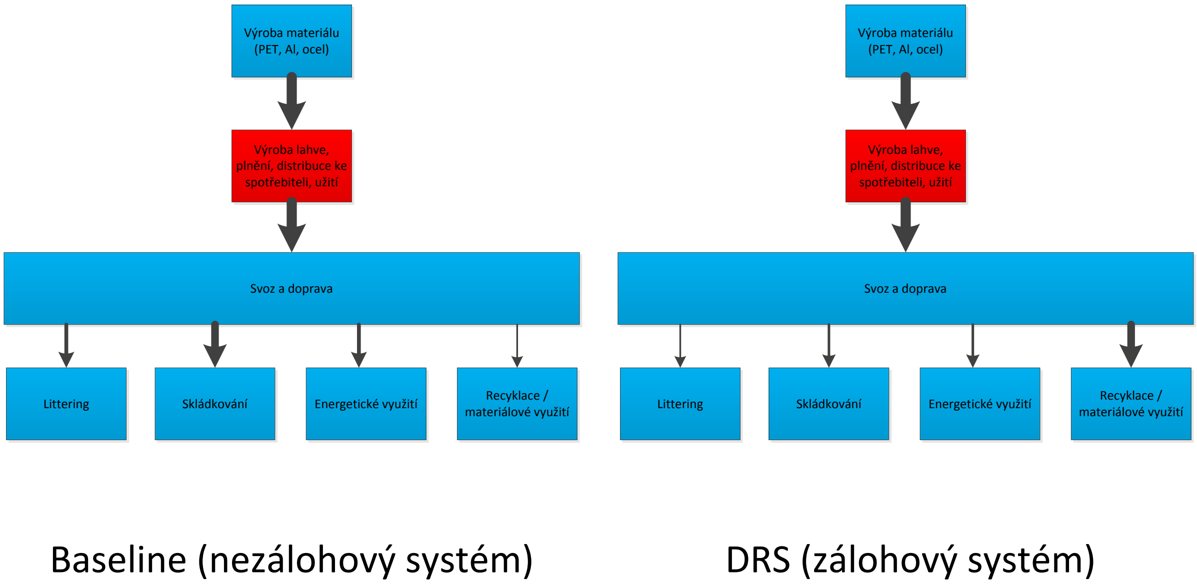
The basic material flow scheme of both assessed systems is identical, it differed in the amount of respective flows that end in material or energy utilization or at a landfill site or as litter in the countryside or public spaces (littering). The groups of operations involved in the system boundaries are specified in the following scheme. The processes in blue are included in the system boundaries, the processes in red are not. The processes involved in filling bottles or their distribution to the customer may be considered the same for both variants, and thus may be excluded from the system boundaries.

Figure 1 Processes included in the system boundaries



To perform the LCA modelling and assess both systems, the assumption was made that the implementation of a deposit-refund system would result in a decrease in the amount of littered bottles (in the countryside and elsewhere), landfilled bottles and bottles used in waste-to-energy facilities. It is also assumed that the implementation of the deposit-refund system will increase the waste-to-material ratio of used bottles, which is depicted in the following figure by the varying width of arrows, showing the smaller or a larger size of the waste material flow. Changes in the quantities of the respective flows before and after implementation of a deposit-refund system were defined by the company Eunomia (see Table 1 and Table 2 in the next section).

Figure 2 Example of changes in material flow sizes after the implementation of DRS (arrow widths are merely indicative).



3 Definition of the aims and scope of the study

3.1 The aim of the LCA study

This study is intended for the company Karlovarské minerální vody, a.s. and is aimed at helping determine whether the implementation of a deposit-refund system for beverage bottles would result in a decrease in the environmental impacts of manufacturing and disposing beverage bottles in the Czech Republic, and thus whether there would be any sense in implementing a deposit-refund system from the environmental point of view.

3.2 Definition of the scope of the LCA study

3.2.1 Function of the assessed products

For the purposes of this study, the function of product systems means the provision of materials for manufacturing beverage packaging and the subsequent treatment of used beverage packaging, incl. possible waste-to-material or waste-to-energy utilization.

3.2.2 Functional unit

In the LCA studies, a functional unit is a reference value which is used to compare the respective product system variants. For this LCA study, as our functional unit we selected the treatment of the amount of PET, aluminum or steel packaging that corresponded with the amount of such packaging placed on the Czech market over one calendar year.

3.2.3 Time span

The calendar year 2017 was chosen as the time span of this study.

3.2.4 Geographical scope

The geographical scope of the study is not limited by imported raw materials and thus can be considered global. With respect to the processing of used beverage bottles, it is assumed that bottles will be processed or disposed of in the Czech Republic. Transport distances considered in the calculations are detailed below.

3.2.5 Reference flow

The reference flow is represented by the quantity of assessed products necessary for realizing the functional unit. The following table clearly show the values of respective flows as determined by the company Eunomia[4] based on the underlying MFA (Mass Flow Analysis) data of the company EKO-

[4] Eunomia Research & Consulting, 70 Cowcross Street, London, EC1M 6EJ, United Kingdom, http://www.eunomia.co.uk/

KOM a.s., processed by INCIEN, Institut cirkulární ekonomiky, z.ú. These values were subsequently used for LCA modelling in this study.

Table 1 Reference flow values of particular commodities, Baseline[4]

Baseline, Flow Weight, Tons	PET	Steel	Al
Market placement	49,446.0	444.5	8,455.0
Total Recycling	32,148.0	133.4	2,536.5
Mixed plastics/Metal	1,148.0	133.4	2,536.5
PET	31,000.0	0.0	0.0
Waste Management	16,068.0	300.1	5,708.2
Waste-to-Energy	2,598.0	69.5	1.322.6
Cement Plant	5,020.0	0.0	0.0
Landfilling	8,450.0	230.6	4,385.6
Littering	1,230.0	11.1	210.3

Table 2 Reference flow values of particular commodities, DRS[4]

DRS, Flow Weight, Tons	PET	Steel	Al
Market placement	49,446.0	444.5	8,455.0
Total Recycling	46,324.0	406.0	7,810.9
Mixed plastics/Metal	82.2	406.0	7,810.9
PET	46,241.7	0.0	0.0
Waste Management	3,322.3	40.2	676.9
Waste-to-Energy	722.9	10.4	186.3
Cement Plant	297.1	3.1	5.6
Landfilling	2,302.3	26.7	484.9
Littering	246.0	2.2	42.1

3.3 Applied impact categories

The possible environmental impacts of inventory outputs were expressed by means of the ReCiPe method, which is currently considered the best designed comprehensive approach for assessing life cycle impacts. This study uses the ReCiPe 1.08 characterization model[5,6] which compared to the newer ReCiPe 2016 version, also offers – to a certain extent and with certain level of simplification – standardization and weighting factors enabling the inter-comparison of results for different impact categories. The ReCiPe methodology includes inventory data expressed as possible impacts on the following midpoint and endpoint impact categories. The midpoint evaluation is based on comparing the effects of respective emissions with a reference substance, and is expressed as kilograms of equivalents of this reference substance. The endpoint evaluation is based on quantification of measurable changes in the environment that are considered as unfavorable.

Table 3 Environmental impact categories used in the study. The applied model is ReCiPe 1.08 (E).

Impact category	Name of endpoint impact category [unit]	Name of midpoint impact category [unit]	Brief description
Climate changes/Global warming	Climate change Ecosystems, default, excl biogenic carbon [species.yr] Climate change Human Health, default, excl biogenic carbon [DALY]	Climate change, default, excl biogenic carbon [kg CO_2-Equiv.]	The midpoint potential of global warming (GWP), which is expressed in kg CO_2-eq, is the basic indicator of the carbon footprint. The endpoint level involves climate changes and consequent biodiversity losses [species.yr] or increase of damage to human health expressed as Disability-Adjusted Life Years (DALY).
Fossil fuel depletion	Fossil depletion [$]	Fossil depletion [kg oil eq]	Fossil fuel depletion is expressed monetarily at the endpoint level (usually in USD) and as kilograms of oil equivalents at the midpoint level.
Freshwater ecotoxicity	Freshwater ecotoxicity [species.yr]	Freshwater ecotoxicity [kg 1,4-DB eq]	The effects of toxic substances on the balance of freshwater ecosystems is expressed in quantities of biological species of animals affected in the territory multiplied by the number of years under such influence at the endpoint level. At the midpoint level, ecotoxicity is expressed by the quantity of kilograms of 1.4-dichlorobenzene equivalents.

[5] Mark A.J. Huijbregts, Zoran J.N. Steinmann, Pieter M.F. Elshout, Gea Stam, Francesca Verones, Marisa Vieira, Michiel Zijp, Anne Hollander, Rosalie van Zelm. ReCiPe2016: a harmonized life cycle impact assessment method at midpoint and endpoint level. International Journal of LCA, DOI 10.1007/s11367-016-1246-y.

[6] https://www.rivm.nl/en/Topics/L/Life_Cycle_Assessment_LCA/Downloads

Impact category	Name of endpoint impact category [unit]	Name of midpoint impact category [unit]	Brief description
Freshwater eutrophication	Freshwater eutrophication [species.yr]	Freshwater eutrophication [kg P eq]	The pollution of freshwater ecosystems by a surplus of nutrients and biodegradable substances – eutrophication – is expressed in quantities of biological species of animals affected in the territory multiplied by the number of years under such influence at the endpoint level. At the midpoint level, it is expressed by kilograms of phosphorus equivalents.
Human toxicity	Human toxicity [DALY]	Human toxicity [kg 1,4-DB eq]	The emission of substances toxic to humans is expressed as the number of Disability-Adjusted Life Years (DALY) at the endpoint level. At the midpoint level, human toxicity is expressed by the quantity of kg of 1.4-dichlorobenzene equivalents.
Ionizing radiation	Ionizing radiation [DALY]	Ionizing radiation [kg U^{235} eq]	The emission of ionizing radiation is expressed as the number of Disability-Adjusted Life Years (DALY) at the endpoint level. At the midpoint level, it is expressed by kilograms of U^{235} uranium equivalents.
Metal depletion	Metal depletion [$]	Metal depletion [kg Fe eq]	Metal depletion is expressed monetarily at the endpoint level (usually in USD) and as kilograms of metal equivalents at the midpoint level.
Ozone depletion	Ozone depletion [DALY]	Ozone depletion [kg CFC-11 eq]	The decomposition of stratospheric ozone is expressed as the number of Disability-Adjusted Life Years (DALY) at the endpoint level. At the midpoint level, it is expressed by kilograms of CFC11 Freon equivalents.
Particulate matter formation	Particulate matter formation [DALY]	Particulate matter formation [kg PM10 eq]	The adverse impacts of particulate matter formation and its release into the atmosphere is expressed as the number of Disability-Adjusted Life Years (DALY) at the endpoint level. At the midpoint level, it is expressed by kilograms of PM10 particulate matter equivalents.
Photochemical oxidant formation	Photochemical oxidant formation [DALY]	Photochemical oxidant formation [kg NMVOC]	The release of reactive and radical emissions into the atmosphere is expressed as the number of Disability-Adjusted Life Years (DALY) at the endpoint level. At the midpoint level, it is expressed by kilograms of volatile hydrocarbons (with exclusion of methane).
Terrestrial acidification	Terrestrial acidification [species.yr]	Terrestrial acidification [kg SO_2 eq]	The effects of acid-forming substances on the balance of terrestrial ecosystems is expressed at the endpoint level in the number of biological species of animals affected in the territory multiplied by the number of years under such influence. At the midpoint level, terrestrial acidification is expressed in kilograms of sulfur dioxide equivalents.

Impact category	Name of endpoint impact category [unit]	Name of midpoint impact category [unit]	Brief description
Terrestrial ecotoxicity	Terrestrial ecotoxicity [species.yr]	Terrestrial ecotoxicity [kg 1,4-DB eq]	The effects of toxic substances on the balance of terrestrial ecosystems are expressed at the endpoint level in the numbers of biological animal species affected in the territory multiplied by the number of years under such influence. At the midpoint level, terrestrial ecotoxicity is expressed in kilograms of 1,4-dichlorobenzene equivalents.
Marine eutrophication	-	Marine eutrophication [kg N-Equiv.]	The pollution of marine ecosystems by a surplus of nutrients and biodegradable substances is not expressed at the endpoint level. At the midpoint level, it is expressed by kilograms of nitrogen equivalents.
Water depletion		Water depletion [m^3]	Water depletion is assessed at the midpoint level only, and is expressed in m^3 of depleted water.

3.4 Applied LCA software

Dedicated software and an inventory data database are used for calculations and to model the life cycles of products or organizations. Professional GaBi 8[7] LCA software was used in this study.

3.5 Assumptions made and limitations on the validity of the study

- When making the model for this LCA study, it was necessary to make certain assumptions. The HDPE PET bottle caps have not been included into the model. This is a material flow that would operate identically (share the same scenario) in the deposit refund system being considered as it does in the current state. When comparing the current state and the deposit-refund system, it is therefore a constant that may be excluded from the assessed system.
- Secondary and tertiary packaging has not been included in the system boundaries, since they would represent identical items for both the current system and for the deposit-refund system.
- Other partial assumptions related to the respective processes are specified in more detail in the following section, devoted to inventorying the life cycle. In general, a so-called conservative approach to the choice of assumptions was selected for the study. By a conservative attitude, we mean making such assumptions that would rather favor the

[7] https://www.thinkstep.com/software/gabi-lca/

current system, i.e. treatment of used bottles without a deposit-refund system. Assessing the new alternative – the deposit-refund system – must be done conservatively, i.e. with a greater degree of caution.

- The effect of some assumptions influencing the resulting evaluation of the assessed systems is described in the following table. The symbol ↘ means that the stated assumption decreases the resulting values of environmental impacts and it “helps” or “favors” the system involved in the assessment. The symbol ↗ means that the stated assumption increases the resulting values of the environmental impacts of the system involved.

Table 4 Effects of some assumptions influencing the resulting values of the environmental indicators of both assessed systems. The symbol ↗ means that the stated assumption increases the resulting values of the environmental impacts of the system involved.

Assumption	Current system	Deposit-Refund System (DRS)
Containers for the separate collection of plastics have not been included in the system boundaries. Containers for plastics are not necessary for bottles in the deposit-refund system.	↘	↗
1 paper return ticket for returning 5 pcs of bottles	↘	↗
Exclusion of the possible impacts of microplastics released into the environment from littering	↘	↗
More conservative estimates of transport distances	↘	↗

- In this study, the fact that multicolored PET bottles have limited recycling ability and secondary use has not been considered. The usability of PET bottles as a secondary raw material would only increase if single-color (or colorless) PET bottles were used.
- The repeated use of PET bottles has not been considered in this study. The model is based upon processing PET bottles as a secondary raw material that substitutes the primary raw material. Re-using bottles (repeated filling of bottles with beverages) would result in impact category indicator achieving even lower results in the case of a deposit-refund system, since the process that dominates the resulting environmental impacts is the manufacture of PET materials (as will be explained below).

4 Life cycle inventory analysis

4.1 Data collection

All generic processes used for the LCA modelling derive from the database of the GaBi Professional Software (thinkstep) and from the Ecoinvent 3.4 database.

Specific material flow values for beverage bottles entering the Czech market and particular waste management operations, as well as operations related to waste-to-material and waste-to-energy utilization have been determined by the company Eunomia; see paragraph 3.2.5.

Specific values related to the manufacture and operation of collection facilities (RVM – Reverse Vending Machine) have been acquired from the manufacturer (Tomra). Other specific information related to waste collection has been acquired from the organization Pražské služby, a.s. Specific values for particular processes of the LCA model are stated in the following paragraph, which describes unit processes.

4.2 Unit processes of the LCA model and specific values of the assumptions made

The LCA model comprises partly general (generic/database) processes and partly processes created for specific (site specific) operations. Processes that had to be created for this study are described in more detail in the following paragraphs.

4.2.1 Littering

In the case of PET, littering has not been part of environmental impact assessment since there are no relevant characterization factors for plastics in the environment (including microplastics) available. Also, information about the particular adverse effects of microplastics on biota is rare. The amount of plastics released into the environment has only been inventoried and expressed by weight in this study. According to the Eunomia data, the implementation of DRS would result in decrease of plastics released into the environment from 1,230 tons to 246 tons. The implementation of DRS would result in a decrease of plastics released into the environment from beverage bottles by 80%.

With regard to adding a quantification of the environmental impacts of littering aluminum and sheet steel bottles, the characterization would be made based on the material composition of bottles provided by Department of Metals and Corrosion Engineering of UCT Prague[8]. The aluminum bottle is made from two alloys. The case is made from Al-Mn (max. approx. 2% Mn) and the cap is Al-Mg (approx. 3% by weight Mg). With respect to the steel bottle/can, poorer quality steel than stainless

[8] doc. Ing. Pavel Novák, Ph.D., Department of Metals and Corrosion Engineering of UCT Prague.

steel is assumed, i.e. the following composition may be expected in these bottles: 0.05–1% C; 0.2–2% Mn; to 6% Cr; 0.3–2% Si; to 3% Mo; to 3% V; to 5% Ni; traces of sulfur and phosphorus (usually to 0.01%) and the rest is made by iron. All numbers in % by weight. To characterize environmental impacts, the assumption was made that 1/3 of weight will be released into agricultural or forest land, 1/3 of weight will be released into industrial land and 1/3 into surface water. The specific values of elementary flows released by littering into particular environment components are stated in the following tables.

Table 5 Aluminum bottle littering

Elementary flow [environmental component]	Amount of released elementary flow into the environmental component from 1 kg of littering, kg
Aluminum [Inorganic emissions to industrial soil]	0.316667
Aluminum [Inorganic emissions to fresh water]	0.316667
Aluminum [Inorganic emissions to agricultural soil]	0.316667
Magnesium [Inorganic emissions to industrial soil]	0.01
Magnesium [Inorganic emissions to fresh water]	0.01
Magnesium [Inorganic emissions to agricultural soil]	0.01
Manganese [Heavy metals to industrial soil]	0.006667
Manganese [Heavy metals to fresh water]	0.006667
Manganese [Heavy metals to agricultural soil]	0.006667

Table 6 Steel bottle littering

Elementary flow [environmental component]	Amount of released elementary flow into the environmental component from 1 kg of littering, kg
Chromium [Heavy metals to industrial soil]	0.016667
Chromium [Heavy metals to fresh water]	0.016667
Chromium [Heavy metals to agricultural soil]	0.016667
Iron [Heavy metals to industrial soil]	0.273333
Iron [Heavy metals to fresh water]	0.273333
Iron [Heavy metals to agricultural soil]	0.273333
Manganese [Heavy metals to industrial soil]	0.006667
Manganese [Heavy metals to fresh water]	0.006667
Manganese [Heavy metals to agricultural soil]	0.006667
Molybdenum [Heavy metals to industrial soil]	0.01
Molybdenum [Heavy metals to fresh water]	0.01
Molybdenum [Heavy metals to agricultural soil]	0.01
Nickel [Heavy metals to industrial soil]	0.016667
Nickel [Heavy metals to fresh water]	0.016667
Nickel [Heavy metals to agricultural soil]	0.016667
Vanadium [Heavy metals to industrial soil]	0.01
Vanadium [Heavy metals to fresh water]	0.01

Vanadium [Heavy metals to agricultural soil]	0.01

4.2.2 Transport distances

Conservative transport distances were used in models, which meant using greater distances than actually expected. Thus, the total concept of the model overvalues the importance of transport environmental impacts. In the real-life situation, we expect the influence of transport to be lower than the influence arising from the results of this study. Here, we might as well confirm that, based on the below-stated results, with respect to LCA, transport distances have no significant influence on the environmental impacts of the system as a whole, nor therefore on the evaluation and inter-comparison of both assessed systems (see Section 5.4 Influence of particular technology spheres). The more conservative estimates for transport distances were especially considered for DRS. Specific distances applied in calculations for the LCA model are given in the following table.

Table 7 Transport distances applied in calculations for the basic LCA model

Type of transport	Current system	DRS – deposit-refund system
Return of bottles by customers	–	15 km
Collection of waste in containers	35 km	35 km
Transport to a landfill site	20 km	20 km
Transport for waste-to-energy use (to a waste-to-energy facility, cement plant)	150 km	150 km
Transport to a collection center		250 km
Transport to a recycling line	200 km	150 km

According to information provided by waste-to-energy plants (ZEVO)[9], the collection rounds in Prague represent approx. 35 km and the collection round is completed twice a day. To transport the average waste in Prague, a distance of 35 km must be travelled by the collection vehicle. However, in the Czech Republic, there are regions where waste is transported longer distances (more than 100 km) to a waste incinerator (SAKO Brno).

4.2.3 Return of bottles by customers

More attention should be paid to modelling the method for the transport of used bottles by consumers to a buyback point. Information regarding people's average transport distance to purchase points (especially with respect to the return of bottles) is not available. The variability in driving distances and the variability in numbers of returned bottles creates significant uncertainty in

[9] Ing. Tomáš Baloch, ZEVO Praha Malešice

the system. To model the deposit-refund system, the following conservative approach has been adopted:

The driving distance to a buyback point has been given a value of 15 km, which is most probably an overstated value (conservative approach) since a significant number of people go shopping on foot, or do the shopping when returning by car from work or during another car drive. The number of returned bottles in one drive was estimated at 10 pcs. If the number was smaller, inhabitants would most probably walk when returning the bottles, or do so during another drive past a shop/buyback point. Since it may be assumed that most drives related to the return of bottles will not be made for the sole purpose of bottle returning, but also for purposes of shopping, it is necessary to split (allocate) the transport environmental impacts between the returned bottles and the shopping itself. To allocate the environmental impacts between the purchased goods and returning of bottles, an allocation rule based on the ratio of the weight of purchased goods and the weight of returned bottles has been selected. The weight of bottles has been determined by multiplying the weight of one bottle by the quantity returned (10 pcs) and the weight of purchased goods has been selected as 30 kg. The weight of 30 kg for purchased goods may be considered as rather low and conservative (a higher weight of purchased goods would result in a lower allocation of impacts related to bottle returning in the model). To illustrate, it is worth mentioning that when returning 10 pieces of 1.5L PET bottles and buying the same quantity of full bottles, the purchased goods will weigh at least 10*1.5 = 15 kg.

4.2.4 Number of containers

The number of containers necessary for collecting a certain quantity of bottles may vary a lot and will depend on the overall logistics of the system and priorities of involved parties. The necessary number of containers may also vary significantly depending on consumer behavior, for example, whether bottles are returned to containers compressed or in their original condition. Containers for separate collection have not been included in the system boundaries. Because DRS does not use containers for deposited bottles, this assumption is to the detriment of DRS.

4.2.5 Sorting line/conveyor belt

The sorting line has been modelled as a conveyor belt having a specific energy consumption. Energy consumption has been determined based on data provided by the company Respono[10], a.s. Annual energy consumption for sorting has been determined from the known volume of sorted plastics (2,099 tons in 2016; 2,769.33 tons in 2017), conveyor belt power input (0.55 kW)[11], lighting power

[10] Zuzana Ambrožová; Respono, a.s., https://www.respono.cz/

[11] Conveyor belt 6.0 m CXL6000 HD

input, and the number of hours of a 2-shift operation for one calendar year. Since the ratio of PET to the total amount of plastics in separated plastics represents approx. 0.8/(5.7+0.8) = 0.12[12], a value of 12% of electricity consumed for sorting has been assigned to PET.

4.2.6 RVM

The number of machines for the return of bottles (denoted as RVM – Reverse Vending Machine) necessary to ensure DRS in the Czech Republic is estimated by the company Eunomia at 3.808 pieces. A reverse vending machine has been modelled based on data given in the following table:

Table 8 Inputs of the unit process for manufacturing a reverse vending machine

Inputs				
Parameter	**Flow**	**Quantity**	**Amount**	**Unit**
	Polystyrene part (PS) [Plastic parts]	Mass	65	kg
	Steel sheet 1.5mm hot dip galvan. (0.01mm;1s) [Metals]	Mass	520	kg
	Styrene-butadiene-rubber (SBR) [Plastics]	Mass	16.5	kg
	Glass blocks [Minerals]	Mass	16.5	kg
	GLO: electronics, for control units [allocatable product]	Mass	32	kg
Outputs				
Parameter	**Flow**	**Quantity**	**Amount**	**Unit**
	Reverse vending machine [Assemblies]	Number of pieces	1	pcs.

The reverse vending machine is powered by electricity. According to the manufacturer, the RVM TOMRA T-9 needs 65 W in its sleep mode. A more conservative value of 100 W has been used for model calculations. Total annual energy consumption is determined at 876 kWh. In comparison with the value of 525 kWh used in the Norwegian study[13] and provided by the RVM manufacturer Tomra[14], this value is higher, i.e. also more conservative. The life cycle of the paper necessary for printing deposit-refund tickets has been included in the model. A situation in which one ticket is issued for returning 5 bottles has been used in calculations. Again, this is a conservative estimate and it may be assumed that customers will return a higher number of bottles in one buyback. This conservative estimate leads to a higher consumption of paper when returning bottles, and therefore it increases possible DRS impacts.

