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Turning Waste Into Value: A Design Strategy for Sustainable Deposit-Refund Systems

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ABSTRACT

The challenge of single-use plastics (SUPs) and packaging waste has intensified in recent years, with deposit-refund systems (DRS) emerging as one of the most effective solutions. Although DRS improve recycling rates, their adoption is often hindered by high setup costs and uncertain cost-effectiveness. This study addresses a central question in waste management: how to design economically viable and scalable DRS. Adopting a design science research strategy, the study proceeds in three phases. First, it reviews existing DRS operating modes and identifies key design parameters. Second, it tests a set of recommendations, ‘technological rules’ in design science, through a scenario-based analysis applied to a DRS for polyethylene terephthalate (PET) in Italy. Third, it generalises the results into a transferable adoption procedure. The findings reveal trade-offs between environmental ambition and economic sustainability, underscoring the importance of designing systems that are adaptable to specific national and regional contexts. The study provides policymakers with a structured procedure for adopting economically viable DRS aligned with circular economy goals.

1 | Introduction

The packaging industry is a major contributor to municipal solid waste, generating large volumes of materials such as paper, metals, glass and composites every year (Blasenbauer et al. 2024; Di Pillo et al. 2023). Among these, single-use plastics (SUPs) constitute a significant and growing fraction (Lau and Wong 2024; Borg et al. 2022; Schmidt and Laner 2021; Chen et al. 2021), largely because of their low cost, durability and suitability for high-demand sectors like food and beverage (Sharifian and Asasian-Kolur 2022; Benyathiar et al. 2022). However, these same characteristics have led to increasing environmental concerns: SUPs are derived from fossil fuels and persist in the environment, contributing to pollution in marine and terrestrial ecosystems (Chen et al. 2021; Li et al. 2022). In 2023 alone, global SUP production reached 400 million tonnes, underscoring the

urgency of implementing effective waste management strategies (Borrelle et al. 2020; Farrukh and Sajjad 2024; Plastics Europe 2024).

In response, governments across the world have introduced a variety of legislative measures to curb SUP consumption and improve resource management (Borrelle et al. 2020; Da Costa et al. 2020). Countries such as China, Japan and the United States have enacted ambitious policies to reduce SUP, while developing regions have focused more on outright bans (Zhu et al. 2019; Japan Waste Research Foundation 2021; U.S. Department of the Interior 2022; Nagarajan 2022; Adam et al. 2020).

Within Europe, the Packaging and Packaging Waste Regulation (PPWR) fosters circularity with a focus on the packaging industry (Council of the European Union 2024). This legislative

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initiative imposes specific collection and recycling targets for SUPs and other packaging materials, including paper, metals, glass, composites and other hazardous substances. PPWR supplements the EU Directive 2019/904 issued in 2019, also known as the SUP Directive (European Parliament and the Council 2019), which outlines community guidelines to enhance plastic waste management. Polyethylene terephthalate (PET) bottles, a major SUP, are a specific focus of the PPWR and SUP directives. For this material, regulations mandate that 77% of PET bottles be collected separately by 2025, with the target rising to 90% by 2029.

Previous studies highlight extended producer responsibility (EPR) as a key policy approach to improve PET collection (Seay and Ternes 2022; Laubinger et al. 2022), with deposit-refund systems (DRS) emerging as one of the most effective implementations. In a DRS, consumers pay a deposit when purchasing a product, which is refunded upon its return (Zhou et al. 2023; Simon et al. 2016; Bohm 1981). Anecdotal evidence indicates that regions adopting DRS achieve significantly higher PET return rates compared with those relying on other EPR schemes (Basuhi et al. 2024; Martinho, Alves, et al. 2024; Oosterhuis et al. 2014). According to Consulting and ReLoop (2024a), several European countries with DRS, such as Denmark, Finland, Norway, Germany and Lithuania, have already met the EU's 2025 and 2029 PET collection targets, while others like the Netherlands and Latvia are close to doing so. High return rates (HRRs), including 98% in Germany, 97% in Finland and 92% in Norway, demonstrate the system's effectiveness. In contrast, countries without a DRS lag behind: Spain reported only a 37% PET collection rate in 2022, while France, Italy and Portugal remain around or below 50%, revealing inefficiencies in their current systems.

Despite their proven efficacy, DRS are not widely adopted due to their high setup costs and complex implementation requirements. Moreover, economic viability varies significantly across contexts, and evidence-based guidance for tailoring DRS to local conditions remains limited (Lu et al. 2022; OECD 2024). This reflects a key research gap: while the environmental benefits of DRS are well documented, there is insufficient understanding of how to design economically sustainable systems adaptable to diverse regulatory and economic environments. As a result, scholars have increasingly called for research capable of supporting policymakers in the design of context-specific DRS solutions that effectively respond to local challenges and constraints (Larrain et al. 2024; Goyal et al. 2021; Walls 2011).

This paper contributes to this research agenda by proposing a structured procedure to support decision-makers in the adoption of economically viable and context-sensitive DRS. Drawing on a design science research strategy (van Aken 2004), the study develops and tests a set of technological rules through field-based scenario analysis. These rules are then generalised into a transferable adoption procedure. Italy is used as an illustrative case to demonstrate how key design variables, such as collection mode, deposit value, return rate and environmental contribution (EC), interact to influence DRS economic viability under real-world conditions.

The remainder of the paper is structured as follows: Section 2 reviews background literature on DRS; Section 3 outlines the design science research strategy; Sections 4–6 present the definition, field testing and validation of the design strategy's technological rules, culminating in their translation into a transferable adoption procedure; Section 7 discusses key insights and conclusions; and Section 8 highlights limitations and directions for future research.

2 | Background on DRS

Various mechanisms grounded in the EPR principle have been proposed to improve PET waste collection (Seay and Ternes 2022; Laubinger et al. 2022), typically relying on either positive incentives, such as subsidies, or negative ones, such as taxes or levies (Gupt and Sahay 2015). Positive incentives encourage consumers, recyclers and manufacturers to support PET recycling efforts through financial compensation (Helinski et al. 2024; De Giovanni et al. 2016). An example of promoting recycling through positive incentives is RecycleBank, a private organisation in the United States that rewards customers for recycling by offering discount coupons from local vendors (Park and Berry 2013). On the other hand, negative incentives mainly include taxes levied on environmentally harmful products to cover disposal costs (Matheson 2022; Gupta and Sahay 2015). An instance is the advanced recycled fee reported by Hong et al. (2014), a levy charged to companies to cover the costs of managing the end-of-life disposal of electronic devices, such as laptop computers.

However, relying exclusively on a single type of incentive presents inherent limitations, as previous research shows that this approach often yields short-term effects rather than fostering long-term outcomes and may undermine social equity (Walker et al. 2020; Dikgang et al. 2012). Consequently, scholars suggest that EPR mechanisms that incorporate both positive and negative incentives are more effective (Walker et al. 2020; Palmer and Walls 1999; Yi et al. 2021; Chang et al. 2019). Nonetheless, combined EPR schemes have also drawn criticism for their limited equity, as they predominantly target producers at the upstream stage. Such an approach only partially adheres to the polluter pays principle (PPP), neglecting the role of other contributors to waste generation, particularly consumers (Glazyrina et al. 2006). For this reason, scholars increasingly argue for integrated EPR systems that not only employ a balanced mix of incentives but also more fully reflect the PPP by addressing all actors involved in the lifecycle of waste (Zhou et al. 2020; OECD 2001).

DRS represent a form of EPR that combines positive and negative incentives while closely adhering to the PPP (Laubinger et al. 2022; Campbell et al. 2016; Bohm 1981). Under a DRS, consumers pay an upfront deposit, a negative incentive, added to the product price, which is refunded upon return of the packaging. This refund acts as a positive incentive, promoting proper recycling and reducing littering. By reallocating the cost of waste management through the deposit mechanism, DRS ensure that all actors contributing to potential pollution (particularly consumers) bear a share of responsibility, thereby strengthening

alignment with the PPP (Picuno et al. 2025; Zhou et al. 2023; Laubinger et al. 2022; Zhou et al. 2020).

