ENVIRONMENTAL IMPACT ASSESSMENT OF THE IMPLEMENTATION OF A DEPOSIT-REFUND SYSTEM FOR PACKAGING WASTE IN SPAIN: A SOLUTION OR AN ADDITIONAL PROBLEM?

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Abstract

Food and beverage packaging represent a relevant fraction of municipal solid waste, and its adequate management is critical. Selective waste collection by an authorized organization according to an Extended Producer Responsibility System (EPRS) is the current option implemented in Spain for packaging. Other European countries have selected an alternative or a complement: a Deposit-Refund System (DRS) for certain type of beverage packaging. The selection of an EPRS or a DRS is a complex task and this work developed an universal methodology for the evaluation of optimal waste packaging management systems, focused on food and beverage. Life Cycle Assessment (LCA) approach was applied to compare the current EPRS vs the implementation of a new system, with the coexistence of a DRS and a reduced EPRS. Although the environmental savings of the new system are superior to its impacts, even if the DRS would reach a value of 90% for the package return index, the current EPRS obtains significantly better environmental results. All impact categories are favorable to the current EPRS, except ADP, where the potentially higher DRS recycling rate is manifested. The impact associated to the flow of specific DRS packages in the new system is clearly higher than that linked to the flow of DRS excluded packages and it is even higher that the impact of the total joint flow in the current EPRS for all categories except ADP. The fundamental cause of this high impact is the backhauling stage to transport the recovered packages to the counting plants without compacting. A sensitivity analysis confirmed the robustness of the preference of the current EPRS over the combination of a DRS and a reduced EPRS. The developed approach supposes a methodological advance that can be extended to previously realized studies about the implementation of waste management systems in other contexts.

Keywords: Life Cycle Assessment (LCA); Deposit-Refund; Extended Producer Responsibility; Packaging Waste; Beverage Packaging; Selective Collection.

1. Introduction

The growing world population will require more and more food, and the increasing number of people that is moving from rural to urban areas enhances the needs of adequate transport of all this food from producers to consumers. Food packaging must guarantee protection, commercial, and logistics requirements. Therefore, the selection of the most appropriate package must take into account that packaging conserves the food's quality and freshness, ensures organoleptic properties and hygienic conditions, offers a pleasant image and good marketing appeal, identifies the product correctly, provides information required by the consumers and is easy to store and transport (Pasqualino et al., 2011; Vitale et al., 2018). When food packaging fails in these functions, it contributes directly to food loss and waste, which has gradually become a critical environmental, economic and social concern (Vázquez-Rowe et al., 2019).

The environmental impacts of food packaging depend on package material and characteristics, but the design is a fundamental aspect from a sustainability perspective (Simon et al., 2016), and the chosen packaging influences the products's overall impact (Flanigan et al., 2013; Navarro et al., 2018). Plastic is frequently chosen for food packaging production (Gallego-Schmid et al., 2018). In 2016, global production of plastics reached 322 million Tn, with a large portion (around 40% in Europe) being used in packaging (Prata et al., 2019). Environmental issues associated with waste plastics are a worldwide concern because ineffective waste disposal pollutes the environment and creates health risks (De Feo et al., 2019; Khoo, 2019; Civancik-Uslu et al., 2019). In addition to plastic packages, alternative packaging made of glass or metals can severely affect the environment too (Laso et al., 2017), so adequate waste management has become a critical issue, not only to decrease the environmental impact related to the disposal but also to reduce the consumption of raw materials (Rigamonti et al., 2015). Consequently, the implementation of a sustainable waste management system is an excellent opportunity to recover resources and energy. The Packaging and Packaging Waste Directive (EU, 1994), which establishes targets for recycling and recovery of packaging waste, has greatly impacted the configuration of local waste management systems, since used packaging materials account up to 20% of municipal solid waste (Dace et al., 2013; Marques et al., 2014). Evidently, the recycling of packaging waste is expected to imply a favorable balance between positive and negative environmental impacts, but to achieve a really sustainable waste management, economic and social impacts should also be considered besides the environmental impacts from a circular economy point of view (Ferreira et al., 2017; Yildiz-Geyhan et al., 2019).

Circular economy encourages the movement from the current linear 'take-make-use-dispose' economic model to a new one that is restorative and regenerative by design (Hahladakis and Iacovidou, 2019). This new model must provide the tools to restore, retain and redistribute materials, components and products in the best possible way and for as long as it is environmentally, technically, socially and economically feasible. This economy, which should sustainably generate prosperity without compromising healthy environment and social equity throughout current and future generations, promotes recycling, among other strategies such as reuse or renewables (Abejón et al., 2020; Blanca-Alcubilla et al., 2019), to reduce environmental impacts and improve resource efficiency (Faraca et al., 2019; Ferrão et al., 2014). It is clear that, to assure circular economy solutions, the recycling of packaging waste is regarded to be an important prerequisite, but it must be complemented with indispensable requirements for the design, production, and commercialization of packaging that enable their reuse, recovery and recycling (Hahladakis et al., 2018).

Different waste collection systems and recycling technologies are carried out in different European countries to meet the requirements of the Packaging and Packaging Waste Directive. Nevertheless, all systems proposed can be categorized into two main groups: Extended Producer Responsibility Systems (EPRS) and Deposit – Refund Systems (DRS).

On the one hand, EPRS is based on an environmental policy approach in which the producer's responsibility (physical or financial) for a product is extended to the post-consumer stage of a product's life cycle (Pires et al., 2015). This perspective implies two main consequences: the shifting of responsibility upstream towards the producer and away from municipalities, and the incentives to producers to include environmental considerations in their product design. Producers can select between two alternatives to fulfill their responsibilities: a producer can make its own plan and implement its individual system to collect and manage packaging materials derived from its products or it can transfer the responsibilities to an authorized organization by paying a fee (Özdemir-Akyildirim, 2015). Many countries in Europe and Asia have adopted this latter scheme with authorized producer responsibility organizations financed by the producers to manage wastes, specifically the selective collection and sorting of wasted packages (Cheng et al., 2019; Ferreira et al., 2017; Hanisch, 2000). Nonetheless, the design and implementation of EPRSs must be supported by an exhaustive understanding of the environmental and economic costs and benefits of end-of-life package collection and recovery (Geyer et al., 2016).

On the other hand, DRSs for packages (these systems are very frequently used for beverage) combine two types of economic incentives (Dace et al., 2013). First, a surcharge is placed on the purchase of the package, reflecting the potential for inefficient or polluting disposal (burial in a landfill or littering of public spaces). Then, a rebate, covering part of the surcharge, is provided to whomever returns the package to the system, in perfect conditions to be identified, in order to be managed in the environmentally preferred way (Lavee, 2010). This approach intends to finance waste management but also to increase recovery rates and divert certain materials from the mixed municipal waste stream, reducing landfilling and littering (Kim and Mori, 2015; Numata, 2009). However, the handling and administration economic costs and the real environmental impacts must be considered (Linderhof et al., 2019).

Several studies of both types of systems for the collection and management of these wastes have investigated the most sustainable option, including technical, economic, environmental, and social aspects (Pires et al., 2017). The conclusions of this scientific research have caused controversial discussion about the optimal solution for each territory to recover and recycle beverage packages, because the completed cost-benefit analyses were highly dependent on specific conditions and the methodologies employed differed (Schwanse, 2011).

This study seeks to obtain and present rigorous, systematic, transparent and objective information about environmental considerations, based on scientific methodologies, which could be a broad knowledge base to facilitate decision-making by the competent administrations and provide valuable information to all the stakeholders involved in the definition, design and implementation of waste management systems. The selection of an EPRS or a DRS for selective collection of wastes is not a simple task. While in Spain or France packaging producers have established an EPRS, Finland or Denmark, have preferred the implementation of a DRS, but in other countries like Germany, Sweden or Norway there is coexistence of a DRS for certain types of packaging and an EPRS for the rest (Bala et al., 2020). The main aim of this work is laying the foundations to develop a rigorous analysis applicable to the universal evaluation of the optimal system for waste packaging management, with particular focus on food and beverage packages. As case study, the direct comparison of the environmental impacts of the current Spanish EPRS and the introduction of a new system, with the coexistence of a DRS and a reduced EPRS, was selected. Additionally, considering the sources of uncertainty that this type of study may entail, its consistency has been reinforced with a sensitivity analysis to consider alternative scenarios and conditions, which supposes a methodological advance that can be extended to previously realized studies in other contexts. Finally, a step wise procedure for critical review and improvement was followed, including: an along the way review by interested parties; a post study review by a panel of experts; a public exposure during one year on the website; and a series of papers sent to scientific journals, including the one presented here.

The paper is structured as follows: Section 2 presents the Life Cycle Assessment (LCA) methodology including the goal of this study, the definition of the functional unit and the system boundaries, the allocations methods and the selected environmental categories and the data, limitations, assumptions and hypotheses considered in this study; Section 3 gives a detailed description of the system and presents the life cycle inventory; Section 4 explains the obtained results and the sensitivity analysis; and lastly Section 5 provides the main conclusions of the work.

2. Methodology

The LCA methodology was used, following the recommendations provided by the ISO 14040 and 14044 standards (ISO 2006a, 2006b). This method enables the analysis of the environmental impact generated throughout the life cycle of the management systems, offering results both in the use of resources and in the emissions to the environment. As prescribed by the standards, this LCA study comprises the definition of goal and scope, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA) and interpretation of the results.