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[12] http://www.nemcicenh.cz/files/zivotni-prostredi/vysledky_rozboru_nemcice_nad-hanou.pdf
[13] Hanne Lerche Raadal, Ole Magnus Kålås Iversen and Ingunn Saur Modahl: LCA of beverage container production, collection and treatment systems. Østfoldforskning, Kråkerøy 2016, ISBN no.: 978-82-7520-746-1
[14] https://www.tomra.com/

4.2.7 Bottle counting and pressing centers

Based on data provided by the organization Eunomia, it will be necessary to build 2 centers containing 5 counting machines and 2 presses. The values used in creating the LCA processes for the manufacture of machines for counting and pressing bottles are stated in the following table. The energy consumption for the manufacture of machines has not been included into the model. The energy consumption for the operation of machines forms a part of the model.

Table 9 Inputs of the unit process for the manufacture of a machine for counting bottles (Counting machine)

Inputs				
Parameter	**Flow**	**Quantity**	**Amount**	**Unit**
	Aluminum part [Metal parts]	Mass	9.831143	kg
	Brass component [Metal parts]	Mass	1.179737	kg
	Cast iron part [Metal parts]	Mass	56.17796	kg
	Copper sheet [Metals]	Mass	0.019803	kg
	Nylon 6 part (PA 6) [Plastic parts]	Mass	0.983114	kg
	Polyester resin (unsaturated; UP) [Plastics]	Mass	4.213347	kg
	Polyethylene high density part (HDPE/PE-HD) [Plastic parts]	Mass	12.64004	kg
	Polyurethane (PU) [Plastics]	Mass	4.381881	kg
	Polyvinylchloride injection molding part (PVC) [Plastic parts]	Mass	2.808898	kg
	Steel billet (20MoCr4) [Metals]	Mass	44.38059	kg
	Styrene-butadiene-rubber (SBR) [Plastics]	Mass	5.140283	kg
Outputs				
Parameter	**Flow**	**Quantity**	**Amount**	**Unit**
	Counting machine [Assemblies]	Number of pieces	1	pcs.

Table 10 Inputs of the unit process for the manufacture of a machine for counting bottles (Baler machine)

Inputs				
Parameter	**Flow**	**Quantity**	**Amount**	**Unit**
	Aluminum part [Metal parts]	Mass	14.15685	kg
	Brass component [Metal parts]	Mass	0.786491	kg
	Cast iron part [Metal parts]	Mass	383.8827	kg
	Copper sheet [Metals]	Mass	0.013202	kg
	Nylon 6 part (PA 6) [Plastic parts]	Mass	0.65541	kg
	Polyester resin (unsaturated; UP) [Plastics]	Mass	1.947503	kg
	Polyethylene high density part (HDPE/PE-HD) [Plastic parts]	Mass	5.730152	kg
	Polyurethane (PU) [Plastics]	Mass	3.295774	kg
	Polyvinylchloride injection molding part (PVC) [Plastic parts]	Mass	1.498079	kg
	Steel billet (20MoCr4) [Metals]	Mass	22.8457	kg

Inputs				
Parameter	**Flow**	**Quantity**	**Amount**	**Unit**
	Styrene-butadiene-rubber (SBR) [Plastics]	Mass	3.426855	kg
Outputs				
Parameter	**Flow**	**Quantity**	**Amount**	**Unit**
	Baler machine [Assemblies]	Number of pieces	1	pcs.

4.2.8 Cement Plant

The use of PET in cement plants has been modelled as the substitution of another fuel (brown coal) based on the energy contents of waste PET material.

4.3 LCA model schemes

Based on the input information, the following life cycle models of the individually assessed scenarios for non-deposit-refund and deposit-refund systems for the treatment of beverage packaging were made, and were subsequently used for calculating environmental indicators. Behind each process illustrated in the figure is a dynamically linked database of environmental impacts that is used for the calculations. The respective processes are divided into the following groups (distinguished by color) reflecting their affiliation to a given technology unit. The groups have been established as follows:

- Yellow: manufacturing and the use of materials used for manufacturing beverage bottles.
- Light green: transport as part of waste management.
- Dark green: transport as part of utilizing materials.
- Brown: waste management, incl. benefits gained by utilizing waste management outputs (e.g. waste-to-energy in the case of landfill gases).
- Pink: littering.
- Light blue: Return of deposited bottles by customers.
- Blue: Recycling of bottles.

In the case of the scheme showing operations involved in the deposit-refund system (Figure 9 – DRS operations), the following colors have been used to illustrate the grouping of the processes involved:

- Orange: Manufacture, operation and removal of reverse vending machines, incl. the manufacture and disposal of paper deposit-refund tickets.
- Green: Manufacture, operation and disposal of a sorting station.

Figure 3 Life cycle scheme of a non-deposit-refund system for PET bottles (PET Baseline)

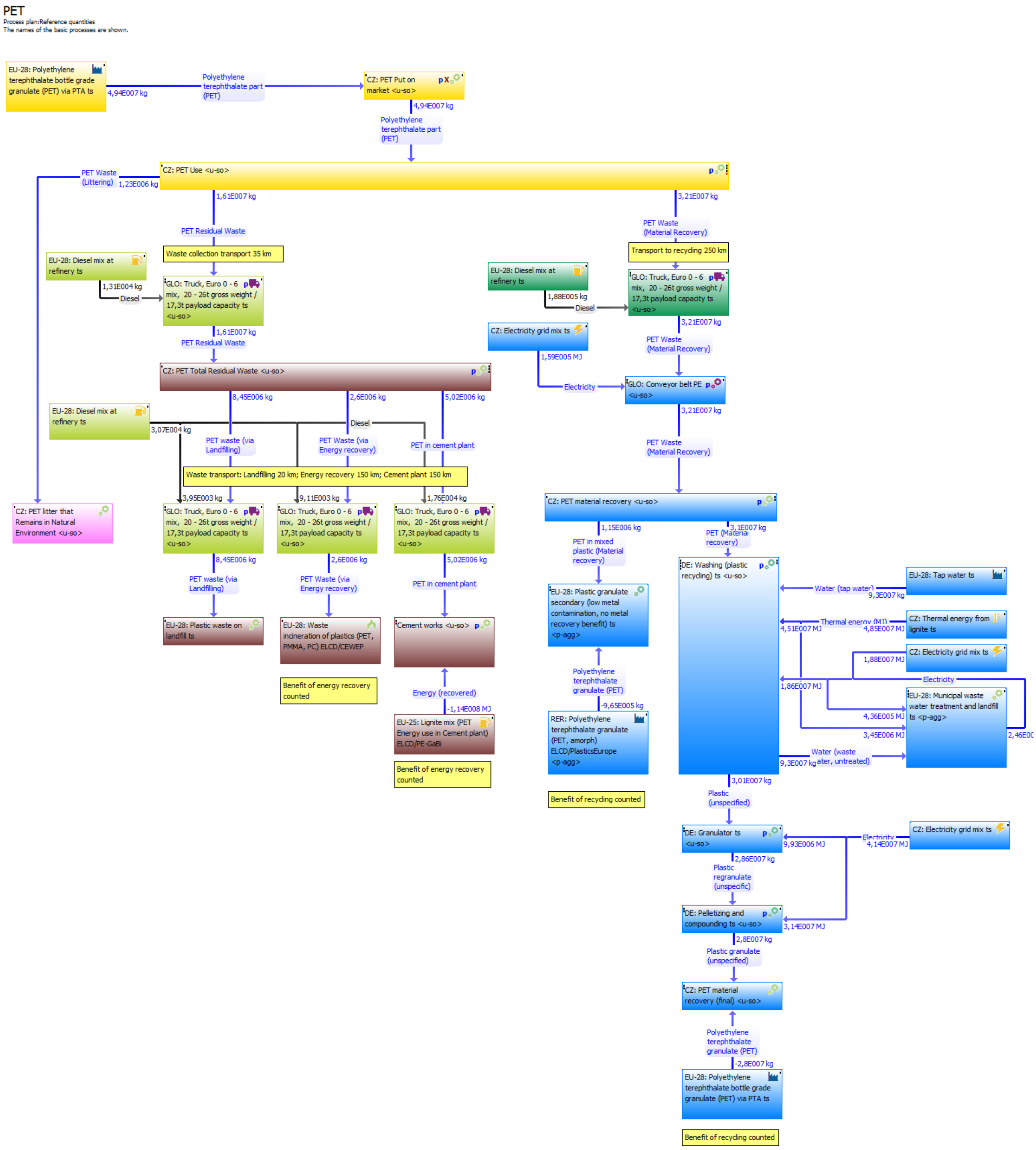


Figure 4 Life cycle scheme of a deposit-refund system for aluminum bottles (Aluminum Baseline)

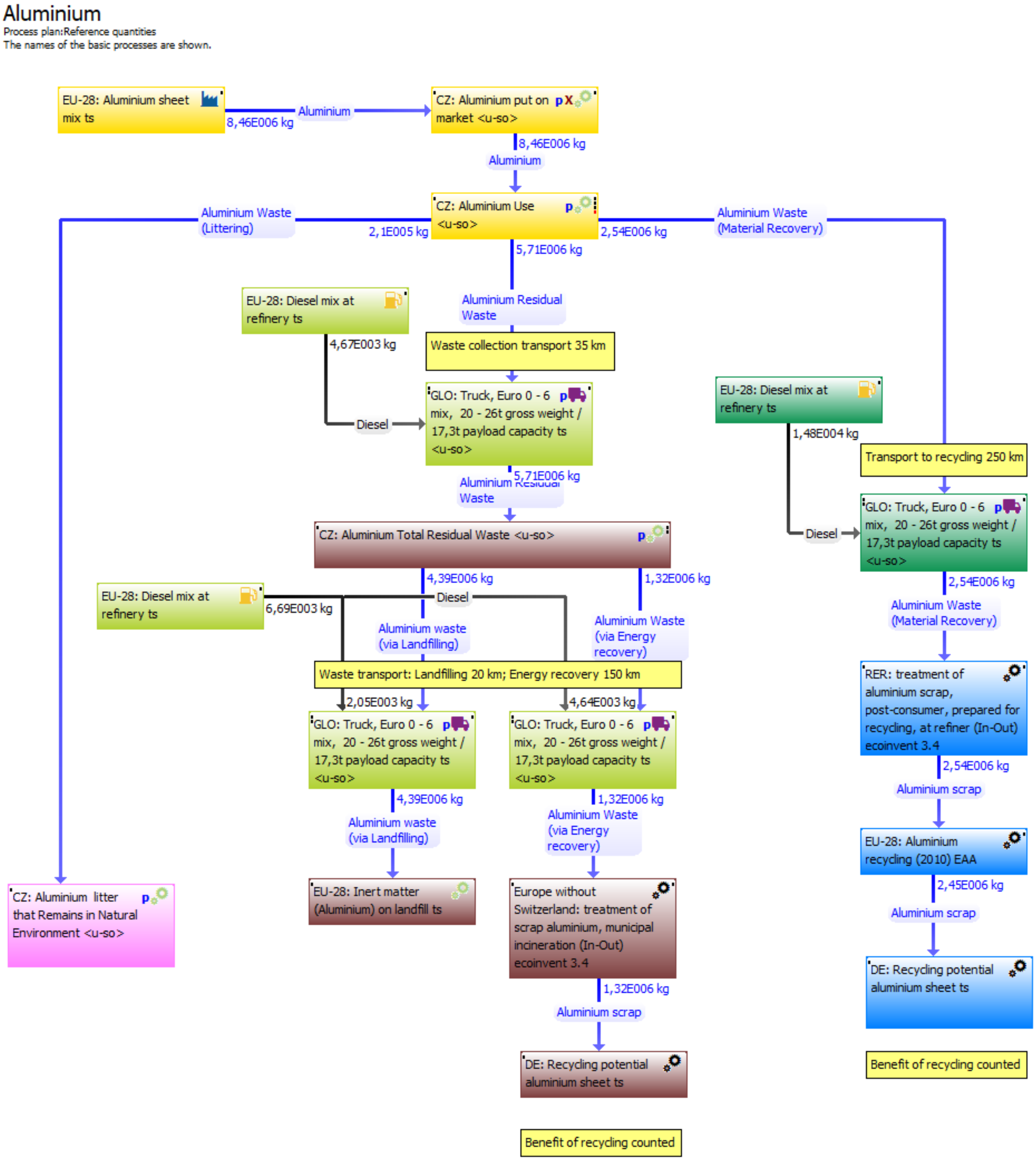


Figure 5 Life cycle scheme of a deposit-refund system for steel bottles (Steel Baseline)

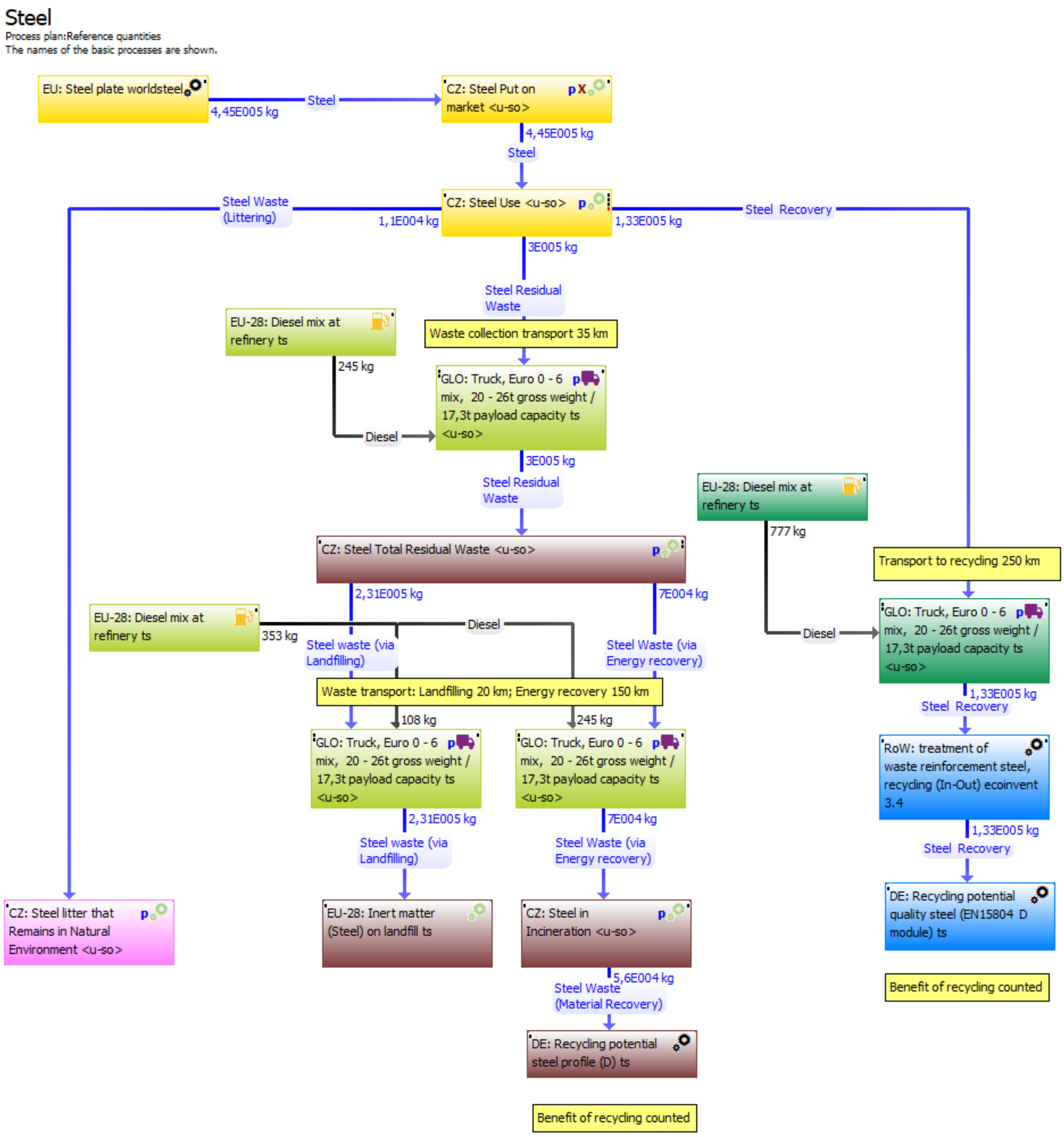


Figure 6 Life cycle scheme of a deposit-refund system for PET bottles (PET DRS)

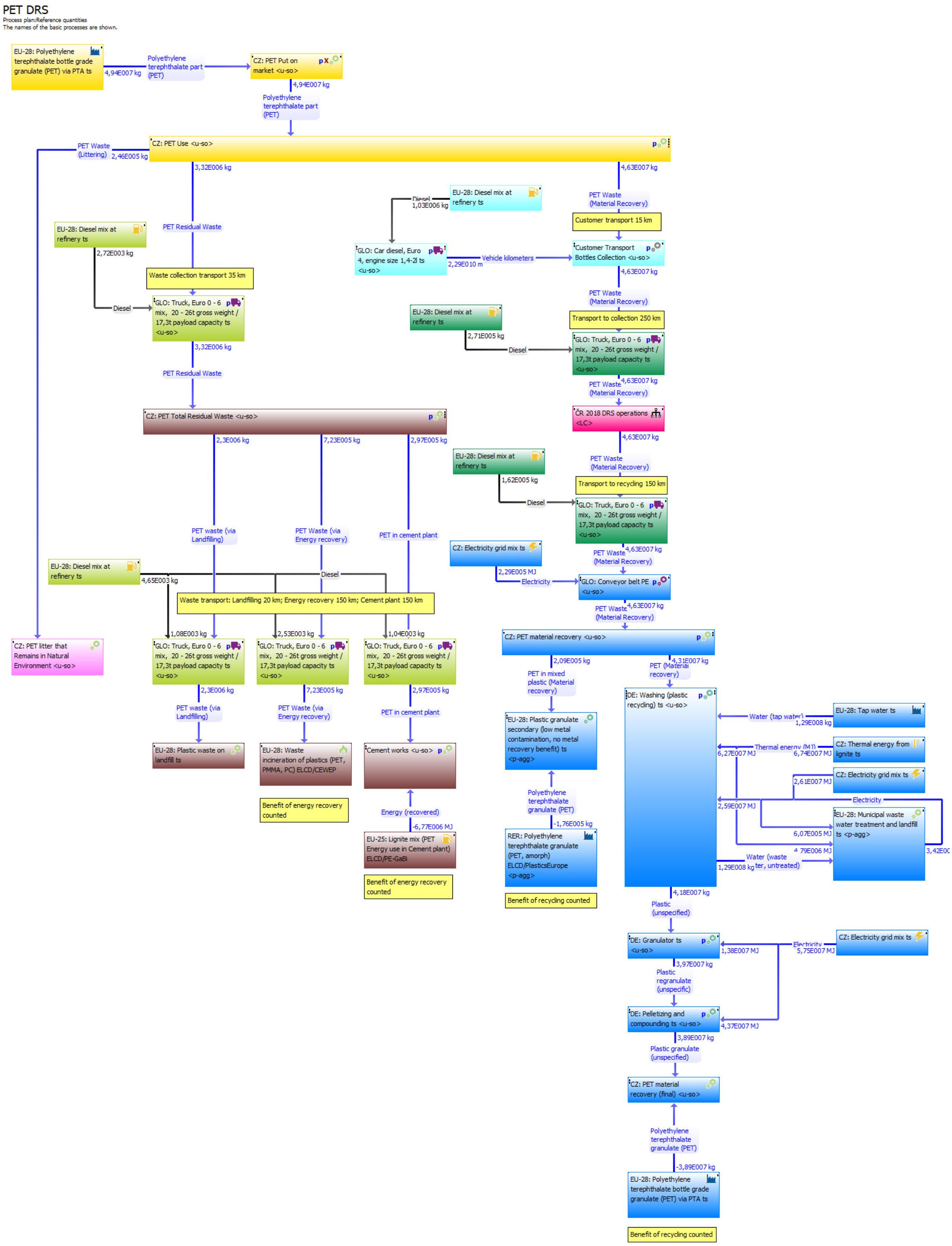


Figure 7 Life cycle scheme of a deposit-refund system for aluminum bottles (Aluminum DRS)

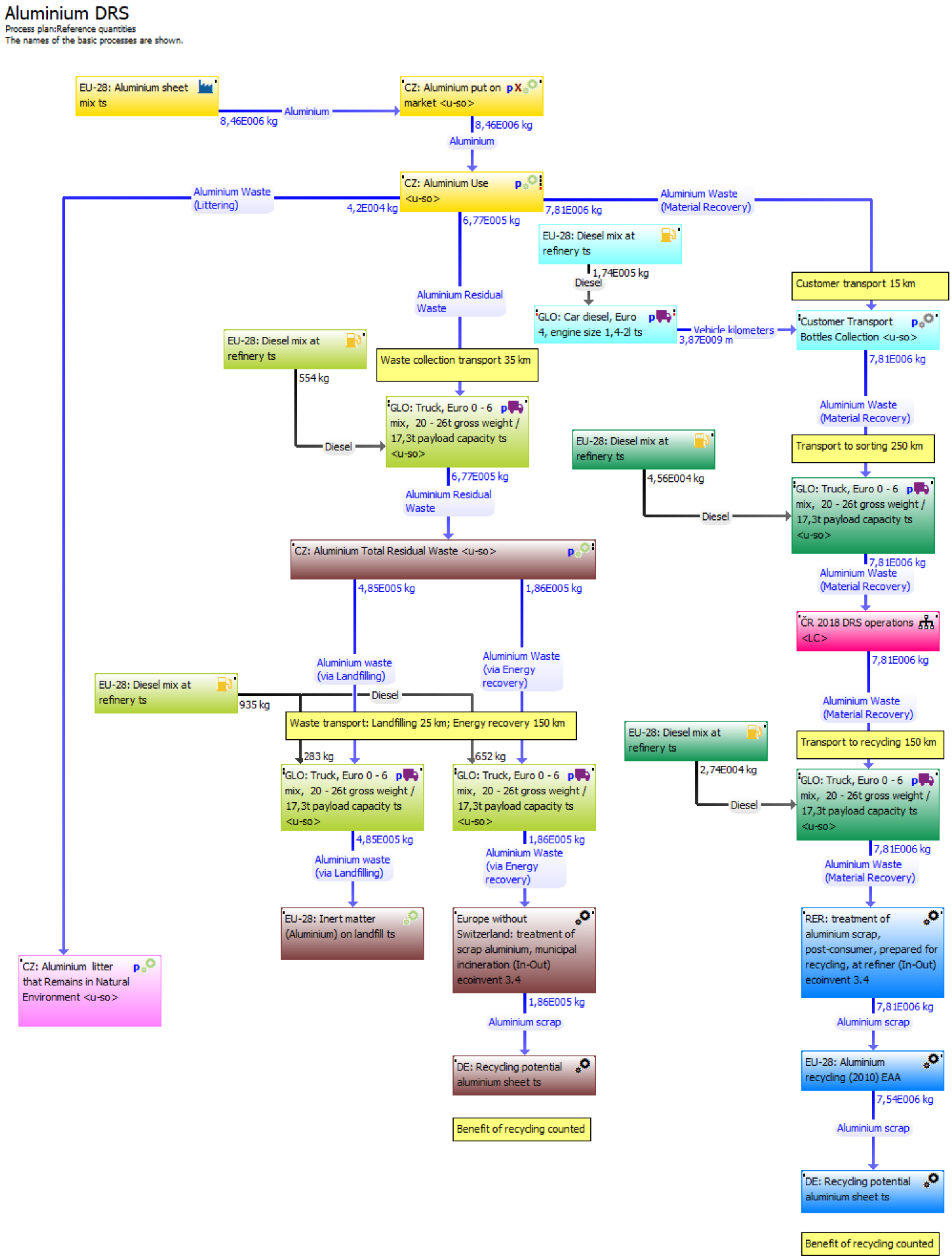


Figure 8 Life cycle scheme of a deposit-refund system for steel bottles (Steel DRS)

