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Life Cycle Analysis of an Innovative Oligomineral Water Dispensing System

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Abstract

This thesis presents a comprehensive Life Cycle Assessment (LCA) of a sustainable vending machine system designed to dispense oligomineral water in reusable paper bottles. Motivated by the urgent need to reduce single-use plastic waste and support the transition toward a circular economy, this study evaluates both the production and use stages of the vending machine and the paper bottles, with particular focus on material consumption, energy use, and environmental impact.

Using standardized LCA methods, including Environmental Footprint (EF) method, Single issue method IPCC 2021 and Single issue method CED (Cumulative Energy Demand), the research identifies major contributors to the system environmental impact, such as fossil resource dependency and emissions generated during material production.

Key findings suggest that replacing traditional energy sources with renewables and reducing material waste can markedly improve environmental outcomes. Recommendations include adopting a renewable energy mix to power the vending machines, minimizing stand-by energy consumption, and optimizing the bottle material composition and design to reduce emissions and waste. This thesis demonstrates that eco-innovative vending solutions can offer an impactful alternative to single-use plastic bottles, aligning with European sustainability goals and paving the way for more responsible water consumption.

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BOPA	Biaxially Oriented Polyamide
CED	Cumulative Energy Demand
EPD	Environmental Product Declaration
EVOH	Ethylene Vinyl Alcohol
HDPE	High-Density Polyethylene
IMPACT	Integrated Membrane Pre-activated Carbon Technology
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LCT	Life Cycle Thinking
LDPE	Low-Density Polyethylene
PE	Polyethylene
SUP	Single Use Plastic
VM	Vending Machine

1. INTRODUCTION

1.1 Context

The consumption of plastic-bottled water is a significant environmental issue, particularly due to the challenges in waste management and the associated CO_2 emissions.

The global climate changes have led many nations to develop protocols and regulations aimed at reducing the global warming. The European Commission has introduced the Green Deal, a series of political initiatives with the goal of achieving climate neutrality by 2050. It establishes specific objectives to facilitate the transition to a circular economy. The plan underscores the importance of innovation, research and development too, with financial incentives and support tools aimed at fostering the adoption of innovative technologies and processes that enhance material circularity and reduce environmental impact. Frans Timmermans, Executive Vice-President for the European Green Deal, stated on November 30, 2022, that the proposals reduce packaging waste, promote reuse and refill, increase the use of recycled plastics, and facilitate the recycling of packaging. [1]

In Italy, the production and consumption of single-use plastic products pose a substantial problem, especially within the food and beverage industries. Italy is the leading country in Europe for bottled water consumption. [2]

The Single Use Plastics (SUP) directive [3], adopted by Italy through Legislative Decree No. 196 of November 8, 2021 [4], aims to reduce the environmental impact of single-use plastic products, particularly on the oceans, and to promote a circular economy. The directive introduces restrictions and bans on a range of single-use plastic items, including cutlery, plates, straws, and polystyrene food containers, and obliges producers to bear the costs of waste management and to inform consumers about proper disposal methods. Although the directive does not explicitly prohibit the use of plastic bottles, the promotion of more sustainable alternatives and the improvement of recycling practices are encouraged to reduce the environmental impact of plastic bottles, which remain a significant part of daily consumption. Since the directive does not ban the use of plastic bottles, it is up to responsible companies to differentiate themselves and implement eco-innovations to enhance sustainable development.

It is crucial to shift our focus towards more sustainable solutions. Given the public concern about tap water, often perceived as risky and potentially unsafe, it is important to develop alternatives. One of them is an innovative vending machine exploiting a water treatment process that produces low-mineral water (oligomineral) from municipal water infrastructure, this solution is filled in a sterilized and sealed paper bottle, usable up to 10 times. This solution is totally safe and aligned with the current regulations concerning water security.

1.2 Objective

The objective of this thesis is to assess the environmental impact and energy consumption of an innovative vending machine using a Life Cycle Assessment (LCA). The LCA focuses on both the production and use phases, with particular attention to emissions related to transportation. Additionally, energy consumption has been thoroughly analysed using the SimaPro software (version 9.6.0.1) and the "Ecoinvent 3.10 – Allocation, cut-off by classification" database. This research was conducted in collaboration with ABC Servizi, a consulting company based in Racconigi (CN).

1.3 Structure

The study is structured into the following chapters:

- Chapter 2 presents a literature analysis.
- Chapter 3 explains the LCA methodology used for the study.
- Chapter 4 defines the goal and scope
- Chapter 5 analyses the production stage of paper bottle and vending machine
- Chapter 6 analyses the use stage if the system composed of the paper bottle, the vending machine and the filtration system
- Chapter 7 provides the interpretation and improvements of the system
- Chapter 8 presents a comparison with single use plastic bottle.
- Chapter 9 presents the conclusion of this study.

2. LITERATURE ANALYSIS

Bottled water purchasing motivations are complex and multifaceted. They include health concerns, convenience, taste preference, and distrust of tap water. Despite these benefits, bottled water consumption has serious environmental implications, particularly regarding plastic waste.

Italy leads Europe in bottled water consumption, this use significantly contributes to the environmental footprint from production to disposal. Globally, about 67 million plastic bottles are discarded every day, underscoring the urgency of addressing single-use plastic pollution. Single-use plastics, including water bottles, form a significant portion of plastic waste, which is often not disposed properly. This improper disposal leads to environmental degradation, with plastics littering landscapes, clogging waterways, and posing a threat to wildlife. The waste problem is worsened by the fact that plastics can take hundreds of years to decompose, thus accumulating in the environment and contributing to pollution on a massive scale. In particular, the accumulation of plastic waste in the oceans leads to the formation of large garbage patches, such as the Great Pacific Garbage Patch. This patch is a vast area of floating debris, primarily consisting of microplastics, which are small plastic pieces resulting from the breakdown of larger plastics. These microplastics are ingested by marine life, entering the food chain and potentially impacting human health. [5]

Recycling presents a critical solution to the plastic waste problem. However, recycling rates for plastic bottles vary widely. In Italy, there is a growing movement towards sustainable waste management, with an increasing number of consumers and organizations advocating for better recycling practices and the use of eco-friendly packaging. This shift is part of a broader push towards a circular economy, where products and materials are kept in use for as long as possible, minimizing waste and environmental impact. Educating the public about the importance of recycling and reducing single-use plastics is essential. By raising awareness and encouraging responsible consumer behavior, it is possible to mitigate the impact of plastic waste on the environment. This involves not only the proper disposal and recycling of plastic bottles but also a greater emphasis on choosing sustainable alternatives, such as reusable water bottles, which can significantly reduce the environmental footprint. Thus, understanding and influencing consumer behavior, especially among younger demographics, is key to addressing the plastic waste problem. By adopting eco-friendly alternatives and supporting recycling initiatives, individuals can play a vital role in reducing plastic pollution and promoting a more sustainable future. [5]

Although most Italians report engaging in sustainable practices, only a minority regularly consumes tap water. This behavior contradicts the notion of a population dedicated to sustainability, as drinking tap water is a straightforward and effective method to minimize environmental impact compared to purchasing bottled water. The predominant concern deterring Italians from consuming tap water is apprehension regarding its quality. This persists despite Italy having some of the highest standards for tap water quality in Europe, indicating a misalignment between public perception and the objective reality of water safety. [2]

Analysing water consumption in Italy from a European perspective, the consumption of bottled mineral water is notable. With an annual per capita consumption of 223 litres, Italy leads both Europe and the world in bottled mineral water consumption, as it is shown in Figure 1. The disparity between Italy and other European nations in terms of bottled water consumption is substantial, with Italians consuming 67% more than Spanish, who are in second place in this category. This underscores the extensive reliance on bottled water despite the high quality of available tap water. [2]

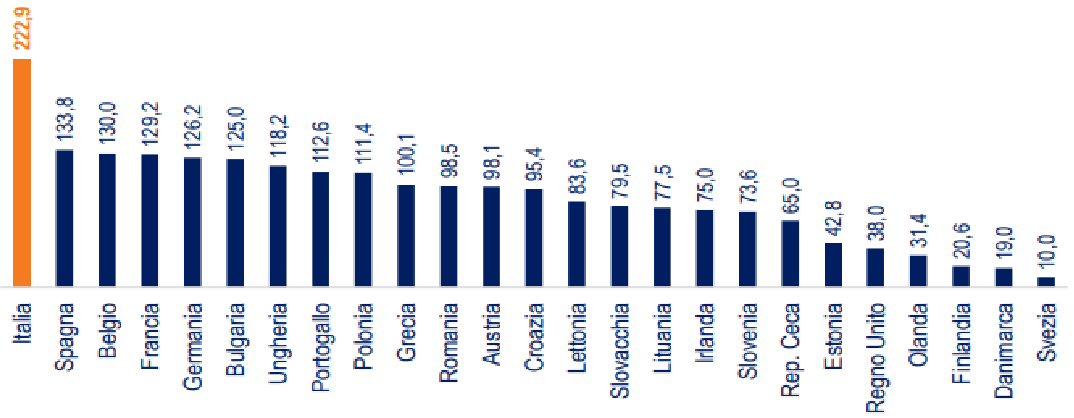
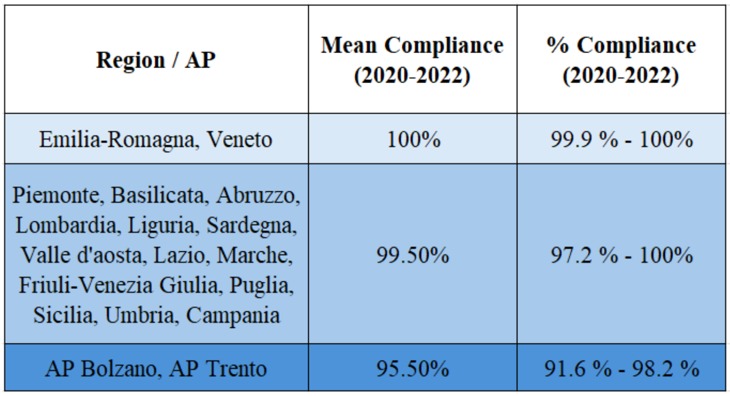


Figure 1 - Bottled water consumption of UE-27 Countries + UK (annual litres pro capite) [2]