Given their broad applicability and regulatory relevance, DRS have been the subject of extensive academic analysis. Bohm (1981) laid the theoretical foundations, highlighting their effectiveness in addressing environmental externalities. Subsequent studies have confirmed that DRS are successful instruments for pollution prevention and resource recovery (Zhou et al. 2023; Linderhof et al. 2019; Hahn and Stavins 1992; Farber 1991; Belzer 1989). These systems also facilitate the collection of high-quality PET bottles, a critical factor that significantly affects recycling outcomes (Martinho, Santos, et al. 2024; Amirudin et al. 2023; Snell et al. 2017). In addition to environmental gains, DRS are associated with social benefits, including litter reduction, cleaner public spaces and job creation (Picuno et al. 2025; Eunomia 2023; Consulting and Reloop 2021; Hogg et al. 2010).

Despite the proven environmental and social benefits of DRS, their main challenge lies in ensuring economic sustainability. Several studies adopting an economic perspective have highlighted that implementing DRS in new regions often entails substantial setup and operational costs. For instance, a quantitative analysis of a potential DRS programme in Latvia found that establishing such systems requires significant upfront investment, particularly in infrastructure development, such as setting up take-back points and acquiring reverse vending machines (RVMs) (Dace et al. 2013). Similar findings have been reported in other regions, including Slovakia and Croatia (Malindzakova et al. 2022; Schneider et al. 2021). Italy further illustrates the implementation challenges of DRS: a voluntary pilot programme launched in 2017 under the coordination of MASE demonstrated initial feasibility, but broader adoption has since stalled, primarily due to persistent economic concerns among key stakeholders (MASE 2017; Eunomia 2023; OECD 2024).

Despite their substantial initial investment costs, DRS remain a potentially economically sustainable solution for the collection of all types of packaging waste, as evidenced by various ex ante studies assessing their costs and benefits across different regions and implementation scales (Laubinger et al. 2022). A notable example is the study by Schneider et al. (2021), which conducted a comprehensive cost–benefit analysis of various scenarios in the Croatian PET market, identifying the most viable option by determining an optimal deposit value to ensure the system's economic sustainability. A similar approach has been employed to evaluate the cost and revenue per unit in other regions, such as Ireland and the United States (Edwards et al. 2019; Woods et al. 2019).

However, existing ex ante studies typically assess DRS costs and revenues within specific national or regional contexts, limiting the transferability of their findings. Addressing this limitation requires a structured analytical framework capable of evaluating DRS economic viability and scalability across diverse implementation settings. To this end, the study adopts a design science research strategy, moving beyond context-specific evaluations by integrating key design parameters into a scenario-based analysis. Operationalising critical variables,

such as return rate, deposit value and handling fees, enables the comparative simulation of DRS configurations under varying conditions.

3 | Design Science Research Strategy

This paper develops an adoption procedure for economically viable DRS in countries where it has never been introduced. Therefore, the research is prescription-driven and solution-focused rather than description-driven, making a design science methodology the most appropriate approach (van Aken 2004). The design science research strategy is particularly suited to identifying solutions to complex and context-specific problems (van Aken and Romme 2012). Unlike explanatory approaches, design science aims to generate ‘technological rules’ that translate theoretical insights into effective, actionable solutions. A typical outcome of design science research is a set of tested and contextually grounded technological rules that can be applied by decision-makers (Martina and Oskam 2021; van Aken 2004). The DRS adoption procedure developed in this study exemplifies such a set of technological rules.

Given the high degree of contextual variation in DRS operating modes and financing structures worldwide, a flexible and adaptive research approach is required. Prior studies have documented significant variation in key aspects such as collection methods (e.g., RVMs or designated collection points) and funding mechanisms (e.g., consumer deposits, government subsidies or private investment) (Consulting and Reloop 2024a; Consulting and Reloop 2022; Calabrese et al. 2021; Zhou et al. 2020; Spasova 2019; Tugran 2023). To address this complexity, the study adopts a design science research strategy, which enables the ex ante simulation of real-world scenarios to assess how design variables, such as deposit value, return rate, funding source and operating costs, affect the effectiveness and economic viability of a DRS. This approach is particularly suited to developing solutions for complex, policy-relevant problems, where context-sensitive adaptation is critical.

Although widely applied in adjacent fields, design science has not yet been employed in the context of DRS adoption. However, its potential is demonstrated in related studies: Martina and Oskam (2021) used it to produce practical guidelines for scalable recycling business models, while Coffay and Bocken (2023) and Schoormann et al. (2022) applied it to sustainability-oriented business model design.

In this study, the design science process is articulated in three main phases, as illustrated in Figure 1 (adapted from Martina and Oskam 2021). First, a review of relevant literature is conducted to identify key design principles and contextual patterns that inform the development of a set of technological rules for DRS adoption (Hoang and Böckel 2024; Martina and Oskam 2021). Second, these rules are operationalised and tested through scenario-based simulation applied to an illustrative case, allowing for field-grounded validation under real-world constraints (França et al. 2020; van Aken 2004). Finally, the validated rules are generalised into a transferable adoption procedure designed to support decision-makers in adapting DRS to diverse institutional and market contexts (Holmström

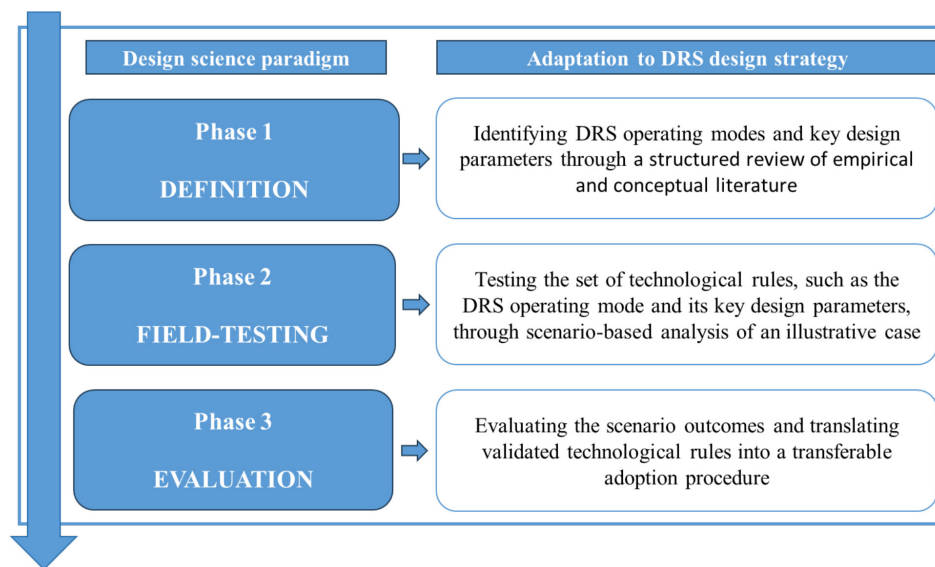


FIGURE 1 | Research process (adapted from Martina and Oskam 2021).

et al. 2009). This iterative process moves from principle identification to case-based testing and procedural translation, ensuring that the proposed solution remains both empirically grounded and adaptable across settings.

4 | Design Principles for DRS Adoption

The initial phase, as shown in Figure 1, aims to derive foundational design principles by reviewing existing literature on DRS configurations. In line with the design science approach (van Aken 2004; Martina and Oskam 2021), this step grounds the development of a set of technological rules in real-world knowledge, identifying recurrent features and context-specific constraints that shape economically sustainable DRS models.

The reports published by Consulting and Reloop (2024a, 2022, 2020, 2018, 2016) are first examined to identify different operating modes adopted by DRS worldwide. These publications offer a global overview, with the most recent edition covering 48 regions. Notably, the reports apply a consistent set of key elements, such as deposit value, types of packaging, return rates and system flows (monetary, material and data), to assess the design features of each system. Similarly, Spasova (2019) and Tugran (2023) offer a comprehensive overview of DRS implementations across European countries. They examine the regulatory steps involved in the adoption of DRS, detail the cost and revenue structures for various actors and provide country-specific performance outcomes.