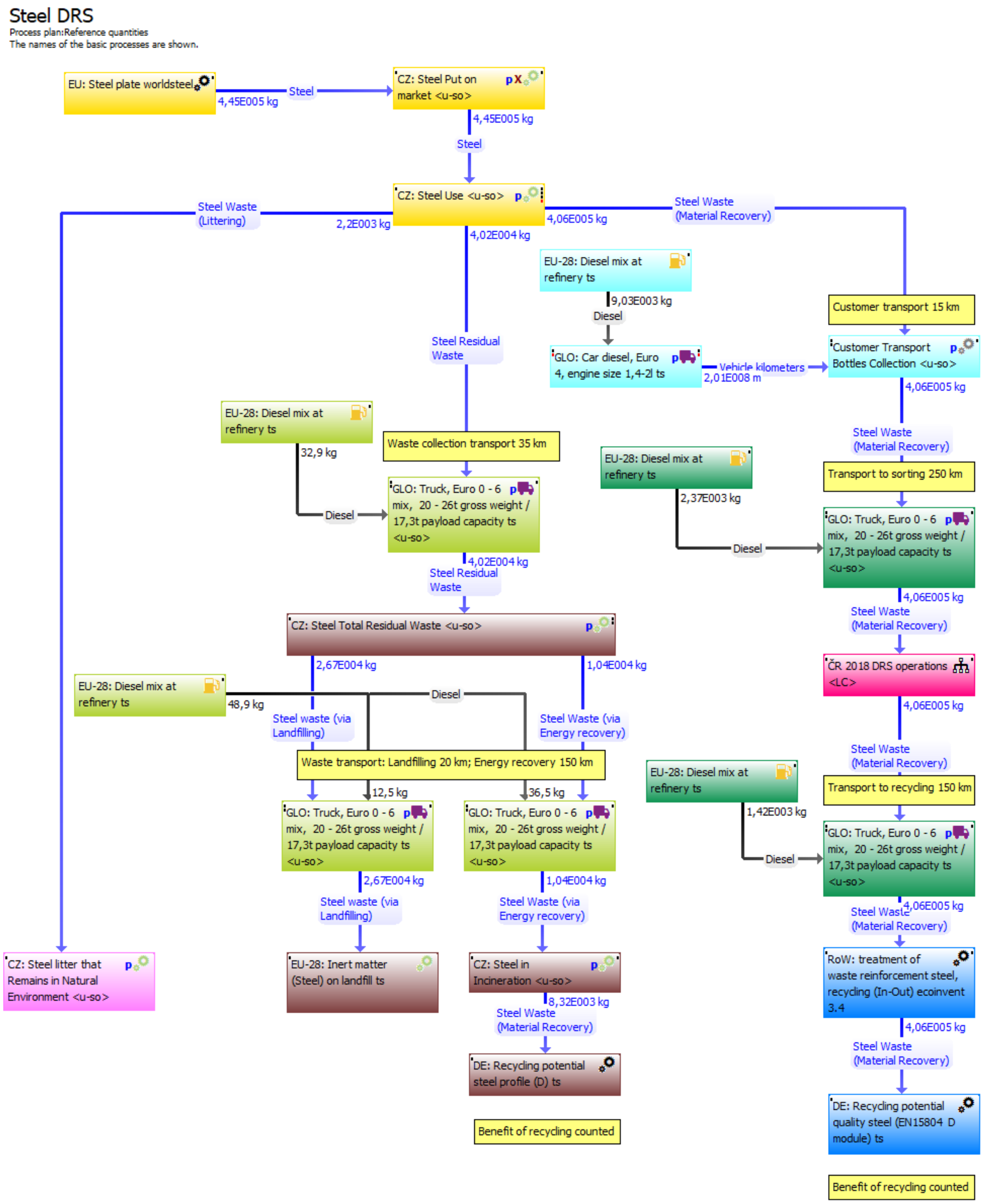
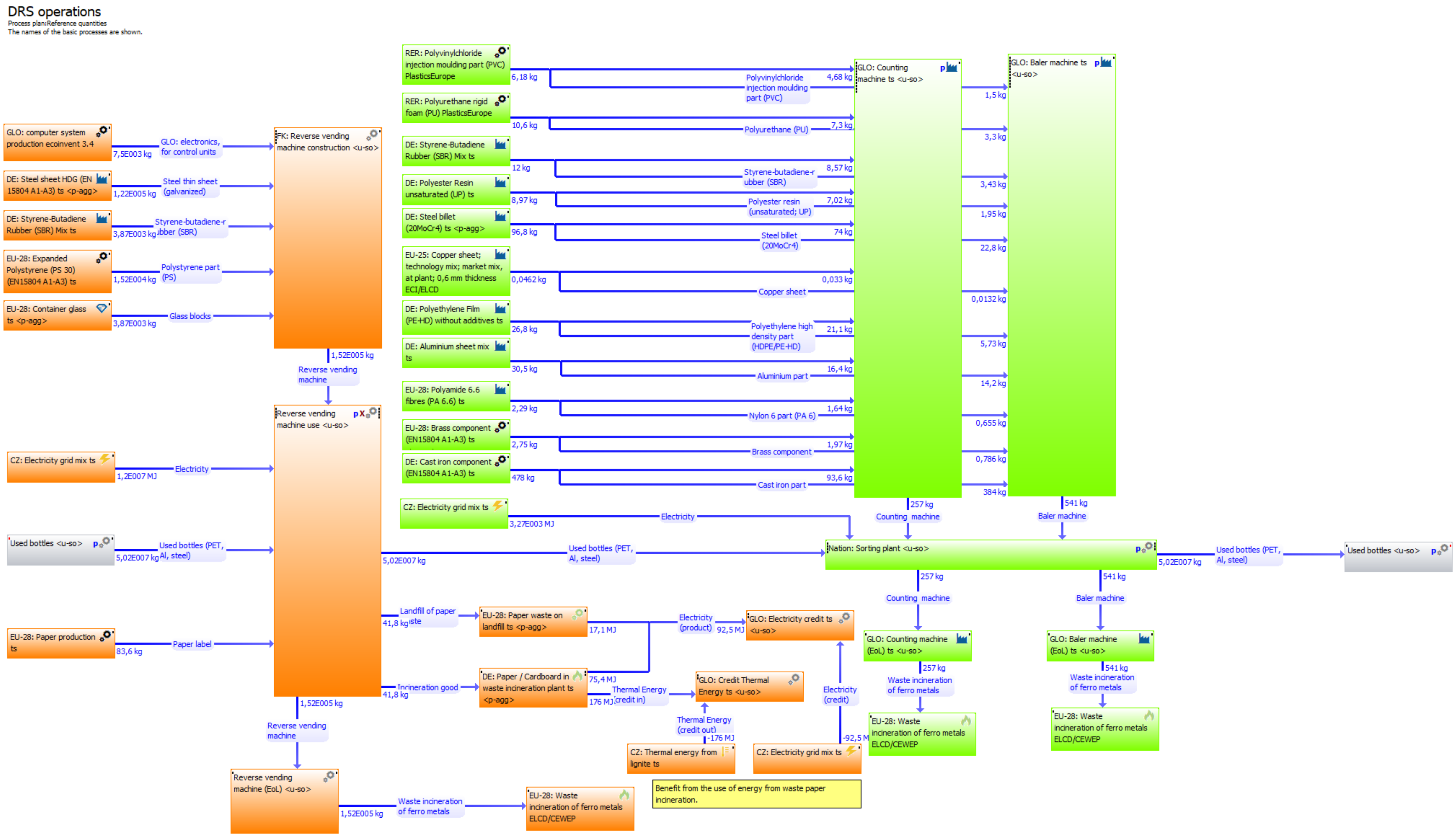


Figure 9 Life cycle scheme of operations involved in deposit-refund system operation



4.4 Life cycle inventory analysis outputs – depletion of raw material resources

The life cycle inventory analysis outputs set out data on the demands of the individually assessed systems on raw material resources and data indicating the quantities of particular substances emitted to the environment. Since this is a rather large data file and since the consumption values of energy resources, incl. oil, are of primary significance for this study, only the results for energy raw materials are stated here. A total summary of the life cycle inventory analysis outputs for the non-deposit-refund system is given in Annex No. 1 and for the deposit-refund system in Annex No. 2.

Table 11 Life cycle inventory analysis outputs – the consumption of energy raw materials of the non-deposit-refund system (Baseline)

Mass, kg	Baseline Total	Aluminum	PET	Steel
Crude oil (resource)	22,104,181	3,396,228	18,687,597	20,356
Hard coal (resource)	5,838,754	4,318,182	1,209,722	310,850
Lignite (resource)	234,550	674,200	-456,571	16,922
Natural gas (resource)	22,181,382	5,742,149	16,409,089	30,144
Uranium (resource)	304.1	130.4	173.3	0.4

The negative value of lignite consumption in the column for PET bottles is caused by coal savings resulting from the incineration of PET as a fuel in cement plants.

Table 12 Life cycle inventory analysis outputs – consumption of energy raw materials of the deposit-refund system (DRS)

Mass, kg	DRS Total	Aluminum DRS	PET DRS	Steel DRS
Crude oil (resource)	12,422,087	1,483,519	10,913,630	24,939
Hard coal (resource)	2,154,819	87,181	1,890,541	177,096
Lignite (resource)	16,453,129	423,208	15,982,021	47,901
Natural gas (resource)	12,860,215	4,115,522	8,701,839	42,853
Uranium (resource)	183.4	-27.5	210.0	0.9

5 Life cycle impact evaluation

The principle for evaluating environmental impacts when assessing a life cycle lies in converting life cycle inventory analysis outputs (quantities of consumed raw materials and emitted substances) into indicators of environmental impact categories. This conversion is done by means of published characterization factors that meet the selected methodology. The ReCiPe methodology (see Section 3.3 Applied impact categories) has been chosen for this project.

5.1 Life cycle impact evaluation results

The following tables show the resulting values of the impact category indicators of the non-deposit-refund system (Baseline) and deposit-refund system (DRS). Aggregated results (Total) and the contributions of particular bottle types (PET, aluminum, sheet steel) are stated for each system in the table, corresponding to their LCA models. In practice, operating a system separately for particular bottle types would have no meaning so the contribution values of respective bottle types must be regarded as approximate.

Table 13 Indicator results of the endpoint and midpoint impact categories of the non-deposit-refund (Baseline) system – ReCiPe 1.08

Impact category	Baseline Total	Aluminum	PET	Steel
ReCiPe 1.08 Endpoint (E) - Climate change Ecosystems, default, excl biogenic carbon [species.yr]	2.26	0.878	1.36	0.0165
ReCiPe 1.08 Endpoint (E) - Climate change Ecosystems, incl biogenic carbon [species.yr]	2.27	0.878	1.37	0.0165
ReCiPe 1.08 Endpoint (E) - Climate change Human Health, default, excl biogenic carbon [DALY]	423	165	256	3.0900
ReCiPe 1.08 Endpoint (E) - Climate change Human Health, incl biogenic carbon [DALY]	426	165	258	3.0900
ReCiPe 1.08 Endpoint (E) - Fossil depletion [$]	8,260,000	2,070,000	6,150,000	41,900
ReCiPe 1.08 Endpoint (E) - Freshwater ecotoxicity [species.yr]	0.021	0.0209	0.00004	0.0001
ReCiPe 1.08 Endpoint (E) - Freshwater eutrophication [species.yr]	0.00010	0.00006	0.00004	0.00000
ReCiPe 1.08 Endpoint (E) - Human toxicity [DALY]	185	80	63	41
ReCiPe 1.08 Endpoint (E) - Ionizing radiation [DALY]	0.159	0.081	0.078	0.000
ReCiPe 1.08 Endpoint (E) - Metal depletion [$]	515,000	451,000	25,000	38,700

Impact category	Baseline Total	Aluminum	PET	Steel
ReCiPe 1.08 Endpoint (E) - Ozone depletion [DALY]	-0.0001	0.0005	-0.0006	0.0000
ReCiPe 1.08 Endpoint (E) - Particulate matter formation [DALY]	28.20	21.10	6.82	0.23
ReCiPe 1.08 Endpoint (E) - Photochemical oxidant formation [DALY]	0.0087	0.0046	0.0040	0.0001
ReCiPe 1.08 Endpoint (E) - Terrestrial acidification [species.yr]	0.0047	0.0033	0.0014	0.0000
ReCiPe 1.08 Endpoint (E) - Terrestrial ecotoxicity [species.yr]	0.0270	0.0033	0.0112	0.0126
ReCiPe 1.08 Midpoint (E) - Climate change, default, excl biogenic carbon [kg CO2 eq.]	1.21E+08	4.69E+07	7.28E+07	8.81E+05
ReCiPe 1.08 Midpoint (E) - Climate change, incl biogenic carbon [kg CO2 eq.]	1.21E+08	4.69E+07	7.35E+07	8.82E+05
ReCiPe 1.08 Midpoint (E) - Fossil depletion [kg oil eq.]	5.00E+07	1.25E+07	3.73E+07	2.54E+05
ReCiPe 1.08 Midpoint (E) - Freshwater ecotoxicity [kg 1,4 DB eq.]	2.52E+07	2.51E+07	4.97E+04	7.33E+04
ReCiPe 1.08 Midpoint (E) - Freshwater eutrophication [kg P eq.]	2,290	1,370	914	1
ReCiPe 1.08 Midpoint (E) - Human toxicity [kg 1,4-DB eq.]	2.66E+08	1.15E+08	9.05E+07	6.00E+07
ReCiPe 1.08 Midpoint (E) - Ionizing radiation [U235 eq.]	9,720,000	4,960,000	4,750,000	10,700
ReCiPe 1.08 Midpoint (E) - Marine eutrophication [kg N eq.]	11,000	4,740	6,150	80
ReCiPe 1.08 Midpoint (E) - Metal depletion [kg Fe eq.]	7,200,000	6,310,000	350,000	541,000
ReCiPe 1.08 Midpoint (E) - Ozone depletion [kg CFC-11 eq.]	0.608	0.949	-0.339	-0.002
ReCiPe 1.08 Midpoint (E) - Particulate matter formation [kg PM10 eq.]	108,000	81,300	26,200	891
ReCiPe 1.08 Midpoint (E) - Photochemical oxidant formation [kg NMVOC eq.]	223,000	117,000	104,000	2,210
ReCiPe 1.08 Midpoint (E) - Terrestrial acidification [kg SO2 eq.]	329,000	230,000	96,100	2,850
ReCiPe 1.08 Midpoint (E) - Terrestrial ecotoxicity [kg 1,4-DB eq.]	178,000	22,100	72,700	83,400

Impact category	Baseline Total	Aluminum	PET	Steel
ReCiPe 1.08 Midpoint (E) - Water depletion [m3]	747,000,000	695,000,000	51,700,000	272,000

Table 14 Indicator results of the endpoint and midpoint impact categories of the deposit-refund system (DRS) – ReCiPe 1.08

Impact category	DRS Total	Aluminum DRS	PET DRS	Steel DRS
ReCiPe 1.08 Endpoint (E) - Climate change Ecosystems, default, excl biogenic carbon [species.yr]	1.530	0.444	1.080	0.010
ReCiPe 1.08 Endpoint (E) - Climate change Ecosystems, incl biogenic carbon [species.yr]	1.540	0.444	1.080	0.010
ReCiPe 1.08 Endpoint (E) - Climate change Human Health, default, excl biogenic carbon [DALY]	287	83	202	2
ReCiPe 1.08 Endpoint (E) - Climate change Human Health, incl biogenic carbon [DALY]	289	83	203	2
ReCiPe 1.08 Endpoint (E) - Fossil depletion [$]	5,380,000	1,100,000	4,250,000	33,100
ReCiPe 1.08 Endpoint (E) - Freshwater ecotoxicity [species.yr]	0.064	0.064	0.000	0.000
ReCiPe 1.08 Endpoint (E) - Freshwater eutrophication [species.yr]	0.00029	0.00019	0.00009	0.00000
ReCiPe 1.08 Endpoint (E) - Human toxicity [DALY]	202	120	74	9
ReCiPe 1.08 Endpoint (E) - Ionizing radiation [DALY]	0.0302	-0.0365	0.0663	0.0004
ReCiPe 1.08 Endpoint (E) - Metal depletion [$]	340,000	275,000	41,700	23,300
ReCiPe 1.08 Endpoint (E) - Ozone depletion [DALY]	0.001410	0.001430	-0.000022	0.000004
ReCiPe 1.08 Endpoint (E) - Particulate matter formation [DALY]	22.500	14.200	8.180	0.160
ReCiPe 1.08 Endpoint (E) - Photochemical oxidant formation [DALY]	0.0066	0.0028	0.0037	0.0001
ReCiPe 1.08 Endpoint (E) - Terrestrial acidification [species.yr]	0.0037	0.0021	0.0016	0.0000
ReCiPe 1.08 Endpoint (E) - Terrestrial ecotoxicity [species.yr]	0.0167	0.0073	0.0069	0.0025
ReCiPe 1.08 Midpoint (E) - Climate change, default, excl biogenic carbon [kg CO2 eq.]	8.18E+07	2.37E+07	5.75E+07	5.55E+05

Impact category	DRS Total	Aluminum DRS	PET DRS	Steel DRS
ReCiPe 1.08 Midpoint (E) - Climate change, incl biogenic carbon [kg CO2 eq.]	8.22E+07	2.37E+07	5.79E+07	5.54E+05
ReCiPe 1.08 Midpoint (E) - Fossil depletion [kg oil eq.]	3.26E+07	6.64E+06	2.58E+07	2.01E+05
ReCiPe 1.08 Midpoint (E) - Freshwater ecotoxicity [kg 1,4 DB eq.]	7.73E+07	7.71E+07	1.60E+05	1.59E+04
ReCiPe 1.08 Midpoint (E) - Freshwater eutrophication [kg P eq.]	6,430	4,370	2,050	14
ReCiPe 1.08 Midpoint (E) - Human toxicity [kg 1,4-DB eq.]	2.91E+08	1.72E+08	1.06E+08	1.27E+07
ReCiPe 1.08 Midpoint (E) - Ionizing radiation [U235 eq.]	1.84E+06	-2.23E+06	4.04E+06	2.23E+04
ReCiPe 1.08 Midpoint (E) - Marine eutrophication [kg N eq.]	11,200	3,550	7,610	82
ReCiPe 1.08 Midpoint (E) - Metal depletion [kg Fe eq.]	4,760,000	3,850,000	584,000	326,000
ReCiPe 1.08 Midpoint (E) - Ozone depletion [kg CFC-11 eq.]	2.890	2.920	-0.033	0.001
ReCiPe 1.08 Midpoint (E) - Particulate matter formation [kg PM10 eq.]	8.66E+04	5.45E+04	3.15E+04	6.14E+02
ReCiPe 1.08 Midpoint (E) - Photochemical oxidant formation [kg NMVOC eq.]	169,000	71,600	95,900	1,730
ReCiPe 1.08 Midpoint (E) - Terrestrial acidification [kg SO2 eq.]	260,000	148,000	110,000	2,130
ReCiPe 1.08 Midpoint (E) - Terrestrial ecotoxicity [kg 1,4-DB eq.]	110,000	48,500	45,000	16,800
ReCiPe 1.08 Midpoint (E) - Water depletion [m3]	419,000,000	377,000,000	41,500,000	414,000

When comparing the results of the non-deposit-refund and the deposit-refund systems, it may be said that the deposit-refund system shows lower environmental impacts in most impact categories, whereas in some categories it is the non-deposit-refund system that has better results.

The deposit-refund system (DRS) shows lower environmental impacts in the following impact categories at both the endpoint and midpoint levels:

- **Climate changes** – at the ecosystem level [species.yr] and the human health level [DALY], and also at the midpoint impact level, such as increasing the greenhouse effect (GWP) [CO_2 eq.]
- **Fossil fuel depletion**

- **Ionizing radiation**
- **Metal depletion**
- **Particulate matter formation**
- **Photochemical oxidant formation**
- **Terrestrial acidification**
- **Terrestrial ecotoxicity**
- **Water depletion**

The non-deposit-refund system shows lower environmental impacts in comparison to the deposit-refund system in the following impact categories:

- **Human toxicity**
- **Freshwater ecotoxicity**
- **Freshwater eutrophication**
- **Loss of stratospheric ozone**

To assist interpretation, the values given in the tables are illustrated in following graphs and the systems are compared. Since different impact categories have different units and numbers of different orders, it is not possible to show them all in the same graph (this will be done later in the text for standardized and weighted results). The following graphs show the results of particular life cycle scenarios in the respective impact categories. Since the trends among the results of particular scenarios at midpoint and endpoint levels are similar, only graphs for the endpoint evaluation level and selected graphs for the midpoint level (GWP, loss of fossil fuel raw materials, water depletion) are given here. The total values of the non-deposit-refund and deposit-refund systems are marked in red in the graphs, while the contributions of the respective bottle types (aluminum, PET, steel) are in blue. Owing to their respective numbers placed on the market, PET and aluminum bottles have a dominant influence on the total results, whereas steel bottles contribute only marginally to the total results.

Figure 10 Comparison of results for impact category indicators, Climate changes – impact on ecosystems

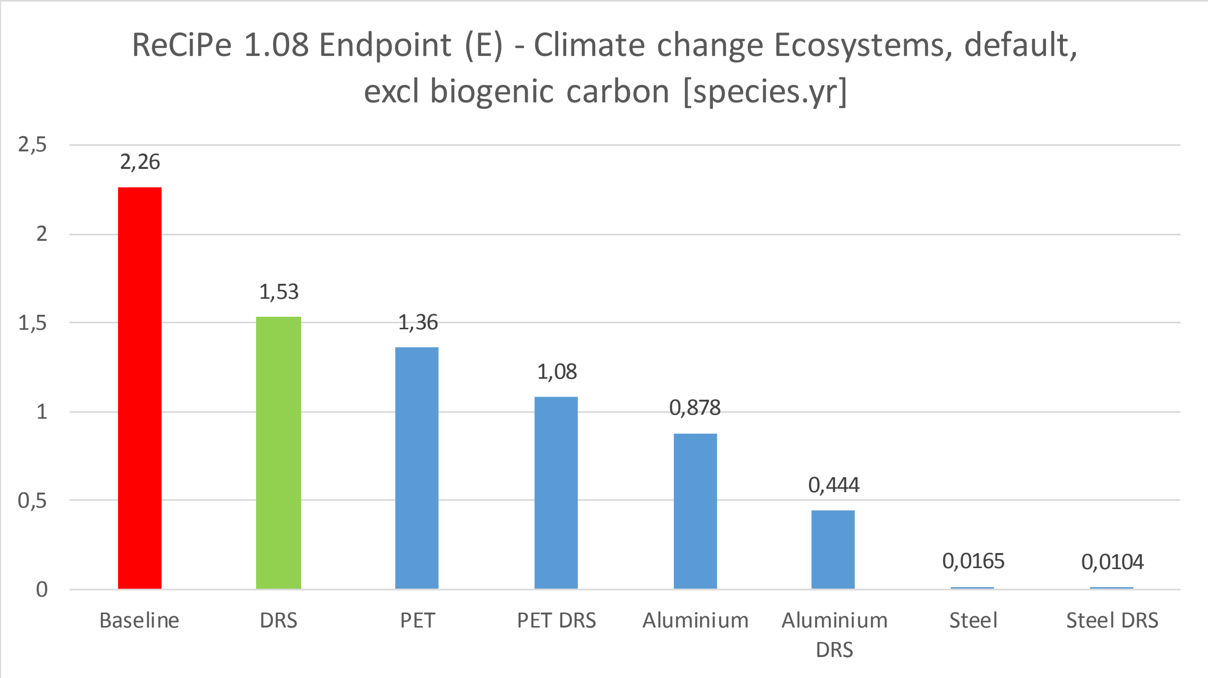


Figure 11 Comparison of results for impact category indicators, Climate changes – impact on human health

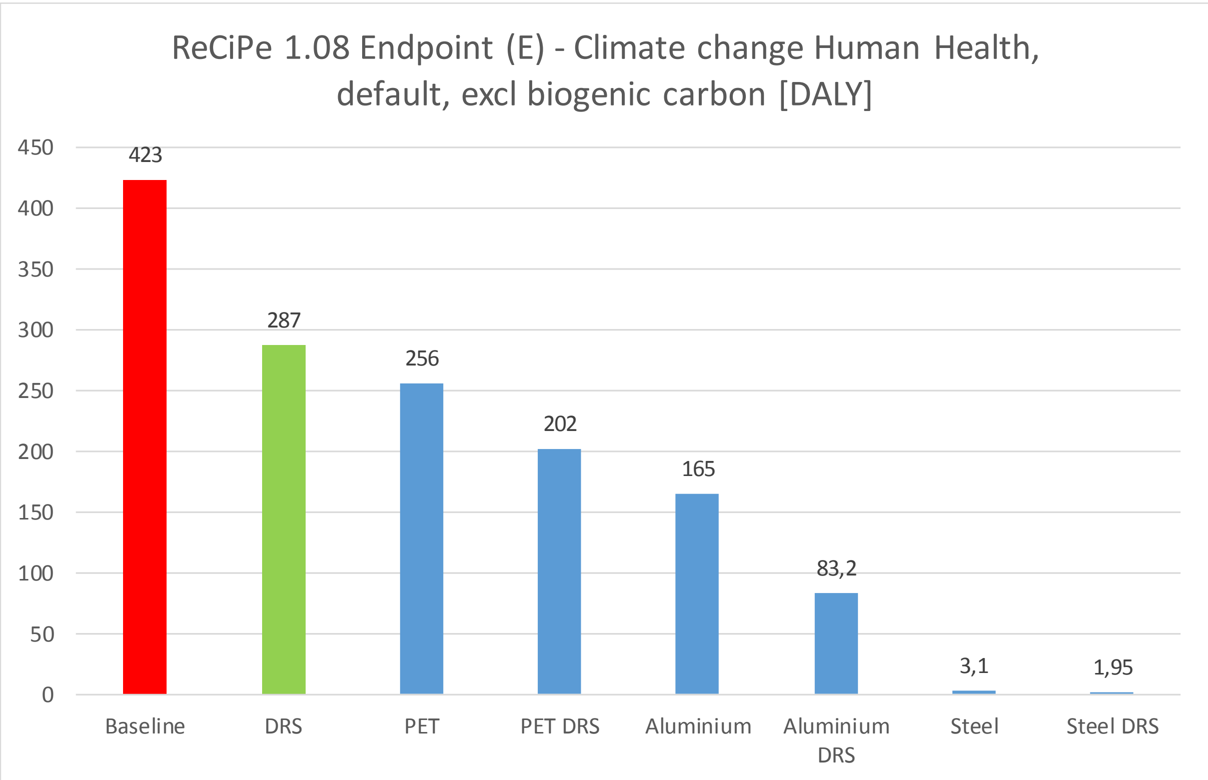


Figure 12 Comparison of results for impact category indicators, Increasing the greenhouse effect, GWP, CO_2 eq.

