Packaging and reusability: POLITECNICO DI MILANO engineers revisit glass bottles life cycle

Comprehensive examination of the impact on the environment of glass bottle re-use in Italy had POLITECNICO DI MILANO researchers Camilla Tua and Professors Mario Grosso and Lucia Rigamonti visiting mineral water bottling sites to consult delivery logistics. All from the Department of Civil and Environmental Engineering the trio further factored in production, washing and end-of-life data while analysing bottle rotations via life cycle assessment - also in comparison to single-use alternatives.

According to Markets and Markets (2018), of late there's been a burgeoning demand for reusable packaging across various industrial sectors - driven not only by industry but also by end-consumers seeking to reduce their reliance upon disposable items. Here comprehensive assessment of actual environmental benefits inherent to the practice of reuse calls for a reliable evaluation tool. Nestled within the overarching concept of the circular economy, the pre-eminent choice in this regard, recognized across the board, is that of Life Cycle Assessment (LCA). In like manner, prior research has scrutinised different types of reusable packaging - consistently affirming the superiority of reusability over single-use alternatives. That said, it's crucial to acknowledge the existence of certain ecological hotspots -primarily in the regeneration phase- warranting due attention (Biganzoli et al., 2018; Biganzoli et al., 2019; Tua et al., 2019).

BEVERAGES AND PACKAGING

Unlike many sectors, the beverage industry holds predominantly to single-use packaging. Indeed the market share of refillable beverage containers plummeted Europewide from 41 percent (90 billion units sold) in 2000 to a mere 21 percent (55 billion units) in 2015 (Reloop Inc 2019). Notwithstanding this decline, refillable bottles present themselves as a viable, sustainable alternative to single-use counterparts within various sub-sectors. For instance, a recent study on beer packaging from Germany revealed commendable environmental performance for glass refillable bottles, especially when catering to local markets within a 100 km radius and enduring over at least 25 cycles (Deutsche Aluminium Verpackung Recycling GmbH 2010). Similar findings were yielded by the French context. An analysis based upon a system of refillable beer glass bottles, subjected to 20 reuses and distributed over a 250 km radius, demonstrated substantially lower environmental impacts compared to an equivalent system reliant on single-use glass bottles: reductions of 86 percent in acidification, 79 percent in climate change impact and 76 percent in primary energy consumption (Deroche Consultants 2009). Even in the carbonated soft drinks sector, refillable glass bottles emerge as a sustainable option. A British study determined that reusing glass bottles thrice over could render the carbon footprint of drink distribution comparable to that of single-use 0.5-litre virgin PET bottles and aluminium cans (Amienyo et al., 2013). This study seeks to assess the environmental ramifications associated with the Refillable Glass Bottles (RBs) system concerning the number of deliveries within the Italian mineral water sector. Such an analysis assumes particular relevance in Italy given that it's among the largest consumers of bottled water both in Europe and globally - consuming 13.5 billion litres in 2017, equivalent to 222 litres per inhabitant (Bevitalia 2018). Primary data pertaining to the reconditioning process and distribution logistics were meticulously compiled from four bottled water companies, collectively representing a substantial 25 percent market share in RBs in Italy.

MATERIAL AND METHODS

The environmental assessment adhered to the LCA methodology, guided by ISO 14040 (ISO 2006) and ISO 14044 (ISO 2018) standards, in tandem with the Product Environmental Footprint (PEF) Guide (Zampori and Pant, 2019). Data processing

Table 1. Main characteristics of the packaging under study.

Component of RBs	Material	Amount (g/bottle)
Bottle (refillable)	Glass	452
Screw cap (single-use)	Aluminium (body)	1.4
	Plastic (seal and liner)	0.4
Label (single-use)	Paper	1.0

was facilitated by SimaPro software (version 9.0). In accordance with the aforementioned standards and documents, the LCA entails four primary phases: goal and scope definition, inventory analysis, impact assessment, and interpretation.

DEFINING GOALS

The study's overarching objectives encompass:

- Assessing the impacts of the RBs system with regard to the number of deliveries (hereinafter denoted as 'n') for mineral water distribution in Italy.
- Identifying the contribution of key stages (RBs production and end of life, RBs reconditioning, and RBs distribution) towards environmental impact, thereby offering insights for more sustainable management to companies.
- Ascertaining the circumstances under which the RBs system outperforms an alternative system predicated on Single-use Glass Bottles (SBs) of equivalent capacity.

SCOPE DELINEATION

System Description

The RBs system centres on glass bottles equipped with screw caps and informative labelling (Table 1). While bottles are available in diverse sizes, the 1-litre variant reigns supreme and serves as the reference point.