2.1. Goal and scope

The main objective of this work is the analysis of the sustainability of the implementation of a mandatory DRS for certain types of single-use beverage packaging, currently managed under the EPRS. This new system would necessarily have to coexist with the current one, which would continue managing the rest of packages not accepted by the DRS. In order to study the impact of the introduction of the DRS in the package waste management, two different scenarios will be compared. The first one, referred as current EPRS, corresponds to the real situation of the Spanish management of household packaging waste in 2014, where all domestic packages were subject to EPRS. A detailed description of this current Spanish system for the management of packaging waste can be consulted in a previously published article (Bala et al., 2020), which includes the corresponding LCA (taken as reference in this work). The second one, referred as new system, corresponds to a hypothetical situation that would have considered the management of household packaging waste in 2014 under a full-performance DRS (90% return percentage without learning curve) for certain beverage packaging, coexisting with an EPRS for the rest of packages.

2.2. Function and functional unit

The functional unit is the measurement of the function of the systems analyzed which enables these to be comparable. In this case, the functional unit is defined as the amount of single-use light and glass packaging collected, managed and recycled in Spain in 2014. The packaging included in the functional unit is composed of the following materials: steel, aluminum, polyethylene terephthalate (PET), high-density polyethylene (HDPE), film, mixed plastic, beverage carton and glass. Therefore, the packaging made of cardboard, paper, wood, ceramics, cork and textile material remains outside the functional unit of this study. Table 1 compiles the baseline amounts collected in Spain in 2014 of the different types of packaging under study. The flow of packages subject to the new DRS is called Flow 1, while the flow of other packages not included in the DRS is called Flow 2. In fact, the single-use packages that would be accepted by the new DRS are defined by a triple criterion (type of packaging material, type of product and capacity):

- Materials: steel, aluminum, briks, HDPE, PET and glass.

- Products: water, soft drinks, juices, beer, wine, spirits, sparkling and cava.
- Capacities: between 0.1 and 3 liters.

Table 1. Characterization of the reference flows of the different types of packaging (Flow 1 of packages included in DRS and Flow 2 of packages excluded from DRS).

		Tn	Units
Flow 1 (included in DRS)	Briks	26,031	1,646,836,464
	Metals	166,005	7,270,461,217
	Plastics	138,782	5,214,729,075
	Glass	1,092,656	3,670,766,604
	TOTAL	1,423,474	17,802,793,360
Flow 2 (excluded from DRS)	Briks	107,352	
	Metals	164,556	
	Plastics	530,710	
	Glass	274,629	
	TOTAL	1,077,247	
Flow 1 + 2	Briks	133,383	
	Metals	330,561	
	Plastics	669,492	
	Glass	1,367,285	
	TOTAL	2,500,721	

2.3. System boundaries

This study contemplates the full life cycle of the waste management system after the implementation of the new system (Figure 1) compared to the current EPRS (Figure 2), considering all stages of the packaging waste management from the moment when they are deposited in the container until their materials are recycled, incinerated or deposited in a controlled landfill. This includes the stages of collection and transport, the transfer plants or logistic centers, the packaging selection plants, the glass treatment plants, the treatment plants of the rest fraction, the recycling plants of the different materials, the installations for energetic valorization (incinerators) and the landfills (Figure 1). Intermediate transport is also included among all these facilities.

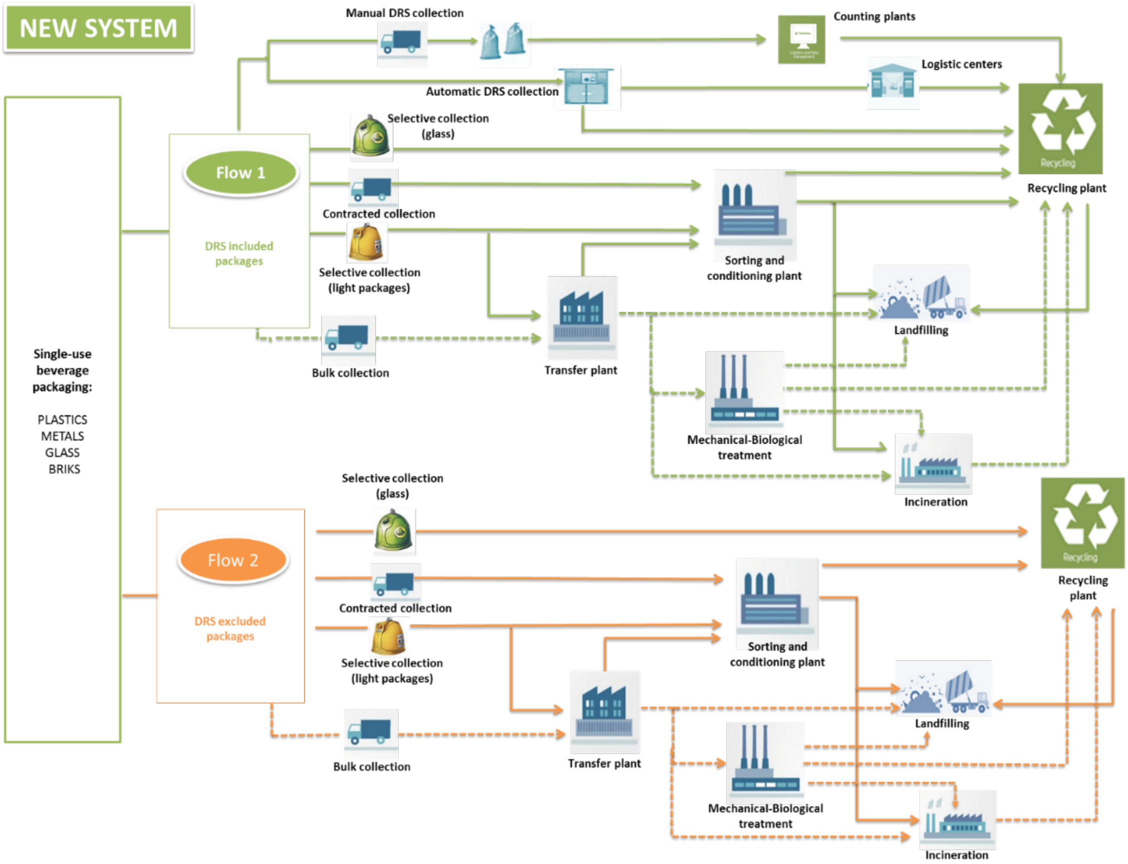

Figure 1. System boundaries overview of the new system.

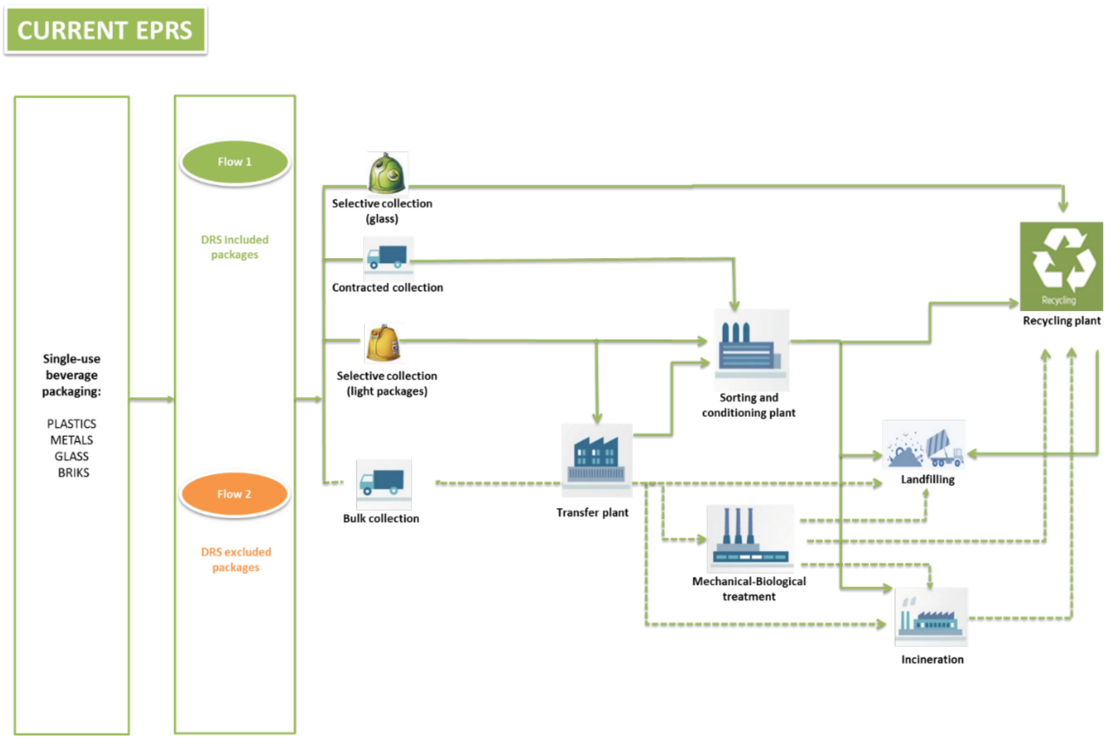

Figure 2. System boundaries overview of the current EPRS.

Additional tasks taken into account are: the manufacture, cleaning and maintenance, as well as the transport to the recycler of the selective and mass collection containers used; the production of specific packaging return machines, taking into account the materials used and their production processes, their management as waste and their energy consumption during the use stage; the production of cardboard boxes and HDPE bags for manual and automatic collection of light packages through automatic DRS, as well as HDPE bags and plastic boxes for manual collection of light packages and glass; the manufacturing processes of alternative sources of the materials that are recovered (aluminum, steel, glass, HDPE, PET and brik), as well as the electrical energy recovered in the energy recovery plants; and the environmental impact of the collection and transport of the improper materials in the selective collection containers for light packages and glass.