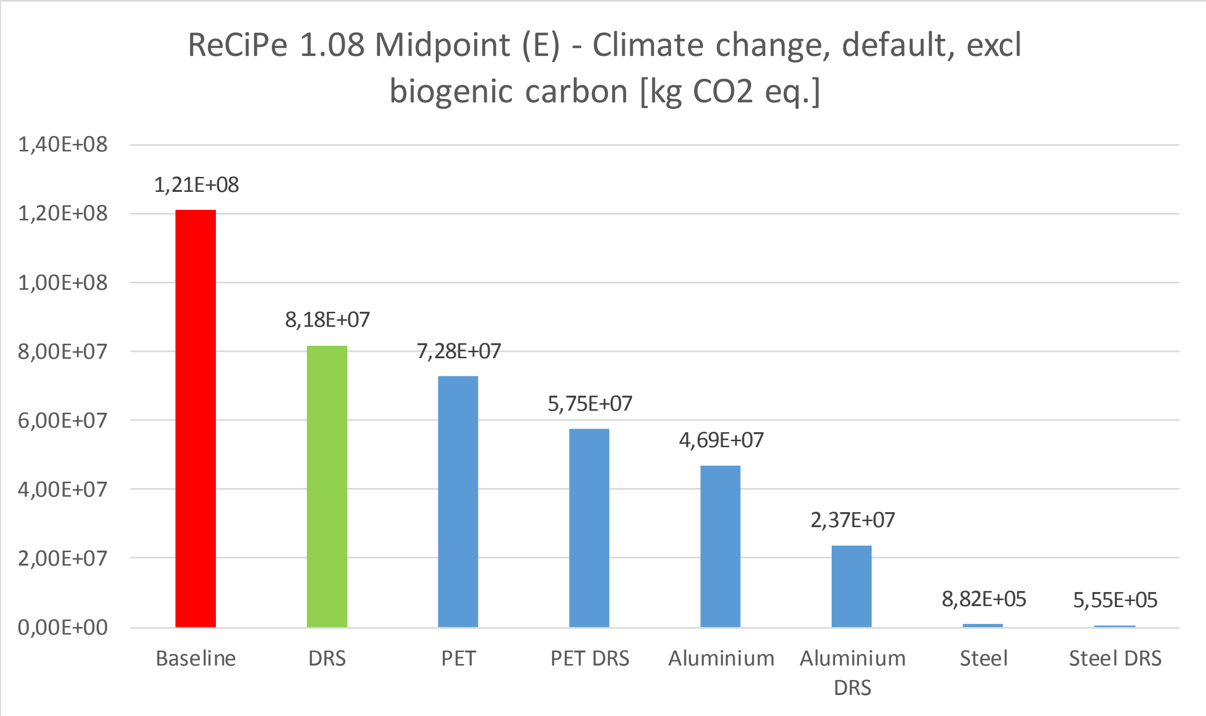


Figure 13 Comparison of results for impact category indicators, Fossil fuel depletion [$]

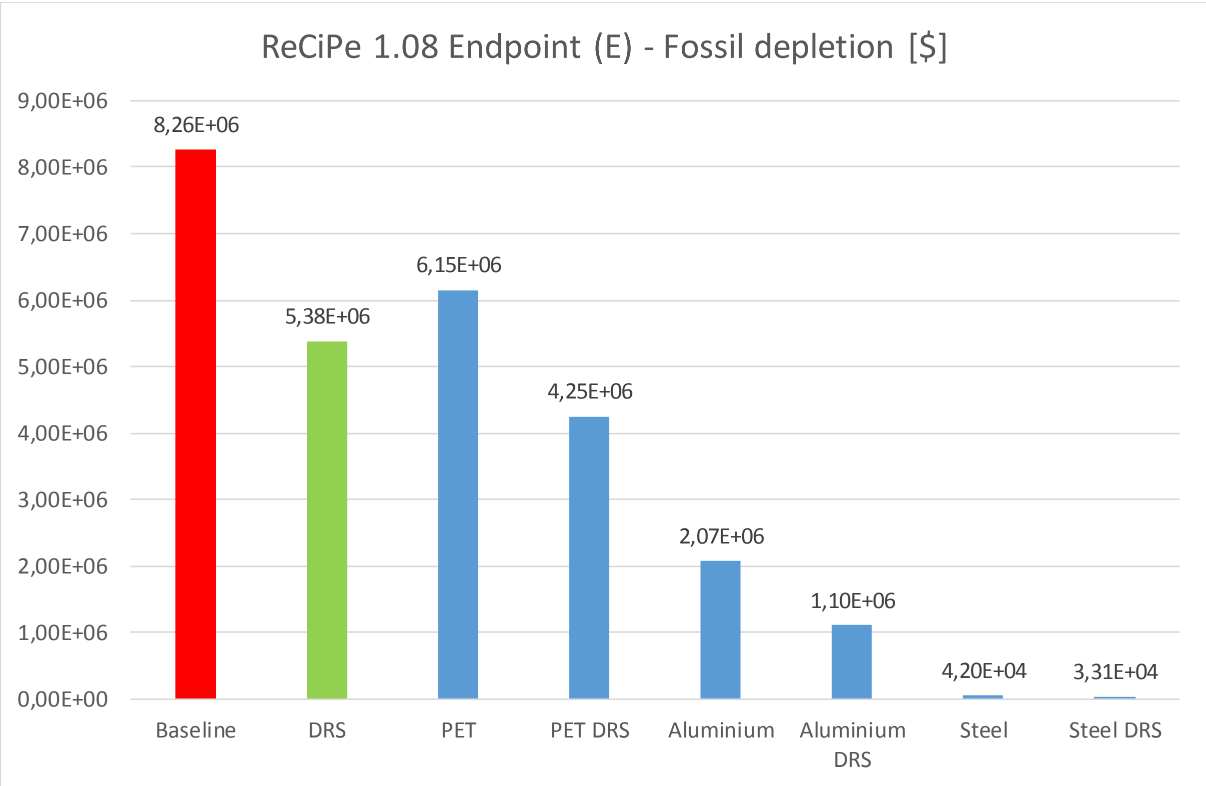


Figure 14 Comparison of results for midpoint impact category indicators, Fossil fuel depletion [kg oil eq.]

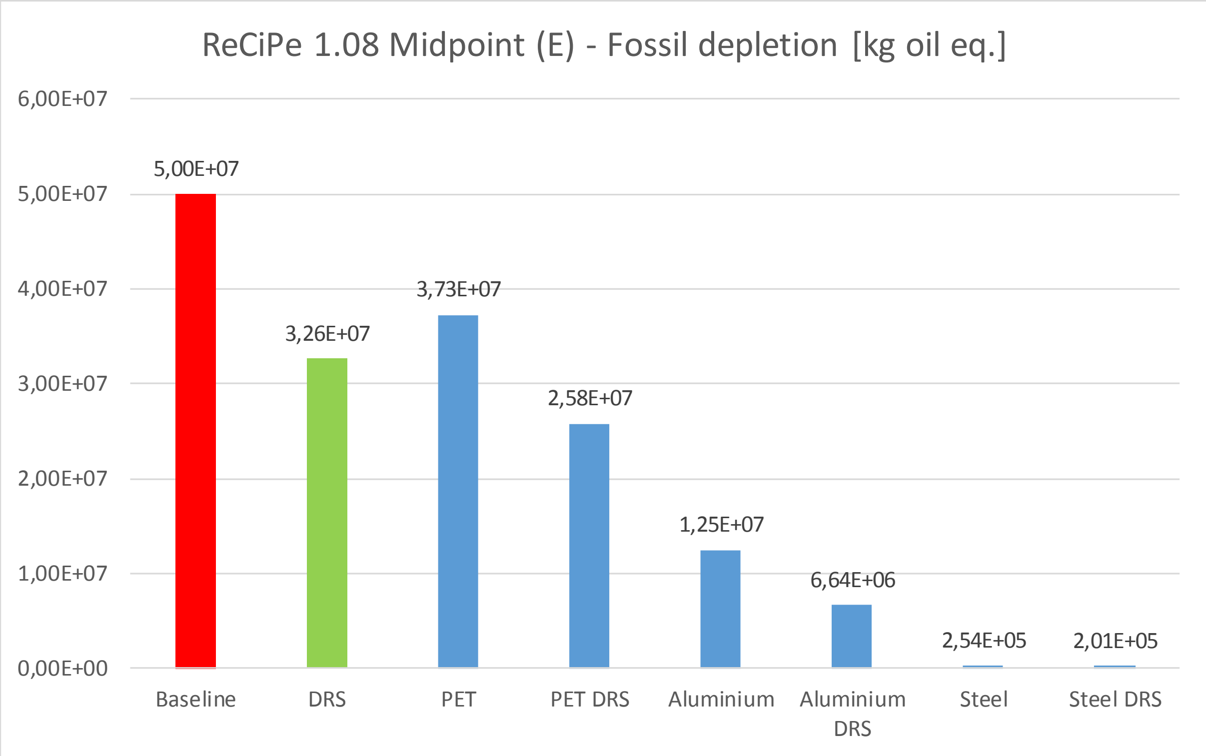


Figure 15 Comparison of results for impact category indicators, Freshwater ecotoxicity

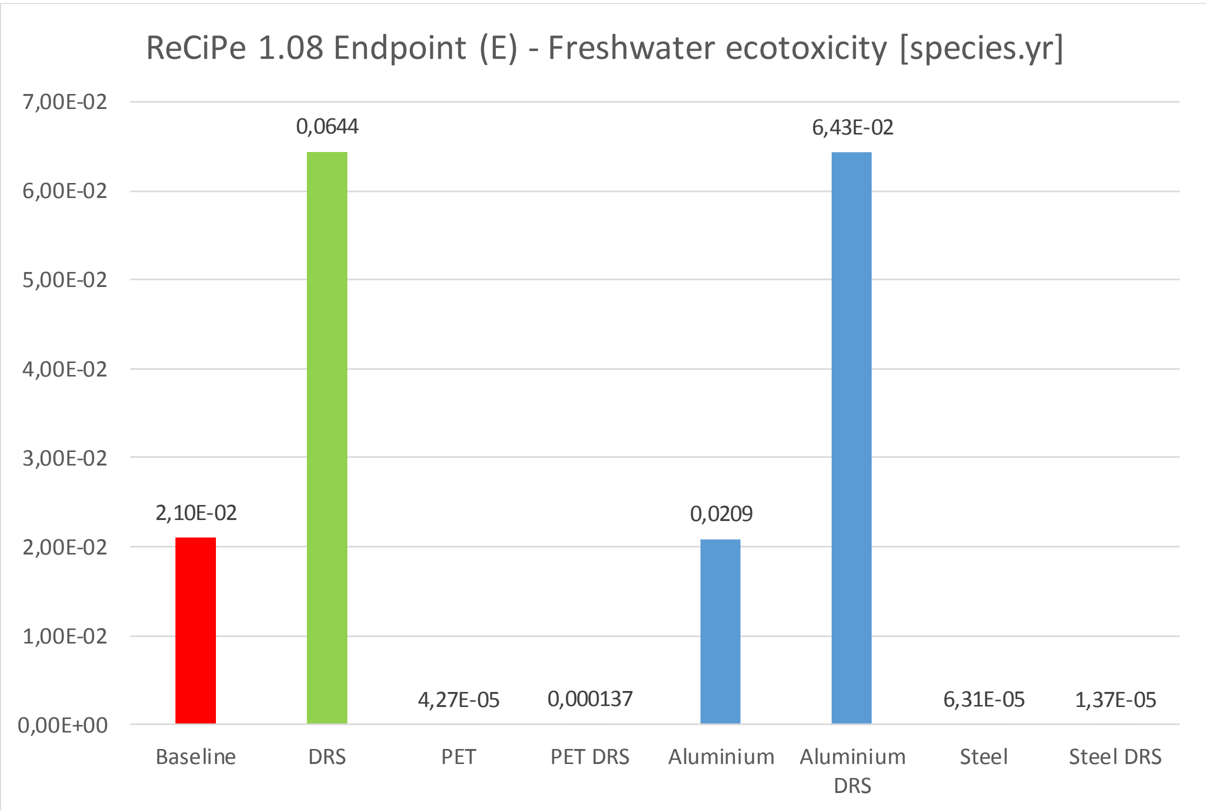


Figure 16 Comparison of results for impact category indicators, Freshwater eutrophication

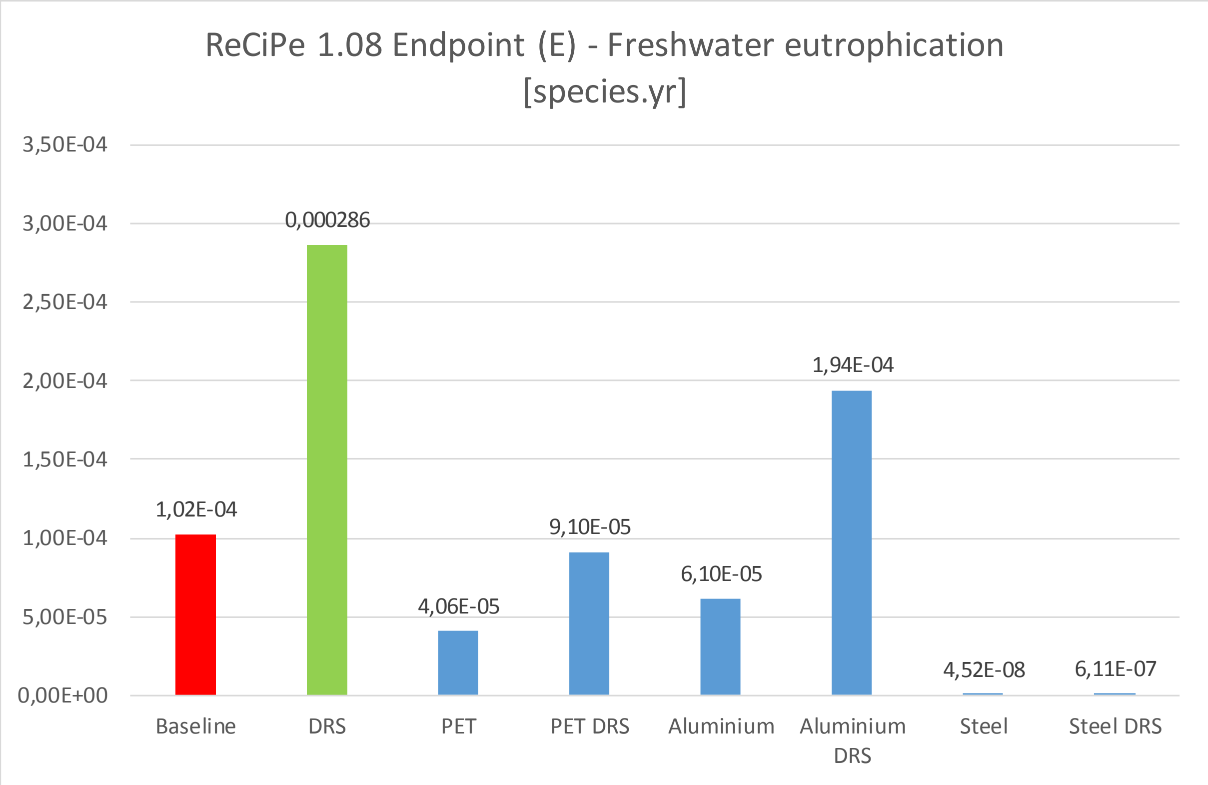


Figure 17 Comparison of results for impact category indicators, Human toxicity

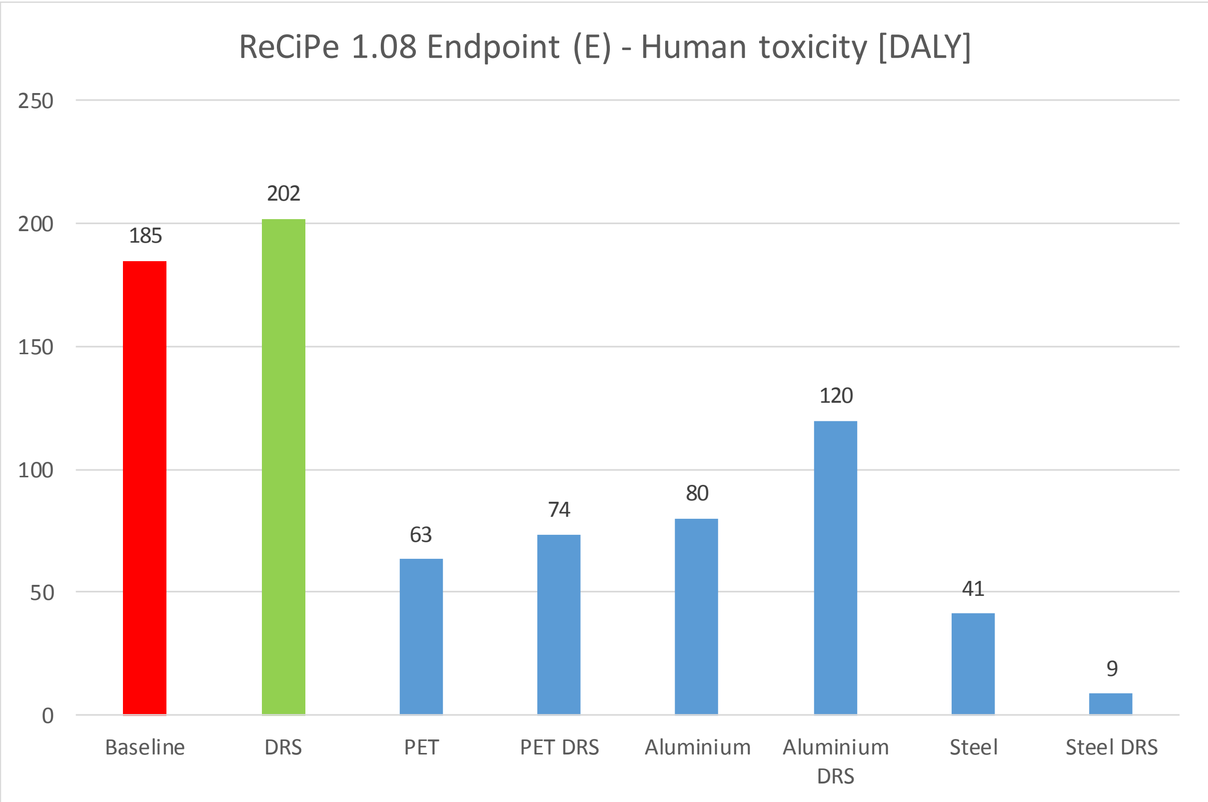


Figure 18 Comparison of results for impact category indicators, Ionizing radiation