In the RBs system (Fig. 1), the constituent elements of refillable packaging undergo dedicated manufacturing in specialised facilities before being transported to a bottling facility. Here, bottles undergo

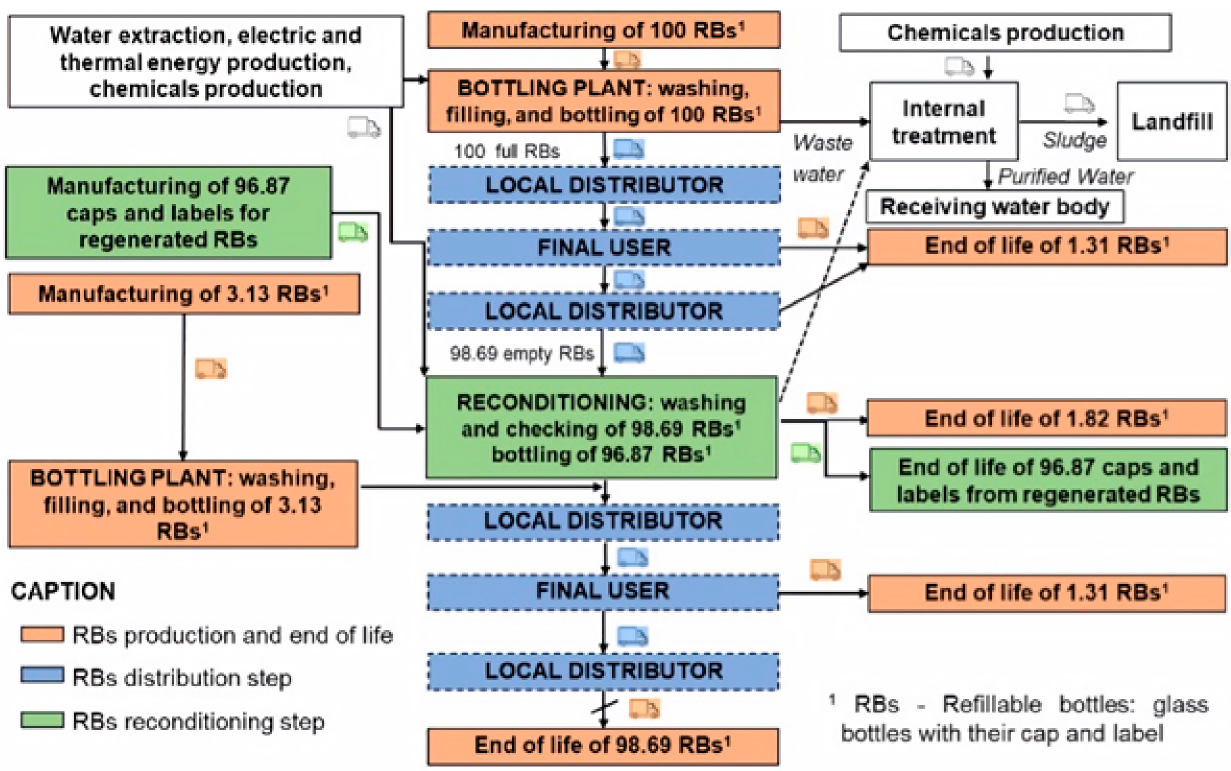

Fig. 1. Analysed system with the relative system boundary.

a sequence of processes, including washing with hot water and chemicals (detergent, release agent for labels, acid product, and disinfectant), filling with water, capping, labelling and packaging for distribution. Subsequently, full bottles are dispatched to local distributors, who simultaneously retrieve empty ones. An impressive 98.69 percent of empty bottles are reclaimed (primary data sourced from the surveyed companies), while losses during distribution (1.31 percent per delivery) are anticipated to be handled through separate collection and recycling of glass.

During the regeneration phase, caps are removed from all returned bottles, which then undergo manual and electronic inspections to detect any damage. At this stage, approximately 1.85 percent of washed bottles are deemed unsuitable for reuse. Regenerated bottles, along with new ones to compensate for distribution and regeneration losses, are filled, capped and labelled with fresh caps and labels before being packaged for delivery.

The bottling facility generates wastewater and solid waste, including discarded caps, labels and damaged bottles. Wastewater is subjected to chemical-physical treatment within an internal plant to adjust pH and reduce surfactant concentrations. Purified wastewater is subsequently discharged into a receiving water body, while process sludge is periodically dehydrated and sent to landfill. Solid waste is directed to a dedicated sorting and recycling facility.