In Italy, the quality of potable water is rigorously monitored and maintained, as evidenced by a comprehensive report assessing over 2.5 million water analyses conducted between 2020 and 2022. [6] This extensive evaluation, coordinated by the Italian Ministry of Health and the National Institute of Health, indicates a high level of compliance with regulatory standards across the country, the data are reported in Table 1. Nationally, the average compliance rate for health-related microbiological and chemical parameters is remarkably high at 99.1%, while compliance for indicator parameters, which reflect anomalies in water quality such as taste and odour, stands at 98.4%. Regional data reveal that all Italian Regions and Autonomous Provinces exhibit compliance rates exceeding 95%, with Emilia-Romagna, Veneto, and

Piemonte emerging as top performers. In contrast, lower compliance rates are observed in the Autonomous Provinces of Trento and Bolzano for health-related parameters and in Umbria and Trento for indicator parameters. Although occasional issues with microbiological and environmental contaminants, such as fluoride and arsenic, have been recorded, these instances are localized and managed effectively, underscoring the robust control mechanisms in place. This high standard of water quality is further supported by Italy active role in advocating for stringent European water regulations and its model approach to water safety and access, as highlighted in international forums. The emphasis on maintaining high-quality water across all regions reflects Italy commitment to ensuring safe and reliable water resources for its population. [6]

Table 1 – Regional compliance rate for potable water [6]



Region / AP	Mean Compliance (2020-2022)	% Compliance (2020-2022)
Emilia-Romagna, Veneto	100%	99.9 % - 100%
Piemonte, Basilicata, Abruzzo, Lombardia, Liguria, Sardegna, Valle d'aosta, Lazio, Marche, Friuli-Venezia Giulia, Puglia, Sicilia, Umbria, Campania	99.50%	97.2 % - 100%
AP Bolzano, AP Trento	95.50%	91.6 % - 98.2 %

Dorigoni et al. [7] explores how policymakers can implement interventions to encourage tap water consumption over bottled water, specifically by examining the impact of using descriptive social norms in restaurants to decrease plastic bottled water consumption. Johnstone et al. [8] analysed the determinants of households' decisions to purchase bottled water through a survey of 10,000 households. Their findings reveal that household income, urban residence, and car ownership (for transporting bottled water) positively influence bottled water consumption, while concern about solid waste negatively affects it. Additionally, research by Saylor et al. [9] indicates that socio-demographic factors play a role, with women and undergraduate students consuming more bottled water than men and graduate students. Dolnicar et al. [10], along with Etale et al. [11], highlight psychographic factors such as satisfaction with organoleptic properties, risk perception, trust in water authorities, and perceptions of chemicals, as discussed by Levallois et al. [12], and Doria [13].

Vending machines (VMs) have become a crucial technology for product distribution, providing convenient access to goods, particularly in isolated areas. The COVID-19 pandemic further amplified their importance.

With Japan leading the global market, having around 5.5 million machines (one for every 23 people), the VM industry represents a significant market, generating over $60 billion in annual sales [14].

Manzano-Agugliaro et al. [15] emphasizes the significant role of energy consumption by vending machines, particularly in buildings like universities, where monitoring energy use is essential for improving efficiency and reducing environmental impact. Vending machines, especially those that chill beverages, consume large amounts of electricity daily. For example, over 3 million vending machines in the U.S. in 2006 consumed over 12 billion kWh annually [16]. By 2017, there were 4.6 million vending machines, with cold drinks accounting for 56% of sales and having the highest energy consumption [17]. Studies show that refrigerated vending machines consume between 7 and 11 kWh per day [18], while Energy Star-certified machines use 40% less energy, around 9.5 kWh per day [19]. Research from the University of British Columbia confirmed similar findings, with conventional machines consuming between 9 and 10 kWh per day for beverages [20].

The literature review highlights how the consumption of plastic water bottles in Italy is a significant environmental issue. The use of vending machines presents an alternative that, if properly studied and implemented, could help reduce the environmental impact associated with plastic consumption. To assess the actual sustainability of these technologies, it is essential to analyse them using rigorous and scientifically established tools. In this context, the LCA methodology proves to be a key instrument for measuring and comparing the environmental impact of an innovative vending machine throughout its entire life cycle. The following chapter will explore the application of LCA to better understand the impact of these solutions.

3. LIFE CYCLE ANALYSIS (LCA) METHODOLOGY

3.1 LCA and Life Cycle Thinking (LCT)

The assessment of the sustainability of processes, products, and services using Life Cycle Thinking (LCT) approaches has gained significant importance in both theory and practice. The life cycle perspective is widely acknowledged in global policies, business models, and strategies. In Europe, the eco-design directive, for instance, mandates that the design of goods and services should consider potential environmental impacts across their entire life cycle. This directive also emphasizes the use of the LCA method, with careful attention to the social and economic implications of the proposed measures. [21]

The primary goal is to minimize resource use and emissions while enhancing socioeconomic performance. LCA serves as a practical tool within LCT, offering an objective evaluation of the energy consumption and environmental impacts associated with a product, process, or activity from raw material extraction to end-of-life disposal, this approach is known as "cradle-to-grave". LCA provides a systematic method for evaluating the environmental impacts and resource consumption associated with each stage of a product life cycle. This comprehensive approach includes raw material extraction, manufacturing, transportation, use, reuse, and disposal. The strength of LCA lies in its ability to assess all stages of a process as interconnected and dependent, thereby enabling a multidisciplinary view of environmental performance. [22]

3.2 Regulatory Standards for LCA

In an international framework, the methodology for LCA is regulated by standards, ISO 14040 and ISO 14044 are the main references.

- **ISO 14040**: This standard outline the principles and framework for developing LCA, including planning, execution, interpretation, and communication of results. It provides the guidelines for performing life cycle analyses.
- **ISO 14044**: This standard provides detailed requirements for implementing LCA, including life cycle inventory compilation, impact assessment, and result interpretation. It specifies the procedures necessary for practical application of the LCA methodology.

The stages of an LCA study are interconnected through a feedback loop aimed at refining the model based on the goal of optimizing environmental performance, in Figure 2 is presented a schematic.

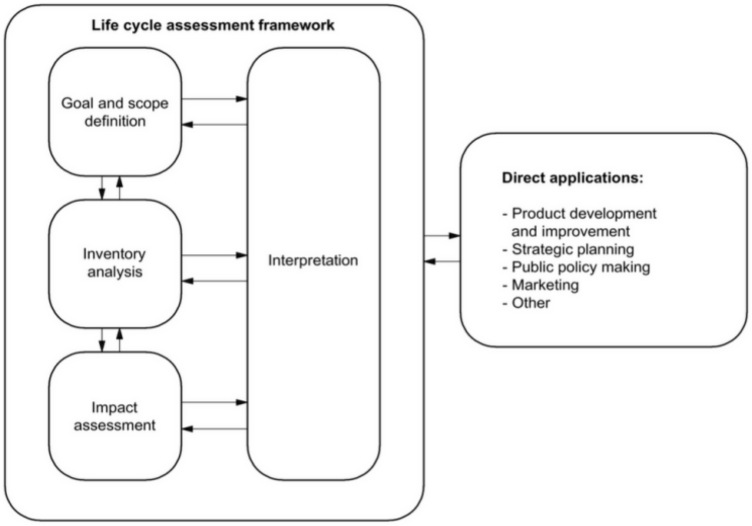


Figure 2 - Life Cycle Assessment Framework [23]

The core stages include:

1. **Definition of Goals and Scope**: Clearly defines the objectives and boundaries of the LCA study. Objectives specify the study purpose, while the scope includes parameters such as functional unit, system boundaries, cut-off criteria, allocation methods, and data quality requirements.
2. **Inventory Analysis**: Involves the collection, organization, and quantification of data related to the material and energy flows throughout the life cycle of a product. This phase includes data collection, calculations, and allocation of input and output flows to co-products.
3. **Impact Assessment (LCIA)**: Transforms inventory data into potential environmental and health impacts. This phase includes selection of impact categories, classification, characterization, and optionally normalization and weighting.
4. **Interpretation and Improvement**: Focuses on analysing results to understand the influence of assumptions and choices made during the study. This phase includes checks for completeness, sensitivity, and consistency, followed by drawing conclusions and making recommendations for improvements.

3.3 Goal and Scope Definition

The initial phase of an LCA involves defining the objectives and scope of the study. Objectives determine the purpose of the analysis, while the scope is detailed through:

- **Functional Unit**: A standardized parameter used to describe the results, providing a reference against which inputs and outputs are normalized.
- **System Boundaries**: Define which process units are included in the LCA, impacting the study's outcomes.
- **Cut-off Criteria**: Rules for excluding certain processes or flows based on their contribution to the overall system.
- **Allocation**: Determines how to assign input and output shares to co-products.
- **Data Types and Sources**: Include both primary data (directly collected) and secondary data (from various sources).
- **Data Quality Requirements**: Ensure data accuracy and relevance.
- **Critical Review Considerations**: Identify the reviewer and their qualifications if a review is necessary.

3.4 Inventory Analysis

In this phase, data related to material and energy flows are collected and quantified. The steps include:

1. **Data Collection**: Gathering quantitative and qualitative data for each process unit.
2. **Calculations**: Processing data to establish inventories.
3. **Allocation**: Assigning shares of input and output flows to co-products, with normalization against the functional unit.

3.5 Impact Assessment (LCIA)

The LCIA phase converts inventory data into potential impacts on the environment and human health. It includes:

1. **Selection of Impact Categories**: Identifying significant environmental impact categories.
2. **Classification**: Associating impacts with the emissions or activities causing them.
3. **Characterization**: Calculating impacts using specific factors for each category.
4. **Normalization (Optional)**: Providing a relative perspective on impact categories.
5. **Weighting (Optional)**: Assigning relative importance to different impacts based on stakeholder priorities.

3.6 Interpretation and Improvement

The final phase involves interpreting results to understand the impact of assumptions and decisions. Key aspects include:

- **Completeness**: Ensuring all relevant data and aspects have been considered
- **Sensitivity**: Assessing the impact of methodological variations on results
- **Consistency**: Verifying that methods and assumptions align with the study goals

Conclusions and recommendations are drawn based on the analysis, focusing on identifying improvements to reduce environmental impacts and enhance sustainability. [24]

3.7 Supporting software for the modelling

The analysis was conducted using SimaPro software (version 9.0). SimaPro is produced by the Dutch company Pré Consultants (Amersfoort, The Netherlands); it was first launched in 1990 and is currently one of the leading software tools for performing Life Cycle Assessments (LCAs), used by industries, universities, and consulting firms in more than 60 countries worldwide. It offers great flexibility through various modelling parameters, enabling interactive analysis of the results [24].