Nevertheless, other tasks that remain outside the limits of the proposed system include: the transport of the packaging waste from the homes to the collection containers; the construction, demolition and waste management of the treatment facilities; the manufacture of the machinery used in the treatment facilities and the employed trucks; the construction, demolition and waste management of the facilities used by the transport company for fleet storage; the emissions, consumptions or energy expenses that could be derived from the offices necessary for the administrative management; the emissions, consumptions or energy expenses derived from the means of transport used by workers for commuting; the biological treatment in the corresponding plants. Besides, the environmental impact and credits associated with the treatment and recycling of selective and mass collection containers, or return machines, cardboard boxes, bags or plastic boxes used in the DRS were not considered, since the cut-off rule has been applied (Ekvall, 2000). However, a specific sensitivity analysis to check the effects of not having included them in the analysis was also performed.

2.4. Allocation

Some processes included in the packaging waste management cycle are simple, since all material and energy consumption, as well as the process emissions, are directly associated with the product (or flow) entering or leaving that process. However, in other processes, such as the recovery in packaging selection plants or the energy recovery, the system can treat more types of goods or products (co-products) than those of interest for this particular study. This can be clearly exemplified in the case of incineration. All waste streams collected in the mass container can reach an incinerator. However, for this study, the interest is focused on the assessment of the impact of managing light packages and glass materials (aluminum, steel, PET, HDPE, glass and brik are the only considered materials).

In this case, it becomes necessary to establish a method to allocate the energy and material consumption and the emissions and residues generated. A hierarchy to perform this impact allocation is defined by ISO 14044 (ISO, 2006a). Table 2 compiles the different allocation methods applied in this study. Therefore, most of the allocations were based on the mass amounts, but causality relationships derived from chemical compositions or energy contents by the corresponding mass and energy balances have been also considered.

Table 2. Allocation methods used in the different waste treatment stages.

<table>
<tr><th>Stage</th><th>Process</th><th>Allocation method</th></tr>
<tr><td>DRS collection</td><td>Containers collection and transportation to the transfer or counting or sorting plant</td><td>Mass
(according to the average composition of the container)</td></tr>
<tr><td>Selective collection</td><td>Containers collection and transportation to the transfer or sorting plant</td><td>Mass
(according to the average composition of the container)</td></tr>
<tr><td>Sorting plants</td><td>Energy consumption</td><td>Mass</td></tr>
<tr><td rowspan="4">Incineration</td><td>Consumption of fuel and auxiliary materials</td><td>Mass</td></tr>
<tr><td>Emissions of carbon and heavy metals compounds, sulfur, HCL, HF compounds and dioxins and furans</td><td>Causality
(based on the carbon, chlorine, sulfur, fluorine, and heavy metal content of the corresponding material)</td></tr>
<tr><td>Emissions of nitrogen compounds (NO_x, N_2O and NH_3) and particles</td><td>Mass</td></tr>
<tr><td>Energy generation</td><td>Energy
(based on the low heating value of each material)</td></tr>
<tr><td rowspan="6">Landfill</td><td>Soil and diesel consumption and emissions linked to the disposal and compaction of the waste</td><td>Mass</td></tr>
<tr><td>Water and energy consumption along the waste degradation</td><td>Mass</td></tr>
<tr><td>Emissions to water and air, and inert along the waste degradation</td><td>Causality
(based on the chemical composition of the corresponding material)</td></tr>
<tr><td>Emissions to air due to gas treatment and biogas burning</td><td>Causality
(based on waste composition)</td></tr>
<tr><td>Emissions to water and air, and sludge generation due to leachate treatment</td><td>Causality
(based on waste composition)</td></tr>
<tr><td>Energy generation</td><td>Energy
(based on the low heating value of each material)</td></tr>
</table>

2.5. Life cycle impact categories

The LCIA phase has been performed by application of a mix of impact categories from different assessment methods following the recommendations provided by the Joint Research Centre of the European Commission (ILCD, 2011). Table 3 details the environmental methods and impact categories employed in this study. Sometimes, for the sake of practicality, simplifications may be performed in this life cycle phase (Bala et al., 2010; Baitz et al., 2013, Puig et al., 2013); however, as our case may have important repercussions for decision making, a complete set of categories has been studied.

Table 3. Impact categories and environmental assessment methods considered in the study.

Impact category	Measuring unit	Environmental method	Reference
Global warming potential (GWP)	kg CO_2 eq	100-year time horizon	IPCC, 2013
Ozone layer depletion potential (ODP)	kg R11 eq	ReCiPe midpoint	Van Zelm et al., 2008
Acidification potential (AP)	mol H^+ eq	Accumulated Exceedande	Seppälä et al. 2006; Posch et al. 2008
Eutrophication potential (EP)	mol N eq	Accumulated Exceedande	Seppälä et al. 2006; Posch et al. 2008
Abiotic Depletion Potential (ADP)	kg Sb eq.	CML 2002	Guinée et al. 2002
Photochemical oxidant creation potential (POCP)	kg C_2H_4 eq	Impact 2002+	Jolliet et al. 2003

These categories have been selected because they are based on the most recent scientific consensus. These characterization factors recommended by the ILCD guide are also being used in the pilot tests for the development of the environmental product footprints promoted by the European Commission. The only exception is the Photochemical Oxidant Creation Potential category, since the characterization factors developed by the Impact 2002+ method (Jolliet et al., 2003) were preferred. This choice was made according to technical reasons, since it can be considered a more suitable method for this study. This method is also included in the recommended methods of the ILCD and has enough scientific endorsement. Finally, the list of impact categories and the methodology followed was checked within the critical review.

2.6. Data

Different data sources have been used in this study. The data sets for the production of diesel, auxiliary materials used in the processes and production of electricity, and also truck models for the transport of waste (except for the collection stage with trucks waste collectors), have been obtained from the commercial database GaBi (GaBi, 2016). The LIFE + FENIX project database, which has been updated to 2016 within the ARIADNA project (Fullana-i-Palmer et al, 2017) but is not public, has been employed to obtain data for transfer processes, packaging sorting plants, mechanical-biological treatment plants, plants of glass treatment, recycling plants of the different materials (steel, aluminum, PET, HDPE, glass and brik) and incineration and discharge, also differentiated by type of material. The substitution factors of the recovered materials in relation to the virgin materials have been taken from the models and the methodological base developed in

FENIX. Besides, the transport model developed in the LIFE + FENIX project has been used to determine the environmental impact associated with the collection of containers and the waste collection trucks. The EPRS operators (Ecoembes and Ecovidrio) manage available public sources (duly audited) that provide the light packaging generation data in Spain and further information to determine the collection percentages through the different management channels. Relevant data have been provided by the members of the panel of interested parties who have participated in the study. The contacted 27 associations involved in different areas of this study have provided technical information on the aspects that are linked to their sector or activity. Some primary data on mass generation and collection of waste, as well as its treatment percentages for each of the routes (incineration, discharge or mechanical-biological treatment), have been extracted from official sources. The data concerning the DRS, both at the operation level and the estimation of the impact associated with the operation of the recovery machines, have been extracted from the information provided by the experts from companies that manufacture these types of equipment.

2.7. Limitations

The major limitation of this study is due to the lack of real data about a DRS to be implanted in Spain and the corresponding need to have information about it with the same degree of detail and knowledge as the management of the packaging by the EPRS. It is usual to find that, when the sustainability of different systems is compared, the best-known option, with more available data, has a greater impact just by the simple fact of this greater availability of information. Therefore, whenever there have been several plausible options, an attempt has been made to select those options that favor the implementation of the DRS (conservative hypotheses). Moreover, in the sensitivity analysis, the influence of less favorable options has been investigated. Although DRS has been implemented in other European countries, differences between Spain and these countries, such as the mix of packaging materials, the presence of reusable packages in the market, the distribution of commercial establishments, the habits of consumption and behavior, or the population dispersion, hinder the direct establishment of analogies. Moreover, the prediction of the real consequences and repercussions that the implementation of the DRS will produce on the packaging excluded from this system, which will continue to be managed through the EPRS, is not easy.

The proportion of points of sale of each size that will use manual or automatic collection in the DRS has been defined after several meetings with experts that represent the different types of commercial establishments. Since the DRS packaging recovery percentage is unknown, the value that the promoters of the DRS claim that can be achieved in Spain has been considered: 90%. Besides, the transition period from the implementation of the DRS until it is functioning at full capacity has been discarded.

About the technical repercussions of the implementation of the DRS and its coexistence with the EPRS, the decrease in the arrival of waste to the selection plants is assumed. In addition, the changes in its composition can affect the effectiveness of the selection plants for the different materials. Therefore, to have a clearer idea about this new framework, experts from these plants have been contacted. Moreover, the implementation of the DRS may affect the containerization of the EPRS as well as the collection frequency. In order to define the resulting scenario, experts from the public administrations in charge of the municipal waste management have been contacted.

2.8. Main assumptions and hypotheses

The amount of packaging waste generated in 2014 has been considered equivalent to the placing on the market in that same year, which corresponds to the packaging attached to EPRS operators in 2014. The introduction of the DRS means a decrease in the number of households that carry out selective waste collection by 3.7% in the case of light packages and 6.7% in the case of glass. These information was obtained from a specific survey performed to citizens during the project implementation. In all scenarios it is assumed that 1% of the materials that are not collected selectively become environmental littering. The effectiveness and quality of the materials recovered through the DRS and the selective collection in the private sector has been considered maximal (value 1) in both cases.