Based on collected primary data, the study assumes a maximum of 30 deliveries. This reusability rate aligns with recommendations found in the PEF guide (Zampori and Pant, 2019).

Functional Unit

The functional unit revolves around provision of a specific volume of mineral water to end users through 1-litre glass bottles. Consequently, the functional unit (FU) equates to 100 litres of mineral water (equivalent to 100 bottles) per delivery, with the number of deliveries (n) ranging from 1 to 30. For n=1, refillable bottles are employed only once and subsequently discarded, setting the reference flow at 100 new bottles. For n=2, refillable bottles are returned to the bottling plant after the first use, resulting in 3.13 bottles being discarded (1.31 during distribution and 1.82 during reconditioning), while 96.87 are made available for the second delivery. Thus, the reference flow stands at 103.13 new bottles. In a general context, the reference flow translates to (100 + 3.13(n-1)) new bottles, as illustrated in Fig. 2.

System Boundary

The system boundary (Fig. 1) encompasses:

- Manufacturing of RBs components and their transportation to the bottling plant (comprising 100 new RBs and replacements for losses).
- Initial washing, filling, capping and labelling of RBs (involving energy, water and chemical consumption, along with wastewater treatment, including sludge management).
- RBs distribution (covering transportation from the bottling plant

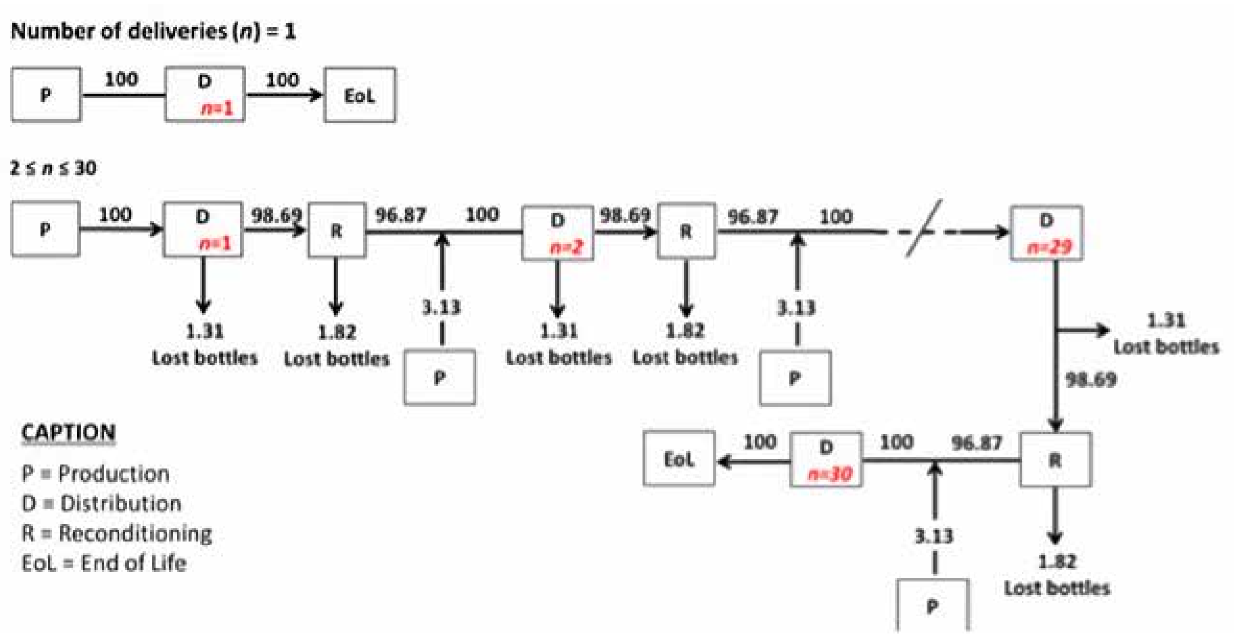

Fig. 2. Simplified chart of the life cycle of 100 RBs as the number of deliveries changes.

to local distributors and subsequently to end users).

- Reconditioning process for RBs (encompassing energy, water, chemicals, wastewater treatment and cap/label replacements).
- End of life of RBs components, including transportation and waste treatment at dedicated facilities (RBs after n uses and RBs discarded at each use). In certain instances, multifunctionality linked to the recovery of energy and materials was addressed by expanding the system boundary (Finnveden et al., 2009).