While these reports offer valuable insights, they tend to evaluate each DRS as an isolated case, even when systems share similar operational characteristics. For example, although the DRS models in Denmark and Finland exhibit comparable design and functioning, they are treated as distinct cases. This fragmented approach limits the ability to perform systematic comparisons across systems.

To address this issue, Zhou et al. (2020) introduced a significant conceptual advancement by proposing a global classification

of DRS based on shared design features, an effort that culminated in the definition of three primary DRS operating modes: reverse logistics, retail recycling and repo recycling. Based on Consulting and Reloop's datasets, their study also mapped out the main challenges for stakeholders, including regulatory burdens, cost structures and transport-related constraints, thus enabling comparative evaluation across the identified modes. However, their contribution lacked detailed data on the specific cost and revenue allocations for individual stakeholders.

Expanding on this framework, Calabrese et al. (2021) refined the categorisation of operating modes and addressed the prior data gap by providing a detailed analysis of the financial flows within each model. Their work offers a more granular understanding of how costs and revenues are distributed across actors, thus enhancing the analytical precision of comparative studies.

Drawing on this body of research, three primary funding streams have been identified across DRS operating modes: (1) the EC or environmental tax, (2) revenues from the sale of returned packaging materials and (3) unredeemed deposits (Consulting and Reloop 2024a; Calabrese et al. 2021). Importantly, the latter should ideally tend toward zero, as effective DRS are designed to incentivise full consumer participation in returns. Bohm (1981) noted that true economic sustainability should rely solely on the first two funding sources.

5 | Field-Testing and Scenario-Based Validation of the Technological Rules

As illustrated in Figure 1, the second phase of the design science research strategy involves field-testing the proposed technological rules in a realistic context. This section develops an illustrative application based on a prospective DRS operator and explores its economic viability through a series of what-if scenarios. The aim is to assess how key variables, such as return rates, deposit value and EC, affect the system's performance under different configurations, providing empirical validation of the design solution.

5.1 | Illustrative Case Study

Italy offers a particularly relevant context for examining the economic sustainability of a DRS for PET one-way beverage containers. In 2017, Italy launched a voluntary pilot programme under the supervision of MASE. However, nationwide implementation has remained stalled due to stakeholder concerns over high costs and uncertainty about consumer participation (OECD 2024, 110–111; Consulting and Reloop 2022). The recent approval of the PPWR has renewed pressure on member states to comply with EU targets, increasing interest in tools such as DRS to achieve these objectives.

The ongoing debate on DRS implementation in Italy has prompted several actors within existing EPR schemes to explore it as a viable alternative. Among these, CORIPET, a voluntary, non-profit consortium officially recognised by MASE, has emerged as a particularly relevant example. CORIPET currently operates an industrial-scale circular business model for PET bottles, managing a nationwide infrastructure of RVMs without applying a deposit scheme (CORIPET 2022).

While not formally a DRS operator, CORIPET's operational model and financial data provide a robust empirical foundation for testing and validating the proposed design solution. As such, CORIPET serves as the illustrative case in this study, allowing technological rules to be examined within a realistic context, a key requirement in the design science methodology (van Aken 2004; Martina and Oskam 2021).

The economic sustainability of the hypothetical nationwide DRS operator is evaluated through a set of scenario-based simulations. Scenario analysis is a well-established method in strategic design, as it enables the structured exploration of uncertainty, the assessment of alternative configurations and the generation of actionable insights for both policy and operational decision-making (Duinker and Greig 2007; Postma and Liebl 2005). In this study, the scenarios are grounded in CORIPET's Income Statement, which provides the core economic data used to estimate key performance variables across different return rates, costs and funding configurations.

All economic data in this study, as detailed in Table 1, were collected in accordance with International Financial Reporting Standard 13 (IFRS 13), ensuring accuracy, reliability and comparability across data sources (Filip et al. 2021). IFRS 13 classifies inputs into three levels based on their degree of observability, supporting fair value estimation in a transparent and consistent manner. Level 1 inputs consist of directly observable, market-based data, typically derived from active market prices for identical items. In this study, they include financial figures from CORIPET's 2021 Income Statement. Level 2 inputs refer to indirectly observable data, such as quoted prices for similar items or other relevant market information. In this study, they include financial data from DRS operators in other regions, offering insights into operational costs and funding mechanisms. Level 3 inputs comprise unobservable, model-based estimates, commonly known as mark-to-model inputs, derived from projections or assumptions when direct market data is unavailable. In this study, they are informed by internal estimates grounded in prevailing market conditions.

5.2 | Scenario Design and Assumptions

The prospective DRS operator, CORIPET, is currently implementing a circular business model aimed at closing the loop for PET bottles, primarily through a network of RVMs distributed across Italy. Interviews with CORIPET's management suggest that the current operational setup is closely aligned with the operator-closing mode described by Calabrese et al. (2021) and Zhou et al. (2020), making this configuration particularly suitable for adoption by the prospective DRS operator.

As illustrated in Figure 2, the process unfolds in six phases. In Phase (1), retailers purchase beverages in one-way PET packaging and pay a deposit to the producers, who then transfer it to the DRS operator. In Phase (2), consumers purchase the product from retailers, paying the deposit in addition to the product price. In Phase (3), consumers return the empty PET containers to the retailer and receive a refund of the deposit. In Phase (4), the DRS operator collects the returned packaging, refunds the deposit to the retailers and takes responsibility for managing the collected packaging. Phase (5) involves transporting the packaging to collection centres, where it awaits recycling and/or resale operations (not depicted in Figure 2). Finally, in Phase (6), the DRS operator pays a management fee to the municipality for the portion of packaging that was not returned through its network and is instead managed via the standard separate collection system.

To determine the conditions under which the prospective DRS operator could achieve economic sustainability, a series of what-if scenarios has been developed. These scenarios are constructed by varying three key factors known to influence the economic viability of DRS operations: the return rate of PET containers, the amount of the EC and the deposit value associated with the packaging (Consulting and Reloop 2024b; Di Foggia and Beccarello 2022; Calabrese et al. 2021; Cossu and Masi 2013).

While these variables could generate an infinite number of possible configurations, the objective of the analysis is not to exhaust all potential combinations. Rather, it is to demonstrate how changes in specific parameters critically affect the economic sustainability of the system. Figure 3 presents the details of the analysed scenarios.

5.3 | Economic Viability Across Scenario Configurations

5.3.1 | Scenario Variables

The scenarios investigate how the gross profit of the prospective DRS operator, measured in million euros (mil. €), varies according to changes in the scenario variables considered in Figure 3. As reported in Table 2, the PET resale price is disaggregated into three categories: blue ($\text{Price}_{\text{PETblue}}$), coloured ($\text{Price}_{\text{PETcolored}}$) and transparent ($\text{Price}_{\text{PETtransparent}}$). This distinction is particularly beneficial as each PET type has a distinct resale price (Liu et al. 2021; Snell et al. 2017). Such prices, in euros per tonne (€/t), were sourced from official PET auctions conducted between January 2021 and March 2024.

TABLE 1 | Income statement of a prospective DRS operator.