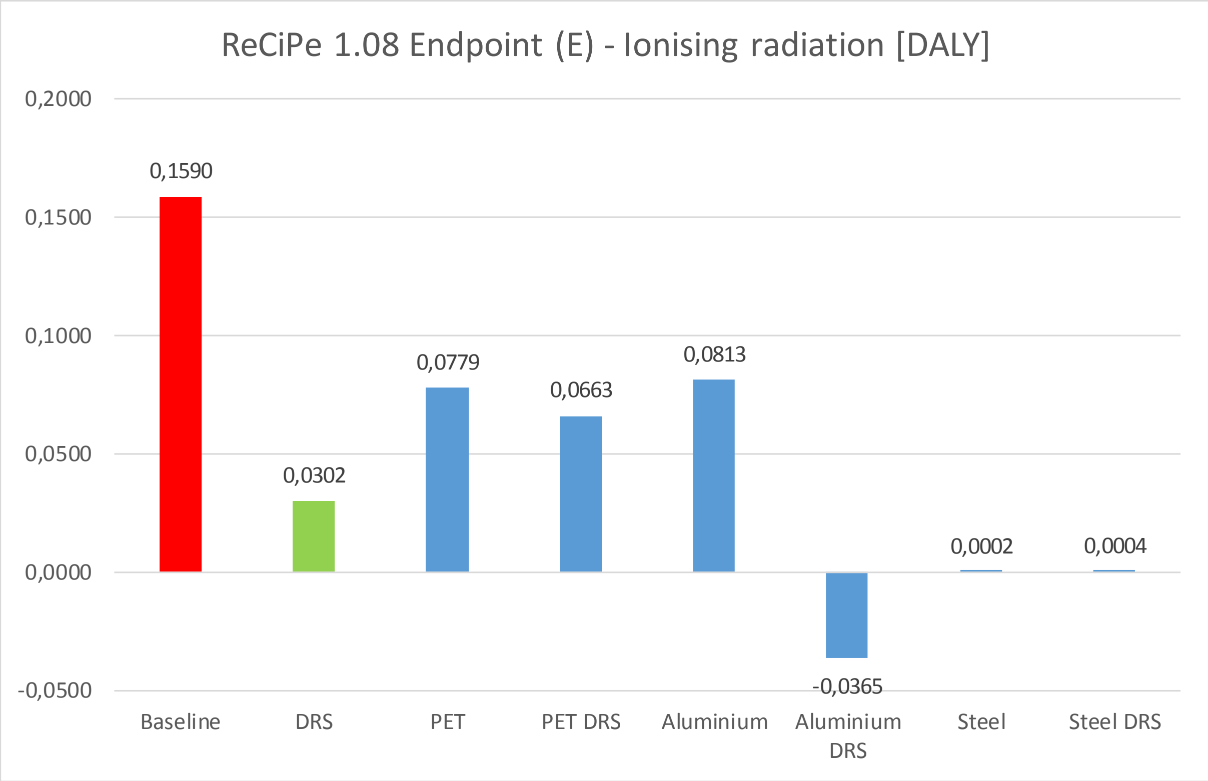


Figure 19 Comparison of results for impact category indicators, Metal depletion

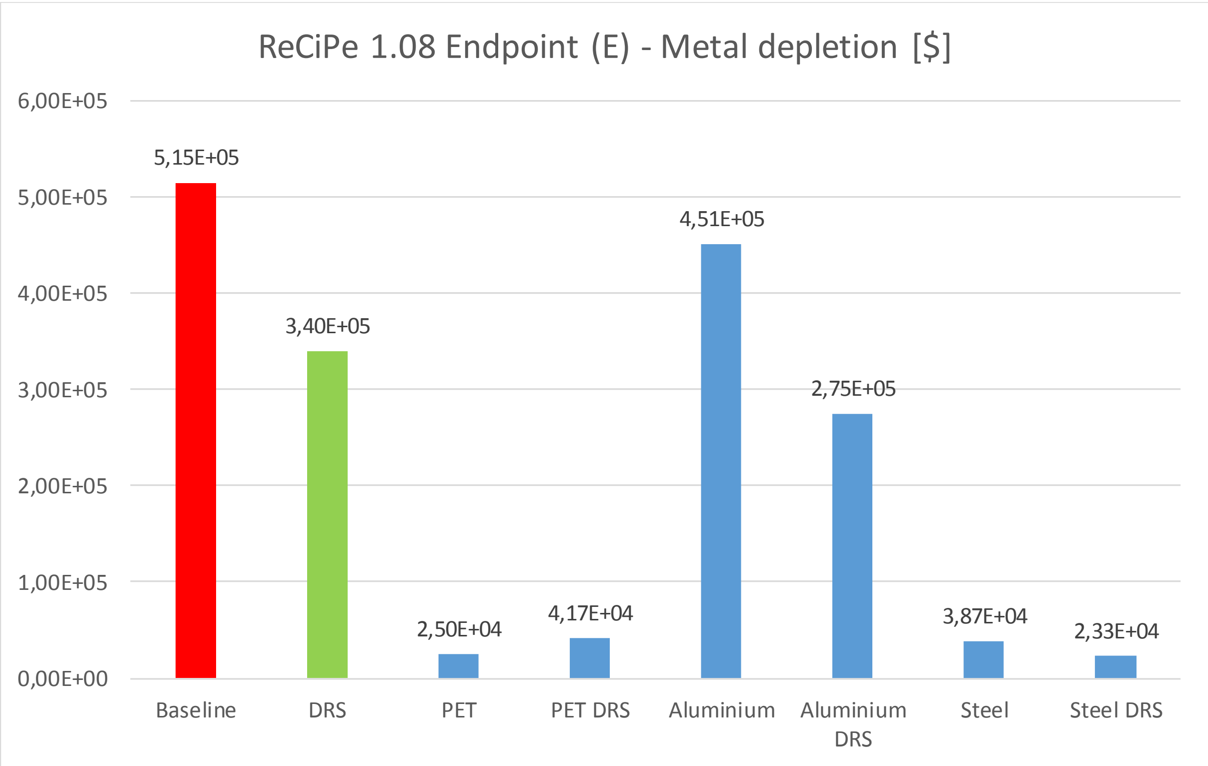


Figure 20 Comparison of results for impact category indicators, Ozone depletion

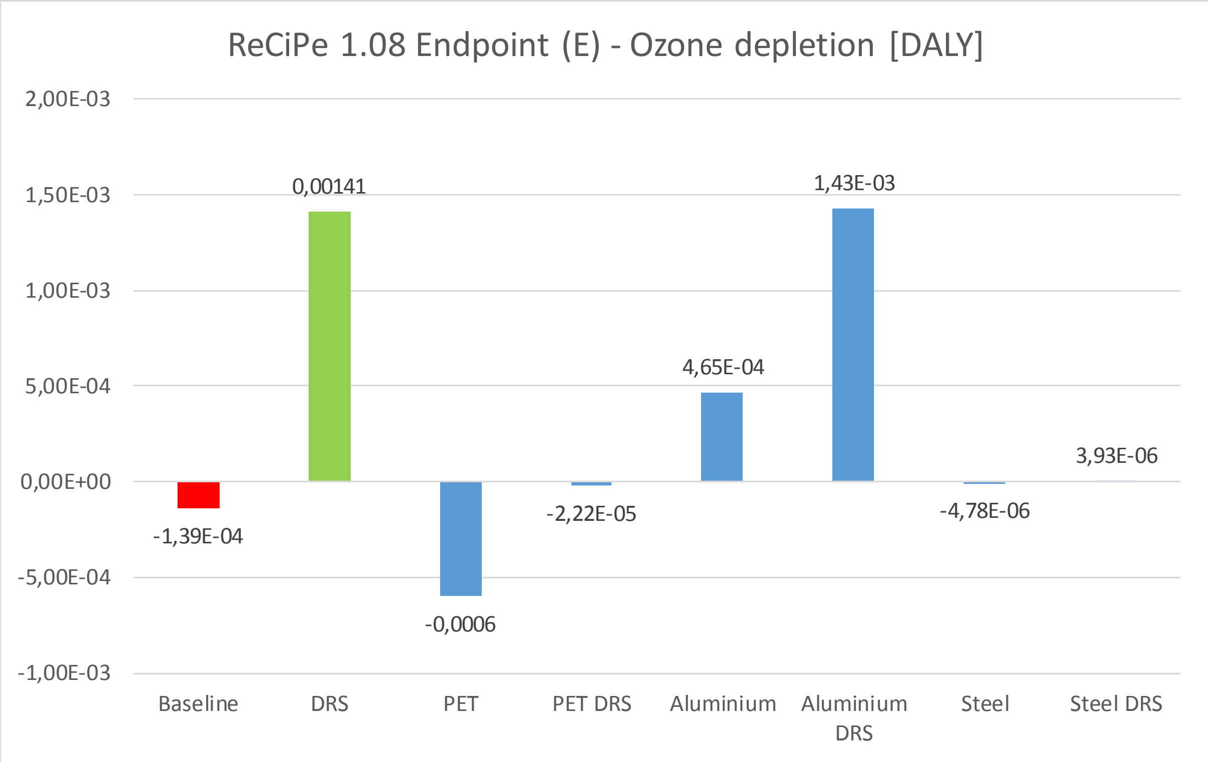


Figure 21 Comparison of results for impact category indicators, Particulate matter formation

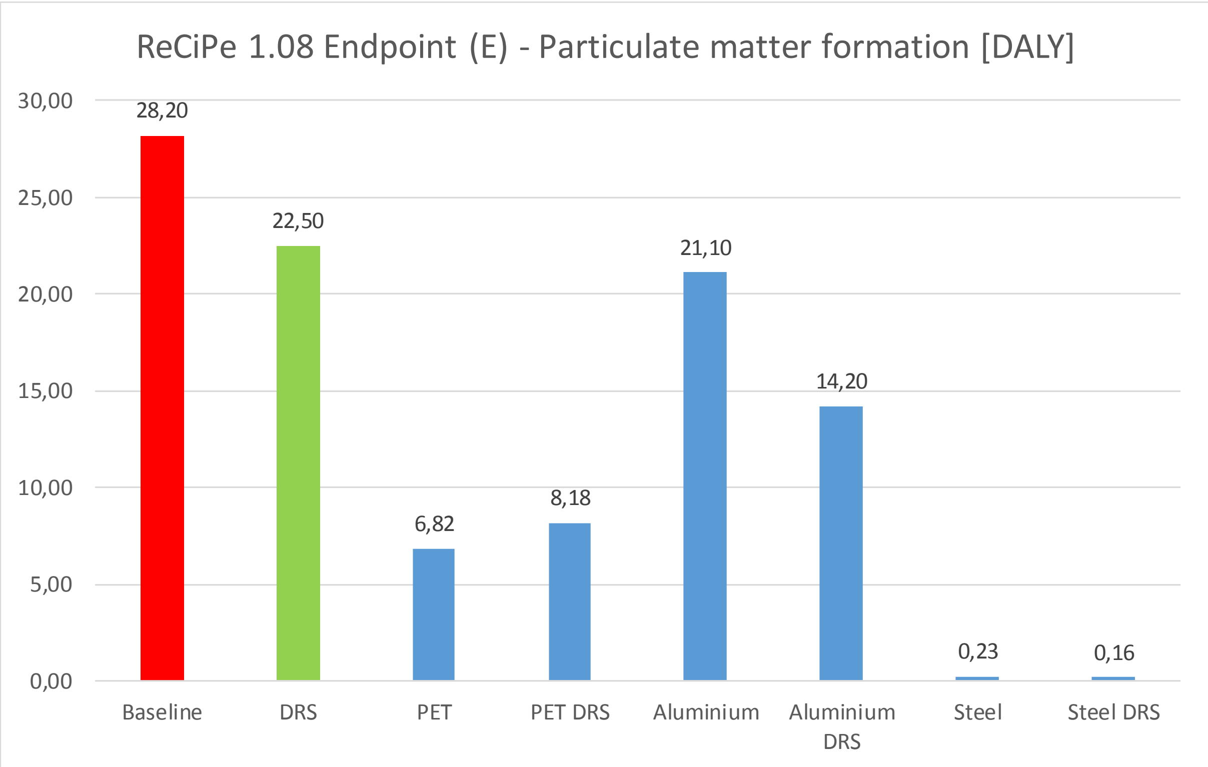


Figure 22 Comparison of results for impact category indicators, Photochemical oxidant formation

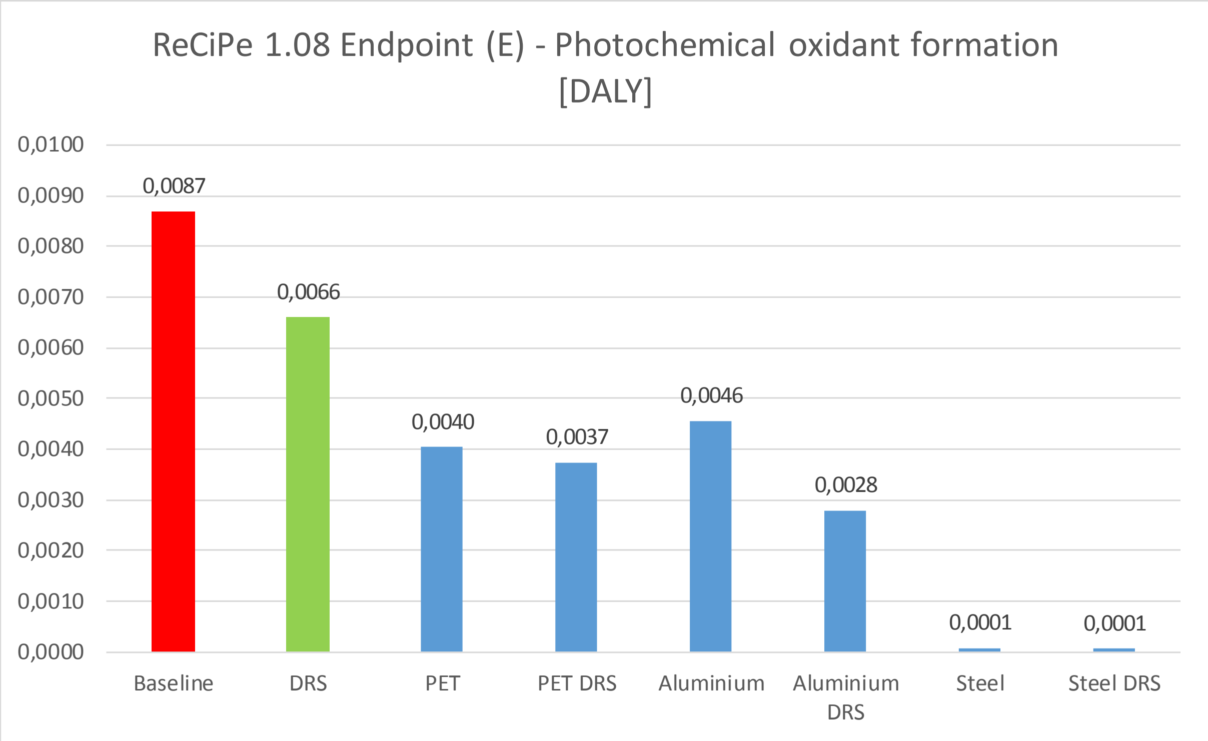


Figure 23 Comparison of results for impact category indicators, Terrestrial acidification

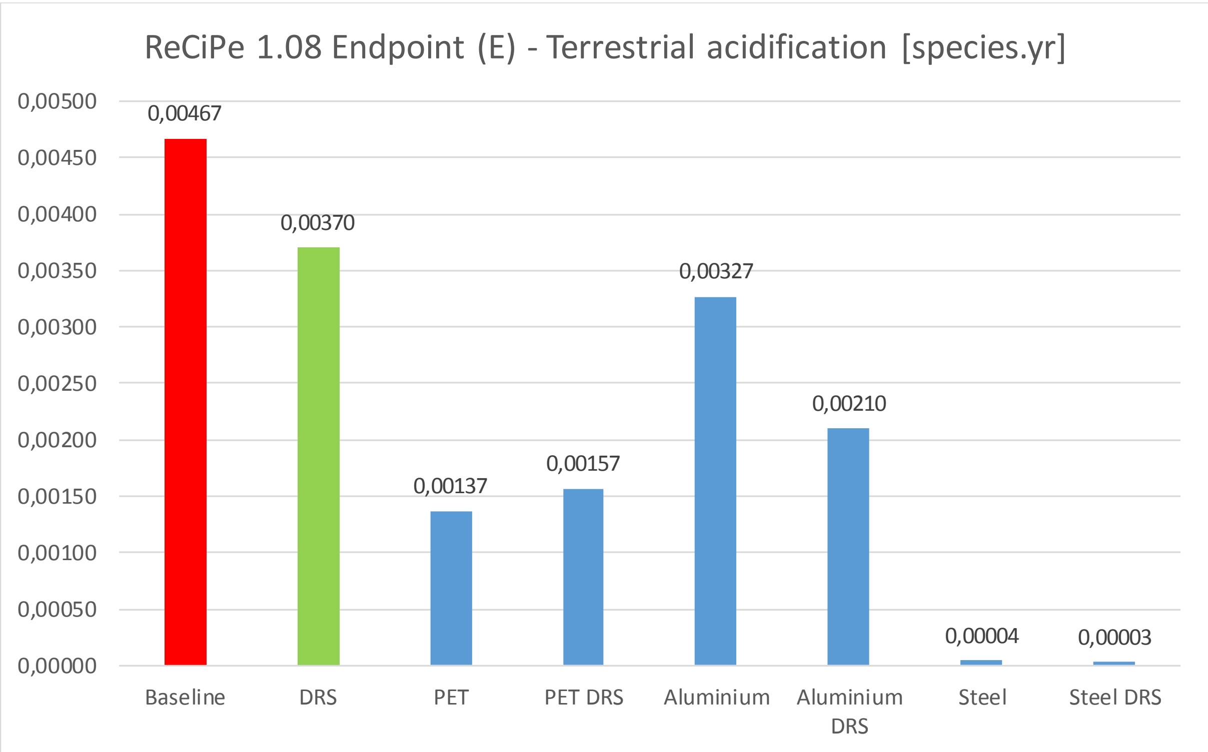


Figure 24 Comparison of results for impact category indicators, Terrestrial ecotoxicity

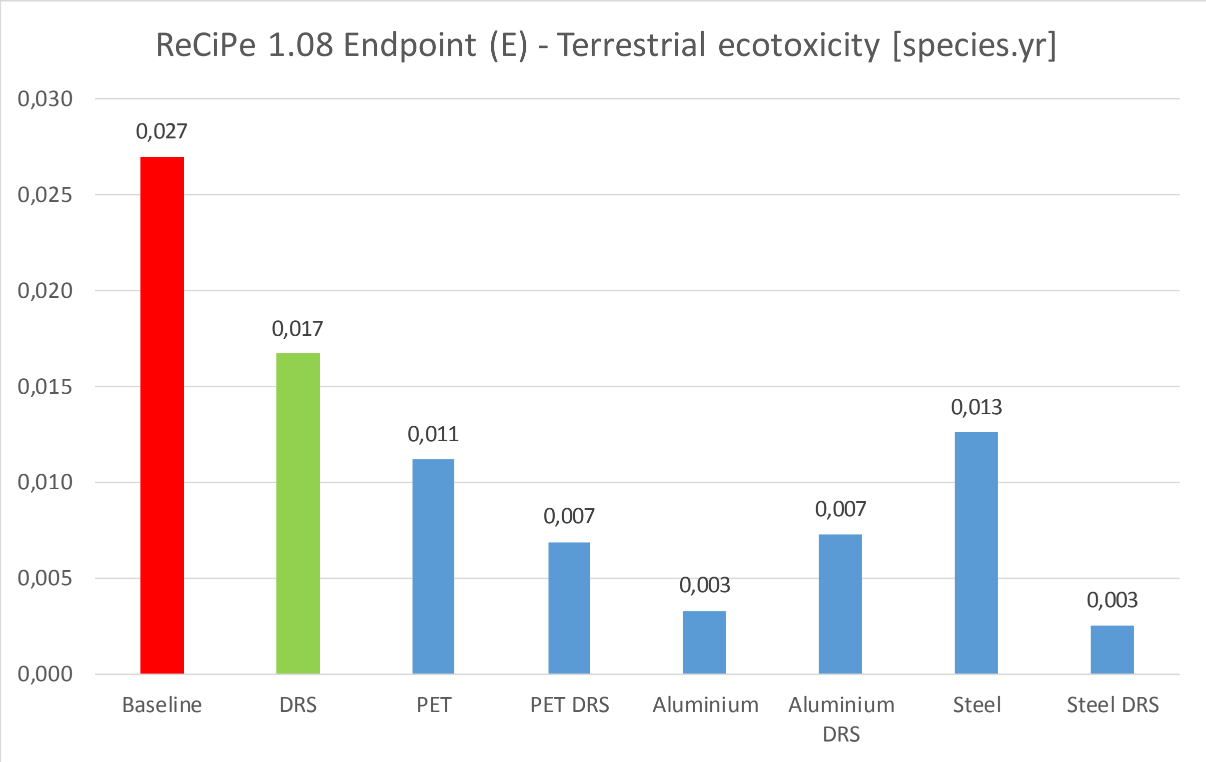
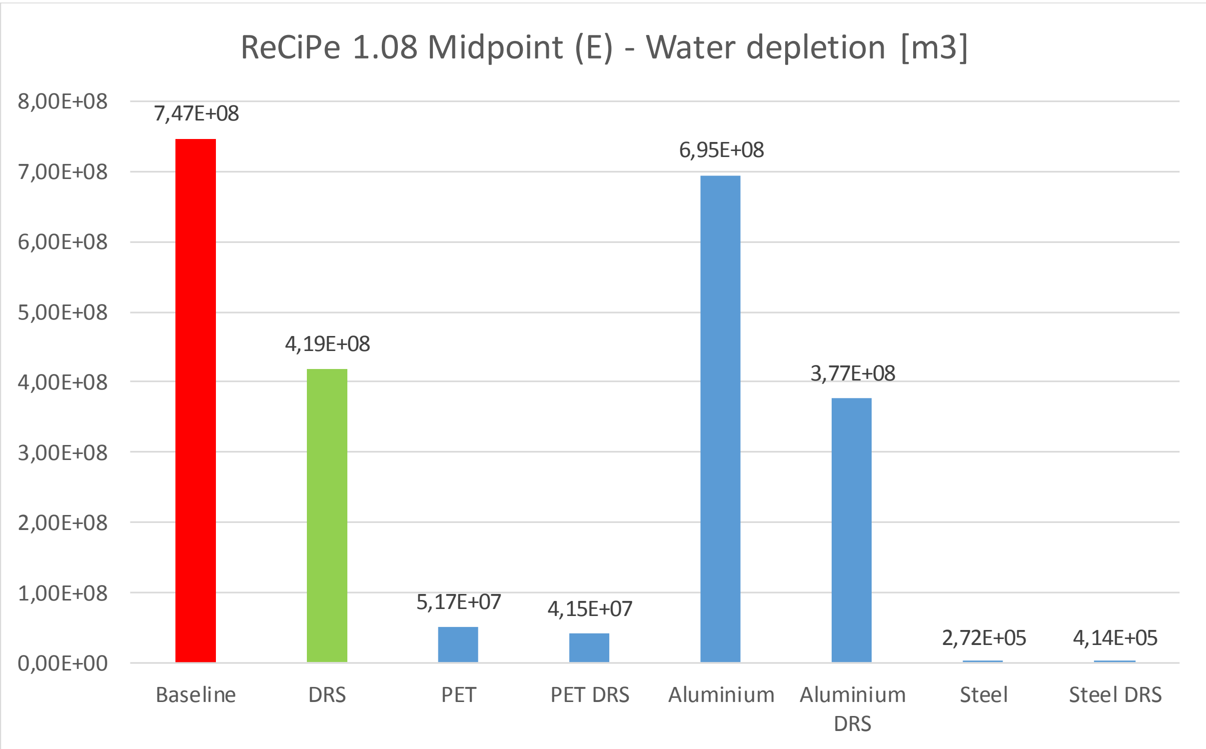


Figure 25 Comparison of results for impact category indicators, Water depletion



5.2 Verification of the concordance rate of the results of individual systems using the Monte Carlo methodology

The stochastic Monte Carlo method has been used to determine the confidence intervals of the results of the impact category indicators. In accordance with the estimate for material flows from MEA made by INCIEN based on data from EKO-KOM a.s., a 10% variability for the non-deposit-refund system and deposit-refund system flows (see Table 1 and Table 2) has been selected for calculating total system variability.

The average values of the results of impact category indicators and their standard deviations have been calculated by means of the stochastic approach – using 1,000 of iterations. A simplified summary of this calculation is stated in the following tables.

Table 15 Outputs of the variability calculation using the Monte Carlo method for the non-deposit-refund system (Baseline)

Type of Flow	Impact category	Unit	Result	Mean value	Standard deviation	10% Percentile	25% Percentile	Median	75% Percentile	90% Percentile
Outputs	ReCiPe 1.08 Endpoint (E) - Climate change Ecosystems, default, excl biogenic carbon	species.yr	2.26E+00	2.26E+00	6.75%	2.06E+00	2.16E+00	2.26E+00	2.36E+00	2.45E+00
Outputs	ReCiPe 1.08 Endpoint (E) - Climate change Ecosystems, incl biogenic carbon	species.yr	2.33E+00	2.34E+00	6.56%	2.14E+00	2.24E+00	2.34E+00	2.44E+00	2.53E+00
Outputs	ReCiPe 1.08 Endpoint (E) - Climate change Human Health, default, excl biogenic carbon	DALY	4.23E+02	4.24E+02	6.75%	3.87E+02	4.05E+02	4.25E+02	4.43E+02	4.59E+02
Outputs	ReCiPe 1.08 Endpoint (E) - Climate change Human Health, incl biogenic carbon	DALY	4.38E+02	4.38E+02	6.56%	4.02E+02	4.20E+02	4.39E+02	4.58E+02	4.74E+02
Inputs	ReCiPe 1.08 Endpoint (E) - Fossil depletion	$	8.26E+06	8.27E+06	12.80%	6.94E+06	7.58E+06	8.29E+06	9.02E+06	9.57E+06
Outputs	ReCiPe 1.08 Endpoint (E) - Freshwater ecotoxicity	species.yr	2.10E-02	2.10E-02	9.78%	1.84E-02	1.96E-02	2.10E-02	2.24E-02	2.36E-02
Outputs	ReCiPe 1.08 Endpoint (E) - Freshwater eutrophication	species.yr	1.02E-04	1.02E-04	6.47%	9.34E-05	9.71E-05	1.02E-04	1.06E-04	1.09E-04
Outputs	ReCiPe 1.08 Endpoint (E) - Human toxicity	DALY	1.85E+02	1.85E+02	5.44%	1.72E+02	1.79E+02	1.86E+02	1.92E+02	1.98E+02
Outputs	ReCiPe 1.08 Endpoint (E) - Ionizing radiation	DALY	1.59E-01	1.59E-01	6.94%	1.46E-01	1.52E-01	1.59E-01	1.67E-01	1.74E-01
Inputs	ReCiPe 1.08 Endpoint (E) - Metal depletion	$	5.15E+05	5.15E+05	3.43%	4.93E+05	5.03E+05	5.15E+05	5.27E+05	5.38E+05
Outputs	ReCiPe 1.08 Endpoint (E) - Ozone depletion	DALY	-1.39E-04	-1.39E-04	-67.50%	-2.59E-04	-2.03E-04	-1.39E-04	-7.64E-05	-1.44E-05
Outputs	ReCiPe 1.08 Endpoint (E) - Particulate matter formation	DALY	2.82E+01	2.82E+01	3.94%	2.67E+01	2.74E+01	2.82E+01	2.89E+01	2.96E+01

Type of Flow	Impact category	Unit	Result	Mean value	Standard deviation	10% Percentile	25% Percentile	Median	75% Percentile	90% Percentile
Outputs	ReCiPe 1.08 Endpoint (E) - Photochemical oxidant formation	DALY	8.69E-03	8.69E-03	6.33%	7.99E-03	8.34E-03	8.70E-03	9.06E-03	9.39E-03
Outputs	ReCiPe 1.08 Endpoint (E) - Terrestrial acidification	species.yr	4.67E-03	4.67E-03	4.10%	4.42E-03	4.55E-03	4.68E-03	4.80E-03	4.92E-03
Outputs	ReCiPe 1.08 Endpoint (E) - Terrestrial ecotoxicity	species.yr	2.71E-02	2.71E-02	6.13%	2.51E-02	2.59E-02	2.71E-02	2.83E-02	2.93E-02
Outputs	ReCiPe 1.08 Midpoint (E) - Climate change, default, excl biogenic carbon	kg CO2 eq.	1.21E+08	1.21E+08	6.75%	1.10E+08	1.16E+08	1.21E+08	1.26E+08	1.31E+08
Inputs	ReCiPe 1.08 Midpoint (E) - Water depletion	m3	7.55E+08	7.55E+08	3.22%	7.26E+08	7.39E+08	7.56E+08	7.72E+08	7.87E+08

Table 16 Outputs of the variability calculation using the Monte Carlo method for the deposit-refund system (DRS)

Type of Flow	Impact category	Unit	Result	Mean value	Standard deviation	10% Percentile	25% Percentile	Median	75% Percentile	90% Percentile
Outputs	ReCiPe 1.08 Endpoint (E) - Climate change Ecosystems, default, excl biogenic carbon	species.yr	1.41E+00	1.39E+00	19.50%	1.02E+00	1.22E+00	1.41E+00	1.58E+00	1.72E+00
Outputs	ReCiPe 1.08 Endpoint (E) - Climate change Ecosystems, incl biogenic carbon	species.yr	1.49E+00	1.47E+00	18.50%	1.10E+00	1.30E+00	1.49E+00	1.66E+00	1.80E+00
Outputs	ReCiPe 1.08 Endpoint (E) - Climate change Human Health, default, excl biogenic carbon	DALY	2.65E+02	2.61E+02	19.50%	1.92E+02	2.29E+02	2.65E+02	2.97E+02	3.23E+02
Outputs	ReCiPe 1.08 Endpoint (E) - Climate change Human Health, incl biogenic carbon	DALY	2.81E+02	2.76E+02	18.50%	2.07E+02	2.44E+02	2.80E+02	3.12E+02	3.38E+02

Type of Flow	Impact category	Unit	Result	Mean value	Standard deviation	10% Percentile	25% Percentile	Median	75% Percentile	90% Percentile
Inputs	ReCiPe 1.08 Endpoint (E) - Fossil depletion	$	4.54E+06	4.38E+06	44.30%	1.77E+06	3.19E+06	4.52E+06	5.77E+06	6.77E+06
Outputs	ReCiPe 1.08 Endpoint (E) - Freshwater ecotoxicity	species.yr	6.44E-02	6.45E-02	10.50%	5.58E-02	5.99E-02	6.49E-02	6.91E-02	7.29E-02
Outputs	ReCiPe 1.08 Endpoint (E) - Freshwater eutrophication	species.yr	2.87E-04	2.88E-04	8.15%	2.57E-04	2.71E-04	2.88E-04	3.04E-04	3.18E-04
Outputs	ReCiPe 1.08 Endpoint (E) - Human toxicity	DALY	1.95E+02	1.94E+02	7.61%	1.75E+02	1.85E+02	1.95E+02	2.04E+02	2.13E+02
Outputs	ReCiPe 1.08 Endpoint (E) - Ionizing radiation	DALY	2.50E-02	2.38E-02	111%	-1.08E-02	5.64E-03	2.35E-02	4.22E-02	5.92E-02
Inputs	ReCiPe 1.08 Endpoint (E) - Metal depletion	$	3.38E+05	3.37E+05	11.80%	2.88E+05	3.11E+05	3.35E+05	3.64E+05	3.89E+05
Outputs	ReCiPe 1.08 Endpoint (E) - Ozone depletion	DALY	1.41E-03	1.41E-03	10.80%	1.21E-03	1.31E-03	1.42E-03	1.51E-03	1.60E-03
Outputs	ReCiPe 1.08 Endpoint (E) - Particulate matter formation	DALY	2.20E+01	2.19E+01	9.31%	1.92E+01	2.05E+01	2.19E+01	2.33E+01	2.46E+01
Outputs	ReCiPe 1.08 Endpoint (E) - Photochemical oxidant formation	DALY	6.23E-03	6.15E-03	15.60%	4.87E-03	5.53E-03	6.21E-03	6.79E-03	7.30E-03
Outputs	ReCiPe 1.08 Endpoint (E) - Terrestrial acidification	species.yr	3.61E-03	3.58E-03	9.87%	3.13E-03	3.34E-03	3.59E-03	3.82E-03	4.04E-03
Outputs	ReCiPe 1.08 Endpoint (E) - Terrestrial ecotoxicity	species.yr	1.70E-02	1.71E-02	6.51%	1.57E-02	1.64E-02	1.70E-02	1.79E-02	1.86E-02
Outputs	ReCiPe 1.08 Midpoint (E) - Climate change, default, excl biogenic carbon	kg CO2 eq.	7.56E+07	7.45E+07	19.50%	5.47E+07	6.52E+07	7.55E+07	8.45E+07	9.19E+07
Inputs	ReCiPe 1.08 Midpoint (E) - Water depletion	m3	4.45E+08	4.43E+08	14%	3.67E+08	4.02E+08	4.40E+08	4.85E+08	5.24E+08

A comparison of the Monte Carlo analysis results for both assessed systems is shown in the following graphs.