Data Quality

The study primarily relies upon the operations of four bottling companies situated in northern Italy, collectively responsible for water distribution across the national territory in 2017. Data sources are predominantly primary, encompassing distribution, initial bottling, reconditioning, as well as input from operators at waste treatment facilities in northern Italy regarding the end-of-life processes for RBs components and sludge. For background system processes (such as chemical production), data from the ecoinvent 3.5 database were utilised (with allocation cut-off by classification approach) (Ecoinvent 2018).

Selected Indicators

A comprehensive assessment was conducted, encompassing 14 impact categories derived from the Environmental Footprint Life Cycle Impact Assessment Method, version 2.0 (Fazio et al., 2018). These categories encompass climate change (CC), ozone depletion (OD), photochemical ozone formation (POF), particulate matter (PM), human toxicity (non-cancer effects - HTNC and cancer effects - HTC), acidification (A), aquatic freshwater eutrophication (FE), aquatic marine eutrophication (ME), terrestrial eutrophication (TE), freshwater ecotoxicity (FEC), water scarcity (WS), resource use (energy carriers - RUEC, minerals and metals - RUMM).

Inventory

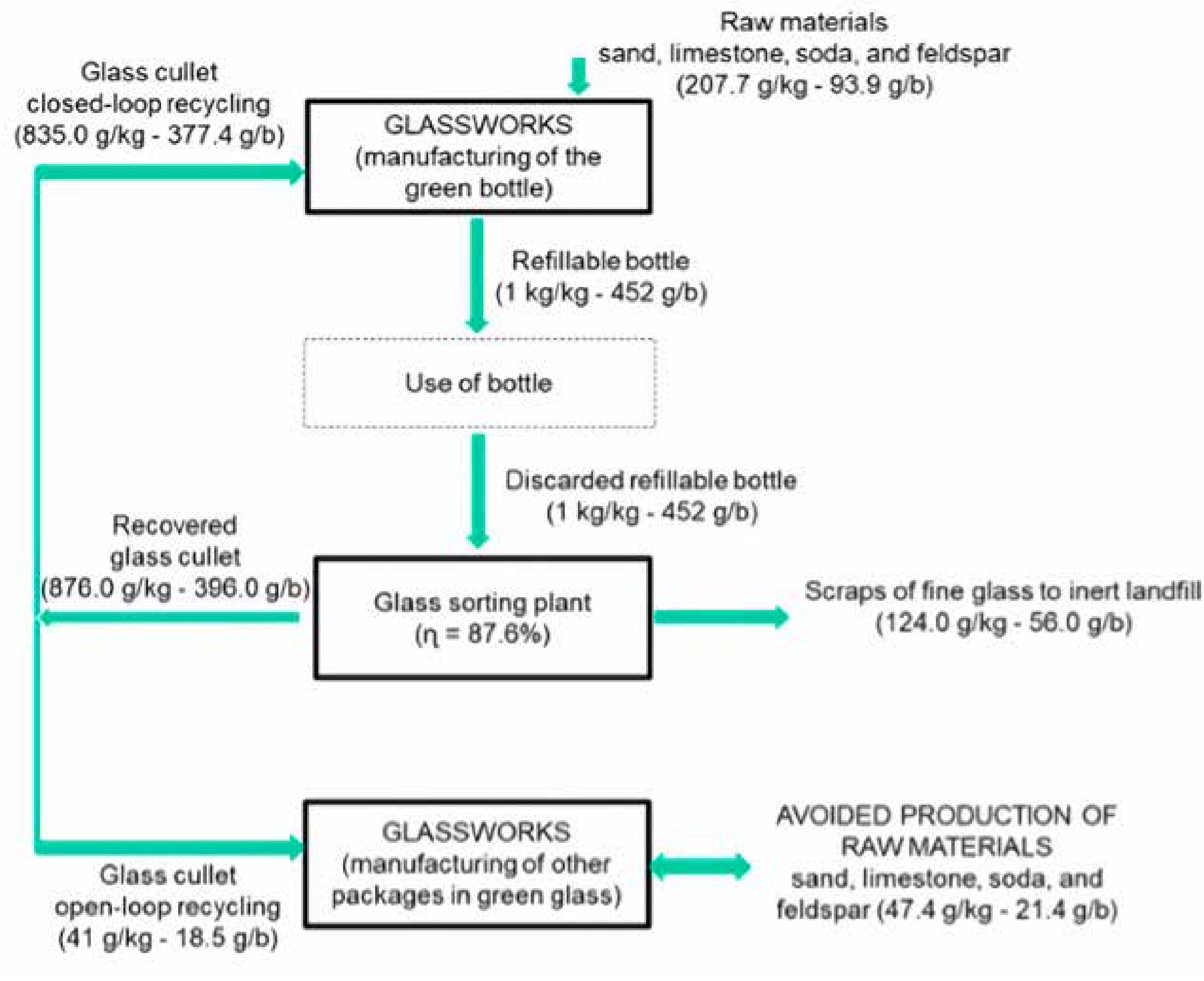

Fig. 3. Mass balance related to the production of a green glass bottle according to a process of closed-loop recycling. g/b = g/bottle.