The percentage of municipal containers for bulky waste made of each material (HDPE, steel or fiberglass) has been taken equal to that of light packages, whose amount was known. The number of bulky containers has been estimated to be twice the minimum necessary calculated from the packaging waste that is generated, with a filling percentage of 100%.

Regarding the return machines, it is assumed that there exist return machines that can pick up HDPE and brik, and that their operation is similar to those currently managing PET: they compact the material and have the same capacity and technical characteristics. No rejection in this type of machines has been proposed. In the case of glass, the return machines are considered to have inside cardboard boxes that are replaced every time the machine is emptied. For the rest of the materials, the cardboard boxes of the machines are considered to be changed only 4 times a year and to contain inside a plastic bag, similar to that of manual collection, which is the one that is changed every time the machine is emptied. To ensure stocks, the calculated number of boxes required in commercial establishments for manual collection of glass subject to DRS has been increased 150%.

The implementation of the DRS has consequences on the separation efficiencies of the packaging selection plants that must manage the packaging material not subject to DRS, specifically in the cases of aluminum and PET.

The distance used for the transport of the recovered material through packaging selection plants, selective collection in the private sector, counting plants and packaging conditioning plants for the different types of materials have been considered equal in all cases. These correspond to the weighted average values of the current system (Bala et al., 2020). The distance from packaging selection plants and mechanical-biological treatment plants to landfill and incineration has been assumed to be 50 km.

3. System description and life cycle inventory

A detailed description of the Spanish current EPRS for the management of packaging waste and the corresponding modelling were provided in a previously published work (Bala et al., 2020). Therefore, this work includes only the detailed description of those stages that differ from the current system in the new one, as well as the specific stages associated with the introduction of a DRS. Within the system boundaries, the new system was divided into several stages, from the waste production at households to the last step of its treatment. For each of these stages, the corresponding data inventory was prepared to quantify the energy and material flows that enter and leave the systems. Resource consumption and emissions to water, soil and air were considered in the analysis.

According to ISO 14044 (ISO, 2006b), the LCI involves the compilation and quantification of inputs and outputs of the system under study throughout its life cycle. The LCI showed in Table 4 includes the material balances of all the stages of the new system, including their effectiveness values (Bala et al., 2020).

Table 4. Summary of the material balances (Tn) for the waste management.

	Briks	Metals	Plastics	Glass
Input	133,383	330,561	669,492	1,367,285
Selective collection	67,430	58,947	288,024	196,222
Bulk collection	42,206	121,921	254,277	186,254
SDR	23,427	149,404	124,904	983,390
Littering	319.80	288.53	2,286	1,418
SORTING				
Input	43,896	37,746	220,945	4,243
Output	35,318	34,115	168,022	1,146
Effectivity	**0.80**	**0.90**	**0.76**	**0.27**
Reject to incineration	1,372	581	8,468	496
Reject to landfilling	7,205	3,050	44,456	2,602
GLASS TREATMENT				
Input				1,188,113
Output				1,164,351
Effectivity				**0.98**
Reject to landfilling				23,762
MECHANICAL BIOLOGICAL (MB) TREATMENT				
Input	32,245	93,148	194,268	142,298
Output	18,369	82,125	73,393	11,598
Effectivity	**0.57**	**0.88**	**0.38**	**0.08**
Reject to incineration	2,498	1,984	21,758	13,070
Reject to landfilling	11,379	9,038	99,118	117,630
CONTRACTED COLLECTION				
Input	23,534	21,201	67,080	51,882
Output	23,534	21,201	67,080	51,882
Effectivity	**1.00**	**1.00**	**1.00**	**1.00**
Rejection	0	0	0	0
INCINERATION				
Inputs	**7,880**	**14,147**	**54,382**	**31,260**
Collected to incineration	4,010	11,582	24,156	17,694
Sorting rejection	1,372	581	8,468	496
MB treatment rejection	2,498	1,984	21,758	13,070
Outputs	**7,880**	**14,147**	**54,382**	**31,260**
Effectivity	**1.00**	**0.94**	**1.00**	**0.85**
Material recycling	0	13,280	0	26,687
Energy recovery	7,880	0	54,382	0
Rejection (unrecovered)	0	867	0	4,572
LANDFILLING				
Inputs	**24,535**	**30,146**	**179,426**	**151,066**
Collected to landfilling	5,951	17,191	35,853	26,262
Sorting rejection	7,205	3,050	44,456	2,602
MB treatment rejection	11,379	9,038	99,118	117,630
Incineration rejection	0	867	0	4,572
RECYCLING				
Input	100,649	300,126	433,398	1,214,800
Output	97,964	280,289	400,103	1,191,038
Rejection	2,684	19,837	33,295	23,762

3.1. Return of DRS packages (manual and automatic)

The DRS adapts its return structure to the fact that the packages are collected by the retailers, which can be included in two categories: shops and Horeca (Hotels, restaurants and catering) establishments. In summary, the total number of retailers involved in the DRS was 317,206: 62,323 shops (19.6%) and 254,883 Horeca establishments (80.4%). Once the information about the retailers was known and taking into account the Flow 1 of DRS packages, the mean number of packages that each establishment would manage was determined. This assessment resulted in a wide range of packaging quantities to be managed annually by the different establishments: from 17,316 units in a bar to 3,723,082 units in a hypermarket. Precisely, this great dispersion indicated the need to propose different collection systems to satisfy these different situations, which must consider the different frequency and contribution of packages by family units in each establishment.

In the case of establishments with manual return, their own staff is responsible for recognizing, accepting and managing the packaging returned by consumers. According to the operation in other countries, the light packages (plastic bottles, cans and briks) would be collected together in standardized transparent plastic bags made of low-density polyethylene (LDPE) (500 L capacity and 350 g of weight), distributed by the DRS manager. In the case of glass, due to the characteristics of the material (mainly its weight and fragility), bottles would be transported in rigid plastic boxes to ensure that they arrive intact to the counting plants. The total number of plastic bags and boxes needed for the functional unit is displayed in Table 5.

Table 5. Inventory of the consumable items (boxes and bags) needed for the correct operation of the manual and automatic return of packaging in the DRS.

Consumable items	Units required	Unitary weight (kg)	Total weight (tonnes)
Manual return			
LDPE bag	31,260,812	0.35	10,941
HDPE box	4,569,934	2.23	10,191
Automatic return			
Cardboard box (1 m^3)	492,556	7.20	3,546
Cardboard box (0.5 m^3)	4,854,844	3.50	16,992
LDPE bag	14,470,612	0.35	5,065

The DRS proposed in this study involves the collection of 6 different fractions or materials (steel, aluminum, PET, HDPE, brik and glass). A single machine that collects the 6 fractions is not feasible, since there are no machines in the market capable of managing this situation properly. A different machine for each fraction would imply that each establishment should have a minimum of 6 machines, a possibility not feasible for most of them. Therefore, the solution proposed in this study is intermediate: 3 different machines should be installed in each establishment for the selective return of metals (steel and aluminum), plastics (PET, HDPE and brik) and glass.

The different distribution channels are very heterogeneous and implies choosing machines with great management capacity for larger establishments and other machines with medium and smaller capacity for the rest of establishments. As a result, the total number of machines required and their most relevant characteristics are displayed in Table 6, while the information about the consumable items (cardboard boxes and plastic bags) needed for the correct operation of the machines are included in Table 5.

Table 6. Total number of machines required for automatic return of packaging and their most relevant characteristics.

Machine model	Units required	Weight (kg)	Power in use (W)	Power at rest (W)
Multipack cabinet (1 backroom)	553	644	1370	170
Multipack cabinet (2 backrooms)	90	994	2170	220
Multipack cabinet (3 backrooms)	733	1344	2970	270
Dual cabinet	23,813	390	1600	50
Single cabinet	13,562	370	500	50

The necessary information required to assess the environmental impact of the machine models used in the study is not available. Therefore, this environmental impact has been estimated using the Input-Output FORWAST database and the corresponding inventory of the environmental impact associated with the production of 1 kg of machinery in Europe derived from it (FORWAST, 2010). From the machine power values and considering the hours of use per establishment of (10 hours per day and 313 days per year) and the mean percentages in use and at rest of the machines (18.23% and 81.77% respectively), the annual electricity consumption of the machines was determined, resulting 32,788 MWh. The environmental impact of this electricity was calculated using the mix of electricity production for Spain from the GaBi database (GaBi, 2016). The environmental impacts of cardboard boxes, HDPE boxes and LDPE have been estimated using the GaBi database (GaBi, 2016). Additional information about the return of DRS packages in Section S1 in the Supplementary Material (SM).

3.2. Containerisation

The introduction of the new DRS would not imply a reduction in the number of containers installed in the municipalities of Spain, since containerization is offered as a service to citizens not directly linked to the contribution of packages. Thus, the number of containers remained the same as previously described for the current EPRS (Bala et al., 2020), although some collection frequencies were modified (the collection frequency of containers for glass was reduced 50%). The total number of containers of each type considered in this study is displayed in Table 7. Other alternative collection systems that are used in Spain, like door-to-door or mobile pneumatic systems (Laso et al., 2019), have not been taken into account in this study because of their minority presence. Additional information about the characteristics of the containers in Section S1 in the SM.

Table 7. Number of containers of each type considered for the management of DRS excluded packaging.

	Number of containers		
	HDPE	Steel	Fiberglass
Selective collection	228,791	107,246	210,531
Bulk collection	17,495	8,747	17,495

3.3. Collection and transportation

The packaging included in the DRS and manually collected in point of sales is considered to be transported without compacting to the counting center, while those collected through return machines are compacted before the transport to the separation and conditioning plant. While for the transport of manually collected light packages 3.5 t trucks has been selected, 5 t trucks have been considered in the case of manual glass collection. Besides, due to the differences in the management of light packages and glass by the establishments (storage and acceptance system) and subsequent destination of the fractions, two differentiated and independent transport subsystems were proposed.