Table 17 Comparison of the Monte Carlo analysis results for the impact category ReCiPe 1.08 Endpoint (E) – Climate change Ecosystems, excl. biogenic carbon

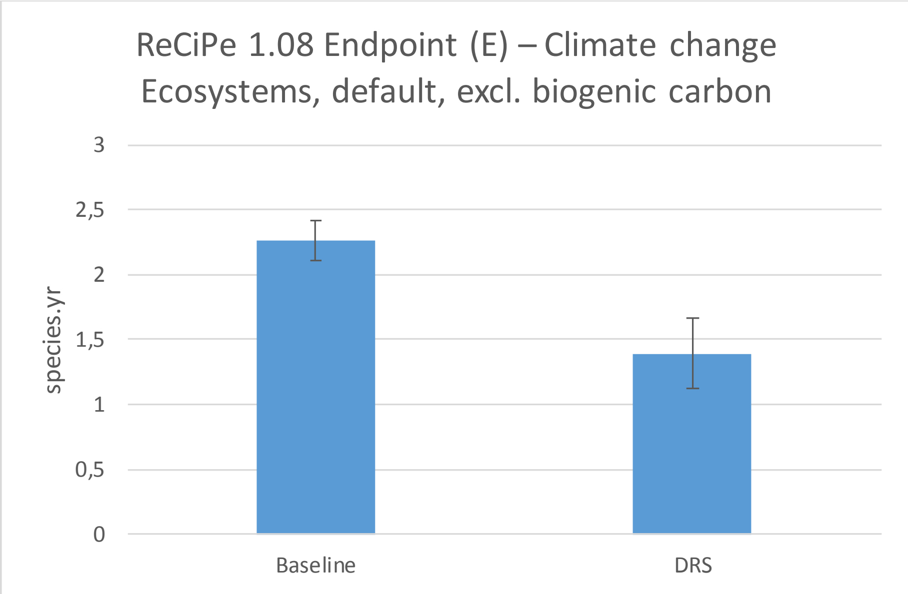


Table 18 Comparison of the Monte Carlo analysis results for the ReCiPe 1.08 Endpoint (E) – Climate change Human Health, excl. biogenic carbon

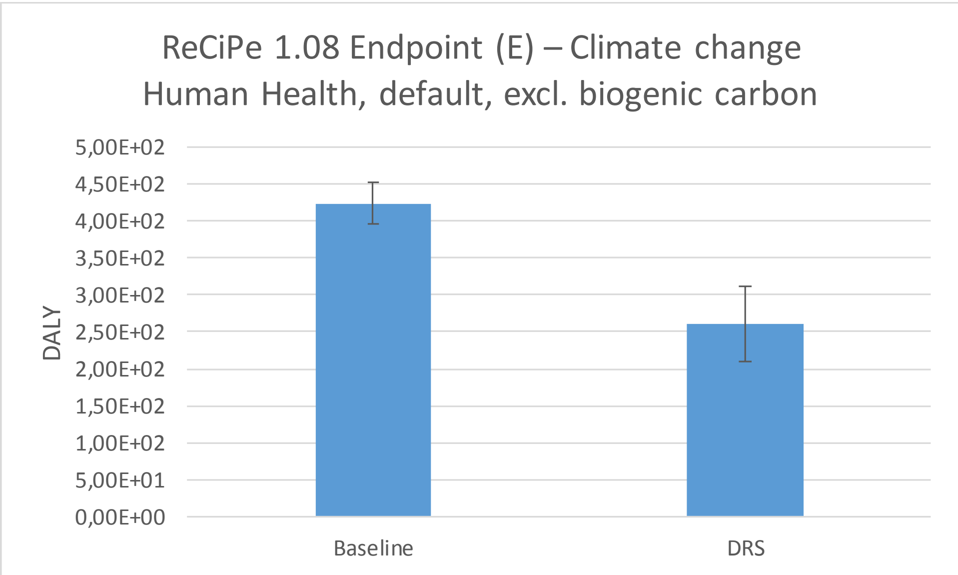


Table 19 Comparison of the Monte Carlo analysis results for the impact category ReCiPe 1.08 Endpoint (E) – Climate change Ecosystems, incl. biogenic carbon

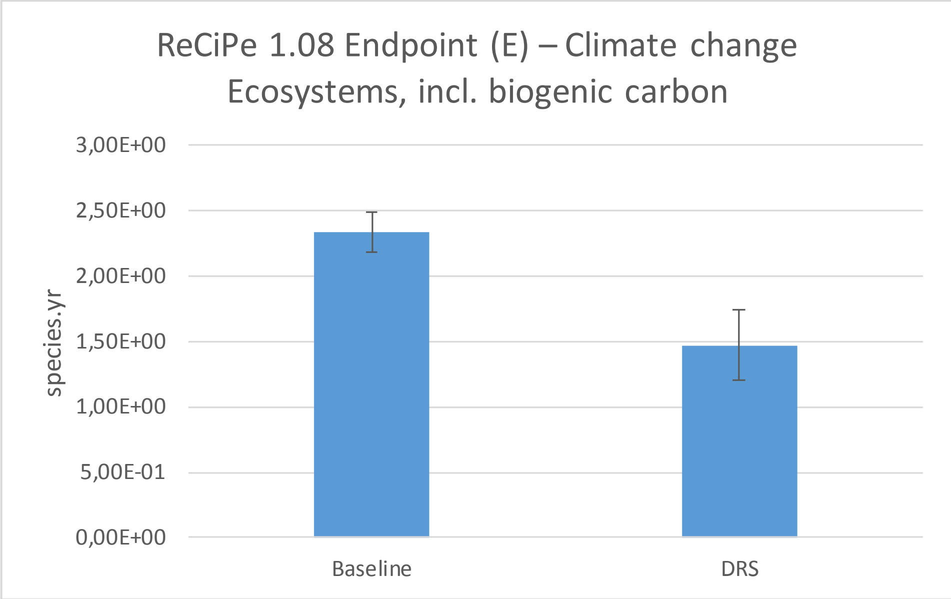


Table 20 Comparison of the Monte Carlo analysis results for the ReCiPe 1.08 Endpoint (E) – Climate change Human Health, incl. biogenic carbon

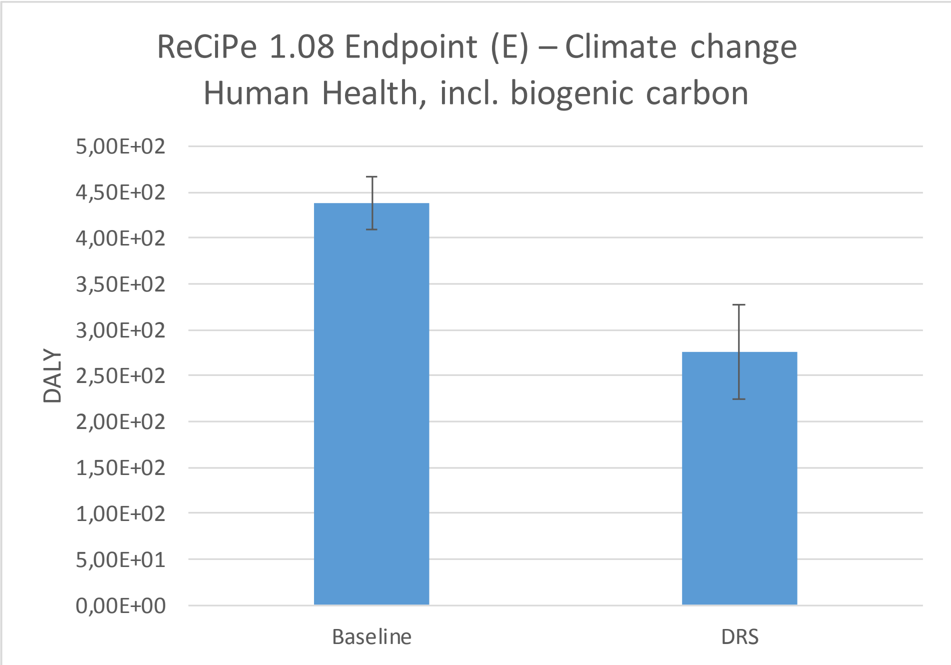


Table 21 Comparison of the Monte Carlo analysis results for the ReCiPe 1.08 Endpoint (E) – Fossil fuel depletion

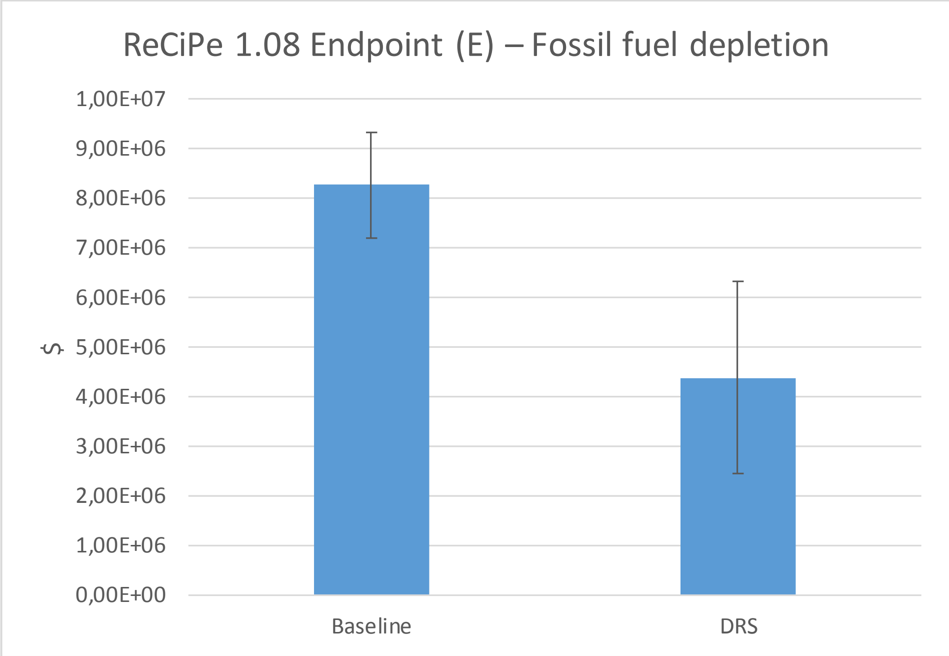


Table 22 Comparison of the Monte Carlo analysis results for the ReCiPe 1.08 Endpoint (E) – Freshwater ecotoxicity

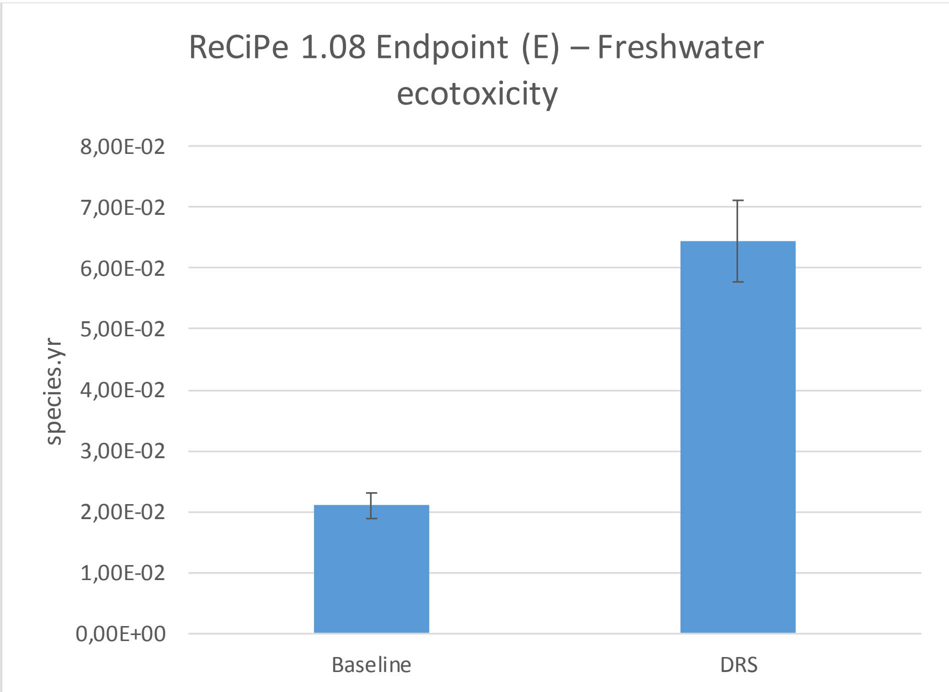


Table 23 Comparison of the Monte Carlo analysis results for the ReCiPe 1.08 Endpoint (E) – Freshwater eutrophication

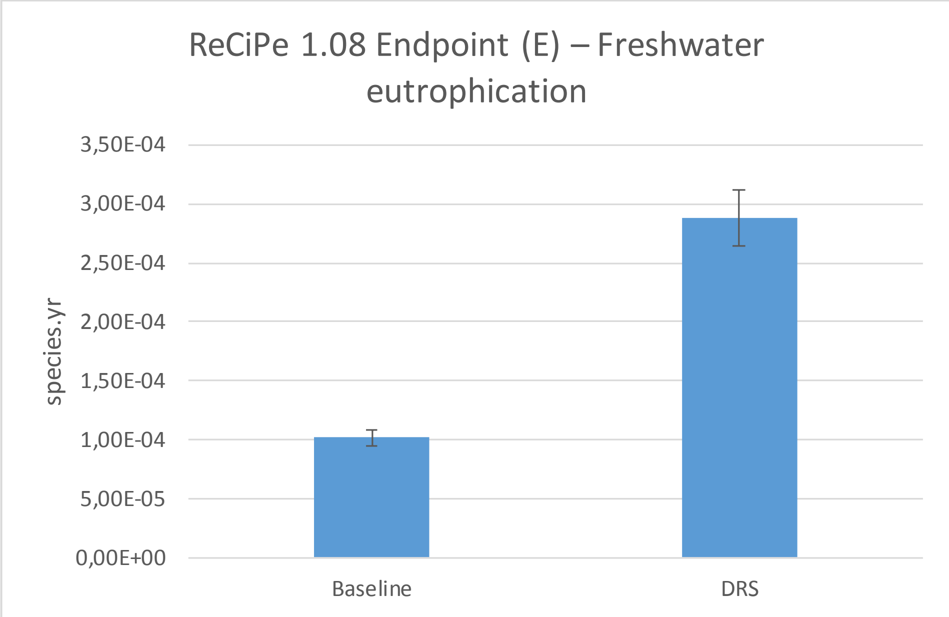


Table 24 Comparison of the Monte Carlo analysis results for the ReCiPe 1.08 Endpoint (E) – Human toxicity

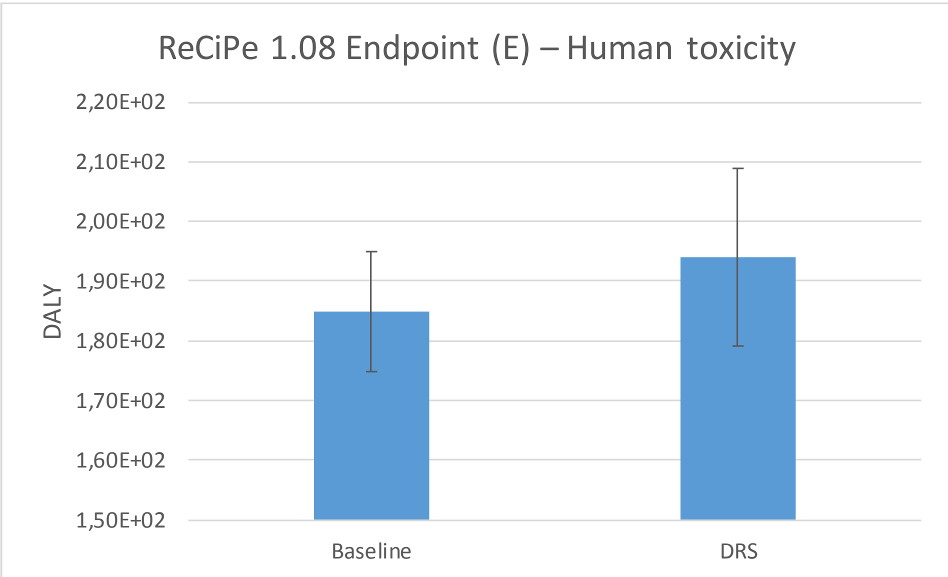


Table 25 Comparison of the Monte Carlo analysis results for the ReCiPe 1.08 Endpoint (E) – Ionizing radiation

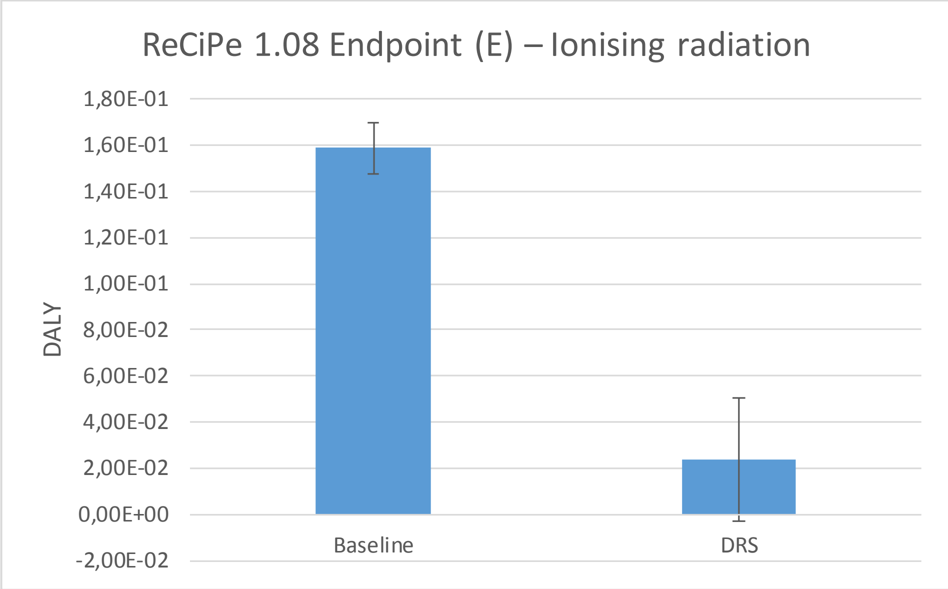


Table 26 Comparison of the Monte Carlo analysis results for the ReCiPe 1.08 Endpoint (E) – Metal depletion

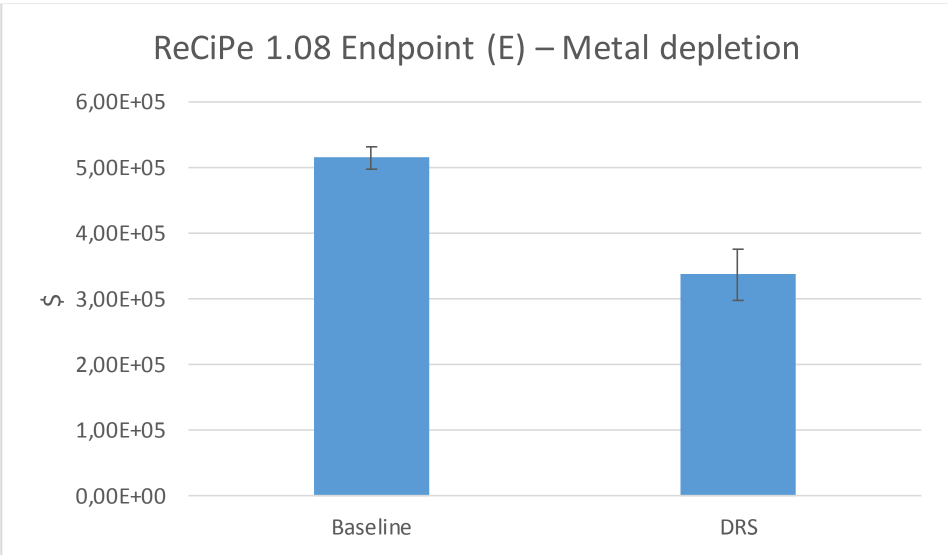


Table 27 Comparison of the Monte Carlo analysis results for the ReCiPe 1.08 Endpoint (E) – Particulate matter formation

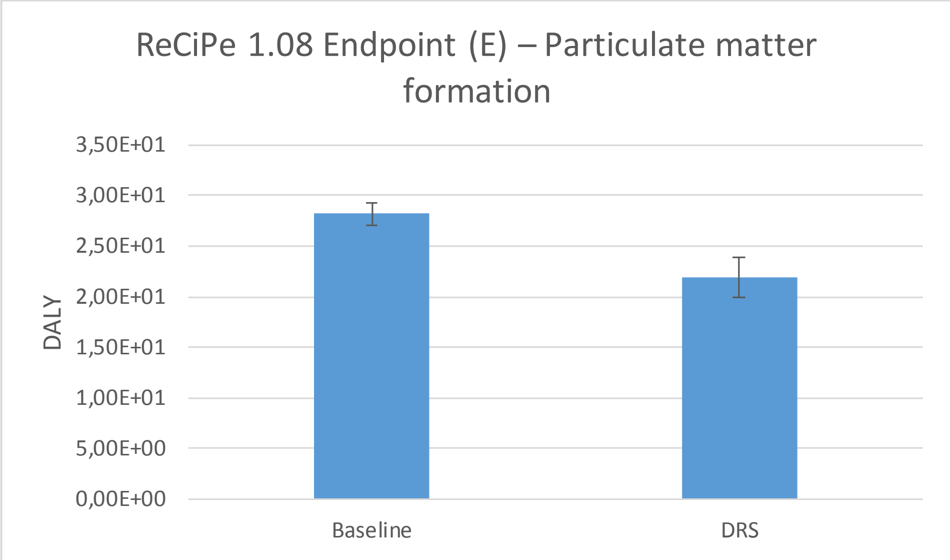


Table 28 Comparison of the Monte Carlo analysis results for the ReCiPe 1.08 Endpoint (E) – Photochemical oxidant formation