Revenues (R)		
Revenue	Description	Formula/estimates
R1	Environmental contribution ^a	This item is determined by the total PET managed by the DRS operator (q_{entered_t}), expressed in €/t. $EC * q_{\text{entered}_t}$
R2	Resale of compacted packaging ^a	This item is determined by the total PET returned to the DRS operator ($q_{\text{entered}_t} * \%PET_{\text{returned}}$) distributed proportionally between the various types of PET ($PET_{\text{transparent}}$, PET_{blue} and PET_{colour}). $q_{\text{entered}_t} * \%PET_{\text{returned}} * (\text{Price_of_} PET_{\text{transparent}} * \%PET_{\text{transparent}} + \text{Price_of_} PET_{\text{blue}} * \%PET_{\text{blue}} + \text{Price_of_} PET_{\text{colour}} * \%PET_{\text{colour}})$
R3	Unredeemed deposits ^a	This item is determined by the total packaging managed by the DRS, expressed in units (q_{entered_u}), and the revenues derived from deposits not returned to consumers and/or retailers due to failure to return the packaging ($DEP * (1 - \%PET_{\text{returned}})$). $q_{\text{entered}_u} * (DEP * (1 - \%PET_{\text{returned}}))$
Variable costs (VC)		
Variable cost	Description	Formula/estimates
VC1	Refund for collection and selection of returned packaging ^b	The item is determined considering the DRS in Lithuania (the only case with available information for this item) provided in Spasova (2019). The management cost for the empty packages collected by retailers is 0.0175 €/u with RVM ($PET_{\text{returned}_{\text{RVM}}}$) and 0.0138 €/u manually ($PET_{\text{returned}_{\text{Manual}}}$). The overall percentage of empty packages managed by RVM is assumed to be 37.1%. $q_{\text{entered}_u} * \%PET_{\text{returned}} (0.0175 * PET_{\text{returned}_{\text{RVM}}} + 0.0138 * \%PET_{\text{returned}_{\text{Manual}}})$
VC2	Transport of returned packaging ^c	The item is determined considering the DRS in Lithuania and insights from CORIPET managers. According to Spasova (2019), the DRS in Lithuania foresees 7.2 €/t for transporting empty packages from retailers to collection centres. However, this figure has been modified to a more conservative value of 250 €/t based on discussions with CORIPET's managers. This figure is significantly different because it includes further transport of items from collection centres (see the following item). $q_{\text{entered}_t} * 250 * \%PET_{\text{returned}}$
VC3	Management of collection centres ^c	The item is determined considering the DRS programme in Croatia and the discussions with CORIPET's managers. According to Schneider et al. (2021), the DRS in Croatia foresees 0.0058 €/u for compacting a vacuum unit at collection centres (incoming vacuum logistics, compaction, storage, outgoing bale logistics). However, this figure is modified to 0.0035 €/u. The figure is lower because some vacuum logistics items are included in VC2 from the consortium's internal accounting. $q_{\text{entered}_u} * 0.0035 * \%PET_{\text{returned}}$
VC4	Management of non-returned packaging ^c	The item represents the cost of collecting unreturned empty packages by DRS. It is determined as the product between the unit cost (per tonne) of managing PET packaging returned by the traditional EPR system and their quantity expressed in tonnes. The unit management cost is calculated by adding the items relating to operational services, including costs for selection services, costs for separate waste collection and transportation costs (CORIPET's 2021a financial statements, page 30) divided by the tonnes of PET managed by the CORIPET consortium in 2021, 192,078.10 t (CORIPET's 2021b management report, page 2). $536.19 * q_{\text{entered}_t} * (1 - \%PET_{\text{returned}})$

TABLE 1 | (Continued)

Fixed costs (FC)			
Fixed costs		Description	Formula/estimates
FC1	Raw materials ^a	CORIPET's (2021a) financial statements, page 30.	82,527
FC2	Personal ^a	CORIPET's (2021a) financial statements, page 31.	893,534
FC3	Maintenance ^a	The item represents overall maintenance costs: maintenance used within the operational services and maintenance within the commercial and administrative services (CORIPET's 2021a financial statements, page 30).	101,134
FC4	Marketing ^a	CORIPET's (2021a) financial statements, page 30.	765,585
FC5	Management software ^b	The item derives from the expenses incurred by the DRS in Croatia for management software and other administrative costs and from those incurred by the CORIPET consortium for legal and technical consultancy (Schneider et al. 2021, page 25; CORIPET's 2021a financial statements, page 30). Because it was impossible to single out only the expenditure relating to the software, a nominally higher value is conservatively included (Schneider et al. 2021).	1,100,000
FC6	Administrative services ^a	CORIPET's (2021a) financial statements, page 30.	163,751
FC7	Depreciation ^a	CORIPET's (2021a) financial statements, page 31.	789,724
FC8	Research and development ^b	Because this item is not in CORIPET's IS, it has been borrowed from the COREPLA Consortium's IS (COREPLA's 2021 financial statements, page 22).	371,000
FC9	Costs for the use of third-party assets ^a	CORIPET's (2021a) financial statements, page 31.	872,935
FC10	Other charges ^a	CORIPET's (2021a) financial statements, page 31.	26,473

Note: IFRS 13 standard.

^aLevel 1 entry.

^bLevel 2 entry.

^cLevel 3 entry.

With regard to the composition of returned PET, it is assumed that the proportions reflect current market shares: 45% blue, 25% coloured and 30% transparent.

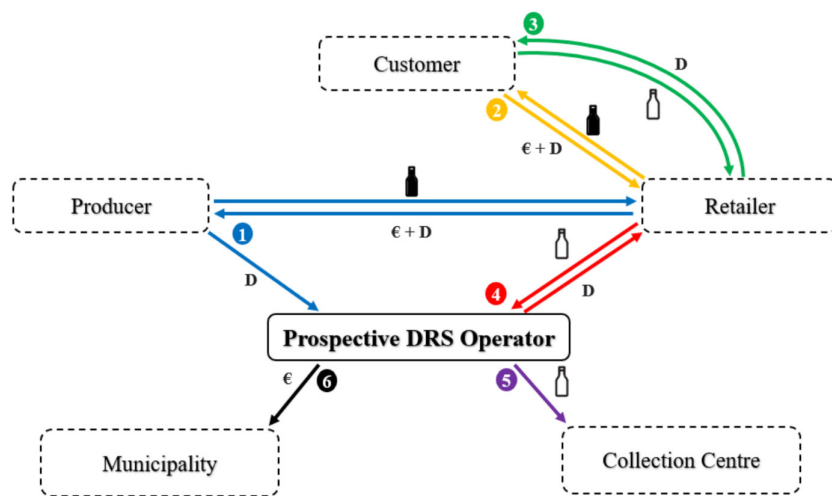
Finally, regarding the total quantity of PET packaging entering the system, q_{entered} several levels are considered. The baseline corresponds to the volume currently managed by the CORIPET consortium, approximately 190 kilotonnes (kt), with variations ranging from 160 to 220 kt, representing a $\pm 15\%$ deviation from the baseline. Additionally, a separate scenario considers the total volume of PET placed on the Italian market, estimated at 380 kt (Independent Commodity Intelligence Services—ICIS 2022).

Given the relatively modest variation ($\pm 15\%$) around the baseline, FCs are assumed to remain within their relevant range and are thus treated as constant, while VCs are assumed to scale linearly. For the 380 kt off-chart scenario, linearity is likewise assumed for VCs. However, a multiplicative factor of 2 is applied to FCs to reflect a neutral stance regarding the presence of economies or diseconomies of scale at that expanded operational level.

5.3.2 | Comparative Results Across Return-Rate Scenarios

To assess the economic sustainability of the prospective DRS operator, scenario outcomes are evaluated based on their capacity to reach the break-even point (BEP), the threshold at which total revenues equal total costs. The BEP serves as the central benchmark in Figures 4–6, providing a consistent reference for comparing the economic viability of different system configurations. Scenarios are grouped into three categories based on the system's core performance indicator: the percentage of returned material (Zhou et al. 2020; Bohm 1981). These include low return rate (LRR), moderate return rate (MRR) and HRR scenarios.

In the LRR scenarios (Scenarios 1–3 of Figure 4), the prospective DRS operator is assumed to collect 75% of PET bottles. This exceeds Italy's current rate of approximately 60% in the absence of a DRS and is comparable to the lower range of return rates reported in European countries with established systems, such as the Netherlands, which reaches 68% (Consulting and Reloop 2024a, 56; ICIS 2022).



Legend

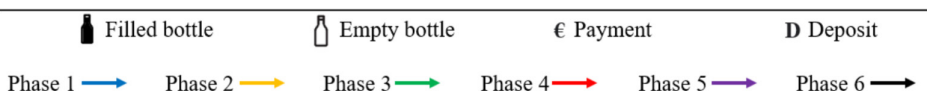


FIGURE 2 | Prospective DRS operator's operating mode (adapted from Calabrese et al. 2021).