For the transport from establishments with automatic collection, different trucks have been considered. Table 8 shows the amounts of DRS packaging collected by manual and automatic return, the type of truck, and the distances and average load percentages resulting from the model developed. The model of a conventional truck for freight transportation from GaBi 2016 database was adapted to the garbage truck characteristics (GaBi, 2016).

Table 8. Amounts of DRS packaging collected by automatic and manual and return, the type of trucks used for the collection, and the distances and average load percentages.

Return model	Truck type	Light packages subsystem			Glass subsystem		
		Waste amount (t)	Distance (km)	Load (%)	Waste amount (t)	Distance (km)	Load (%)
CA	9.3t truck	3,110	107	5.1	10,328	92	12.2
CB[1]	9.3t truck	15,290	59	4.3	44,503	60	11.6
CB[2]	22.0t truck		15	10.0		15	37.0
CC	5.0t truck	48,970	111	6.9	140,298	140	22.7
CD	5.0t truck	83,910	124	6.4	243,020	136	21.6
Manual	3.5t truck	146,455	143	1.4			
	5.0t truck				545,241	93	8.6

CA: high capacity machines and external collection; CB[1]: transport from the supermarket to the logistic center; CB[2]: transport from the logistic center to the sorting and conditioning plant; CC: automatic acceptance with grouping (storage in establishment) and external collection; CD: automatic acceptance without grouping (no storage in establishment) and external collection.

As stated before, the introduction of the DRS requires the co-existence of a reduced EPRS to collect and recover the packaging not covered by the DRS. This considers 3 collection sources: the municipal selective collection and the bulk collection, both through specific street containers, and the direct packaging waste collection by means of contracts with big producers such as hospitals or stadiums. For selective and bulk collection, this stage includes both the collection of waste and its transportation to the transfer plants. However, in the case of the contracted waste collection, waste is directly addressed to sorting and conditioning plants. The amounts of light packages and glass collected selectively, by contract and in bulk are presented in Table 9, including information about the distances and percentages of load as well. For selective collection, the improper wastes were considered to calculate the impact associated with this collection stage: the percentage of improper waste for light packages was 29.83% and 2% for glass (Fullana-i-Palmer, 2017).

Table 9. Amounts of light packages and glass collected selectively, by contract and in bulk, the type of trucks used for the collection, and the distances and average load percentages.

Return model	Truck type	Waste amount (t)	Distance (km)	Load (%)
Selective collection (light packages)	9.3t truck	431,199	123	10
Selective collection (glass)	9.3t truck	181,793	169	29
Contracted collection (light packages)	9.3t truck	111,815	100	85
Contracted collection (glass)	9.3t truck	51,882	100	85
Bulk collection	5.0t truck	604,658	93	49

3.4. Counting of manually returned DRS packages

The bags with light packages and the boxes with glass bottles from the manual DRS return are transported to a counting plant, were they are emptied and the packages are counted, in order to make the payment to the establishments for the deposit, and classify the materials to be delivered to the corresponding recycler or manager. Additional information about the counting plants in Section S1 in the SM.

The environmental impact associated with the counting plants of the DRS packages manually returned has been calculated from the quantity and power of the equipment necessary for the process, as well as the operating characteristics of the plant. Three counting machines in each counting plant have been assumed, with the corresponding auxiliary equipment as detailed in Table 10. For the assessment of the operating hours, 2 work shifts of 7 hours each have been considered during 351 days per year. The count speed of the machine was 200 packages / minute. Conservatively, the effect of the unavailability of lines due to unforeseen events or the loss of possible time between the counting of the packages in consecutive bags has not been taken into account.

Considering the data in Table 10, the number of operation hours (4,914 h) and applying a yield of 75% of the equipment, the unitary energy consumption resulted 29.3 kWh/t, which implies a total consumption of 20,267 MWh/year. The environmental impact of this electricity has been calculated using the electricity production mix for Spain from the GaBi database (GaBi, 2016).

Table 10. Total number of counting machines and auxiliary equipment required in counting plants and their most relevant characteristics.

Equipment	Units installed	Unitary power (kW)	Total power (kW)
Counting machine	3	2.2	6.6

Conveyor belt	-	-	26.0
Platform scale	1	1.5	1.5
Silo	5	2.0	10.0
Bottle compacter	1	2.0	2.0
Press (plastic)	1	36	36.0
Press (metal)	1	18	18.0
Magnetic separator	1	5.5	5.5
Induction separator	1	7	7.0

3.5. Transfer, sorting and conditioning

The environmental impacts associated with the different types of transfer plants followed a model previously developed to represent the current EPRS (Bala et al., 2020). The average transport distances (65 km and 157 km for transport of light packages and glass respectively) and the percentages of waste that pass through each type of transfer plant (Table 11) remained the same as those considered in the current EPRS.

Table 11. Percentages of waste packaging that pass through each type of transfer plant.

	Selective light packaging collection	Selective glass collection	Bulk collection
No transfer plant	79	47	-
Transfer plant with compaction	21	-	100
Transfer plant without compaction	-	53	-

The packages from the automatic return are transported to sorting and conditioning plants to proceed to the separation of those fractions that are collected together (PET and HDPE fractions and steel and aluminum fractions) or without the sufficient degree of compaction to be sent directly to the recycler. Taking into account that the material entering these plants comes from automatic return (the machines only accept packages that belong to the system and properly labeled), this material was assumed clean and free of improprieties. For this reason, the effectiveness of these plants was considered 1 and, therefore, the existence of possible rejections was not considered.

The environmental impact associated with the conditioning of the DRS packages automatically returned was estimated from the consumption data of automatic selection plants provided by Instituto Andaluz de Tecnología within the framework of the FENIX project (IAT 2012). Additional information about the sorting plants in Section S1 in the SM.

The inventories used to calculate the environmental impact associated with the non-DRS packages sorting process were the same as those used in the analysis of the current EPRS (Bala et al., 2020). The only difference refers to the effectiveness values considered. Based on the information provided by the Spanish association of light packaging sorting plants, it was considered that the introduction of the new DRS would have consequences on the recovery effectiveness of PET and aluminum in the sorting plants (this affectation was estimated 0.5% for PET and 10% for aluminum). In Table 12, a summary table is presented with the inputs, outputs, the average effectiveness applied and the rejection quantities that are going to be landfilled or incinerated for each of the materials under study.

Table 12. Inputs, outputs, average effectiveness and rejection quantities (Tn) that are going to be landfilled or incinerated for each of the materials in sorting plants.

Fraction	Input	Output	Effectiveness	Rejection (landfill)	Rejection (incineration)
Brik	43,896	35,318	0.80	1,372	7,205
Steel	34,404	32,154	0.93	360	1,890
Aluminum	3,342	1,961	0.59	221	1,160
HDPE	36,957	32,079	0.87	781	4,098
PET	29,029	24,265	0.84	762	4,001
Film	97,727	70,138	0.72	4,414	23,174
Plastic mix	57,232	41,539	0.73	2,511	13,182
Glass	4,243	1,146	0.27	496	2,602

3.6. Preparation for recycling

The inventories used to calculate the environmental impact associated with this treatment of glass were developed by Universidad San Jorge (USJ, 2012). The effectiveness of glass recovery was 0.98 and the 100% of the rejected fraction was assumed to be landfilled (Ecovidrio, 2014). Table 13 presents the inputs and outputs of this process, for both the glass recovered by DRS and the rest of glass, which includes the glass recovered through the selective collection of glass and the recovered through mechanical-biological plants, packaging sorting installations and selective collection in the private sector. This study considered that all the glass collected passed through this preparation process, in some cases in specialized treatment plants and the rest of cases in the glass manufacturer installations, but the corresponding environmental impacts were considered equivalent.

Table 13. Inputs and outputs (Tn) of glass preparation for recycling.

Fraction	Input	Output	Effectiveness	Rejection (landfill)
Glass (DRS)	983,390	963,722	0.98	19,668
Glass (rest)	204,723	200,628	0.98	4,094

A conventional truck for freight transportation from GaBi database was used to model the transport of the glass fractions to the landfill and to the recycling plant, considering 50 km and 56 km distances, respectively, and 85% load (GaBi, 2016).

The environmental impacts of mechanical-biological treatment plants were modelled using the inventories developed by Escola d'Enginyeria d'Igualada at UPC (EUETTI-UPC, 2012), which are based on data from EPRS managers and survey data and were updated with GaBi database

(GaBi, 2016). The inventories are specific for each type of material. The effectiveness values used are not empirical, but the theoretical ones that meet the material balance. Similar reductions in the effectiveness of PET and aluminum recovery to those applied in the sorting plants by the implementation of the DRS were applied. The percentual destinations of the rejection of these plants that were applied ranged from 82% of the rejected light-packages that were sent to landfill (the remaining was incinerated) to 90% of the rejected glass that was sent to landfill (again the remaining was incinerated). The summary of the mass balances of these plants is shown in Table 14.

Table 14. Inputs, outputs, average effectiveness and rejection quantities (Tn) that are going to be landfilled or incinerated for each of the materials in mechanical-biological treatment plants.