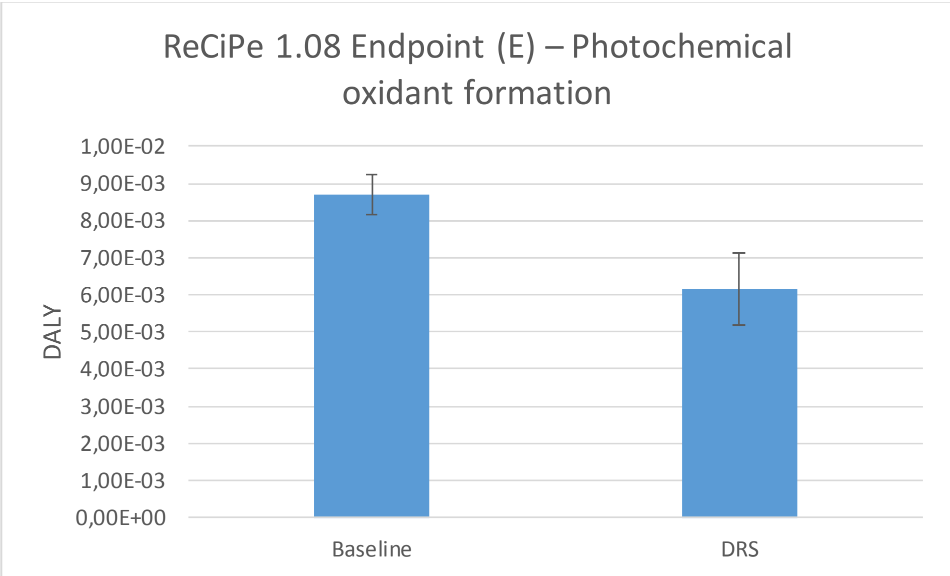


Table 29 Comparison of the Monte Carlo analysis results for the ReCiPe 1.08 Endpoint (E) – Terrestrial acidification

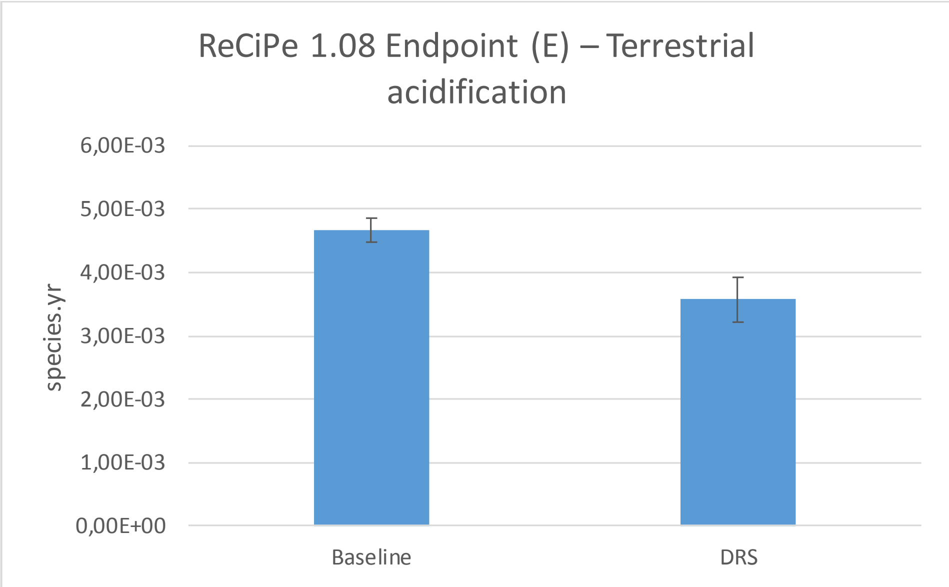


Table 30 Comparison of the Monte Carlo analysis results for the ReCiPe 1.08 Endpoint (E) – Terrestrial ecotoxicity

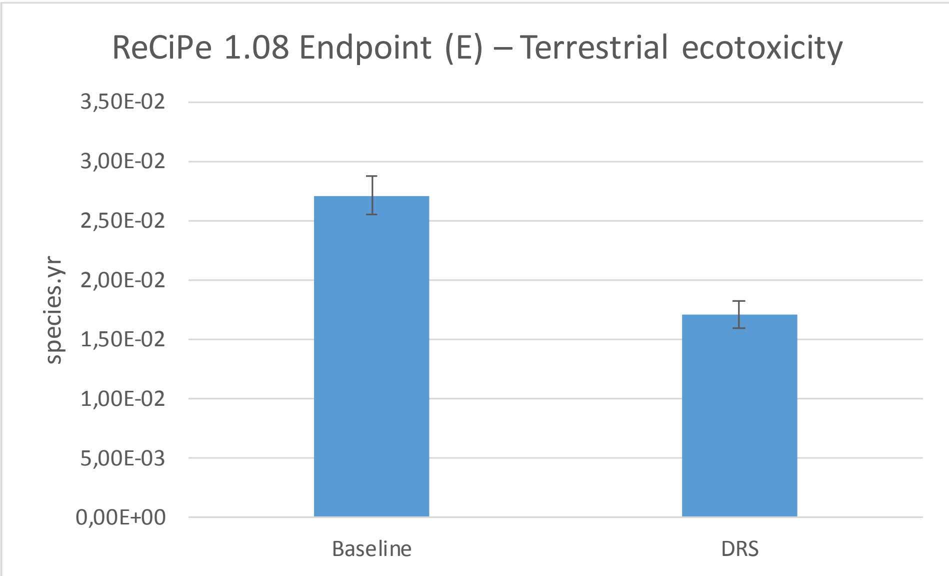
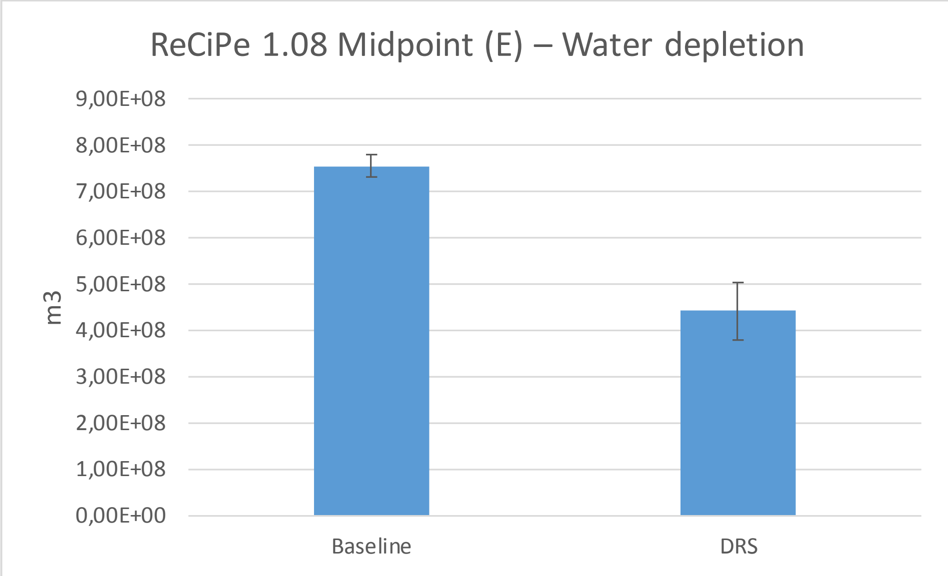


Table 31 Comparison of the Monte Carlo analysis results for the ReCiPe 1.08 Endpoint (E) – Water depletion



The Monte Carlo analysis shows significant differences among the results of the assessed systems in all assessed impact categories. The exception is the impact category "human toxicity", where the differences between the results of both systems are not statistically significant and thus can be evaluated as comparable. In most impact categories, the non-deposit-refund system (Baseline) shows higher environmental impacts than the deposit-refund system (DRS).

5.3 Standardized and weighted results

As the previous graphs show, the deposit-refund system for used bottles does not have lower values in all environmental impact categories. For an overall evaluation of both systems, we have to compare the significance of particular impact categories and consider whether the impact categories in which the deposit-refund system performs worse are more important for the environment. In order to achieve an overall evaluation of the respective systems, it is necessary to find a suitable way of interpreting all impact categories simultaneously, despite the fact that they are expressed in different units. The joint assessment of different impact categories in LCA is made possible (accepting certain limitations) by means of the standardization used for converting impact category indicators to dimensionless quantities, which is followed by weighting to reflect the significance of each impact category.

Taking into consideration the actual significance of particular impact categories is done by weighting the standardized impact category indicator results. The standardization and weighting of impact category indicator results has been done by means of a set of standardized impact category indicator results *ReCiPe 1.08 (E), End-point Normalization, Europe, excl. biogenic carbon (person equivalents)* and by means of weight factors *ReCiPe 1.08 (E/A), excl. biogenic carbon (person equivalents* *weighted)*. This is the latest current version of standardization and weight factors published for the ReCiPe 1.08 methodology. The standardized and weighted results of impact category indicators are summarized in the following tables.

Table 32 Standardized and weighted results of the impact category indicators for the non-deposit-refund system (Baseline). European reference results of impact category indicators, with the inclusion of the biogenic CO2 cycle, have been used for standardization – ReCiPe 1.08 (E), End-point Normalization, Europe, excl. biogenic carbon (person equivalents) and corresponding weight factors – ReCiPe 1.08 (E/A), excl. biogenic carbon (person equivalents weighted) have been used for weighting.

ReCiPe 1.08 (E/A), excl. biogenic carbon (Person equivalents weighted)	Baseline Total	Aluminum	PET	Steel
ReCiPe 1.08 Endpoint (E) - Climate change Ecosystems, excl. biogenic carbon	3.28E+06	1.28E+06	1.98E+06	2.40E+04
ReCiPe 1.08 Endpoint (E) - Climate change Human Health, excl. biogenic carbon	4.13E+06	1.61E+06	2.49E+06	3.02E+04
ReCiPe 1.08 Endpoint (E) - Fossil depletion	5.36E+06	1.34E+06	3.99E+06	2.72E+04
ReCiPe 1.08 Endpoint (E) - Freshwater ecotoxicity	3.05E+04	3.04E+04	62.1	91.8
ReCiPe 1.08 Endpoint (E) - Freshwater eutrophication	148	88.7	59.1	0.0657
ReCiPe 1.08 Endpoint (E) - Human toxicity	1.80E+06	7.82E+05	6.19E+05	4.04E+05
ReCiPe 1.08 Endpoint (E) - Ionizing radiation	1.55E+03	793	760	1.71
ReCiPe 1.08 Endpoint (E) - Metal depletion	3.34E+05	2.93E+05	1.62E+04	2.52E+04
ReCiPe 1.08 Endpoint (E) - Ozone depletion	-1.36	4.54	-5.85	-0.0467
ReCiPe 1.08 Endpoint (E) - Particulate matter formation	2.75E+05	2.06E+05	6.65E+04	2.26E+03
ReCiPe 1.08 Endpoint (E) - Photochemical oxidant formation	84.7	44.5	39.4	0.842
ReCiPe 1.08 Endpoint (E) - Terrestrial acidification	6.80E+03	4.75E+03	1.99E+03	58.9
ReCiPe 1.08 Endpoint (E) - Terrestrial ecotoxicity	3.93E+04	4.80E+03	1.62E+04	1.83E+04

Table 33 Standardized and weighted results of the impact category indicators for the deposit-refund system (DRS). European reference results of impact category indicators, with inclusion of the biogenic CO_2 cycle, have been used for standardization – ReCiPe 2 1.08 (E), End-point Normalization, Europe, excl. biogenic carbon (person equivalents) *and corresponding weight factors* – ReCiPe 1.08 (E/A), excl. biogenic carbon (person equivalents weighted) *have been used for weighting.*

ReCiPe 1.08 (E/A), excl. biogenic carbon (Person equivalents weighted)	DRS Total	Aluminum DRS	PET DRS	Steel DRS
ReCiPe 1.08 Endpoint (E) - Climate change Ecosystems, excl. biogenic carbon	2.22E+06	6.45E+05	1.56E+06	1.51E+04
ReCiPe 1.08 Endpoint (E) - Climate change Human Health, excl. biogenic carbon	2.80E+06	8.12E+05	1.97E+06	1.90E+04
ReCiPe 1.08 Endpoint (E) - Fossil depletion	3.49E+06	7.11E+05	2.76E+06	2.15E+04
ReCiPe 1.08 Endpoint (E) - Freshwater ecotoxicity	9.37E+04	9.35E+04	200	19.9
ReCiPe 1.08 Endpoint (E) - Freshwater eutrophication	416	283	132	0.889
ReCiPe 1.08 Endpoint (E) - Human toxicity	1.97E+06	1.17E+06	7.18E+05	8.57E+04
ReCiPe 1.08 Endpoint (E) - Ionizing radiation	294	-356	647	3.56
ReCiPe 1.08 Endpoint (E) - Metal depletion	2.21E+05	1.79E+05	2.71E+04	1.51E+04
ReCiPe 1.08 Endpoint (E) - Ozone depletion	13.7	13.9	-0.217	0.0383
ReCiPe 1.08 Endpoint (E) - Particulate matter formation	2.20E+05	1.38E+05	7.99E+04	1.56E+03
ReCiPe 1.08 Endpoint (E) - Photochemical oxidant formation	64.4	27.2	36.5	0.657
ReCiPe 1.08 Endpoint (E) - Terrestrial acidification	5.39E+03	3.06E+03	2.28E+03	44.1
ReCiPe 1.08 Endpoint (E) - Terrestrial ecotoxicity	2.43E+04	1.06E+04	1.00E+04	3.68E+03

To show the level of significance and determine the key impact categories having the largest share in the total environmental impacts of the assessed systems, in the following tables the contribution of respective categories is expressed in percentages.

Table 34 Determination of the significant environmental impacts of the non-deposit-refund system (Baseline)

Impact category	Baseline Total	Aluminum	PET	Steel
ReCiPe 1.08 Endpoint (E) - Climate change Ecosystems, excl. biogenic carbon	21.50%	23.06%	21.57%	4.52%

Impact category	Baseline Total	Aluminum	PET	Steel
ReCiPe 1.08 Endpoint (E) - Climate change Human Health, excl. biogenic carbon	27.07%	29.00%	27.12%	5.68%
ReCiPe 1.08 Endpoint (E) - Fossil depletion	35.13%	24.14%	43.46%	5.12%
ReCiPe 1.08 Endpoint (E) - Freshwater ecotoxicity	0.20%	0.55%	0.00%	0.02%
ReCiPe 1.08 Endpoint (E) - Freshwater eutrophication	0.00%	0.00%	0.00%	0.00%
ReCiPe 1.08 Endpoint (E) - Human toxicity	11.80%	14.09%	6.74%	76.04%
ReCiPe 1.08 Endpoint (E) - Ionizing radiation	0.01%	0.01%	0.01%	0.00%
ReCiPe 1.08 Endpoint (E) - Metal depletion	2.19%	5.28%	0.18%	4.74%
ReCiPe 1.08 Endpoint (E) - Ozone depletion	0.00%	0.00%	0.00%	0.00%
ReCiPe 1.08 Endpoint (E) - Particulate matter formation	1.80%	3.71%	0.72%	0.43%
ReCiPe 1.08 Endpoint (E) - Photochemical oxidant formation	0.00%	0.00%	0.00%	0.00%
ReCiPe 1.08 Endpoint (E) - Terrestrial acidification	0.04%	0.09%	0.02%	0.01%
ReCiPe 1.08 Endpoint (E) - Terrestrial ecotoxicity	0.26%	0.09%	0.18%	3.44%
Suma: ReCiPe 1.08 (E/A), excl. biogenic carbon (Person equivalents weighted)	100%	100%	100%	100%

Table 35 Determination of the significant environmental impacts of the deposit-refund system (DRS)

Impact category	DRS Total	Aluminum DRS	PET DRS	Steel DRS
ReCiPe 1.08 Endpoint (E) - Climate change Ecosystems, incl biogenic carbon	20.10%	17.14%	21.88%	9.34%
ReCiPe 1.08 Endpoint (E) - Climate change Human Health, incl biogenic carbon	25.35%	21.58%	27.64%	11.75%
ReCiPe 1.08 Endpoint (E) - Fossil depletion	31.60%	18.90%	38.72%	13.30%
ReCiPe 1.08 Endpoint (E) - Freshwater ecotoxicity	0.85%	2.49%	0.00%	0.01%
ReCiPe 1.08 Endpoint (E) - Freshwater eutrophication	0.00%	0.01%	0.00%	0.00%
ReCiPe 1.08 Endpoint (E) - Human toxicity	17.84%	31.10%	10.07%	53.00%

Impact category	DRS Total	Aluminum DRS	PET DRS	Steel DRS
ReCiPe 1.08 Endpoint (E) - Ionizing radiation	0.00%	0.00%	0.00%	0.00%
ReCiPe 1.08 Endpoint (E) - Metal depletion	2.00%	4.76%	0.38%	9.34%
ReCiPe 1.08 Endpoint (E) - Ozone depletion	0.00%	0.00%	0.00%	0.00%
ReCiPe 1.08 Endpoint (E) - Particulate matter formation	1.99%	3.67%	1.12%	0.96%
ReCiPe 1.08 Endpoint (E) - Photochemical oxidant formation	0.00%	0.00%	0.00%	0.00%
ReCiPe 1.08 Endpoint (E) - Terrestrial acidification	0.05%	0.08%	0.03%	0.03%
ReCiPe 1.08 Endpoint (E) - Terrestrial ecotoxicity	0.22%	0.28%	0.14%	2.28%
Suma: ReCiPe 1.08 (E/A), incl biogenic carbon (Person equivalents weighted)	100%	100%	100%	100%

By calculating the percentage contribution of a given impact category to the total (standardized and weighted) results of environmental impacts, it was possible to approximately define those more significant impact categories which have a dominant influence when comparing which of the two systems – the deposit-refund or non-deposit-refund system – are more favorable from the environmental point of view. Impact categories having a contribution to the sum of environmental impacts of less than 1% are considered to be insignificant or minority. After excluding minority impact categories, impact categories covering more than 98% of environmental impacts in the sum will be included in the following evaluation, as the following table shows.

Table 36 Share of significant impact categories in total environmental impacts.

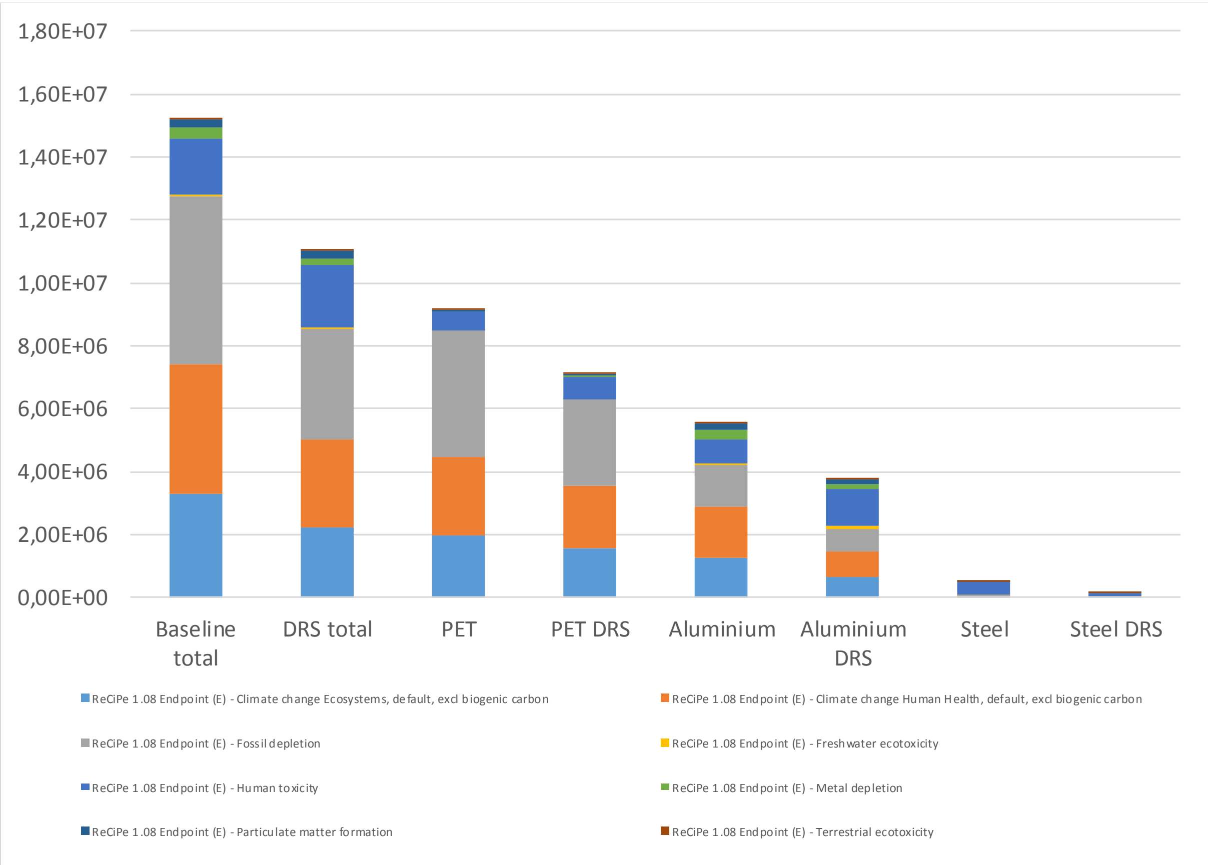
Share in total environmental impacts	Total	Al	PET	Steel
Non-deposit-refund system (Baseline)				
Included impact categories (impact of each category higher than 1%)	99.49 %	99.26 %	99.79 %	98.53 %
Excluded impact categories (impact of each category lower than 1%)	0.51%	0.74%	0.21%	3.47%
Deposit-refund system (DRS)				
Included impact categories (impact of each category higher than 1%)	98.88 %	97.15 %	99.81 %	97.68 %
Excluded impact categories (impact of each category lower than 1%)	1.12%	2.85%	0.19%	2.32%

The following impact categories may be considered significant for assessing the non-deposit-refund and deposit-refund systems in the Czech Republic (each category contributes at least 1% of the environmental impact sum):

- ReCiPe 1.08 Endpoint (E) – Climate change Ecosystems, incl. biogenic carbon
- ReCiPe 1.08 Endpoint (E) - Climate change Human Health, incl biogenic carbon
- ReCiPe 1.08 Endpoint (E) - Fossil depletion
- ReCiPe 1.08 Endpoint (E) - Human toxicity
- ReCiPe 1.08 Endpoint (E) - Metal depletion
- ReCiPe 1.08 Endpoint (E) - Particulate matter formation
- ReCiPe 1.08 Endpoint (E) - Terrestrial ecotoxicity.

The total evaluation of respective scenarios is enabled by the following graph, where the contributions of individual significant impact categories to the total environmental impacts are shown.