The software includes:

- A user interface for modelling the product system
- A life cycle unit process database
- An impact assessment database with data supporting several life cycle impact assessments methodologies
- A calculator that integrates data from the 22 databases according to the product system model in the user interface. [25]

4. GOAL AND SCOPE DEFINITION

In this chapter, the company selling the system analyzed in this thesis will be introduced. The subsequent sections will delve into the collected data, the cut-off rules, the functional unit, the assumptions and limitations of this study, and the system boundaries. Finally, the characterization methods adopted for the analysis will be presented.

The analysis is structured into two main stages. First, the production phase will be examined, focusing separately on the paper bottle and the vending machine. Following this, the use phase will be analyzed, where the water filtration system and its environmental impact will be discussed in detail. This sequential approach ensures a clear understanding of the environmental performance of each component and their combined contribution during the use phase.

4.1 Description of the company and the product

Biodiversity s.r.l. is a company operating in the field of water distribution services, with the aim of reducing the environmental impact caused by using single use plastic bottles. Biodiversity has developed a patent about a vending machine that fills, sterilizes, and seals oligomineral water on the spot, requiring only a connection to the municipal water network for installation. This vending machine uses reusable paper packaging, Figure 3. Biodiversity mission is to sell sustainable oligomineral water at an affordable price, trying to optimize the logistic and to reduce the massive use of single use plastic bottles.

Figure 3 - Biodiversity paper bottle

The vending machine dispenses oligomineral water through a filtration and sterilization system, sourcing water from the municipal supply. The filtration process uses a composite filter with activated carbon and dual UV lamps for thorough purification. Bottles are multi-layered, with a paper layer and protective nylon and polyethylene films, designed for up to ten reuses. Each bottle has a capacity of 0,55 litres, an optimal size for regular consumer use.

Each dispense is 0,55 litres, with the system averaging thirteen servings daily, resulting in consistent demand for the machine energy and water filtration components. The vending machine operates in three modes (fully active, active, and standby) to balance energy efficiency and continuous availability. All data, assumptions, and metrics derived will be described in detail in the subsequent chapters.

4.2 Data, cut-off, and functional unit

The Life Cycle Assessment (LCA) was conducted using SimaPro software, version 9.6.0.1. The dataset for this analysis, drawn from 2024, consists of primary data supplied by manufacturers and vendors critical to the company's production processes. In addition to primary data, secondary data was utilized, sourced from the "Ecoinvent 3.10 – Allocation, cut-off by classification" database integrated into the software, as well as estimates based on specific assumptions, which are elaborated in Section 4.3.

Through the application of cut-off rules, data deemed insignificant was excluded from the analysis. The Ecoinvent library employed utilizes a cut-off allocation method, assigning the environmental impacts of virgin raw material production and waste disposal entirely to the product's initial life cycle. Conversely, recycled materials bear only the environmental burdens associated with the recycling process and final disposal.

The system boundaries in an LCI/LCA study delineate which life cycle stages, activities, processes, products, and elementary flows can be excluded. These exclusions are permissible only if they do not materially affect the overall results of the study; otherwise, they must be addressed during the interpretation phase. The insignificance of cut-offs is determined by setting quantitative criteria to ensure data completeness within acceptable uncertainty and inaccuracy limits. The quality of data components is interdependent, and the lowest-quality component typically dictates the overall data quality. Thus, the cut-off criteria must align with both the study objectives and the quality of other data components.

Finally, the defined functional unit is:

- 0,550 litres of bottled water supplied by the vending machine.

4.3 Assumptions and limitations

In the Inventory Analysis, the assumptions underlying each modelling decision are comprehensively detailed. Specifically, in cases where the precise composition of vending machine components was unavailable or where data gaps existed due to confidentiality constraints, approximations and estimates were derived by integrating available information with relevant datasets. When necessary, data was reconstructed using literature sources, ensuring a conservative approach to uphold accuracy and reliability.

The key assumptions considered in the study are:

- Total Weight of the Vending Machine: The vending machine total weight is assumed to be 175 kg, which includes all major components such as stainless-steel panels, electronic elements, the refrigeration unit, and the water dispensing mechanism. This weight plays a critical role in calculating transportation emissions and assessing material requirements in the Life Cycle Assessment (LCA).
- Bottles Consumed Per Day: Based on projected use patterns derived from industry studies, it is assumed that the machine dispenses an average of 13 bottles per day. This estimate is based on data indicating that, in Italy, water dispensations represent approximately 14,3% of the total 3,9 billion annual vending machine dispensations, corresponding to 564 million water dispensed units. Given the total number of vending machines (835.360 units) and assuming that the percentage of water dispensations is representative of the distribution of water-dispensing machines, the average annual output per machine is calculated. [34] The result is approximately 13 bottles dispensed per day per machine, assuming continuous operation throughout the year. This assumption serves as a foundation for evaluating daily energy consumption, filter system degradation, and associated environmental impacts over the machine operational life. The analysis supporting these calculations is detailed in Section 6.1.4.
- Panel Thickness and Polycarbonate Weight: The vending machine structural design incorporates stainless steel panels with a thickness of 2,33 mm, as well as polycarbonate panels weighing approximately 2 kg. These specifications were chosen to balance durability with overall machine weight, accounting for both environmental impact and transport requirements.
- Rotating disk: The only available information about the rotating disk, which is responsible for moving the paper bottles within the vending machine, was its weight and the materials used, iron and aluminium. Based on the known available space, the disk surface area was calculated, and the distribution between iron and aluminium was estimated based on assumptions regarding the likely composition of such a component.

- Refrigeration machine: The refrigeration unit used in the actual vending machine is a complex component manufactured by a third-party company, and therefore only limited information was available. To model this unit, an existing process from the Ecoinvent database was selected. This process, originally designed to represent the production of a refrigerated unit for transport, combines various components to simulate a similar system. Two key adjustments were made. First, the refrigerant in the database process was R134a, whereas the actual machine uses R290, so this substitution was implemented. Second, to appropriately scale the model, it was decided to use the unit weight as a basis. The total weight of the refrigeration unit in the original database process was calculated, and a scaling factor was applied to match the weight of the actual refrigeration unit in the vending machine.
- LED Strip: The vending machine integrates an LED strip measuring 183 cm with a 5 mm spacing between individual LEDs; these dimensions and spacing were assumed for the purpose of this study. This configuration provides adequate illumination for user interaction while minimizing energy consumption. The LED's low energy demand contributes to reducing the machine's overall energy footprint, especially in standby mode.
- Energy Consumption Calculations: The vending machine nominal power was estimated based on industry standards for vending machines. The vending machine operates in three distinct modes—fully active, active, and standby.

  The machine total daily energy consumption is calculated by combining the power consumption of each mode with its respective operational duration. Dividing this total by the number of daily dispenses provides an average energy consumption per dispense, which serves as a reference for LCA energy impact assessments.

- Maintenance and Spare Parts: Maintenance activities and general replacement of spare parts were not considered in the analysis due to limited data. Instead, only the replacement of filters in the use phase was included, as this was the most reliable data available. This approach focuses on the filter role in maintaining water purity and the environmental impact of filter replacements, which occurs periodically based on filter life. The structure of the filter was partially unknown, so assumptions were made.

The following assumptions regarding the recycled content of metallic materials were directly sourced from the Ecoinvent database and provide insights into the recycling rates and composition of materials used in the production processes:

- For steel, the following internal recycling rates, they represent the amount of material returned as input to the process after being produced, were assumed: 3% for EAF slag, 14% for secondary metallurgy slag, and 10% for dust.
- For cast iron, the production process assumes that the iron input consists of 35% scrap metal and 65% pig iron. This indicates a significant share of recycled material, reducing reliance on virgin raw materials within the production cycle.
- For aluminum, the production of alloyed billets and ingots uses aluminum scrap as the primary input. Specifically, 60% of the secondary aluminum in the final product comes from external scrap sources, while 40% is derived from internal scrap remelted in a closed loop. In addition, up to 30% of the aluminum input is sourced from primary aluminum slabs. This recycling process enables the achievement of the required alloy composition.

These assumptions are further detailed in subsequent chapters, where their role in shaping the LCA findings and environmental impact assessments is fully explored.

4.4 System boundaries

To ensure an accurate analysis, it is essential to establish the boundaries of the system, including which elements are part of the analysis and which are excluded.

The product life cycle is composed of various stages, specifically:

- Production
- Installation
- Use
- End of life
- Reuse.

This study focuses on examining the production phase. The subsequent sections provide detailed information on the specific processes that have been considered, both for the vending machine and the bottle.

The production phase encompasses all the processes shown in Figure 4. Due to the lack of detailed information regarding the extraction specifics or the distance travelled by raw materials to the production site of the components supplied, data from the Ecoinvent library were utilized. Processes analysed in this study are marked with an X, indicating a "declared module."

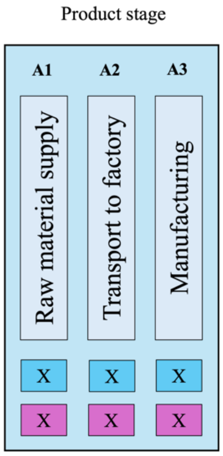


Figure 4 - Production stage for vending machine (blue) and bottle (purple)

The second phase involves the transportation and installation of the vending machine and the bottle at its operational site. Since vending machine are spread across Northern Italy and they are directly sent to the point of use, the analysis does not target any vending machine but rather assesses the machine's overall impact, the transportation phase has been omitted from the study (ND = non-declared module). On the other hand, the bottles are sent to a storage, where they are stock. Additionally, installation is not a relevant factor for the system. This process is showed in Figure 5.

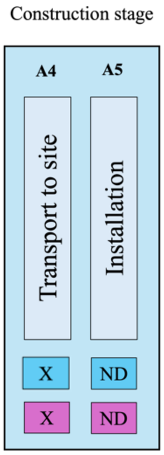


Figure 5 - Construction stage for vending machine (blue) and bottle (purple)

In the use phase, the only aspect that has been studied is the first as shown in Figure 6.