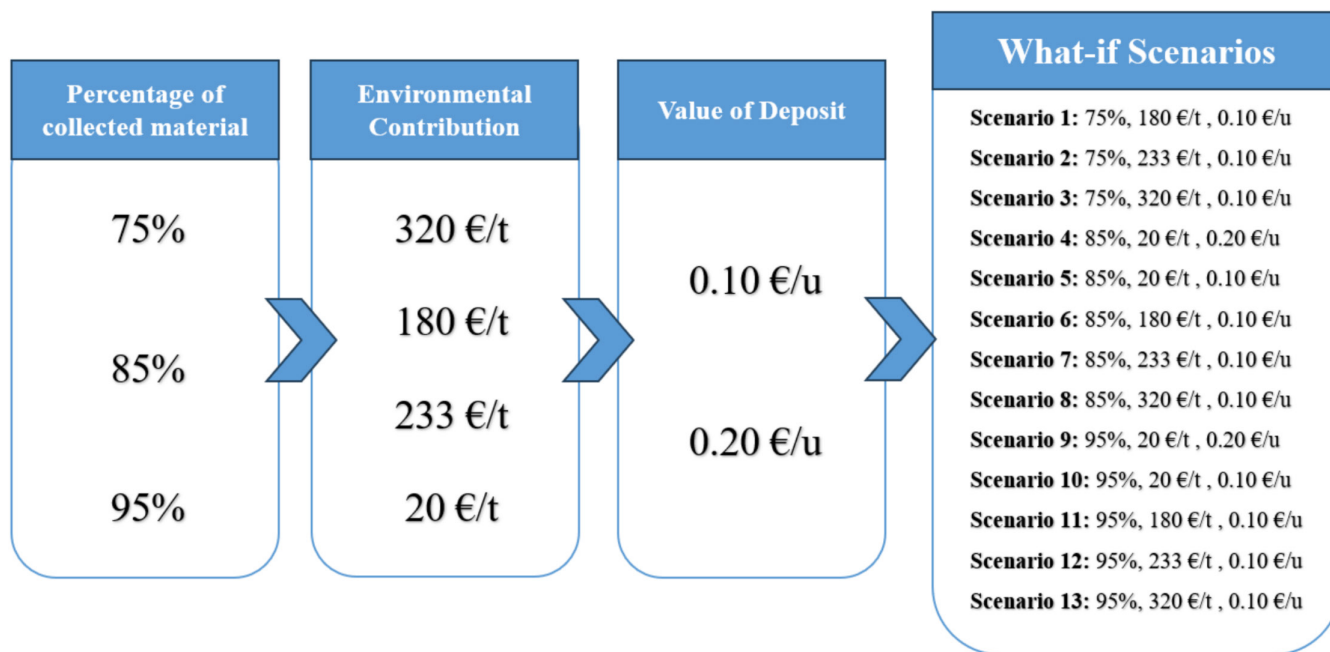


FIGURE 3 | Details of what-if scenarios.

TABLE 2 | PET resale price bundles in each category.

PET category	PET resale price bundles					
	Bundle 1	Bundle 2	Bundle 3	Bundle 4	Bundle 5	Bundle 6
PET _{blue}	389 €/t	390 €/t	390 €/t	504 €/t	707 €/t	825 €/t
PET _{colored}	164 €/t	170 €/t	140 €/t	304 €/t	391 €/t	490 €/t
PET _{transparent}	457 €/t	450 €/t	520 €/t	643 €/t	924 €/t	959 €/t

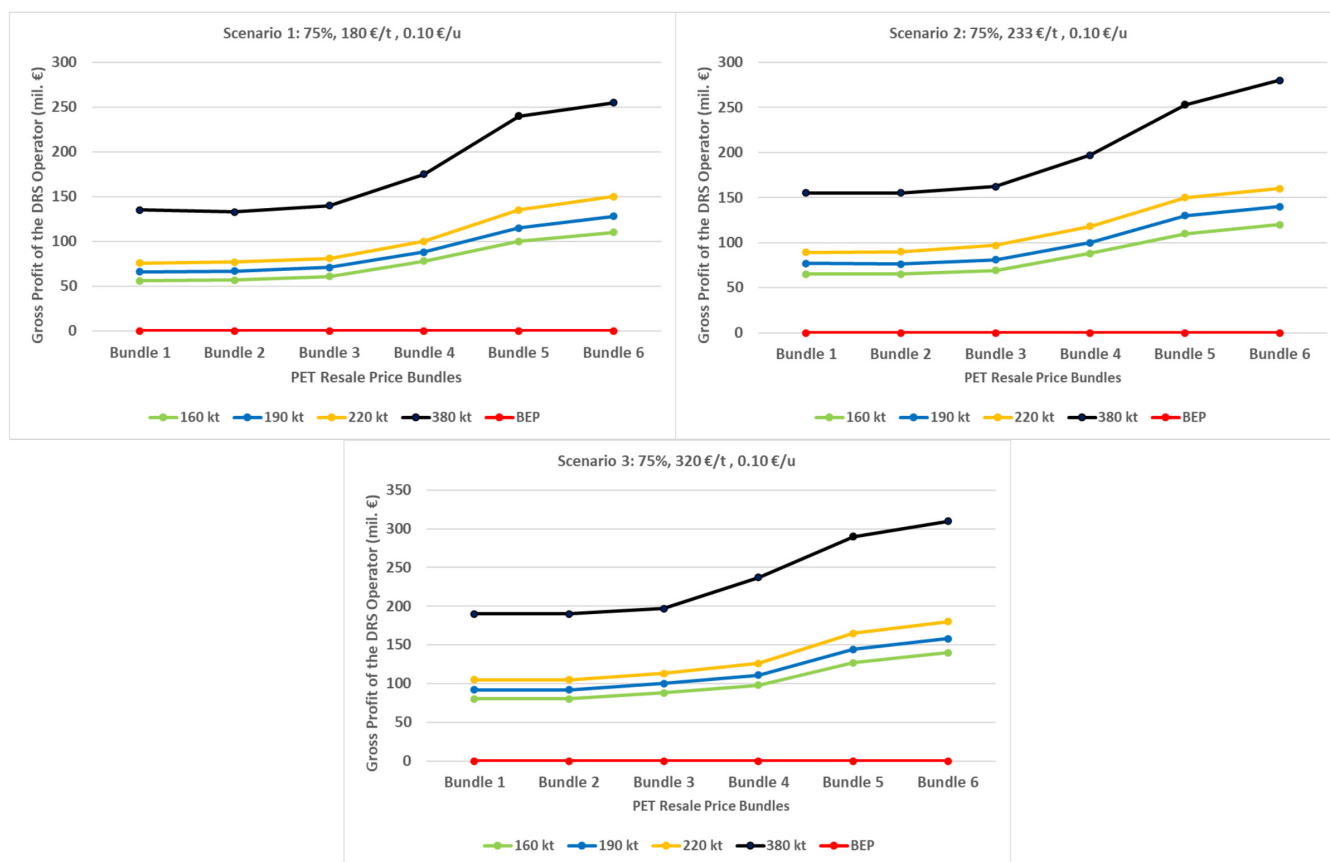


FIGURE 4 | Outcomes of the LRR scenarios.

As illustrated in Figure 4, all LRR scenarios lead to economically sustainable outcomes across the six PET resale price bundles. This result remains consistent despite variations in the total volume of PET entering the system. Specifically, as the volume increases, the profitability of the prospective DRS operator improves. This trend is attributable to the higher revenue generated from unredeemed deposits, which remain substantial under relatively LRR conditions.

The MRR scenarios (Scenarios 4–8 of Figure 5) assume a PET collection rate of 85%, consistent with the target established by PPWR for 2025. Overall, these scenarios confirm the economic sustainability of the prospective DRS operator across most conditions. An exception emerges in Scenario 5, where the operator fails to achieve economic sustainability under the lowest PET resale price configuration (Bundle 1). This outcome highlights the system's sensitivity to material market values when operating at higher return rates, which reduce the volume of unredeemed deposits, a key revenue source in LRR scenarios. Compounding this effect, Scenario 5 also introduces a substantial reduction in the deposit value compared with Scenario 4, dropping from €0.20 to €0.10 per unit. While the return rate remains unchanged, the lower deposit significantly reduces the amount of unredeemed deposits, which, at medium return levels, still represent a meaningful source of revenue for the operator.