This section catalogues the primary data employed in modelling the processes encompassed within the system boundary.

Packaging production and end-of-life

The manufacturing of green glass bottles adhered to the average European composition within the ecoinvent database (Ecoinvent 2018), a configuration consistent with the Italian context. The production process entailed melting glass cullet (835 g/kg bottle) and virgin raw materials such as sand, soda, limestone and feldspar (208 g/kg bottle). As depicted in Fig. 3, glass cullet, procured directly from end-of-life RBs after undergoing a sorting process (efficiency of 87.6 percent and electricity consumption equivalent to 19 Wh/kg bottle), constituted a significant portion of the raw materials. A portion of the reclaimed glass cullet (835 g/kg) was channelled into producing new RBs via closed-loop recycling, while the remaining segment (41 g/kg bottle) was allocated to the creation of other green glass packages through open-loop recycling, substituting virgin raw materials at a ratio of 1:1.15 by mass (Ecoinvent 2018).

Various stages, including melting in the furnace, forming, cooling, testing and packing, were modelled using European data reflecting actual consumption and emission levels within container glass manufacturing (Scalet et al., 2013). Transportation of the manufactured glass bottles from the glassworks to the bottling plant involved large-sized trucks (exceeding 32 tons) and spanned an average distance of 200 km.

The aluminium body of the cap was fashioned through the deep drawing of thin foils, primarily utilising the 8011 alloy (comprising 98.5 percent primary aluminium, 0.8 percent cast iron and 0.7 percent silicon of metallurgical grade; AZoM 2013). The liner and seal, on the other hand, were crafted via the extrusion of plastic granules, constituting a blend of polyethylene and polyvinylidene chloride. Given the cap's production location in Spain, the manufacturing process factored in the electricity mix of this specific region. Subsequent transportation to the Italian bottling plant (averaging 1100 km) was anticipated to involve small trucks, freight trains, and container ships, apportioned accordingly.

Following use, the cap was directed to a metal sorting facility, wherein the aluminium body underwent separation from plastic elements before being crushed and pressed (involving electricity consumption and diesel). The plastic waste was slated for incineration within a municipal solid waste incinerator, yielding electricity and thermal energy recovery (1.5 kWh and 3.2 MJ per kg of input waste). Aluminium scraps, conversely, were dispatched to a smelter, where they substituted primary pure aluminium (99.7 percent) at a ratio of 1:0.7 by mass, predicated on economic evaluation (Koffler and Florin, 2013).

Paper label production employed uncoated, wood-containing paper, followed by transportation to the bottling plant via small trucks (averaging 120 km). The end-of-life processing for labels depended upon the disposal context. In instances where labels were discarded at the bottling plant, they were directed to a paper sorting facility before ultimately reaching a paper mill. In the absence of primary data, the recycling process at the paper mill drew from the BREF document pertaining to pulp, paper, and board production (Suhr et al., 2015). Notably, no credits were factored in for material recovery or reductions in virgin paper production, owing to the low-quality nature of label paper necessitating substantial mixing with other paper types for recycling. Labels discarded by users (due to bottle damage or leaks) were presumed to be collected alongside the glass bottle (via separate glass collection) and sent to a glass sorting facility. Here, they were separated from the glass cullet through light body aspiration and subsequently incinerated for electricity and thermal energy recovery (0.7 kWh and 1.4 MJ per kg of input waste).

First Washing and Bottling / Reconditioning Process

A comprehensive inventory of operations conducted at the bottling facility is presented in Table 2, relying upon primary data sourced from the surveyed companies. In instances of first washing and bottling, cap and label replacements were omitted. Wastewater generated was subjected to treatment in a physical-chemical plant within the bottling facility. This treatment involved electricity (already incorporated into the bottling plant's overall consumption, as detailed in Table 2) and 3.69 kg of sulfuric acid per cubic metre. The process yielded 1 cubic metre of purified water and 0.54 kg of process sludge, with the purified water discharged into a receiving water body, accompanied by emissions comprising 27 g/m^3 BOD5, 54 g/m3 COD, 3 g/m^3 total nitrogen, 0.3 g/m3 total phosphorus, 55 g/m3 sulphate, 13 g/m3 chloride, and 10 g/m3 total suspended solids. Process sludge (at five percent dry matter) was subjected to conditioning and dewatering, entailing the consumption of ferric chloride solution, lime, and electricity. Outflows comprised dewatered sludge (178 g/kg input sludge, with 35 percent dry matter) destined for a nearby landfill and supernatant (0.84 litres per kilogram of input sludge) routed to a municipal wastewater treatment plant.