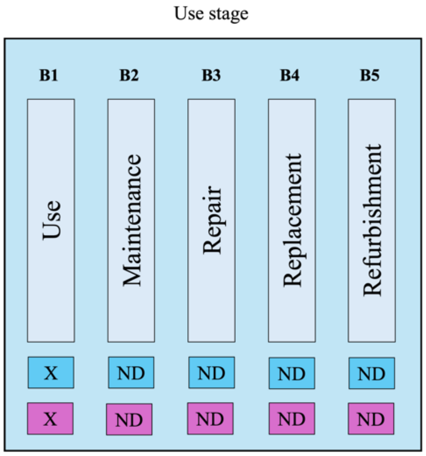


Figure 6 - Use stage for vending machine (blue) and bottle (purple)

The final stages, as depicted in Figure 7 and Figure 8, were not included in this analysis.

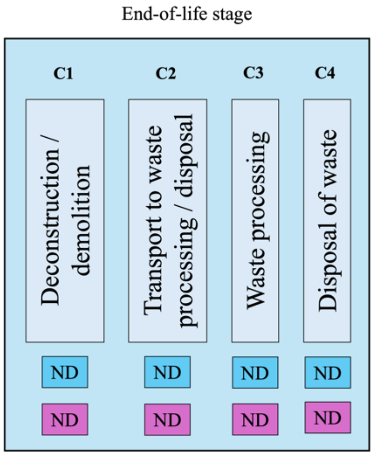


Figure 7 - End-of-life stage for vending machine (blue) and bottle (purple)

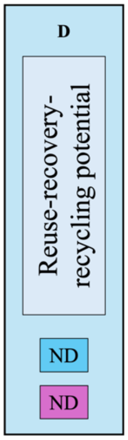


Figure 8 - Reuse stage for vending machine (blue) and bottle (purple)

4.5 Characterization methods

In SimaPro, five categories of methods are presented:

- European: this includes methodologies focused on the European context and they are the most used for European LCA studies.
- Global: it includes comprehensive LCIA methods used for global-level studies.
- North American: for North American studies.
- Single issue: methods focused on a single metric or a single environmental impact, except in the case of a focus on water.
- Water footprint: focused only on water impacts.

For this study, three methods were chosen, which are listed below:

1. The Environmental Footprint (EF) method, developed by the European Commission, is designed to assess environmental impacts within the Product and Organisation Environmental Footprint frameworks. The latest version, EF 3.0, includes updates to key impact categories such as human toxicity, ecotoxicity, and land use. It is used in PEF and OEF studies and adapted for tools like SimaPro, incorporating global factors for flows and adjustments to resource use metrics. This method provides a comprehensive and standardized approach for evaluating environmental performance across sectors. [24]

Table 2 - Impact category and Indicator for Environmental Footprint (EF) method [24]

Impact category	**Indicator**
Climate change	Global Warming Potential 100 years
Ozone depletion	Ozone Depletion Potential (ODP) calculating the destructive effects on the stratospheric ozone layer over a time horizon of 100 years
Human toxicity, cancer	Comparative Toxic Unit for human (CTUh) expressing the expressing the estimated increase in morbidity in the total human population per unit mass of a chemical emitted (cases per kilogramme)
Human toxicity, non-cancer	Comparative Toxic Unit for human (CTUh) expressing the expressing the estimated increase in morbidity in the total human population per unit mass of a chemical emitted (cases per kilogramme)
Respiratory inorganics	Disease Incidence
Ionising radiation, human health	Ionizing Radiation Potential: Quantification of the impact of ionizing radiation on the population, in comparison to Uranium 25
Photochemical ozone formation, human health	Photochemical ozone creation potential (POCP): Expression of the potential contribution to photochemical ozone formation
Acidification	Accumulated Exceedance (AE) characterizing the change in critical load exceedance of the sensitive area in terrestrial and main freshwater ecosystems, to which acidifying substances deposit
Terrestrial eutrophication	Accumulated Exceedance (AE) characterizing the change in critical load exceedance of the sensitive area, to which eutrophying substances deposit
Freshwater eutrophication	Phosphorus equivalents: Expression of the degree to which the emitted nutrients reach the freshwater end compartment (phosphorus considered as limiting factor in freshwater)
Marine eutrophication	Nitrogen equivalent: Expression of the degree to which the emitted nutrients reach the marine end compartment (nitrogen considerate as limiting factor in marine water)
Land use	Soil quality index
Freshwater ecotoxicity	Comparative Toxic Unit for ecosystems (CTUe) expressing an estimate of the potentially affected fraction of species (PAF) integrated over time and volume per unit mass of a chemical emitted (PAF m3 year/kg)
Water use	m3 water eq. deprived

Impact category	Indicator
Resource depletion, fossil	Abiotic resource depletion fossil fuels (ADP-fossil); based on lower heating value
Resource depletion, minerals and metals	Abiotic resource depletion (ADP ultimate reserve)

2. Single issue method IPCC 2021, which stands for Intergovernmental Panel on Climate Change. It is a method developed by the Intergovernmental Panel on Climate Change and is based on the final version of the IPCC report "AR6 Climate Change 2021: The Physical Science Basis," which is still subject to copy-editing, corrigenda, and trickle-back.
3. Single issue method CED (Cumulative Energy Demand), which calculates the cumulative energy demand using data published by Ecoinvent and expanded by PRé for the energy resources available in the SimaPro database.

5. PRODUCTION STAGE

5.1 Inventory analysis

The model used in SimaPro software to simulate the system is described in the following section. Through data collected from the suppliers it was possible to identify all the components that constitute the bottle and the vending machine, understand the manufacturing processes for each, and learn about the processing methods used.

The system under analysis consists of a bottle and a vending machine.

5.1.1 Bottle

The bottle body is made of a paper layer with a grammage of 100 g/m², a 15-micron layer of BOPA (Biaxially Oriented Polyamide), and an additional film composed of PE/EVOH/PE. These layers are produced in Germany in the form of paper rolls. The roll consists of paper produced by an integrated mill, a nylon layer (BOPA) that is already processed into film, and a PE/EVOH/PE layer. The roll is then transported from the German facility to the Italian facility, covering 1.000 km. Once in Italy, the roll is cut to form the paper bottle body. This process results in 56% waste, which is not optimal due to the low production volume, as production is still in its early stages.

Table 3 lists the processes implemented in SimaPro to analyse the production of the Paper Roll.

Table 3 - Production of 1 kg of Paper Roll

Product	Process	Calculation	Value	Unit of measurement
Paper roll	*Paper production, woodfree, coated, at integrated mill*	0,387	0,387	kg
	Nylon 6 production	0,067	0,067	kg
	PE film	2*0,182	0,364	kg
	EVOH production	0,182	0,182	kg
	Transport, freight, lorry 16-32 metric ton, EURO4	1*1.000	1.000	kgkm

Table 4 lists the processes implemented in SimaPro to analyse the production of one kilogram of PE film.

Table 4 - Production of 1 kg of PE Film

Product	Process	Calculation	Value	Unit of measurement
PE film	*Polyethylene, low density, granulate*	1,02	1,02	kg
	Extrusion, plastic film	1,02	1,02	kg

Table 5 lists the processes implemented in SimaPro to analyse the production of the paper bottle body.

Table 5 - Production of 1 unit of Paper Bottle Body

Product	Process	Calculation	Value	Unit of measurement
Paper bottle body	*Paper roll*	0,01121/(1-0,56)	0,0255	kg
	Electricity, medium voltage	53,38/6.725	0,00794	kWh
	Paper (waste treatment) - recycling of paper	0,0255*0,56	0,0143	kg

Table 5 presents a waste factor of 0.56, primarily due to the non-optimized design of the bottle, which leads to a higher level of material loss. Additionally, since production is still in an experimental phase with limited quantities, production waste remains high. In the LCA model, this waste is treated as an output stream intended for recycling as paper, thereby supporting resource recovery within the paper waste management system. A waste factor of 0.56 has therefore been included, as the material composing the bottle body, classified as C/PAP81, is designated as recyclable within the paper waste stream.

The BOPA film possesses excellent properties, and it is suitable for a wide range of high-quality packaging applications. It offers high tensile strength, puncture resistance, flexibility, gas, and aroma barrier properties, as well as good transparency, printability, and durability. [28]

The PE/EVOH/PE material consists of two 20-micron PE (polyethylene) layer, model as PE film, and a 10-micron EVOH (ethylene-vinyl alcohol) layer. It is ideal for advanced packaging applications due to its excellent thermoformability, allowing easy moulding with standard machines. The EVOH layer provides superior gas barrier properties, particularly against oxygen, which helps prevent food oxidation and reduces the need for preservatives. It also retains desirable fragrances while blocking unwanted odours. The material features a high-gloss appearance from the HDPE outer layer, offering hygienic packaging solutions.

Additionally, it is environmentally friendly, being chlorine-free and producing no secondary pollution when incinerated. [29]

The second part of the bottle consists of the spout and the cap, which are produced by a company in Germany. Both are extruded from polyethylene granules. They are shipped in cartons and low-density polyethylene (LDPE) bags to the Italian facility, covering 1.145 km. Subsequently, the paper bottle bodies undergo a process called "capping," during which the spouts are added. At this point, the bottles without caps are packed in cardboard boxes and LDPE bags, along with the boxes containing the caps. Table 6 and Table 7 illustrate the processes used for the modelling of the spout and cap. The production process for a full shipment of these components has been modelled, taking into consideration the packaging used for their transportation. Finally, in Table 8 there are the processes used to model the Paper bottle without the cap.

Table 6 - Production of 1 delivery of Spout

Product	Process	Calculation	Value	Unit of measurement
Spout	*Polyethylene, high density*	0,0018*2.000*24	86,40	kg
	Injection moulding	0,0018*2.000*24	86,40	kg
	Packaging film, low density polyethylene	0,05*24	1,2	kg
	Corrugated board box	0,36*24	8,64	kg
	Transport, freight, lorry 16-32 metric ton, EURO4	(86,4+1,2+8,64)*1.145	110.195	kgkm

Table 7 - Production of 1 delivery of Cap

Product	Process	Calculation	Value	Unit of measurement
Cap	*Polypropylene, granulate*	0,0031*4.000*24	297,6	kg
	Injection moulding	0,0031*4.000*24	297,6	kg
	Corrugated board box production	0,36*24	8,64	kg
	Packaging film, low density polyethylene	0,05*24	1,2	kg

Product	Process	Calculation	Value	Unit of measurement
	Transport, freight, lorry 16-32 metric ton, EURO4	(297,6+8,64+1,2)*1.145	352.019	kgkm

Table 8 - Production of 1 unit of Paper bottle without cap

Product	Process	Calculation	Value	Unit of measurement
Paper bottle w/o cap	*Paper bottle body*	1	1	p
	Spout	0,0018	0,0018	kg
	Electricity, medium voltage	23,178/5.770	0,00402	kWh

The final step of the analysis, detailed in Table 9, is the production stage, where the bottles and caps, packaged in boxes, are delivered to storage, where they remain until purchased. The delivery consists of 675 bottles, calculated based on the volume occupied by each individual bottle within a cardboard box. This approach allows for the allocation of the corresponding weight of the cardboard box and LDPE bag to each bottle. The cardboard and LDPE bag are materials that are treated as waste.