This underscores the dual nature of the deposit: it acts not only as a behavioural incentive to encourage consumer participation but also, in practice, as a financial buffer that supports

system economic viability. When the deposit falls below a certain threshold, this stabilising function weakens, increasing the system's exposure to price volatility in the PET resale market.

Nevertheless, most MRR scenarios remain viable, indicating that an 85% return rate can be achieved without compromising economic feasibility, as long as resale prices remain within moderate-to-high ranges and deposit levels are not set too low to undermine system resilience.

In the HRR scenarios (Scenarios 9–13 in Figure 6), the assumed PET collection rate reaches 95%, exceeding both the PPWR target for 2029 (90%) and the average performance of currently operational DRS. While this HRR reflects an ambitious environmental objective, it also introduces significant economic challenges.

A marked deterioration emerges between Scenarios 9 and 10. In Scenario 9, the operator does not achieve economic viability under the first three PET resale price bundles, while in Scenario 10, this failure extends to the first four bundles. This worsening occurs despite identical conditions in return rate and EC and can be directly attributed to the halving of the deposit value, from €0.20 to €0.10 per unit. At such HRRs, unredeemed deposit revenues, typically a stabilising income stream, are already minimal. Reducing the deposit further undermines the DRS residual financial buffer, especially under unfavourable PET resale prices. In such cases, corrective measures become necessary. One viable option is to increase the EC, thus

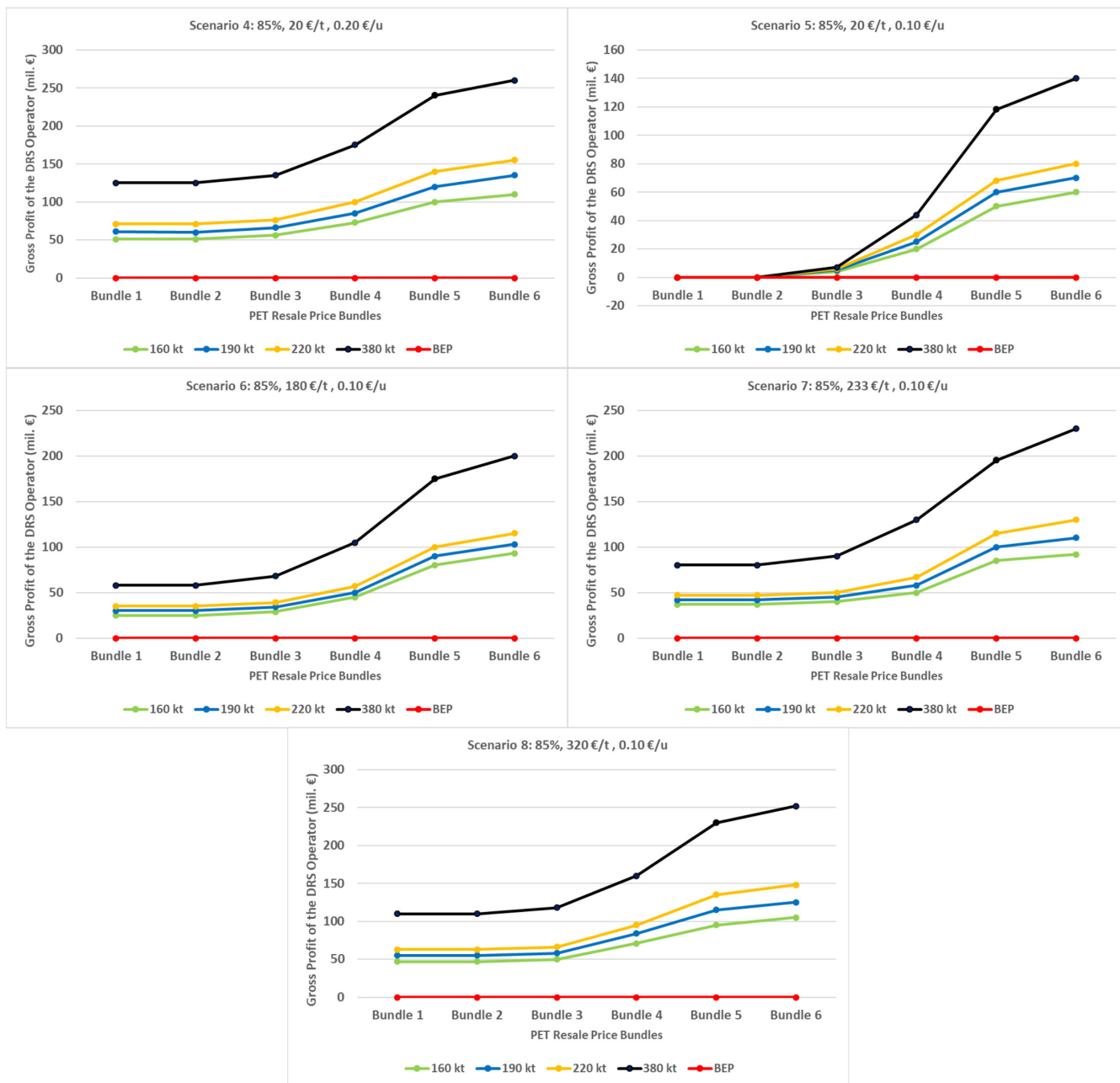


FIGURE 5 | Outcomes of the MRR scenarios.

shifting part of the cost burden to producers and compensating for the revenue loss from unredeemed deposits. Indeed, in the later HRR scenarios (Scenarios 12 and 13), raising the EC restores economic sustainability under the same high-return conditions.

Alternatively, system optimisation strategies, such as improving operational efficiency, exploiting economies of scale or enhancing resale values through better sorting and material quality, may also contribute to rebalancing the system. Overall, these findings underscore the trade-offs between environmental ambition and economic viability, highlighting the need for carefully calibrated design decisions when pursuing very HRRs.

6 | Evaluating and Generalising the Technological Rules

The third phase of the design science research strategy (see Figure 1) focuses on evaluating the broader applicability of the proposed and tested technological rules and drawing actionable guidelines for their adoption. Building on the scenario-based validation presented in Section 5, this part of the study evaluates the key variables that influence the economic performance of DRS, reflects on the trade-offs emerging across configurations and proposes a transferable adoption procedure. The goal is to move beyond the illustrative case and support policymakers and stakeholders in designing context-sensitive, economically viable DRS models.