Table 2. Inventory of the operations in the bottling facility for refillable bottles based on collected primary data. Data refer to one bottle entering the facility.

Input	Amount per bottle
Electricity	44 Wh
Water for washing (well water)	0.67 l
Heating of water (natural gas, conventional boiler)	459 kJ
Detergent (solution of caustic soda)	0.24 g
Disinfectant (based on peracetic acid)	1.15 g
Release agent for label	
Type A (based on EDTA)	0.12 mg
Type B (based on sodium cumene sulfonate)	0.24 mg
Acid product - removal of the mineral residue	
Type A (based on sulfuric acid)	65 mg
Type B (based on lactic acid)	65 mg
Transport of chemicals to the bottling plant	1.52 g × 200 km
Caps substitution in the regenerated bottles (production + end of life) [1]	1.77 g
Labels substitution in the regenerated bottles (production + end of life) [1]	0.98 g
Output	**Amount per bottle**
Wastewater to the internal treatment	0.67 l

[1] The substitution is not performed in the first washing.

Distribution

Distribution of RBs encompasses transportation from the bottling plant to local distributors and onward delivery to end users. Relevant inventory data are detailed in Table 3.

RESULTS AND DISCUSSION

Impact Assessment

Impacts associated with the system involving 100 RBs prepared for the n_{th} delivery encompass the environmental loads of:

- Production and end-of-life processes for [100 + 3.13 (n-1)] RBs.
- Reconditioning of 98.69 × (n-1) RBs.
- Distribution of 100 × (n + 1) RBs.

With an increasing number of deliveries, the contribution of the

Step	Truck type	Transported mass (*kg/bottle*)	Transportation distance
Transport to the local distributor	Large-size lorries (> 32 metric ton) Euro 3: 84% Euro 4: 7% Euro 5: 6% Euro 6: 3%	Outward journey: 1.7 [1] Return trip: 0.7 [1]	200 km (A sensitivity analysis was performed on this parameter)
Transport to the final user	Small-size lorries (< 7.5 metric ton) Euro 3: 84% Euro 4: 7% Euro 5: 7% Euro 6: 2%	Outward journey: 1.65 [2] Return trip: 0.65 [2]	15 km

'production + end-of-life' stage gradually diminishes, consistently falling below 30 percent across all indicators for n = 30 (Fig. 4).

Conversely, the contributions of the reconditioning and distribution stages swell with the number of uses. For n = 30 (Fig. 4), the contribution of distribution generally exceeds 50 percent, surging to 80 percent for the impact category of freshwater ecotoxicity. Meanwhile, the reconditioning process exerts a more modest influence, remaining under 45 percent, except for impact categories such as freshwater eutrophication (53 percent) and water scarcity (59 percent). The principal burdens of the reconditioning process, contingent on the indicators, stem from electricity consumption, heating of washing water (facilitated by a conventional gas boiler), the production of primary aluminium for cap replacement and water usage. Chemicals consumption, wastewater treatment and label replacements exhibit negligible contributions. From an energy standpoint, optimising the reconditioning process could entail reductions in consumption and the promotion of alternative, more efficient energy sources (e.g. a combined heat and power boiler). Concerning

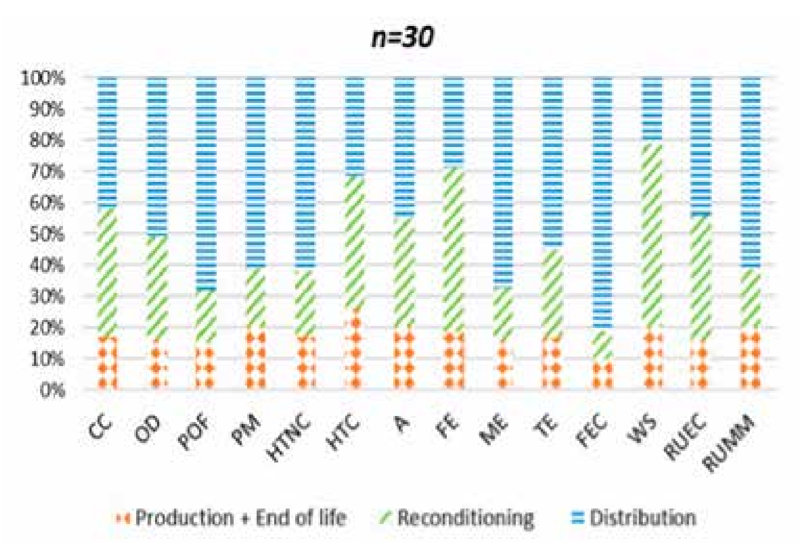

Fig. 4. Percentage contribution of the stages "production + end of life", "reconditioning", and "distribution" to the value of the indicator for n = 30.