Table 9 - Production of 1 unit of Paper bottle

Product	Process	Calculation	Value	Unit of measurement
Paper bottle production	*Paper bottle without cap*	1	1	p
	Cap	0,0031	0,0031	kg
	Packaging film, low density polyethylene	0,05/675	0,000074	kg
	Corrugated board box	0,36/675	0,00053	kg
	Transport, freight, lorry 16-32 metric ton, EURO4	0,0118*217	453.000	kgkm
	Waste polyethylene	0,05/675	0,000074	kg
	Waste paperboard	0,36/675	0,00053	kg

5.1.2 Paper bottle inventory result

To conduct a comprehensive analysis, it is essential to present the inventory results relative to the functional unit employed in the study, specifically 0,55 litres of bottled water. The following table reports the top 20 input flows of raw materials in the production phase of the paper bottle, organized in descending order.

Table 10 - Inventory result for bottle production (input flow)

Substance	Subcategory	Unit	Total
Carbon dioxide, in air	Raw	kg	3,13E-03
Oil, crude, 43.4 MJ per kg	Raw	kg	2,33E-03
Gravel	Raw	kg	1,72E-03
Coal, hard	Raw	kg	1,25E-03
Oxygen	Raw	kg	1,02E-03
Gangue	Raw	kg	9,26E-04
Coal, brown	Raw	kg	7,01E-04
Nitrogen, atmospheric	Raw	kg	4,04E-04
Shale	Raw	kg	3,62E-04
Calcite	Raw	kg	3,27E-04
Carbon dioxide, non-fossil, resource correction	Raw	kg	2,10E-04
Kaolinite	Raw	kg	1,90E-04
Iron	Raw	kg	1,26E-04
Clay, unspecified	Raw	kg	1,09E-04
Sodium chloride	Raw	kg	8,51E-05
Sand	Raw	kg	6,95E-05
Sulphur	Raw	kg	5,90E-05
Granite	Raw	kg	4,67E-05
Barium	Raw	kg	2,25E-05
Argon-40/kg	Raw	kg	5,84E-06

The inventory result for the paper bottle production reveals various raw material inputs required in the production process. Major inputs, such as crude oil, gravel, sand, and calcium carbonate (as calcite), represent the primary resources for creating the bottle structure. Crude oil, used to produce plastic, contributes to the inner layer of the bottle and the polypropylene cap. The presence of minerals like kaolinite and sodium chloride reflects materials frequently used in the paper industry, possibly as fillers or coatings to improve paper durability and surface quality. Sulphur and iron may be linked to the chemical treatments and energy required for polymer and paper processing. Additionally, carbon dioxide (CO_2) and oxygen are related to the energy consumption and industrial processes involved, reflecting emissions and energy inputs throughout the production stages. These resources reflect both the physical materials needed and the energy inputs inherent to the industrial processes, including energy generation, material refinement, and polymer processing. Collectively, these materials demonstrate the complex interdependencies of plastic and paper production systems, where raw inputs range from fossil fuels to minerals, facilitating both structural integrity and manufacturability of the paper bottle.

Table 11 presents the top 20 output flows of emissions to air, water, and soil during the production phase of the paper bottle. These flows are listed in descending order.

Table 11 - Inventory result for bottle production (emission)

Substance	Subcategory	Unit	Total
Carbon dioxide, fossil	Air	kg	8,74E-03
Carbon dioxide, biogenic	Air	kg	1,94E-03
Sulphate	Water	kg	1,89E-04
Nitrogen, atmospheric	Air	kg	1,49E-04
COD (Chemical Oxygen Demand)	Water	kg	1,42E-04
DOC, Dissolved Organic Carbon	Water	kg	8,81E-05
TOC, Total Organic Carbon	Water	kg	7,29E-05
Chloride	Water	kg	7,28E-05
Silicon	Water	kg	6,79E-05
Calcium (II)	Water	kg	6,60E-05
Sodium (I)	Water	kg	6,48E-05
Methane, fossil	Air	kg	5,50E-05
BOD5 (Biological Oxygen Demand)	Water	kg	3,04E-05
Aluminium (III)	Water	kg	2,59E-05
Magnesium	Water	kg	2,58E-05
Nitrogen oxides	Air	kg	2,29E-05
NMVOC, non-methane volatile organic compounds	Air	kg	2,08E-05
Sulphur dioxide	Air	kg	1,86E-05
Carbon monoxide, fossil	Air	kg	1,86E-05
Iron, ion	Water	kg	1,82E-05

The inventory results reveal significant emissions associated with the paper bottle production process, impacting both air and water quality. Carbon dioxide (CO_2) emissions, both fossil-based and biogenic, dominate air emissions, reflecting the reliance on energy derived from fossil fuels during plastic and paper production. Other air emissions, including methane, sulphur dioxide, and non-methane volatile organic compounds (NMVOCs), are byproducts of combustion processes and organic material use, contributing to greenhouse gases and atmospheric pollution. Water emissions reveal substantial chemical oxygen demand (COD), dissolved organic carbon (DOC), and sulphate levels, indicating high organic content and potential contamination in wastewater, likely originating from paper pulping and chemical processing stages. Furthermore, trace amounts of metals such as aluminium, sodium, and calcium appear in water effluents, attributed to chemical additives and fillers used in paper production. Collectively, these emissions underscore the environmental burden associated with paper bottle production, highlighting the dual impact on atmospheric and aquatic environments due to both fossil fuel-based energy requirements and the extensive use of chemical treatments in the production process.

5.1.3 Vending machine

The vending machine is a water production system outsourced on the spot. This means that the process of water treatment and dispensing is managed by an external provider, who handles all production stages based on the specifications given by the contracting company. It draws water directly from the municipal water supply and, through a filtration and sanitization system that includes a composite filter and two UV lamps, dispenses oligomineral water. Oligomineral water refers to water with a low mineral content, typically beneficial for daily consumption as it promotes hydration without adding excessive minerals to the diet. [30] The vending machine is equipped with a display for user interaction. The external structure is composed of six stainless steel sheets with a thickness of 2,33 mm, along with two decorative polycarbonate panels. Inside the machine, there is a CO2 cylinder used to produce sparkling water, which is not considered in the scope of this analysis. Other internal components include electronic parts and fastening hardware. Additionally, the vending machine is illuminated by a 183 cm LED strip with a 5 mm spacing between the LEDs. The machine also features an integrated system for bottling and sealing. Additionally, it includes a refrigeration system that uses R290 as a refrigerant gas. R290, or propane, is a natural refrigerant known for its low environmental impact due to its minimal contribution to global warming. Moreover, it complies with current environmental regulations concerning the use of eco-friendly refrigerants in cooling systems. [31]

In Table 12 there are shown the various components of the vending machine with the corresponding weight distribution.

Table 12 - Vending machine components

	Components	**Value**	**Unit of measurement**
Vending machine	*Painted and galvanized panels*	104,20	kg
	Rotating disk	35	kg
	Refrigerating machine r290	30	kg
	Polycarbonate panels	1,99	kg

	Components	Value	Unit of measurement
	Screws	1,8	kg
	Electronics components	1,61	kg
	Tablet	0,40	kg
TOTAL		**175**	**kg**

The external structure is composed of steel that undergoes a process called hot rolling, where the steel is heated above its recrystallization temperature and then passed through rollers to achieve the desired shape and thickness. After hot rolling, the steel is treated with a powder coating for painting and with zinc for galvanization. These treatments offer several advantages: powder coating provides a durable, high-quality finish that is resistant to corrosion, while galvanization with zinc adds an additional layer of protection against rust and environmental degradation, thereby significantly increasing the lifespan of the steel structure.

Table 13 - Production of 1 unit of Painted and galvanized panels

Product	Process	Calculation	Value	Unit of measurement
Painted and galvanized panels	*Steel, chromium steel 18/8*	104,2	104,2	kg
	Hot rolling, steel	104,2	104,2	kg
	Powder coat, steel	5,98	5,98	m2
	Zinc coat, coils	5,98	5,98	m2

The decorative panels are made from polycarbonate pellets that are extruded into sheets with an efficiency of 0.94. Table 14 describes the production process in detail.

Table 14 - Production of 1 unit of Polycarbonate panels

Product	Process	Calculation	Value	Unit of measurement
Polycarbonate panels	*Polycarbonate*	1,99/0,94	2,12	kg
	Extrusion of plastic sheets and thermoforming, inline	1,99/0,94	2,12	kg

As shown in Table 12 the second more important component, in terms of weight, is the rotating disk, this component functions as a type of wheel that facilitates the movement of the bottle within the machine. It engages the bottle using a fork mechanism, after which the bottle is filled, sealed, and positioned to be retrieved by the user. The processes used in SimaPro to model this component, named *Rotating disk* are shown in Table 15.

Table 15 - Production of 1 Rotating disk

Product	Process	Calculation	Value	Unit of measurement
Rotating disk	*Cast iron*	23,33	23,33	kg
	Hot rolling, steel	23,33	23,33	kg
	Powder coat, steel	0,3	0,3	m2
	Aluminium alloy, AlLi	11,67	11,67	kg
	Sheet rolling, aluminium	11,67	11,67	kg

Assumptions were made regarding the types of materials used and their weights for the Screw process. The specific process employed is detailed in Table 16.

Table 16 - Production of 1 unit of Screw

Product	Process	Calculation	Value	Unit of measurement
Screw	*Steel, chromium steel 18/8*	0,45	0,45	kg
	Steel, low-alloyed	1,17	1,17	kg
	Brass	0,18	0,18	kg

For the tablet, a pre-existing process from the Ecoinvent database, titled *'Consumer electronics, mobile device, tablet'*, was utilized.

The Electronic components were modelled as shown in Table 17, using pre-existing processes from the Ecoinvent database. The router available in the database had a weight of 2 kg. Since our model weighs 0.4 kg, it was scaled accordingly based on the assumptions made.