Fraction	Input	Output	Effectiveness	Rejection (landfill)	Rejection (incineration)
Brik	32,245	18,369	0.57	11,379	2,498
Steel	80,533	80,048	0.99	398	87
Aluminum	12,614	2,077	0.16	8,641	1,897
HDPE	40,522	31,298	0.77	7,563	1,660
PET	71,617	42,094	0.59	24,208	5,314
Film	24,321	0	0.00	19,944	4,378
Plastic mix	57,808	0	0.00	47,403	10,405
Glass	142,298	11,598	0.08	117,630	13,070

The same truck model as in the case of glass was used to model the transport of the rejected fractions to final destination (landfill or recycling), considering 50 km distance and 85% load. Regarding the transport of the recovered material to the pre-treatment, treatment and/or recycling plants, the distances assumed are compiled in Section S1 (Table S1) in the SM.

To estimate the environmental impacts of the preparation of the packaging waste managed directly from high generators (such as football stadiums or music festivals), the model of a manual packaging sorting plant was used (IAT, 2012). Assuming that losses were not generated, effectiveness values equal to unity were considered for every material. The transport of the recovered materials to the treatment and recycling plants was modelled using the distances compiled in Section S1 (Table S2) in the SM and the same truck model as in the case of glass with 85% load. Additional information about mechanical-biological treatment plants in Section S1 in the SM.

3.7. Recycling processes

The assessment of the environmental impacts of the recycling stage is based on different inventories. For plastics and metals, the inventories were built up using survey data from a 24% sample of the companies associated to Ecoembes and Sociedade Ponto Verde, the Green Dot Holders of Spain and Portugal, respectively. The inventories include the consumption of energy, auxiliary materials and water; and the generation of rejected fractions and wastewater. In addition, the transport of the rejected fractions to the landfill was considered, assuming a 50 km average distance. The inventories of plastics recycling were developed by Instituto Tecnológico del Plástico (AIMPLAS, 2012) and are specific for PET, HDPE, film and plastic mix. On the other hand, the inventories for metals recycling were developed by Instituto Tecnológico Metalmecánico (AIMME, 2012) and describe the metal smelting by means of the technologies previously described until obtaining aluminum or steel ingots. The model considers that 30% of the metal goes through recovery installations, 30% is sent to recovery and fragmented installations and the rest goes to recovery and metal separation facilities (detinning in case of steel). For glass, information provided by Universidad San Jorge (USJ, 2012) was used. The corresponding inventory was derived from data provided by 11 companies and complemented with the glass treatment process of Ecoinvent (Hischier, 2007). The inputs of auxiliary materials were sourced from companies, while electricity and lubricating oils consumption were estimated from average data between the companies and Ecoinvent. Finally, a specific inventory for brik was developed by Instituto Tecnológico del Mueble, Madera, Embalaje y Afines (AIDIMA, 2012). This inventory considered the recovery of 75% of the cardboard contained in these packages.

The material recovered through the recycling processes displaces the consumption mix of virgin / recycled material from the market. Regarding the percentages of displaced virgin material, a replacement quality factor of 1 was assumed for metals and glass, 0.91 for PET, 0.79 for HDPE, 0.59 for film and 0.48 for plastic mix (Bala et al., 2015). Additional information about the different recycling processes in Section S1 in the SM.

3.8. Incineration

To assess the environmental impacts related to energy valorization, the inventories developed by Universidad de Cantabria (UC, 2012) were used and updated with GaBi database (GaBi, 2016). Data from the Spanish association of energetic valorization (AEVERSU), characterization inputs provided by Ecoembes, and information available in Integrated Environmental Authorizations were used. The inventories were specific for each type of packaging material and further information can be consulted (Margallo et al., 2014). The electricity recovered by the incineration was considered to displace the mix of electricity production in Spain.

3.9. Landfilling

The inventories developed by Universidade de Santiago de Compostela (USC, 2012) and updated with GaBi database were used to estimate the environmental impacts of packaging landfilling (GaBi, 2016). Inventories are based on experimental values and survey data of different landfill sites, complemented with bibliographic data. They are specific for the different packaging materials and adapted to the Spanish climatic and technical conditions. Further information can be consulted (Camba et al., 2014).

4. Results and discussion

4.1. Life cycle impact assessment

The global results that compare the environmental performance of the current EPRS and the new system are presented in Table 15. As observed, the overall results are negative for all cases, which means that the savings associated with the recovery of materials and energy of the systems are greater than the environmental impacts associated with waste collection and management operations. Therefore, the implementation of both collection and recovery systems of analyzed packages can be considered beneficial for the environment.

Table 15. Absolute environmental impacts (emissions and savings) in the two systems considered.

Impact category	Measuring unit	EPRS			DRS		
		Emissions	Savings	Total	Emissions	Savings	Total
GWP	kg CO_2 eq	1,072,084,939	-1,750,461,092	**-678,376,152**	1,582,282,122	-2,129,021,124	**-546,739,002**
ODP	kg R11 eq	49	-57	**-8**	68	-74	**-6**
AP	mol H^+ eq	2,772,494	-5,526,411	**-2,753,917**	4,875,055	-6,765,241	**-1,890,186**
EP	mol N eq	8,145,188	-13,152,212	**-5,007,023**	14,375,824	-16,171,756	**-1,795,932**
ADP	kg Sb eq.	3,680	-23,566	**-19,886**	5,852	-27,758	**-21,906**
POCP	kg C_2H_4 eq	169,687	-566,909	**-397,223**	291,685	-660,412	**-368,726**

The total environmental impacts of both systems were relativized to offer a more easily comparable outlook to the results obtained, taking as baseline the current EPRS. For all impact categories except ADP, the results associated with the EPRS were better than those of the new system, since they have higher negative value (Figure 3). Considering the inherent uncertainty of data, the impact differences between both systems greater than 30% can be considered significant, while those greater than 10% should be considered indicative and those less than 10% insignificant. Under these conditions, the implementation of DRS would cause an indicative improvement in ADP but would suppose significant worsening in EP and AP and indicative worsening in GWP and ODP.

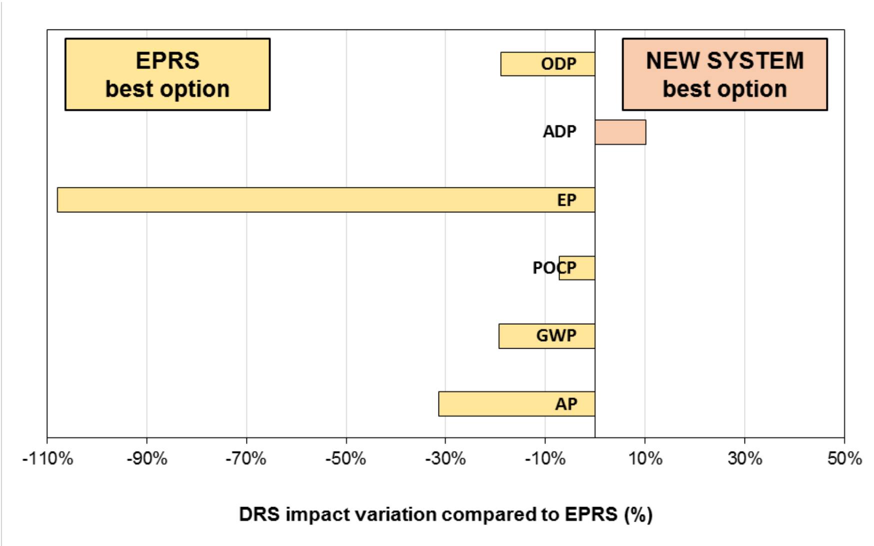

Figure 3. Relative results for the comparison of the impacts of both systems.

The relative breakdown of the corresponding environmental emissions and savings for both systems is graphed in Figure 4. As observed, the credits associated with the new system were always higher than those of the current EPRS. This is due to the implementation of DRS with a theoretical return rate value of 90%, which implied an increase in the packaging recovery (passing from 69.38% packages recovered in the current EPRS to 81.94% in the new system). However, this higher recovery rate was also related to a higher environmental impact associated with the processes required in the waste collection and management stages. This increase in emissions is above the corresponding increase in credits for all categories except ADP, where the higher emissions were compensated with even higher credits.

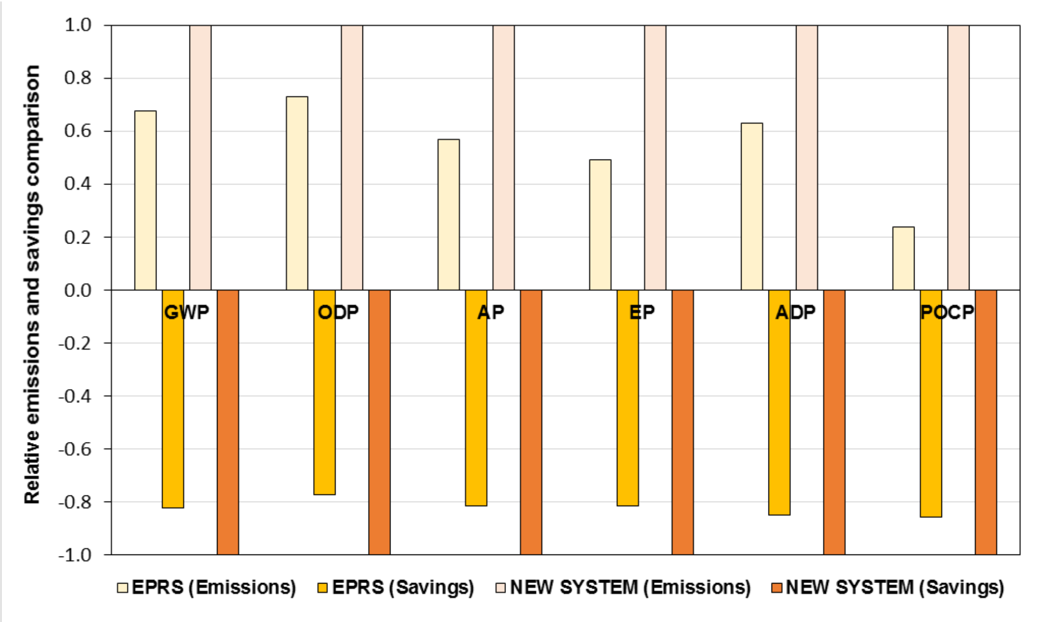

Figure 4. Relative emissions and savings of both systems.