cap production, it lies primarily beyond the control of bottling companies, barring supplier selection (with caps currently sourced from Spain). To address this, exploring alternatives to aluminium or weight reduction for caps may warrant some consideration during the design phase. In the distribution stage, a significant portion of the impact stems from transportation to local distributors. The baseline scenario presupposes an average transportation distance of 200 km, though the sensitivity analysis investigates the influence of this parameter. Promoting the use of vehicles featuring Euro class 5 or 6 motors, instead of class 3, has the potential to reduce transportation burdens.

Reconditioning vs Single-use

This section juxtaposes the RBs system against an alternative Single-use glass Bottles system (SBs). Here, the reference flow for meeting the functional unit (FU) entails 100 × n × SBs. Single-use bottles are portrayed as having identical capacity and weight to refillable bottles. Their production and end-of-life processes mirror the descriptions detailed in the inventory system for refillable bottles, with the distinction that all bottles are disposed of by users in the glass collection, without being returned to the company. In contrast to the RBs system, distribution modelling for single-use bottles differs. Single-use bottles are primarily retailed at large-scale retail stores, with transportation from retailer to user modelled as a roundtrip of four kms via private car, factoring in a purchase of 20 articles. Comparing the two alternatives, the RBs system exhibits superior environmental performance under average operational conditions, beginning with two deliveries. For n = 2, the ratio between the RBs system's impact and that of the SBs system spans from 44 percent to 74 percent, contingent on the indicators. With the maximum number of deliveries (n = 30), this ratio decreases to 17 percent–37 percent (as exemplified by the climate change impact category in Fig. 5).

Sensitivity Analysis

Several sensitivity analyses were conducted on the most crucial parameters within the RBs system (bottle weight and maximum number of uses, average refund rate, and distribution distance) to assess their influence on the results. Of these parameters, only the distribution distance between the bottling plant and RBs distributor (varied up to 1000 km) affected the comparison between SBs and RBs systems. For a 400 km distance, a mini-

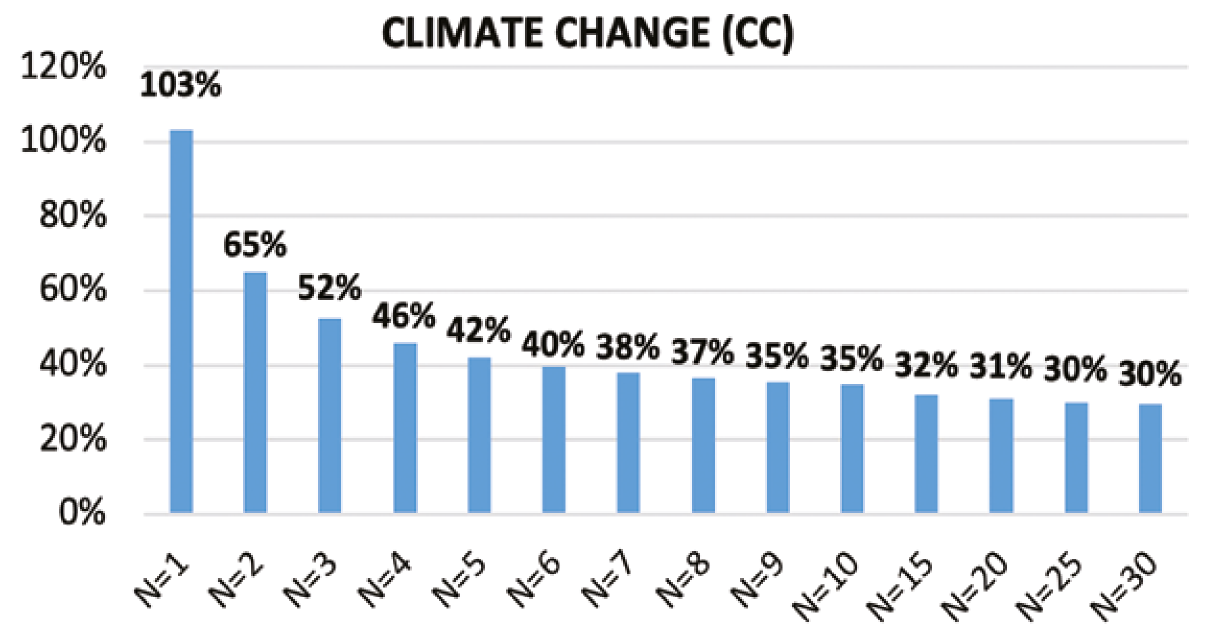

Fig. 5. Ratio between the value of the indicator *climate change* in the RBs and SBs system, for each number of deliveries.