Table 17 - Production of 1 unit of Electronics components

Product	Process	Calculation	Value	Unit of measurement
Electronic components	*Router, internet*	0,4/2	0,2	p
	Cable, unspecified	0,4	0,4	kg
	Electronic component, passive, unspecified	0,4	0,4	kg
	Electronic component, active, unspecified	0,4	0,4	kg

For modelling the refrigeration unit, the 'Refrigerating machine R290' process was used. This is an existing process in the Ecoinvent database, which was modified by changing the refrigerant, from R134a to R290, and scaled according to the actual weight of the refrigeration unit.

As for the transportation of the vending machine, an average distance between the manufacturer and the various customers who have purchased this machine so far has been considered, assuming direct shipment. The average transport distance is 500 km.

Table 18 summarizes the processes used to model the production of the vending machine.

Table 18 - Production of 1 vending machine

Product	Process	Calculation	Value	Unit of measurement
Vending machine production	*Refrigerating machine r290*	30/365,78	0,082	p
	Polycarbonate panels	1,99	1,99	kg
	Painted and galvanized panels	104,2	104,2	kg
	Screw	1,8	1,8	kg
	LED strip	1	1	p
	Rotating disk	1	1	p
	Consumer electronics, mobile device, tablet	1	1	p
	Electronics components	1	1	p
	Transport, freight, lorry 16-32 metric ton, EURO4	175*500	87.500	kgkm

5.1.4 Vending machine inventory result

To conduct a comprehensive analysis, it is essential to present the inventory results relative to the functional unit employed in the study, specifically 0,55 litres of bottled water. Table 19 reports the top 20 input flows of raw materials in the production phase of the vending machine, organized in descending order.

Table 19 - Inventory result for vending machine production (input flow)

Substance	Subcategory	Unit	Total
Gangue	Raw	kg	1,71E+03
Coal, hard	Raw	kg	5,54E+02
Gravel	Raw	kg	2,38E+02
Shale	Raw	kg	1,54E+02
Coal, brown	Raw	kg	1,21E+02
Oxygen	Raw	kg	1,11E+02
Iron	Raw	kg	1,11E+02
Calcite	Raw	kg	8,01E+01
Nitrogen, atmospheric	Raw	kg	7,52E+01
Oil, crude, 43.4 MJ per kg	Raw	kg	6,91E+01
Carbon dioxide, in air	Raw	kg	4,65E+01
Chromium	Raw	kg	2,19E+01
Aluminium	Raw	kg	2,04E+01
Clay, unspecified	Raw	kg	1,86E+01
Carbon dioxide, non-fossil, resource correction	Raw	kg	1,57E+01
Nickel	Raw	kg	1,51E+01
Sodium chloride	Raw	kg	1,28E+01
Sand	Raw	kg	1,11E+01
Magnesite	Raw	kg	4,52E+00
Zinc	Raw	kg	4,19E+00

The inventory analysis for the vending machine production highlights various raw material inputs essential for constructing its components. Key materials, such as iron, aluminium, form the core structural elements of the machine, contributing to the framework, steel panels, and refrigeration system. Crude oil, essential for producing plastic, plays a role in manufacturing polycarbonate panels and other plastic parts, such as electronic housing. Additionally, a portion of its consumption is attributed to transportation processes involved in the production of this component. Minerals like calcite, clay, and sodium chloride are utilized in the production process, possibly serving as fillers, coatings, or stabilizers to enhance the durability and finish of the materials. Elements like chromium and nickel are incorporated into metal parts to improve corrosion resistance, particularly in the steel components. Additionally, gases such as oxygen and atmospheric nitrogen relate to energy-intensive manufacturing processes, reflecting the overall emissions and energy demands associated with producing and assembling the machine. These resources represent both the physical building blocks and the energy inputs required for industrial processes like metal smelting, polymer production, and component assembly. Together, they illustrate the complex interplay of raw materials, from fossil fuels to essential minerals, necessary to ensure the structural integrity and functionality of the vending machine.

Table 20 presents the top 20 output flows of emissions to air, water, and soil during the production phase of the vending machine. These flows are listed in descending order.

Table 20 - Inventory result for vending machine production (emission)

Substance	Subcategory	Unit	Total
Carbon dioxide, fossil	Air	kg	1,68E+03
Silicon	Water	kg	1,07E+02
Carbon dioxide, biogenic	Air	kg	6,72E+01
Sulphate	Water	kg	5,17E+01
Aluminium (III)	Water	kg	4,76E+01
COD (Chemical Oxygen Demand)	Water	kg	4,26E+01
Iron, ion	Water	kg	3,84E+01
Calcium (II)	Water	kg	2,94E+01
Sodium (I)	Water	kg	1,61E+01
DOC, Dissolved Organic Carbon	Water	kg	1,43E+01
Chloride	Water	kg	1,39E+01
TOC, Total Organic Carbon	Water	kg	1,35E+01
Magnesium	Water	kg	1,19E+01
Potassium (I)	Water	kg	7,13E+00
Methane, fossil	Air	kg	6,58E+00
Sulphur dioxide	Air	kg	6,45E+00
Nitrogen oxides	Air	kg	5,18E+00
BOD5 (Biological Oxygen Demand)	Water	kg	5,12E+00
Phosphate	Water	kg	4,20E+00
Nitrogen, atmospheric	Air	kg	4,12E+00

The inventory results also indicate considerable emissions generated during the production process, impacting both air and water quality. Carbon dioxide emissions, from both fossil and biogenic sources, dominate air pollutants, mirroring the energy reliance on fossil fuels in metalworking, plastic formation, and assembly stages. Other atmospheric emissions, such as methane, sulphur dioxide, and nitrogen oxides, emerge from combustion and high-temperature processes, contributing to greenhouse gases and air pollution. Waterborne emissions reveal substantial chemical oxygen demand (COD), dissolved organic carbon (DOC), and sulphate levels, suggesting organic and chemical contamination likely stemming from the washing, cooling, and chemical treatment stages in production. Trace amounts of metals, including aluminium, sodium, and magnesium, are found in wastewater, likely due to leaching from metal parts or additives used in surface treatments. Together, these emissions underscore the environmental impact of vending machine production, highlighting the dual strain on atmospheric and aquatic ecosystems due to the high energy requirements and extensive chemical use throughout the manufacturing process.

5.2 Impact assessment

The following sections describe the results obtained using each of the methods mentioned in paragraph 4.5.

5.2.1 Bottle

a) The Environmental Footprint (EF) method

By using the first method chosen to assess the environmental impact of the paper bottle, namely the Environmental Footprint (EF) method, it was possible to obtain the results for the production stage.

Table 21 - EF method total impact assessment for paper bottle production

Damage Category	**Unit**	**Value for 1 Paper bottle**
Acidification	mol H+ eq	4,27E-04
Climate change	kg CO2 eq	1,10E-01
Ecotoxicity, freshwater	CTUe	5,01E-01
Eutrophication, freshwater	kg P eq	2,70E-05
Eutrophication, marine	kg N eq	1,03E-04
Eutrophication, terrestrial	mol N eq	1,03E-03
Human toxicity, cancer	CTUh	3,34E-10
Human toxicity, non-cancer	CTUh	8,46E-10
Ionising radiation	kBq U-235 eq	8,75E-03
Land use	Pt	1,88E+00
Ozone depletion	kg CFC11 eq	2,57E-09
Particulate matter	disease inc.	6,18E-09
Photochemical ozone formation	kg NMVOC eq	4,96E-04
Resource use, fossils	MJ	2,24E+00
Resource use, minerals, and metals	kg Sb eq	6,21E-07
Water use	m3 depriv.	6,01E-02