The broken-down environmental results of the two systems separated by flows are shown in Table 16. It should be remembered that, for the current EPRS, the two flows are managed through EPRS, while in the new system, Flow 2 is still treated through EPRS, but part of Flow 1 (90%) is managed through DRS and the rest (10%) through EPRS. When focusing on the new system, the impact of collecting packaging subject to DRS (Flow 1) was much higher than that of Flow 2. This is mainly due to the collection stage, since its impact ranged from 2.8 times greater in the case of GWP to 19.8 times greater in the case of POCP. Moreover, just the impact of Flow 1 in the new system was higher than the total impact of the current EPRS. The most extreme categories are POCP, with 64% higher impact, and AP, with 44% higher impact. In fact, two categories (ODP and EP) resulted in positive balance between emissions and savings, which means that the management of the Flow 1 by the new system had negative impact on the environment, since the emissions attributed were higher than the corresponding savings.

Table 16. Break-up of the environmental impacts (emissions and savings) attributable to Flows 1 and 2 in the two systems considered.

Impact category	Measuring unit	Flow 1			Flow 2			System
		Emissions	Savings	Balance	Emissions	Savings	Balance	
GWP	kg CO_2 eq	573,468,090	-937,447,910	**-363,979,820**	498,616,849	-813,013,181	**-314,396,332**	EPRS
ODP	kg R11 eq	39	-39	**0**	10	-18	**-8**	
AP	mol H^+ eq	1,655,465	-2,962,882	**-1,307,417**	1,117,029	-2,563,529	**-1,446,500**	
EP	mol N eq	4,405,671	-7,381,071	**-2,975,400**	3,739,517	-5,771,140	**-2,031,623**	
ADP	kg Sb eq.	2,141	-11,293	**-9,152**	1,539	-12,273	**-10,734**	
POCP	kg C_2H_4 eq	87,405	-244,402	**-156,997**	82,282	-322,507	**-240,226**	
GWP	kg CO_2 eq	1,169,305,625	-1,366,591,266	**-197,285,641**	412,976,497	-762,429,858	**-349,453,361**	DRS
ODP	kg R11 eq	61	-58	**3**	6	-16	**-9**	
AP	mol H^+ eq	3,993,429	-4,326,852	**-333,423**	881,627	-2,438,390	**-1,556,763**	
EP	mol N eq	11,082,786	-10,741,333	**341,452**	3,293,038	-5,430,423	**-2,137,385**	
ADP	kg Sb eq.	4,724	-15,527	**-10,802**	1,128	-12,232	**-11,104**	
POCP	kg C_2H_4 eq	277,647	-359,923	**-82,276**	14,039	-300,488	**-286,450**	

The contribution of the different stages (grouped as equipment, collection and transport, sorting, recycling and incineration/landfilling) to the different impact categories for both systems is compared in Figure 5. In the case of the new system, the stage with the highest environmental impact in all categories (between 42.9% and 96.9%), with the exception of EP (32.3%), was the recycling of materials. The collection and transport stage was the one that contributes most to EP (59.1%), and the second one to AP (39.3%) and GWP (21.5%). The equipment needed for the DRS was the second contribution to POCP, and the third in contribution in the rest of the impact category (between 2.5% and 6.8%). The stage with the lowest contribution in all cases was sorting (in the range between 0.2% and 1.4%).

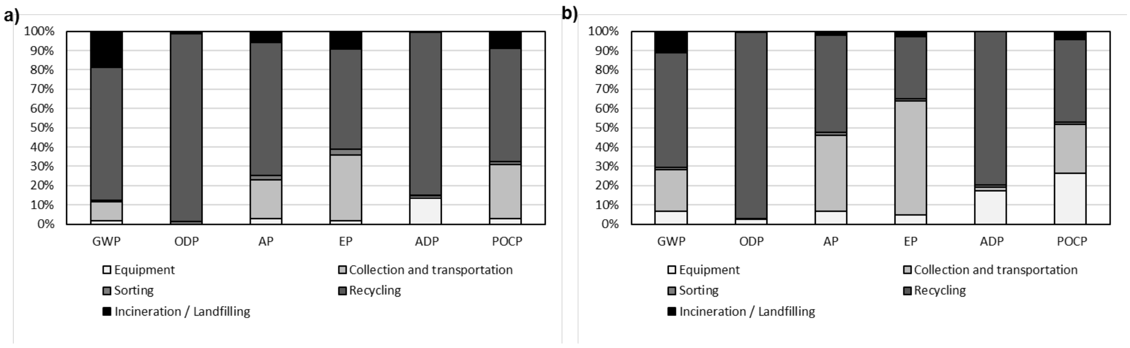

Figure 5. Contribution of the different stages to the impact categories for both systems: a) EPRS and b) DRS.

When the stages of both systems are compared, the new system had higher percentual contributions in most cases. The equipment stage was the one that offers the greatest increase in environmental impact. This is due to the important number of machines required for automatic return or boxes and bags necessary for manual return, which can be avoided in the EPRS. The impact of the collection and transport phase was increased 2-3 times in the case of DRS, as a consequence of the transport of uncompacted packages, which implied a lower use of the truck's load (and the consequent increase in the number of trips and the corresponding diesel consumption). While the sorting processes offered alternative results depending on the impact category, the recycling stage presented impacts between 25% and 50% higher for DRS. This increase is due to the higher material amount managed by the recyclers in DRS. On the contrary, the incineration and landfilling stage had lower impacts than the current EPRS, with improvements between 12% and 44%, since higher material recovery in the new system implies lower amount of packaging waste ending in incineration installations or landfills. Regarding credits, as observed in Table 17, the ones obtained by the generation of energy are slightly lower for the new system, since less material were targeted to incineration. However, the credits obtained by the generation of secondary material increased slightly, since the recycling rate is higher for this system.

Table 17. Break-up of the environmental credits attributable to energy and materials in the two systems considered.

Impact category	Energy credits EPRS	Materials credits EPRS	Energy credits DRS	Materials credits DRS
GWP	3.2	96.8	2.3	97.7
ODP	0.0	100.0	0.0	100.0
AP	3.3	96.7	2.4	97.6
EP	3.3	96.7	2.4	97.6
ADP	0.8	99.2	0.6	99.4
POCP	1.2	98.8	0.9	99.1

4.2. Sensitivity analysis

A sensitivity analysis was performed to evaluate the influence of the variables that, a priori, were supposed to have the greatest influence on the results. The objective of this phase is to determine the robustness of the results in order to identify different possible values of these main variables that can modify the trend derived from the results obtained (Guo and Murphy, 2012). These variables were parameterized in the model and new values for the calculation of new scenarios were proposed. The parameters varied are shown in Table 18, which displays the values of the base and modified scenarios.

Table 18. Parameters and alternative scenarios evaluated in the selectivity analysis.

Code	Parameter	Baseline value	Modified value
P1a	Counting machines per plant	3	2
P1b	Counting machines per plant	3	6
P2	Methodological approach for equipment	Cut-off	Expanded
P3	Rebound effect on the behavior of citizens	Considered	No considered

In all cases, Equation 1 was used to determine the improvement or not in the environmental impact of the systems due to each parameter:

$$\Delta IA = 100\frac{IA_M - IA_B}{IA_B} \qquad (1)$$

where ΔIA is the environmental impact variation, IA_M the environmental impact with the modified parameter and IA_B the environmental impact of the baseline scenario. Therefore, a positive value implies that the option analyzed is worse than the baseline scenario, while a negative value means that the modified option has less environmental impact than the baseline scenario. The results obtained from the sensitivity analysis of the four new scenarios were compared with the baseline scenarios for both the new system and the current EPRS, as graphed in Figure 6. The analysis revealed that none of the new alternative scenarios improved the environmental performance of the current EPRS. In fact, one of these new scenarios (P1b), characterized by a higher number of counting machines per plant, implied a less environmentally-friendly situation that the baseline new system.