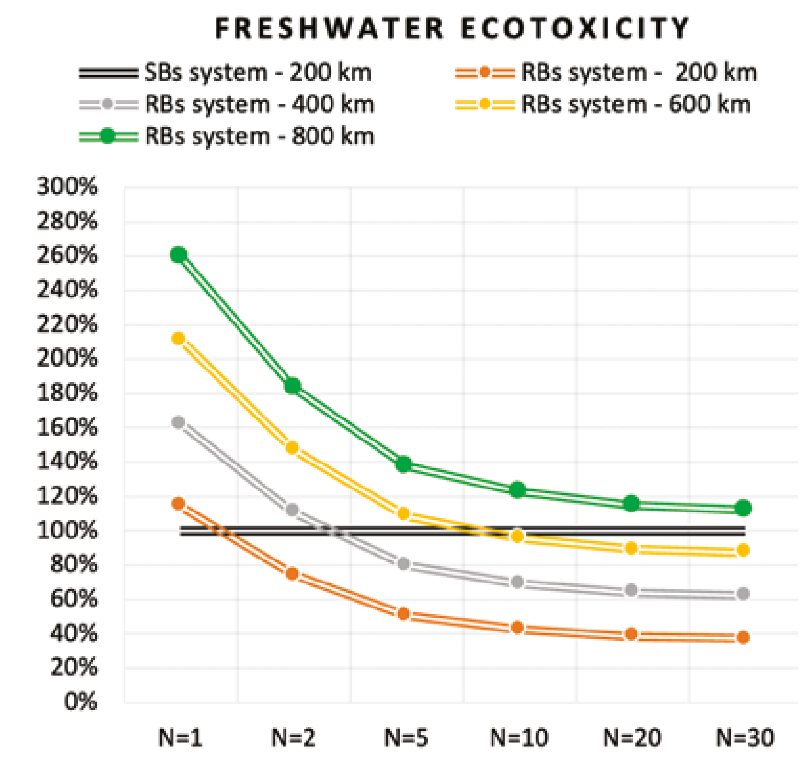

Fig. 6. Comparison between the value of the indicator in the RBs and SBs system (the value of the indicator in the SBs system is put at 100 percent), for each number of deliveries and for different values of transportation distance in the RBs system. The category freshwater ecotoxicity is taken as reference because it is the most influenced by the distance.

mum of four deliveries was required to outperform single-use distribution, while at 800 km or more, the RBs system failed to be cost-effective even for n = 30 (Fig. 6).

Conclusions and Recommendations

This study scrutinised the environmental performance of the refillable glass bottle system for mineral water distribution in Italy, contingent on the number of uses. Findings underscored that the RBs system's impacts were primarily linked to the distribution stage, particularly the transportation of bottles from the bottling plant to local distributors (averaging 200 km). For the maximum number of uses (n = 30), the distribution stage's contribution could reach up to 80 percent of the overall indicator. In contrast, the environmental burdens associated with the reconditioning process were more modest, typically remaining under 45 percent, except for specific impact categories like freshwater eutrophication (53 percent) and water scarcity (59 percent). Major contributors to the reconditioning process' impact included electricity consumption, heating of washing water (facilitated by a conventional gas boiler), primary aluminium production for caps, and water usage. Chemical consumption, wastewater treatment, and label replacements played a minor role.

In comparison to single-use bottles, the use of refillable bottles was substantially more environmentally preferable for a local market (within 200 km), achieving better environmental performance starting from just two deliveries. However, the distance between the bottling plant and the local distributor played a pivotal role in impact evaluation. For a 400 km distance, a minimum of four uses of refillable bottles were necessary to surpass single-use distribution, while at 800 km or more, the RBs system was environmentally disadvantageous even for 30 uses.

This study represents part of a broader research initiative focused on assessing the environmental implications of re-use practices in Italy. Future LCAs targeting other reusable packaging types will be undertaken employing a similar modelling approach. ■

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