Figure 26 Comparison of the non-deposit-refund and deposit-refund systems by means of the sum of weighted results of selected significant environmental impact categories (ReCiPe 1.08 endpoint person equivalents weighted)



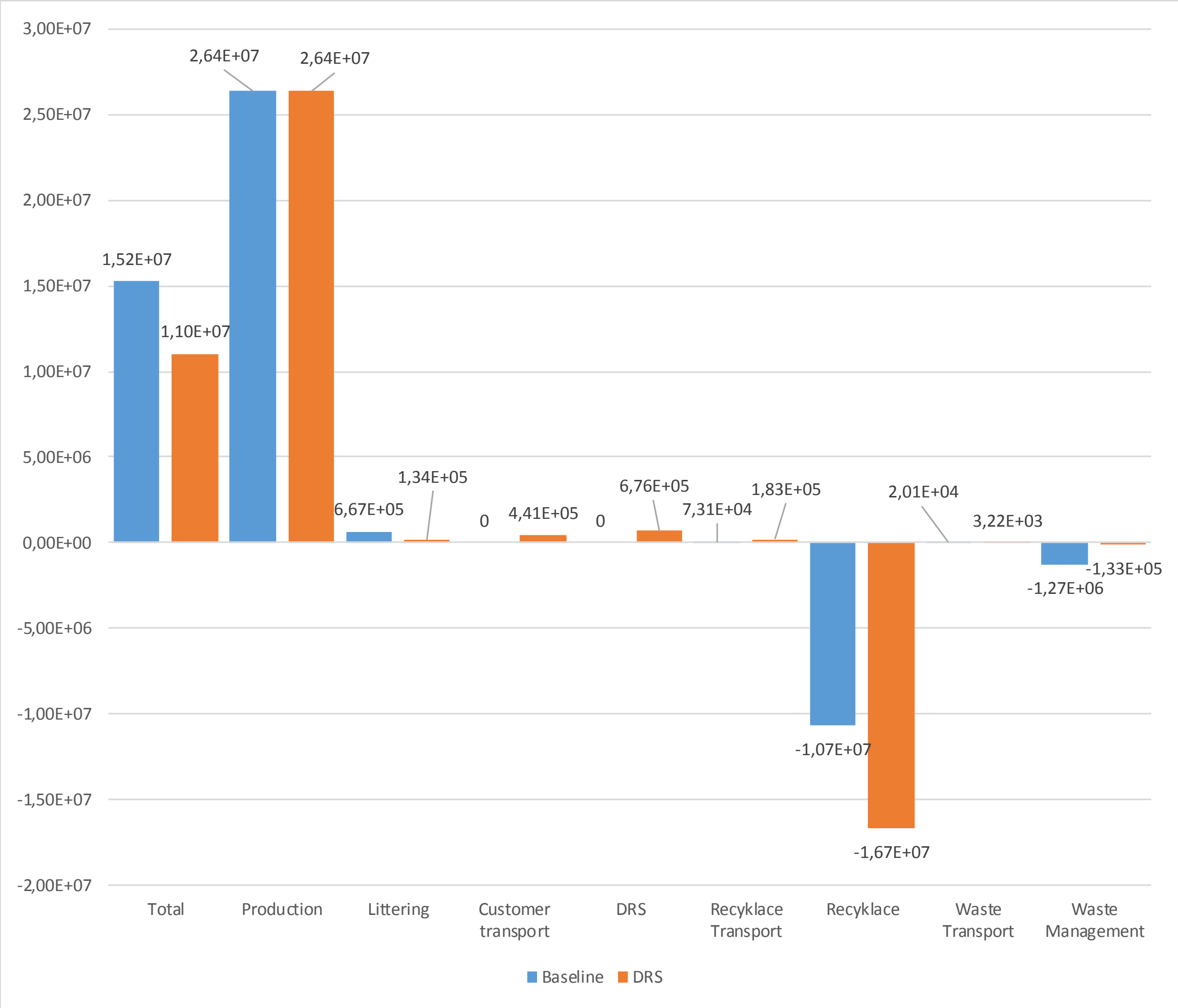
The totaled values of weighted and standardized results of impact category indicators for the non-deposit-refund system are 1.66E+07 [ReCiPe 1.08 (E/A), excl. biogenic carbon (person equivalents weighted)], and for the deposit-refund system 1.04E+07 [ReCiPe 1.08 (E/A), excl. biogenic carbon (person equivalents weighted)]. **The deposit-refund system shows values of total environmental impacts 28% lower than values of the non-deposit-refund system.**

5.4 Influence of particular technology spheres

In order to further improve the individual system, whether it is the non-deposit-refund system or the deposit-refund system for beverage bottle treatment, it is useful to know which stages or which technology spheres substantially contribute to the resulting environmental impacts. The following graph and tables show the contributions of the respective technology spheres to the total environmental impacts of the assessed systems. These are the same technology spheres that are color-coded (Figure 3 to Figure 9) in the above mentioned schemes. The negative values show the environmental benefits of the given technology spheres (recycling, waste-to-energy utilization). These are cases when the environmental impacts which would have otherwise arisen if a corresponding volume of material or energy were produced in the usual manner were averted by the waste-to-material and waste-to-energy utilization of used bottles or waste.

The graph shows the finding that the **manufacture of materials used in the production of bottles (Production) is the main technology sphere which significantly influences resulting environmental impacts. Through the waste-to-material and waste-to-energy utilization of used bottles, waste management – especially material recycling – significantly decreases the total environmental impacts of the assessed systems. Environmental impacts related to the collection and transport of deposited bottles and waste materials do not play a significant role in the system.**

Figure 27 Graphic representation of the contributions of particular technology spheres to total environmental impacts.



6 Interpretation of the LCA study

6.1 Formulation of significant findings

Based on above stated results of the life cycle inventory analysis, and the evaluation of the environmental impacts of the life cycle of non-deposit-refund and deposit-refund systems for treating used beverage bottles, the following significant findings have been formulated.

1) **The implementation of a deposit-refund system for beverage bottles would decrease environmental impacts related to the packaging of beverages by up to 28%.**
2) **The deposit-refund system (DRS) in comparison to the non-deposit-refund system shows lower environmental impacts in the following impact categories at both endpoint and midpoint levels: climate changes/global warming, fossil fuel depletion, ionizing radiation, metal depletion, particulate matter formation, photochemical oxidant formation, terrestrial acidification, terrestrial ecotoxicity and water depletion.**
3) **The following impact categories play the most significant role in the total environmental impacts of the non-deposit-refund and deposit-refund systems: climate changes (global warming) both on ecosystem and human health levels; loss of fossil fuel raw materials; loss of metals; and particulate matter formation. The implementation of a deposit-refund system would result in a statistically significant decrease in the indicator result values of environmental impacts in the stated categories, with the exception of the impact category "human toxicity", where both systems are assessed as comparable.**
4) **Of all the processes involved in the packaging system and the transport of beverages to consumers, the manufacture of PET, aluminum and steel has the greatest environmental impact. Thus, key to decreasing the environmental impacts of the beverage packaging system is to decrease the material demand of packaging, or increase the share of recycled material in the production of bottles.**
5) **Manufacturing materials used in the production of bottles (Production) is the main sphere in the life cycle of bottles that significantly influences the resulting environmental impacts. Through the waste-to-material and waste-to-energy utilization of used bottles, waste management – especially material recycling – significantly decreases the total environmental impacts of the assessed systems. Environmental impacts related to the collection and transport of deposited bottles and waste materials do not play a significant role in the system.**
6) **The implementation of a deposit-refund system (DRS) would result in an 80%-decrease in littering caused by plastic bottles.**

6.2 Sensitivity analyses – alternative scenario results

Sensitivity analyses are used in LCA studies to verify whether the chosen assumptions influence the resulting interpretation of results. Thus, they verify whether results are valid under different input conditions or in alternative scenarios.

6.2.1 Sensitivity analysis on bottle weight and size changes

Since there is a large number of beverage bottles with different shapes and in particular different volumes, it is necessary to verify whether the identified results are also valid for different sizes and therefore also the unit weight of beverage bottles. This LCA study is based on the weight flow of PET, aluminum and steel bottles. Therefore, the size of bottles does not have a major role in the basic technology units (weight-modelled). A different pressing rate is not considered; this mainly influences the level at which collection vehicles are filled, and thus primarily influences transport distances. The third sensitivity analysis is dedicated to changes in transport distances (see 6.2.3). This sensitivity analysis thus primarily covers the allocation of consumer transport to the bottle buyback point, which is based on the ratio of returned bottles to the weight of purchased goods.

To analyze the sensitivity of results to changes in PET bottle weight, the weight range of bottles placed on the market by the company Karlovarské minerální vody, a.s.[15] has been used. To determine the range of values for aluminum bottles, a study by Marie Tichá conducted for the Ministry of the Environment of the Czech Republic has been used[16]. The weight of one bottle made of sheet steel has been used in agreement with Eunomia[4], the project partner. The weight range of steel bottles has been estimated to +/- 5 g. The bottle weight values used in the basic scenario and the bottle weight range are stated in the following table.

Table 37 Weight of bottles in the basic and alternative scenarios. The bottle volume is stated in brackets.

	Basic scenario	**Alternative scenarios – bottle weight range Minimum – maximum weight**
PET	31.5 g	21.7 g–46.4 g
Al	25.0 g	11.4 g–35.0 g
Steel (minority market share)	35 g	30 g–40 g

The results of the sensitivity analysis are summarized in the following table. The table shows percentage differences in the results of the impact category indicators of alternative scenarios, i.e. the results determined for the minimum (Min) and maximum (Max) weight of one bottle.

[15] KMV, a.s., Mgr. Magda Michalíková

[16] Ing. Marie Tichá MT KONZUL, LCA of beverage bottles, Ministry of the Environment of the Czech Republic, VaV project: SP/II/2f1/16/07

Table 38 Results of a sensitivity analysis on bottle weight changes

Alternative scenario	Min	Max	Min	Max	Min	Max
Impact category	PET DRS (21.7 g)	PET DRS (46.4 g)	Aluminum DRS (11.4 g)	Aluminum DRS (35 g)	Steel DRS (30 g)	Steel DRS (40 g)
ReCiPe 1.08 Endpoint (E) - Climate change Ecosystems, default, excl biogenic carbon [species.yr]	0.00%	6.48%	4.25%	0.01%	0.00%	0.00%
ReCiPe 1.08 Endpoint (E) - Climate change Ecosystems, incl biogenic carbon [species.yr]	0.00%	6.48%	4.25%	0.01%	0.00%	0.00%
ReCiPe 1.08 Endpoint (E) - Climate change Human Health, default, excl biogenic carbon [DALY]	0.00%	6.44%	4.25%	0.01%	-0.51%	0.51%
ReCiPe 1.08 Endpoint (E) - Climate change Human Health, incl biogenic carbon [DALY]	0.00%	6.40%	4.25%	0.01%	-0.52%	0.52%
ReCiPe 1.08 Endpoint (E) - Fossil depletion [$]	0.00%	6.35%	4.56%	0.01%	-0.30%	0.30%
ReCiPe 1.08 Endpoint (E) - Freshwater ecotoxicity [species.yr]	0.00%	5.84%	9.58%	0.00%	0.00%	0.00%
ReCiPe 1.08 Endpoint (E) - Freshwater eutrophication [species.yr]	0.00%	6.37%	9.58%	0.00%	0.00%	0.00%
ReCiPe 1.08 Endpoint (E) - Human toxicity [DALY]	-0.14%	6.26%	-7.54%	0.00%	0.00%	0.00%
ReCiPe 1.08 Endpoint (E) - Metal depletion [$]	0.00%	6.24%	5.47%	0.00%	-0.43%	0.43%
ReCiPe 1.08 Endpoint (E) - Ozone depletion [DALY]	0.00%	6.31%	9.60%	0.00%	0.00%	0.00%
ReCiPe 1.08 Endpoint (E) - Particulate matter formation [DALY]	-0.12%	6.23%	6.07%	0.00%	0.00%	0.00%
ReCiPe 1.08 Endpoint (E) - Photochemical oxidant formation [DALY]	0.00%	6.42%	5.52%	0.01%	-0.30%	0.30%
ReCiPe 1.08 Endpoint (E) - Terrestrial acidification [species.yr]	0.00%	6.37%	5.85%	0.00%	-0.33%	0.33%
ReCiPe 1.08 Endpoint (E) - Terrestrial ecotoxicity [species.yr]	0.00%	6.23%	9.17%	0.00%	0.00%	0.00%

Alternative scenario	Min	Max	Min	Max	Min	Max
Impact category	PET DRS (21.7 g)	PET DRS (46.4 g)	Aluminum DRS (11.4 g)	Aluminum DRS (35 g)	Steel DRS (30 g)	Steel DRS (40 g)
ReCiPe 1.08 Midpoint (E) - Climate change, default, excl biogenic carbon [kg CO2 eq.]	0.00%	6.26%	4.25%	0.01%	-0.36%	0.36%
ReCiPe 1.08 Midpoint (E) - Water depletion [m3]	0.00%	6.27%	5.09%	0.00%	0.00%	0.00%

The differences among the results of impact category indicators for minimum and maximum considered weight of bottles in comparison to the basic scenario (PET 31.5 g; Al 25.0 g; steel 35 g) do not even amount to 10%[17], which is less than the percentage change in the weight of bottles. The results of the sensitivity analysis show that the weight change of one bottle has no major influence on the significant findings formulated above.

6.2.2 Sensitivity analysis on changes in quantities of returned bottles

Different numbers of returned bottles on a single journey to the buyback point influences the amount of paper necessary for printing a deposit-refund ticket, and also the allocation of environmental impacts related to transporting bottles to the buyback point. Three alternative scenarios for PET DRS (basic scenario) have been selected for the following sensitivity analysis, where each alternative scenario characterizes a different situation. The first scenario entitled “Small purchase” assumes the return of only 1 bottle for a shorter distance (2 km) combined with a small weight of subsequent shopping (3 kg). The second scenario entitled “Medium purchase” describes a situation in which the customer returns 5 bottles over a distance of 30 km and the purchase of goods weighing 30 kg. The third scenario named “Large purchase” assumes the return of 20 bottles over a distance of 35 km and the purchase of goods weighing 60 kg. These scenarios are summarized in the following table.

Table 39 Scenario characteristics for a sensitivity analysis on changes in the amount of purchased goods

Scenario	Basic model (PET DRS)	Small purchase	Medium purchase	Large purchase
Number of returned bottles, pcs	10	1	5	20
Driving distance for the return of bottles/shopping, km	15	2	30	40

[17] The asymmetry of differences of the Min & Max scenario compared to the median value is not an error but arises from system complexity.

Weight of purchased goods, kg	30	3	30	60

The results of the sensitivity analysis on the assessed scenarios are stated in the following table. The table shows percentage differences in impact category results compared to the basic scenario (since this is a reference scenario, it is not stated in the table).

Impact category	**Small purchase (1 bottle)**	**Medium purchase (5 bottles)**	**Large purchase (20 bottles)**
ReCiPe 1.08 Endpoint (E) - Climate change Ecosystems, default, excl biogenic carbon [species.yr]	2.04%	6.19%	2.04%
ReCiPe 1.08 Endpoint (E) - Climate change Ecosystems, incl biogenic carbon [species.yr]	2.01%	6.08%	2.01%
ReCiPe 1.08 Endpoint (E) - Climate change Human Health, default, excl biogenic carbon [DALY]	2.04%	6.19%	2.04%
ReCiPe 1.08 Endpoint (E) - Climate change Human Health, incl biogenic carbon [DALY]	2.01%	6.08%	2.01%
ReCiPe 1.08 Endpoint (E) - Fossil depletion [$]	1.51%	4.58%	1.51%
ReCiPe 1.08 Endpoint (E) - Freshwater ecotoxicity [species.yr]	0.12%	0.36%	0.12%
ReCiPe 1.08 Endpoint (E) - Freshwater eutrophication [species.yr]	0.30%	0.91%	0.30%
ReCiPe 1.08 Endpoint (E) - Human toxicity [DALY]	1.25%	3.78%	1.25%
ReCiPe 1.08 Endpoint (E) - Ionizing radiation [DALY]	0.08%	0.25%	0.08%
ReCiPe 1.08 Endpoint (E) - Metal depletion [$]	0.12%	0.35%	0.12%
ReCiPe 1.08 Endpoint (E) - Ozone depletion [DALY]	0.00%	0.00%	0.00%
ReCiPe 1.08 Endpoint (E) - Particulate matter formation [DALY]	2.39%	7.24%	2.39%
ReCiPe 1.08 Endpoint (E) - Photochemical oxidant formation [DALY]	3.27%	9.91%	3.27%

Impact category	Small purchase (1 bottle)	Medium purchase (5 bottles)	Large purchase (20 bottles)
ReCiPe 1.08 Endpoint (E) - Terrestrial acidification [species.yr]	2.31%	6.99%	2.31%
ReCiPe 1.08 Endpoint (E) - Terrestrial ecotoxicity [species.yr]	0.13%	0.40%	0.13%
ReCiPe 1.08 Midpoint (E) - Climate change, default, excl biogenic carbon [kg CO2 eq.]	2.04%	6.19%	2.04%
ReCiPe 1.08 Midpoint (E) - Water depletion [m3]	0.17%	0.52%	0.17%

The values stated in the table confirm the validity of the basic scenario. The differences of the alternative scenarios compared to the basic scenario are low, with the maximum value of 9.91% belonging to the *Medium purchase* scenario, which differs in comparison to the basic scenario by its driving distance being twice as long. The total difference of the alternative scenarios from the basic scenario is stated in the following table.

Table 40 Summary of the sensitivity analysis to changes in the amount of purchased goods

Name of scenario	**Small purchase**	**Medium purchase**	**Large purchase**
Difference from the basic scenario	1.80%	5.45%	1.80%

The alternative scenarios for the amount of purchased goods and the number of returned bottles do not substantially influence the formulation of significant findings.

6.2.3 Sensitivity analysis to transport distance changes

Different transport distances driven during the collection and transport of bottles and waste materials, or materials destined for waste-to-material and waste-to-energy utilization, result in different values for the environmental impacts of the transport itself (e.g. exhaust emissions) and processes related to fuel production. By modelling transport distances for an LCA study in different ranges, we attempt to cover significantly variable real-life values within the chosen range. By increasing estimated transport distances, it is also possible to cover the increased transport demand that occurs when collecting a large volume of bottles whose volume has increased when bottles have not been compacted or compressed by consumers. In the sensitivity analysis of the obtained results to changes in transport distances, alternative transport distances in values of 0% (hypothetical scenario with zero transport), 50%, 150% and 300% of the original basic scenario have been assumed. We should also remember that the basic scenario is already based on conservative, i.e. higher, estimates for transport distances (see 4.2.2).

Table 41 Transport distances applied in the sensitivity analysis

Type of transport	**DRS – deposit-refund system Basic scenario (alternative transport distances)**
Collection of waste in containers	35 (17.5; 52.5; 105) km
Transport to a landfill site	20 (10; 30; 60) km
Transport for waste-to-energy use (to a waste-to-energy facility, cement plant)	150 (75; 225; 450) km
Transport to a collection center	250 (125; 375; 750) km
Transport to a recycling line	150 (75; 225; 450) km

The following table shows the outputs of the sensitivity analysis on the results of changes in transport distances. A more significant change in the results (of 2.62%) only happens in the impact category "Climate changes", or "Increasing greenhouse effect", and only in the rather extreme scenario where transport distances double to those in the basic scenario are assumed. Thus, changing transport distances does not result in significant changes in the interpretation of the study results.

Table 42 Results of a sensitivity analysis on transport distance changes

	Alternative scenarios			
Impact category	**0%**	**50%**	**150%**	**200%**
ReCiPe 1.08 Endpoint (E) - Climate change Ecosystems, default, excl biogenic carbon [species.yr]	-2.62%	-1.31%	1.31%	2.62%
ReCiPe 1.08 Endpoint (E) - Climate change Ecosystems, incl biogenic carbon [species.yr]	-2.57%	-1.29%	1.29%	2.57%
ReCiPe 1.08 Endpoint (E) - Climate change Human Health, default, excl biogenic carbon [DALY]	-2.62%	-1.31%	1.31%	2.62%
ReCiPe 1.08 Endpoint (E) - Climate change Human Health, incl biogenic carbon [DALY]	-2.57%	-1.29%	1.29%	2.57%
ReCiPe 1.08 Endpoint (E) - Fossil depletion [$]	-1.94%	-0.97%	0.97%	1.94%
ReCiPe 1.08 Endpoint (E) - Freshwater ecotoxicity [species.yr]	-0.15%	-0.08%	0.08%	0.15%
ReCiPe 1.08 Endpoint (E) - Freshwater eutrophication [species.yr]	-0.39%	-0.19%	0.19%	0.39%
ReCiPe 1.08 Endpoint (E) - Human toxicity [DALY]	-1.60%	-0.80%	0.80%	1.60%
ReCiPe 1.08 Endpoint (E) - Ionizing radiation [DALY]	-0.11%	-0.05%	0.05%	0.11%
ReCiPe 1.08 Endpoint (E) - Metal depletion [$]	-0.15%	-0.07%	0.07%	0.15%
ReCiPe 1.08 Endpoint (E) - Ozone depletion [DALY]	0.00%	0.00%	0.00%	0.00%
ReCiPe 1.08 Endpoint (E) - Particulate matter formation [DALY]	-1.11%	-0.56%	0.56%	1.11%
ReCiPe 1.08 Endpoint (E) - Photochemical oxidant formation [DALY]	-1.18%	-0.59%	0.59%	1.18%

	Alternative scenarios			
Impact category	**0%**	**50%**	**150%**	**200%**
ReCiPe 1.08 Endpoint (E) - Terrestrial acidification [species.yr]	-1.08%	-0.54%	0.54%	1.08%
ReCiPe 1.08 Endpoint (E) - Terrestrial ecotoxicity [species.yr]	-0.17%	-0.08%	0.08%	0.17%
ReCiPe 1.08 Midpoint (E) - Climate change, default, excl biogenic carbon [kg CO2 eq.]	-2.62%	-1.31%	1.31%	2.62%
ReCiPe 1.08 Midpoint (E) - Water depletion [m3]	-0.22%	-0.11%	0.11%	0.22%

6.2.4 Sensitivity analysis summary

Three sensitivity analyses were conducted to verify the validity of the formulated significant findings. Firstly, the influence of different sizes (and therefore weights) of beverage bottles was tested. Next to be tested was the influence of the quantity of returned bottles on a single journey to a buyback point, which simultaneously examined the influence of the different weights of purchased goods, and which in turn affects the allocation of environmental impacts of transporting bottles to a buyback point. The third sensitivity analysis helped to determine the influence of a change in transport distances on the results.

Changes to input parameters in sensitivity analyses did not lead to any significant result changes. In general, the influence of bottle sizes and the amounts of purchased goods on the formulation of significant findings is low. **Based on the sensitivity analysis, the above formulated significant findings may be considered valid.**

7 Conclusion

In this study, the LCA method was used to assess the possible environmental impacts of two systems for the treatment of used beverage bottles made of PET, aluminum and steel – a non-deposit-refund system and deposit-refund system. The environmental impacts of both assessed systems were determined based on a life cycle inventory analysis, followed by description using the ReCiPe methodology. The conclusiveness of the differences between results was tested by the stochastic Monte Carlo method, which showed that the differences between the results of the impact category indicators for the assessed systems are statistically significant, save for the impact category "human toxicity".

- Based on the obtained data, it may be concluded that the implementation of a deposit-refund system would result in a decrease in environmental impacts related to beverage packaging by approx. 28%.
- Compared to the non-deposit-refund system, the deposit-refund system shows lower environmental impacts in the following impact categories at both endpoint and midpoint levels: climate changes/global warming, fossil fuel depletion, ionizing radiation, metal depletion, particulate matter formation, photochemical oxidant formation, terrestrial acidification, terrestrial ecotoxicity and water depletion.
- The following impact categories play the most important role in the total environmental impacts of non-deposit-refund and deposit-refund systems: climate changes (global warming) both on ecosystem and human health levels; loss of fossil fuel raw materials; loss of metals; and particulate matter formation. The implementation of a deposit-refund system results in a statistically significant decrease in the indicator result values of environmental impacts, with the exception of the impact category "human toxicity", where both systems are assessed as comparable.
- Of all the processes involved in the packaging system and the transport of beverages to consumers, the manufacture of PET, aluminum and steel has the greatest environmental impact. Thus, key to decreasing the environmental impacts of the beverage packaging system is to decrease the material demand of packaging, or increase the share of recycled material in the production of bottles.
- The manufacture of materials used in the production of bottles is the main technology sphere with a significant influence on the resulting environmental impacts. Through the waste-to-material and waste-to-energy utilization of used bottles, waste management – especially material recycling – significantly decreases the total environmental impacts of the

assessed systems. Environmental impacts related to the collection and transport of deposited bottles and waste materials do not play a significant role in the system.

- Littering with PET bottles has only been inventoried and has not been part of the environmental impact assessment since there are no relevant characterization factors for plastics in the environment (including microplastics) available. The amount of plastics released into the environment has merely been inventoried and expressed by weight. Based on the data provided by Eunomia, implementation of DRS will result in decreased quantities of plastics being released into the environment (e.g. by littering) by 80%. Littering with aluminum and steel bottles has also been included in the evaluation of environmental impacts because characterization factors for metals contained in metal packaging are available.

The following concluding comments emerge from the wider study, they are not only the product of inventory results or the life cycle impact evaluation. From the perspective of manufacturers placing packaging materials into circulation, it makes sense to consider the material utilization of PET. From this perspective, the implementation of a deposit-refund system might appear to be the type of business relationship in which only a service, not a product, is paid for. The packaging could be seen as rented goods that are returned to the manufacturer. From the perspective of state administration or waste management at the regional level, the implementation of a deposit-refund system could present certain complications. Currently, in waste management PET is the plastic with the largest economic value; indeed, the treatment of other waste plastics is financed from profits gained from PET recycling. If valuable PET is excluded from the treatment system of waste plastics, it may be expected that the separation, recycling or disposal of other plastics will suffer a shortfall in funding. The exclusion of PET from plastic waste flow would necessitate the establishment of new conditions for financing the treatment of waste plastics. This could subsequently lead to the development of new methods for utilizing waste plastics or for preventing their being circulated in the first place. We might also ask the question to what extent resolving the issue of waste plastics *other* than PET (*de facto* co-financing) is a matter for manufacturers of packaged beverages who circulate PET bottles in the market.