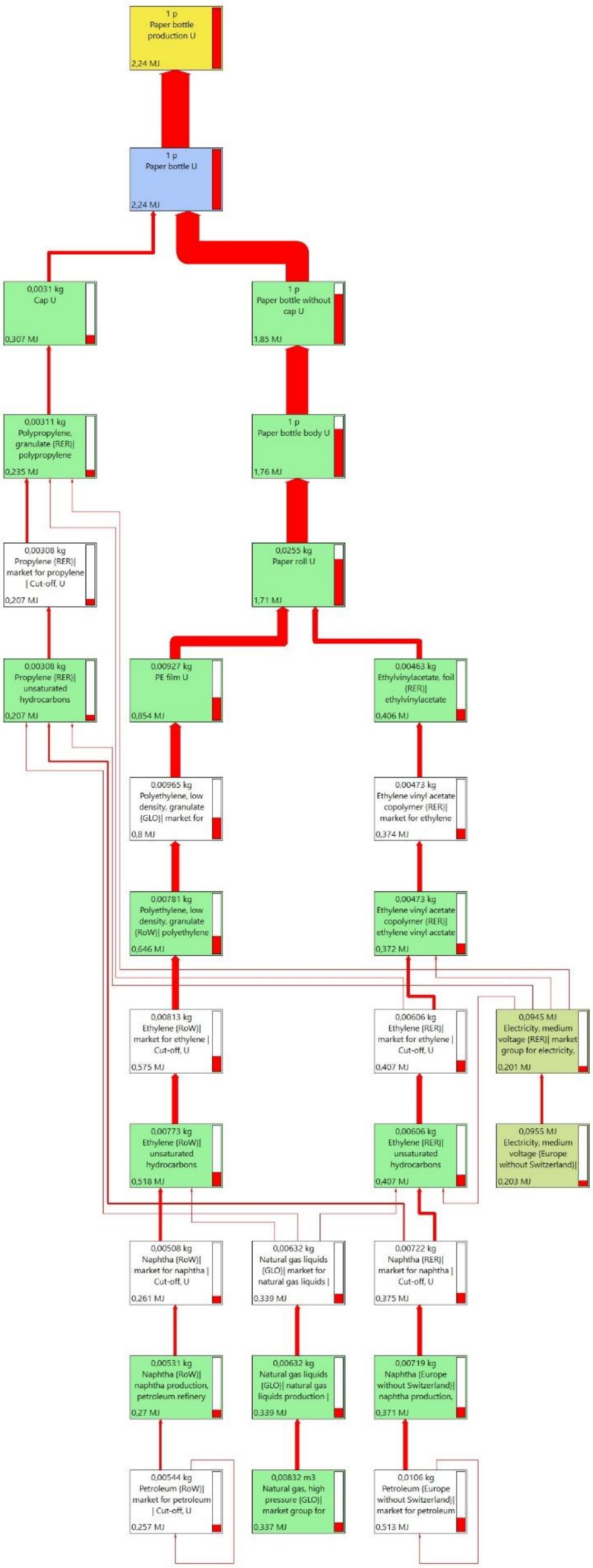


Figure 9 - EF method total for bottle production. Resource use, fossil

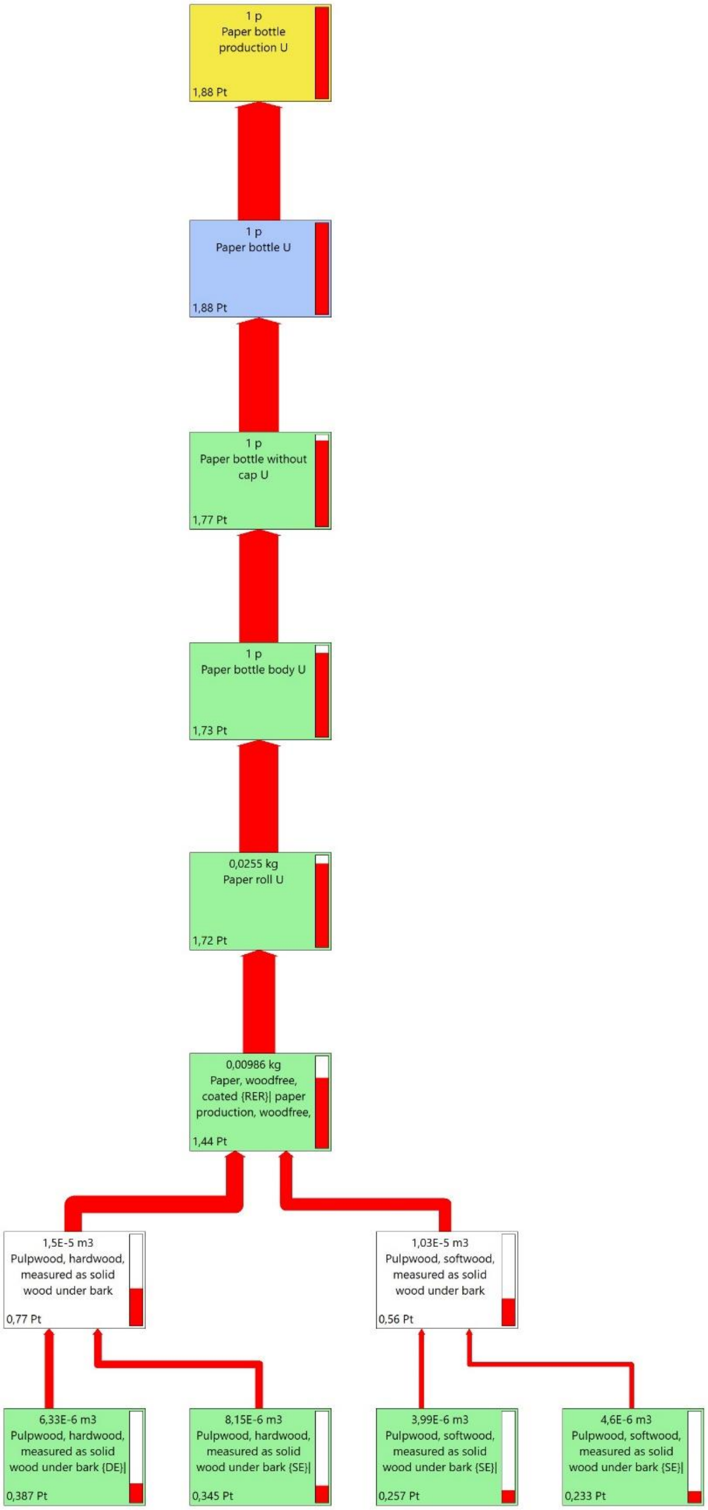


Figure 10 - EF method total for bottle production. Land use

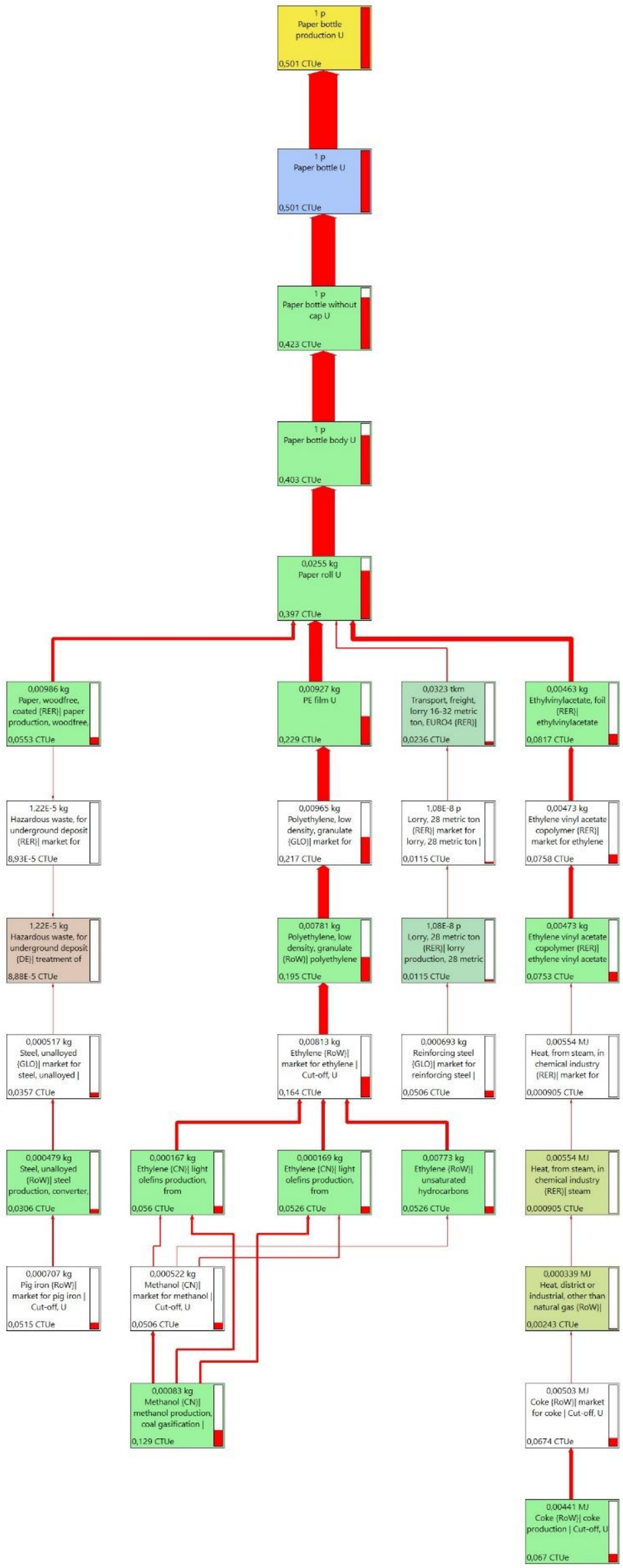


Figure 11 - EF method total for bottle production. Ecotoxicity, freshwater

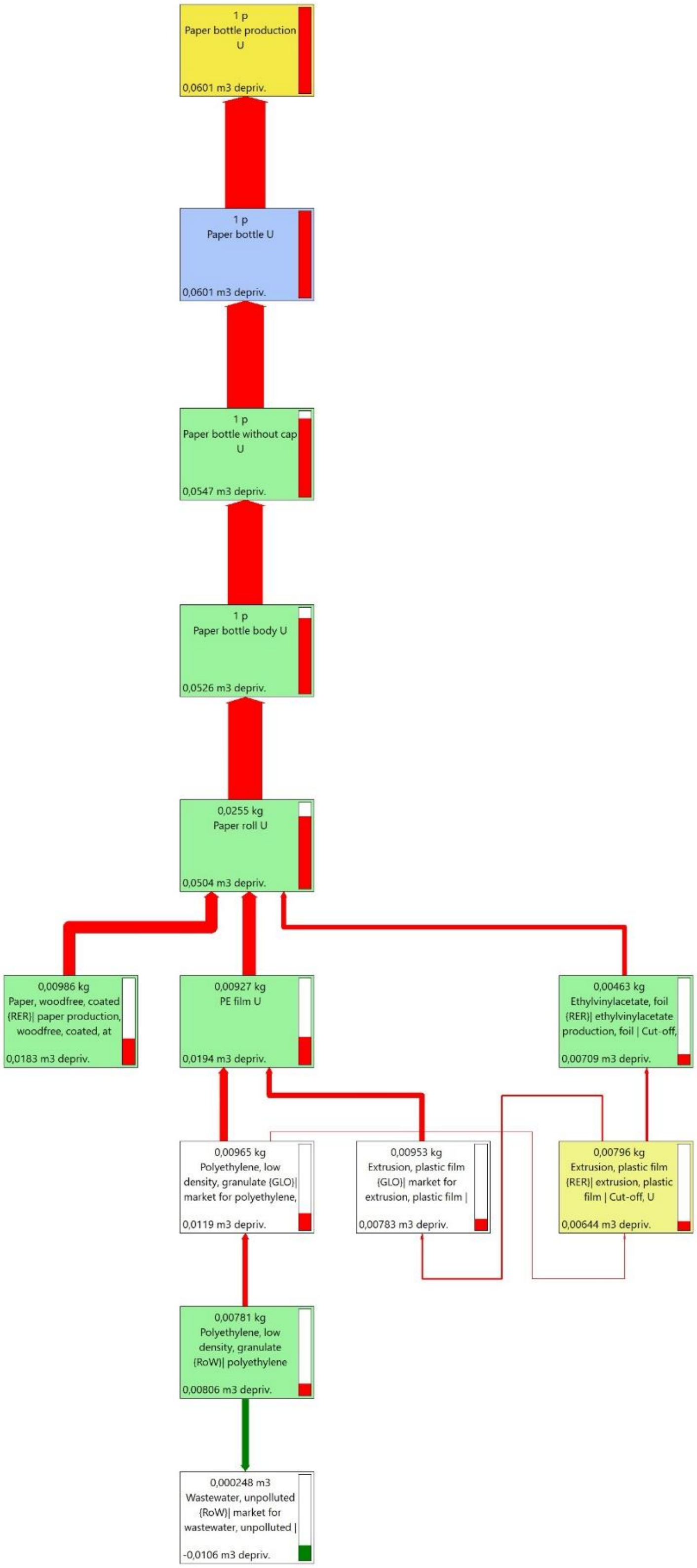


Figure 12 - EF method total for bottle production. Water use

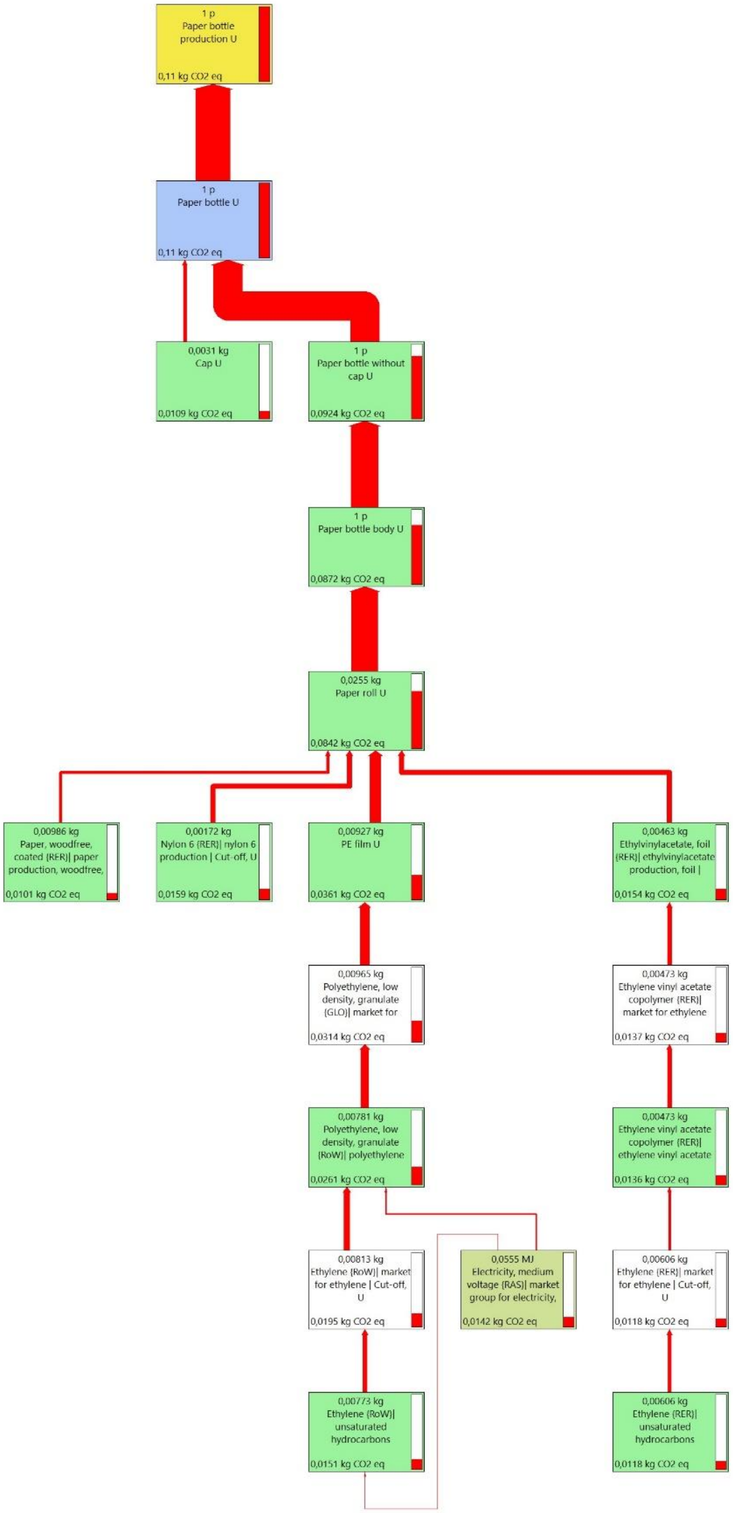


Figure 13 - EF method total for bottle production. Climate Change

The results for the damage category are shown in Figure 9, Figure 10, Figure 11, Figure 12 and Figure 13. In the first graph, we can observe that the most significant contributor to the fossil resource use category, Figure 9, is polyethylene production, which is used in the protective layer of the bottle structure. This high impact is primarily due to the reliance on fossil-based plastics. Regarding land use, Figure 10, paper production contributes the most, as it requires substantial land resources for its raw material, primarily trees. For the freshwater ecotoxicity impact category, polyethylene production once again emerges as the most impactful process. In the water use category, both paper and polyethylene production have significant effects, as these processes require substantial water consumption. Finally, in the climate change impact category, it is evident that the production of a single bottle contributes to the emission of 0,11 kg of CO_2 equivalent, with most emissions linked to the production of polyethylene as a raw material. The paper production process is also energy-intensive and uses various chemicals, further contributing to greenhouse gas emissions and water pollution, as indicated in the Resource Use, Climate Change, and