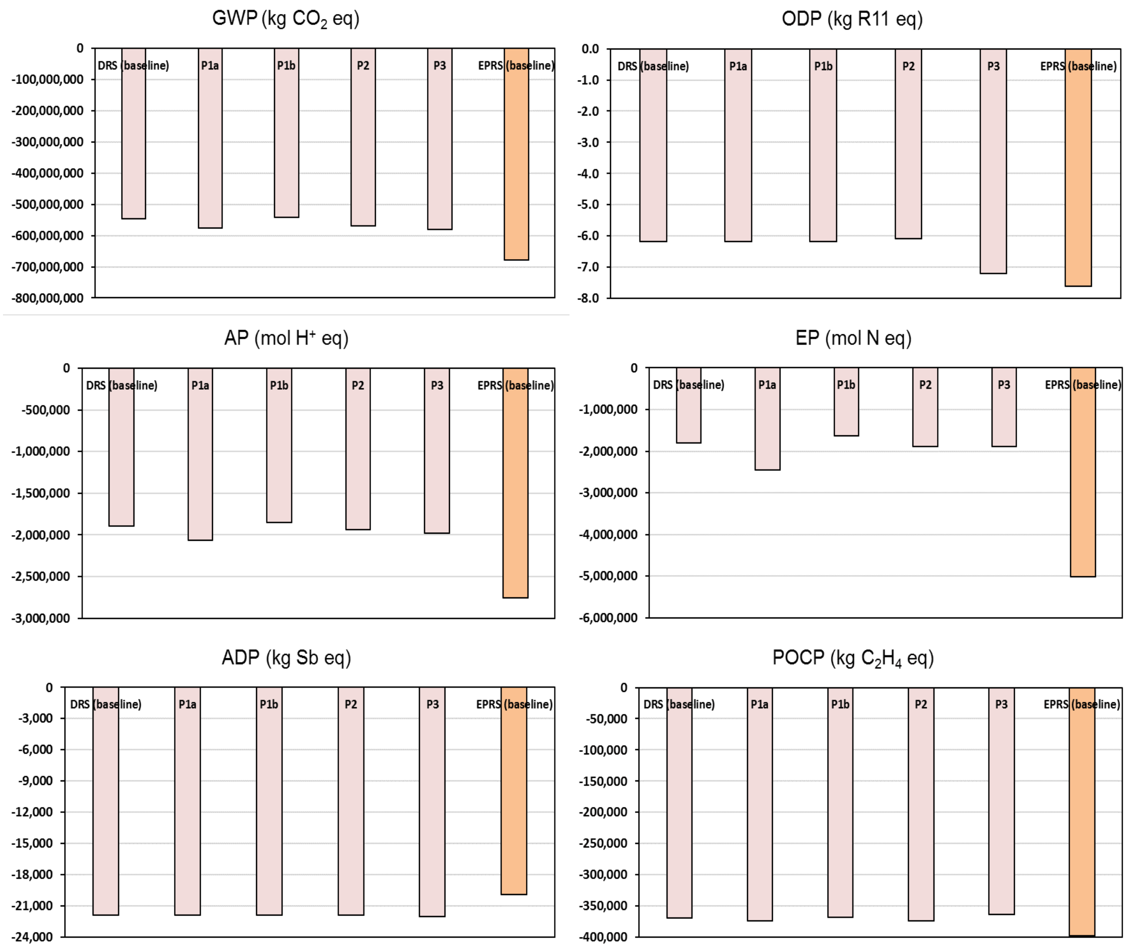

Figure 6. Sensitivity analysis results.

Since the distribution in the territory of the counting plants, and consequently, their distances from the manual collection of DRS packaging points, was uncertain, the baseline value considered in the study (3 counting machines per plant) was modified using alternative values found in other previously published studies. In particular, the selected values were 2 counting machines per plant (Sismega, 2011) and 6 machines per plant (Eunomia, 2012). The total number of required counting plants varied as a consequence of these new machine distributions, and this modification had an impact both on distances for the collection and transport model and on the energy consumption associated with these facilities. The corresponding transport and energy data calculated for the modified scenarios are compiled in Sections S2 (Table S3) in SM. The results of the variation of the number of counting machines per plant are compiled in Table 19.

Table 19. Percentage variation of the environmental impact of each sensitivity analysis to the different impact categories according to Equation 1.

Impact category	P1a (2 counting machines)		P1b (6 counting machines)		P2 (Methodological approach)		P3 (Rebound effect)	
	ΔIA (EPRS Baseline)	ΔIA (DRS Baseline)	ΔIA (EPRS Baseline)	ΔIA (DRS Baseline)	ΔIA (EPRS Baseline)	ΔIA (DRS Baseline)	ΔIA (EPRS Baseline)	ΔIA (DRS Baseline)
GWP	15.1	-5.3	20.2	1.0	16.2	-4.0	14.5	-6.0
ODP	18.9	0.0	18.8	0.0	20.0	1.4	5.4	-16.6
AP	25.1	-9.2	32.8	2.0	29.6	-2.5	28.2	-4.7
EP	50.9	-37.0	67.3	8.7	62.4	-4.9	62.4	-4.8
ADP	-10.1	0.0	-10.2	0.0	-10.1	0.0	-10.7	-0.5
POCP	6.0	-1.3	7.4	0.3	5.8	-1.5	8.6	1.5

The decrease to 2 counting machines per plant (Scenario P1a) had an environmental improvement when compared to baseline new system for all categories, with the exception of ODP and ADP (where there were not practical effects), that ranges between -1.3% for POCP and -37.0% for EP. However, increasing to 6 counting machines per plant (Scenario P1b) implied a worsening of the environmental impact, between 0.3% for the POCP and 8.7% for the EP, while once again there were not practical effects on ODP and ADP. These effects in both directions were directly related to the distance traveled between the collection points and the counting plants. Increasing the number of plants from 45 to 64 in Scenario 1a and the corresponding shorter travel distance (25.3 km) than the one considered in the baseline scenario (32.6 km) had environmental benefits on those impacts related to emission of combustion gases. On the contrary, a reduced network of plants (23) with greater travel distance (43.0 km) had a much higher impact, which was not compensated by the efficiency improvement in larger plants. Regarding comparison to the current EPRS, the variation of the number of counting machines per plant did not significantly modified the preference of this system because of its lower environmental impacts.

As explained in the definition of the boundaries of the system under study, the environmental impact and credits associated with the treatment and recycling of selective and mass collection containers, return machines, boxes cardboard, bags or plastic boxes used in the DRS were not included in the study, as the "cut-off" method was applied (Ekvall, 2000). This method assumes that the environmental impact associated with the recovery processes of the materials obtained by the management as waste of these goods should be attributed to the manufacturing stage of the products that are going to be manufactured with the recycled materials that are obtained. The application of this method to the containers had no effect on the results, since both the new system and the current one maintained equal number of containers. However, the materials recovered from the bags used for the manual collection of the DRS, the cardboard and plastic boxes, as well as the machines, could have a significant effect, since these materials added new functions to the new system. For this reason, the sensitivity analysis studied this situation, expanding the system to include these materials. The environmental impact associated with obtaining these materials from alternative sources was discounted and the impact associated with the recycling process was added. Further information about the considerations of the new applied method and the data required to implement it can be consulted in Section S2 (TableS4) in SM. The total result of the analysis of the expanded system was a net credit (a negative value), which was discounted to the impact of the new system (Table 19).

The new methodological assumption considered in the sensitivity analysis resulted in environmental improvement when compared to the baseline new system for most categories, ranging the improvements between -1.5% (POCP) and -4.9% (EP). The exceptions were ADP, which appeared again insensitive to the parameter modification, and ODP, which displayed a slight impact worsening (1.4%). Once again, the variation of the methodology approach did not imply relevant changes in the comparison of the modified scenario to the baseline current EPRS.

This study, according to data from surveys carried out during the project, considered that the implementation of the DRS would produce a rebound effect on the behavior of citizens, which will cease to selectively separate and throw light packages and glass into the corresponding container. However, the sensitivity study has considered the possibility that this rebound effect does not exist. As you can see in Table 19, this methodological assumption had an environmental improvement respect to the baseline new system for all categories but POCP, ranging from 0.5% (ADP) to 16.6% (ODP). With respect to the current EPRS, the considered scenario was an improvement, but again it was not enough to change the preference for the current EPRS.

5. Conclusions

The environmental savings of the new system including a DRS are superior to its impacts, so it offers a positive environmental service. However, even if the DRS obtained a total development and reached a value of 90% for the package return index, the current EPRS obtains significantly better environmental results. All impact categories are favorable to the current EPRS, except ADP, where the potentially higher DRS recycling rate is manifested.

However, this higher recycling rate is based on less environmentally friendly processes, directly linked to the requirements of new equipment (machines, boxes, bags …) and the less efficient transport of the packages that are manually recovered without compaction (around 54% of the packages in the DRS) by a high number of small commercial establishments.

The impact associated to Flow 1 (specific DRS packages) in the new system is clearly higher than that linked to Flow 2 (DRS excluded packages), and it is even higher than the impact of the total joint flow in the current EPRS for all categories except ADP. The fundamental cause of this high impact is the backhauling stage to transport the recovered packages to the counting plants. When the contributions of the different stages were analyzed in detail, the collection and transportation stage in DRS was confirmed more relevant than in the case of EPRS for all the environmental burdens and particularly for EP category.

The underlying idea of this article is whether the fixation in the increase of the recycling rate (resource depletion) can cause environmental damage in other impact categories, equal or more important than this, such as climate change, acidification potential or eutrophication. This is something that decision-makers should take into account when they decide to apply changes in waste management systems.

Overall, it can be concluded that none of the alternative options analyzed (both in the baseline scenarios and in the sensitivity analysis) advise the replacement of the current EPRS by a new system which includes the introduction of a DRS with the characteristics described by the Government of Catalonia. This fact is consequence of the commercial structure and the specific characteristics of the points of sale that offer beverage in the Spanish context, which can differ from the situations in other European countries where the DRS has been implemented. In addition, the implementation of the DRS does not imply the dismantling of the EPRS, which must be maintained active for the management of the waste packaging not covered by the DRS. The management of these two systems in parallel could result on relevant environmental inefficiencies far away from optimality.

As further work, it would be interesting to perform a Life Cycle Costing and assess social aspects of both systems to take a decision under a sustainability approach.

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Abbreviations

ADP	Abiotic Depletion Potential
AP	Acidification Potential
DRS	Deposit – Refund System
EP	Eutrophication Potential
EPRS	Extended Producer Responsibility System
GWP	Global Warming Potential
HDPE	High-density polyethylene
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LDPE	Low-density polyethylene
ODP	Ozone Depletion Potential
PE	Polyethylene
PET	Polyethylene terephthalate
POCP	Photochemical Oxidant Creation Potential