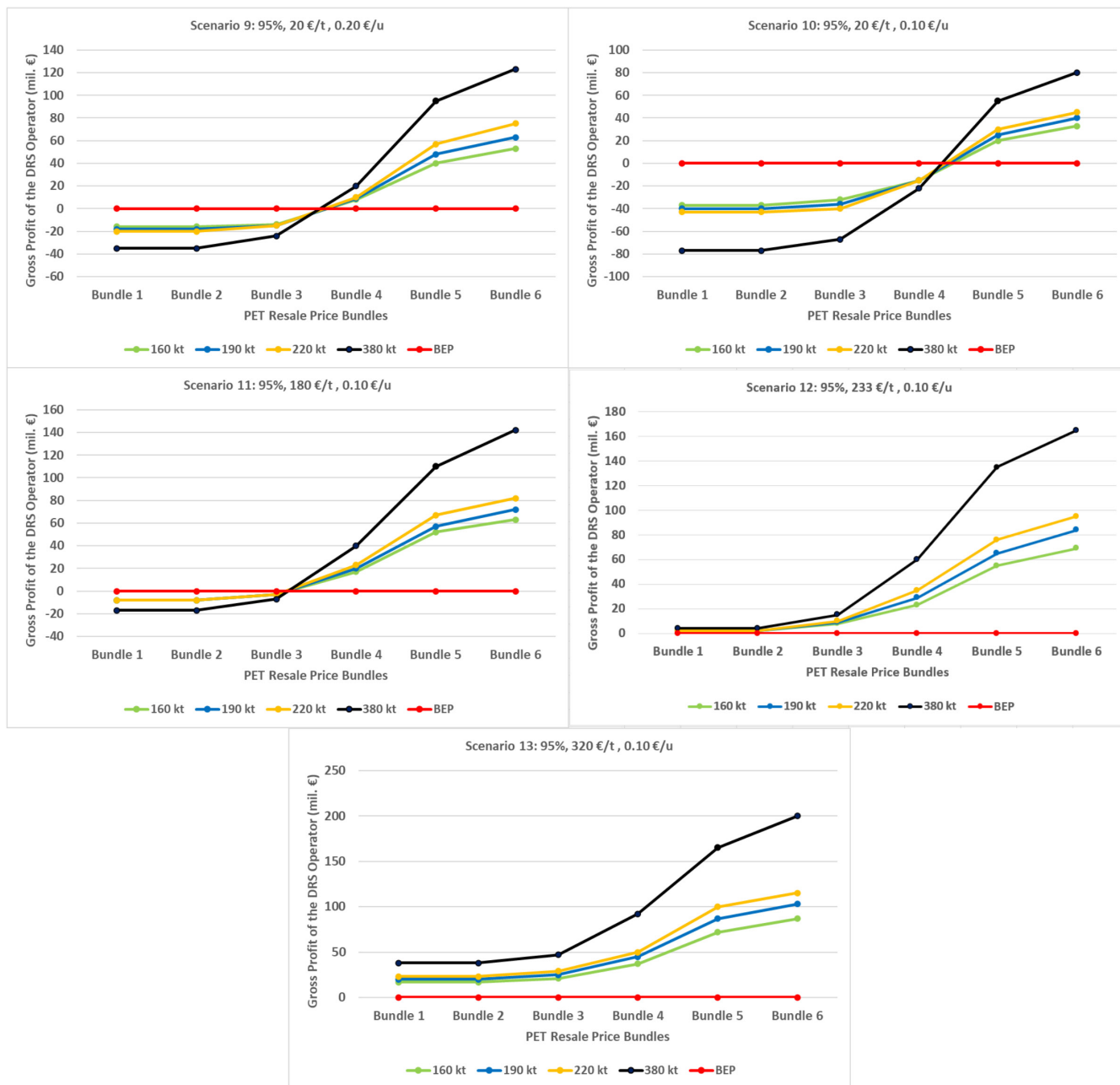


FIGURE 6 | Outcomes of the HRR scenarios.

6.1 | Key Design Variables Shaping DRS Economic Sustainability

DRS are widely recognised as effective tools for collecting high-quality PET packaging (Picuno et al. 2025; Zhou et al. 2023; Calabrese et al. 2021; Snell et al. 2017). Nevertheless, their adoption remains limited in some regions due to the presence of existing EPR programmes and the perceived financial burden of setup and operating costs, which cast doubt on the economic sustainability of DRS (OECD 2024; Dace et al. 2013). This study contributes to this debate by outlining a design strategy for the adoption of economically sustainable DRS.

The results show that five variables are particularly influential in shaping the DRS economic performance: the return rate, the

total volume of PET entering the system, EC, the deposit value and the PET resale price.

The return rate plays a paradoxical role. In LRR scenarios, in line with the PPP, higher profits are generated through unclaimed deposits, as consumers who fail to return their PET packaging effectively forfeit their deposit (Glazyrina et al. 2006). While increasing return rates improve environmental performance, it also reduces the volume of unredeemed deposits, which constitute a significant source of revenue. As shown in the progression from LRR to HRR scenarios, economic viability tends to decline as return rates rise, especially under conditions of low resale prices or reduced deposit values. This interplay underscores a structural tension between environmental objectives and economic sustainability. Noticeably, in publicly mandated

DRS operators, the former should prevail over the latter, as these systems should be designed not to maximise profits, but to operate at break-even while meeting defined environmental performance targets.

The total volume of PET processed also has a substantial effect on economic sustainability. The analysis reveals a positive relation between system scale and economic viability, confirming the presence of economies of scale. This suggests that DRS implementation should be structured at the national or large-regional level, as smaller or fragmented systems are unlikely to reach the scale required for long-term economic sustainability.

Both the EC and the deposit value serve primarily as adjustment mechanisms rather than unchanging revenue sources. Their primary function is to restore economic equilibrium when return rates are high, thus reducing unredeemed deposits, or when PET resale revenues fall below cost recovery thresholds. However, these levers must be carefully calibrated. A deposit that is too low weakens consumer participation, while one that is too high may reduce system acceptance or trigger regressive effects. Similarly, the EC must strike a balance between ensuring the DRS operator's economic sustainability and maintaining fairness among producers. From a policy perspective, this highlights the need for flexible, context-sensitive calibration of both levers, guided by empirical performance monitoring rather than ex ante fixed thresholds.

In addition, a fifth variable, the resale price of collected materials, plays a critical role in determining the economic sustainability of the DRS operator, particularly under high-return scenarios where revenues from unredeemed deposits are minimal. Market volatility in secondary raw material prices can either buffer or undermine the economic balance of the system. While this variable may appear exogenous and beyond the direct control of the operator, resale values can be enhanced through improved sorting and higher material quality, providing an indirect yet effective lever to restore economic balance within the system.

When a surplus is generated, particularly in the early phases, it should be reinvested to support the long-term system's economic

sustainability. Strategic reinvestment may include awareness campaigns to strengthen consumer participation (Van Rensburg et al. 2020), as well as targeted upgrades in system efficiency. In this regard, digital technologies such as real-time monitoring, behavioural analytics and dynamic feedback mechanisms can improve operational performance and consumer engagement (Laubinger et al. 2022). Finally, infrastructure modernization, such as improving the accuracy and reliability of RVMs or reinforcing fraud prevention mechanisms, can further increase cost-efficiency and user trust (Martinho, Alves, et al. 2024).

6.2 | Translating the Technological Rules Into a DRS Adoption Procedure

Following the scenario-based validation of the technological rules, the final stage of the design science research strategy focuses on their generalisation into an actionable and transferable framework. In line with Martina and Oskam (2021), this phase aims to bridge the gap between context-specific insights and broadly applicable design guidelines, enabling practitioners to adapt the solution to diverse regulatory and operational settings.

The objective is to translate the insights gained from the illustrative case into a structured adoption procedure that supports policymakers and stakeholders in designing economically sustainable DRS tailored to their regional conditions.

As Figure 7 shows, a growing number of countries, among them Poland, Portugal, Singapore and Uruguay, plan to launch national DRS (Consulting and Reloop 2024a). However, despite this trend, many of these schemes are still conceived as isolated initiatives, without a shared methodological framework to support comparability, reduce uncertainty and prevent inefficiencies during scale-up.

This study addresses that gap by proposing a generalised adoption procedure derived from the validated set of technological rules, grounded in the operator-closing mode. As summarised in Table 3, this configuration is currently the most widely adopted across Europe (Picuno et al. 2025; Calabrese et al. 2021).

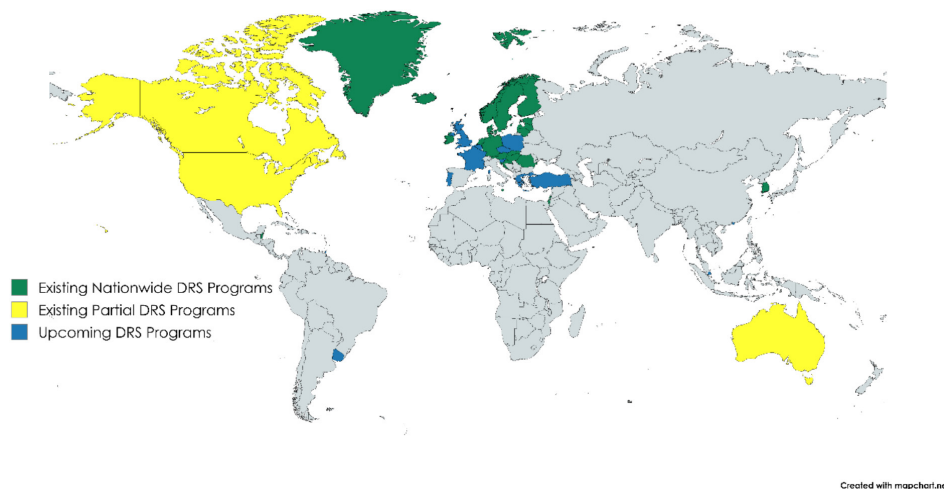


FIGURE 7 | DRS progress worldwide (Source: Consulting and Reloop 2024a).

TABLE 3 | Current DRS programme in Europe (Sources: Consulting and Reloop 2024a; Calabrese et al. 2021).

Country	Year of implementation	Operating mode
Sweden	1984	Operator-closing
Iceland	1989	Consumer-closing
Finland	1996	Operator-closing
Norway	1999	Operator-closing
Denmark	2002	Operator-closing
Germany	2003	Retailer-closing
The Netherlands	2005	Producer-closing
Estonia	2005	Operator-closing
Croatia	2006	Operator-closing
Lithuania	2016	Operator-closing
Latvia	2022	Retailer-closing
Malta	2022	Operator-closing
Slovakia	2022	Operator-closing
Austria	2023	Operator-closing
Romania	2023	Operator-closing
Republic of Ireland	2024	Operator-closing

Its clearly defined governance structure and funding architecture make it a robust reference model for testing the proposed design logic and for ensuring the adoption procedure's replicability across different contexts.

The illustrative implementation developed around CORIPET in the previous sections served not only to validate key assumptions but also to demonstrate how economic sustainability can be systematically assessed prior to full-scale deployment. Yet the operator-closing mode cannot be assumed to be universally appropriate. As the case of Iceland illustrates, regional market structures and regulatory traditions may require alternative configurations, such as the consumer-closing model, where refund management is decentralised (Calabrese et al. 2021). This variability underscores the need for flexible adaptation mechanisms within an overarching design strategy, one that enables standardisation without enforcing uniformity.

Based on these considerations and the insights developed in the previous sections, this study outlines a three-step procedure for the adoption of economically sustainable DRS:

1. Model assessment: Policymakers and stakeholders analyse existing DRS configurations and funding architectures (see Table 3) to identify the operating mode most consistent with the institutional and infrastructural conditions of the target regional context.
2. Model tinkering: The selected model is calibrated to the local context by adjusting key design variables, such as

deposit value, EC and cost structures (e.g., transportation or personnel costs).

3. Model validation: The adapted configuration is then tested through ex ante scenario analysis, simulating plausible return rates, resale price conditions and funding levels to verify whether the system can achieve break-even under varying circumstances while meeting defined environmental performance targets.

By following this sequence, policymakers can reduce implementation risks and design DRS that are both economically viable and operationally resilient, but also tailored to the specific challenges of their regional context. Furthermore, this structured procedure can provide a transferable framework that helps reduce uncertainty and supports informed decision-making in countries where DRS have not yet been introduced. For instance, China, one of the world's largest producers of SUPs, still lacks a national DRS for such material (Zhou et al. 2023). Generalising validated DRS design procedures could significantly advance global waste management efforts, particularly in low-performing regions. From a circular economy perspective, scaling up DRS adoption represents a concrete step toward systemic transformation.

7 | Discussion and Conclusions

Managing SUPs and packaging waste has become a pressing policy concern, leading to increasingly stringent regulatory frameworks. At the European level, instruments such as the PPWR and Directive 2019/904 explicitly require Member States to achieve a 90% collection rate for PET bottles by 2029. However, regulatory mandates alone are not sufficient. The real challenge lies in designing waste management systems that are not only environmentally effective but also economically sustainable and operationally robust, capable of maintaining high performance over time and across diverse implementation contexts.

This study has addressed this challenge by adopting a design science research strategy, through which a set of technological rules was developed, tested and subsequently generalised into a transferable adoption procedure for economically sustainable DRS. The scenario analysis demonstrated how return rates, deposit values, handling fees (EC) and system scale interact to shape economic sustainability.

These findings are consistent with existing international evidence. For instance, Schneider et al. (2021) showed that in Croatia, the profitability of DRS operators declines as the collection rate increases because of the reduction of unredeemed deposits and the additional costs of managing higher return volumes. The importance of economies of scale has been widely recognised in studies on the recycling and reuse of packaging materials (Lu et al. 2022; Schneider et al. 2021). Furthermore, the role of adjustment mechanisms, such as deposit value and the EC, has been emphasised in previous implementations across Europe (Consulting and Reloop 2024a, 2022, 2020). Evidence from Spain and Portugal suggests that deposit levels must be carefully calibrated: if set too low, they fail to incentivise

consumer participation; if too high, they may face resistance and reduce DRS acceptance (Roca et al. 2022; Martinho, Alves, et al. 2024). The outcomes of the design strategy, aligned with the international findings, underscore a key structural trade-off between environmental performance and economic sustainability, reinforcing the importance of designing balanced DRS configurations.

The relevance of this well-designed DRS becomes even clearer when placed in the broader context of global circularity. According to the Circularity Gap Report 2025, only 6.9% of materials consumed globally are currently sourced from recycled or reused streams, the lowest level recorded to date. This marks a continuous decline from 9.1% in 2018 to around 7.2% in 2023, highlighting the growing disconnect between material use and circular economy objectives (Circle Economy 2025).

By promoting reuse and recycling, DRS reduces reliance on virgin materials, mitigates resource depletion and lowers environmental pressures (Zorpas 2024; Ghisellini and Ulgiati 2020). Recent works have also emphasised the importance of implementing eco-innovations not only for their environmental benefits but also for their systemic contribution to circularity (Brogi and Menichini 2024; Calabrese et al. 2024). In this light, DRS should be seen not merely as a compliance tool but also as a strategic investment in the circular economy. Indeed, the transition to circularity is no longer a matter of principle, but of execution. With global circularity currently at just 6.9%, scalable mechanisms such as DRS are urgently needed to reverse the prevailing linear trend, and those actors, public or private, who can align operational design with regulatory intent will be best positioned to lead this transition and deliver durable sustainability outcomes.

Nonetheless, DRS adoption continues to present significant challenges. Variability in the quality of recycled materials, high upfront infrastructure costs and persistent uncertainty around economic sustainability can hinder implementation, particularly in resource-constrained settings. Addressing these barriers requires an evidence-based approach capable of reconciling environmental objectives with financial and operational constraints.

The proposed design strategy provides a structured, scenario-informed methodology for evaluating and adopting DRS across diverse contexts. It enables policymakers and stakeholders to move from ad hoc experimentation toward evidence-based system design, balancing environmental ambition with economic feasibility.

8 | Limitations and Direction for Future Research

This study presents some limitations that suggest directions for further research. First, the field-testing was conducted on a single DRS operating mode, the operator-closing configuration, selected for its widespread adoption in Europe and its compatibility with the Italian context. Future research should examine how the proposed adoption procedure performs in settings better suited to alternative configurations, helping to clarify its broader applicability.

Second, the scenario analysis focused exclusively on PET beverage containers. This choice was deliberate, as PET is not only the most widely used material in the Italian beverage sector but also the subject of specific EU regulatory targets (e.g., PPWR and Directive 2019/904). In addition, the availability of detailed operational and financial data through collaboration with CORIPET enabled a realistic and data-rich scenario-based validation. However, extending the framework to include other materials, such as aluminium and glass, would offer a more comprehensive understanding of how key design variables interact across different packaging systems. Comparative analyses across material streams could yield valuable insights for integrated DRS design.

Third, the evaluation prioritised economic sustainability as the principal criterion. While this focus aligns with the objective of improving adoption feasibility, it does not fully account for the social and environmental dimensions. Future research should incorporate additional variables, such as consumer acceptance and life-cycle environmental impacts, to support the development of a more holistic and multidimensional evaluation framework.

Finally, the generalisability of the proposed adoption procedure should be tested further through applications in diverse national and regional contexts. Although the Italian case provides a credible test environment, its specific institutional and infrastructural features may not reflect those of countries operating under different regulatory or infrastructural conditions. Cross-context validation of the design strategy would enhance its policy relevance and strengthen its potential as a decision-support tool for decision-makers engaged in waste governance and circular economy transitions.

Author Contributions

All authors are listed in alphabetical order. They contributed equally to the conception and design of the study, to the analysis and interpretation of data and to the drafting and critical revision of the manuscript. All authors approved the final version to be published and agreed to be accountable for all aspects of the work.

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Conflicts of Interest

The authors declare no conflicts of interest.

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