Freshwater Ecotoxicity categories. Furthermore, the cultivation of raw materials for paper production, such as wood pulp, demands extensive land resources, which is highlighted in the Land Use category. Across all categories, however, the component exerting the highest overall impact is polyethylene, particularly in its application within protective films.

b) The single issue – IPCC 2021 method

By using the second method chosen to evaluate the environmental impact of the paper bottle, namely the IPCC 2021 method, it was possible to obtain results for the overall case of the paper bottle over its entire useful life.

Table 22 - IPCC 2021 total for paper bottle production

Impact Category	Unit	Value for 1 Paper bottle
GWP100 - fossil	kg CO2-eq	0,1087
GWP100 - biogenic	kg CO2-eq	0,0007
GWP100 - land transformation	kg CO2-eq	0,0002

As can be seen in Table 22, the greatest impact was obtained for the GWP – fossil category.

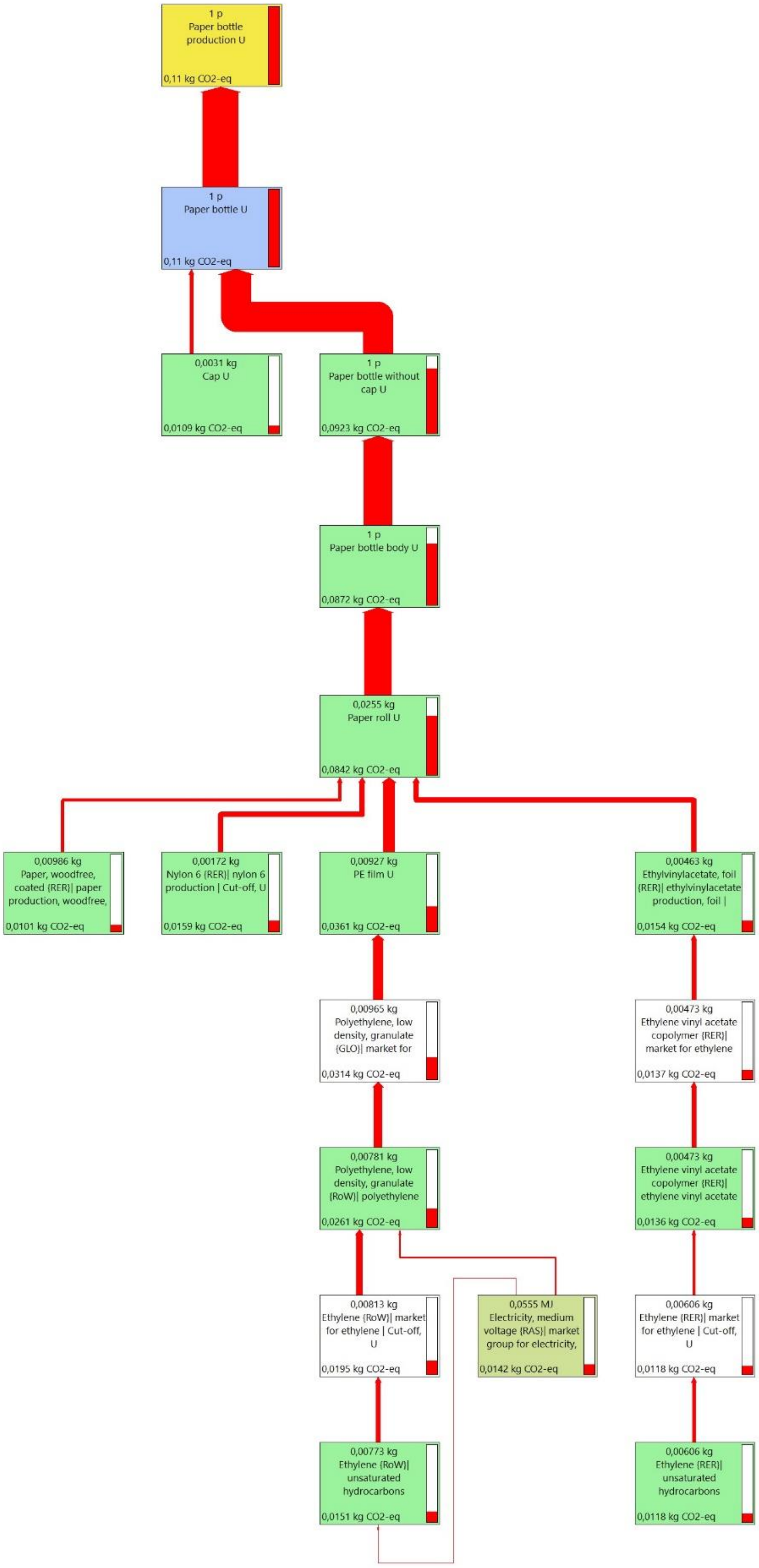


Figure 14 - IPCC 2021 total for paper bottle production.

Figure 14 illustrates the impacts resulting from the sum of the categories presented in Table 22. As observed, the previously identified finding is confirmed: the production of the protective film is the most impactful component.

c) The single issue – Cumulative Energy Demand method

Using the most recent method selected to assess energy consumption in paper bottle production, namely the Cumulative Energy Demand (CED) method, the results are presented in Table 23.

Table 23 - CED total for paper bottle production

Impact Category	Unit	Value for 1 Paper bottle
Non-renewable, fossil	MJ	2,24
Non-renewable, nuclear	MJ	1,66E-01
Non-renewable, biomass	MJ	1,64E-04
Renewable, biomass	MJ	3,47E-01
Renewable, wind, solar, geothermal	MJ	4,16E-02
Renewable, water	MJ	5,24E-02

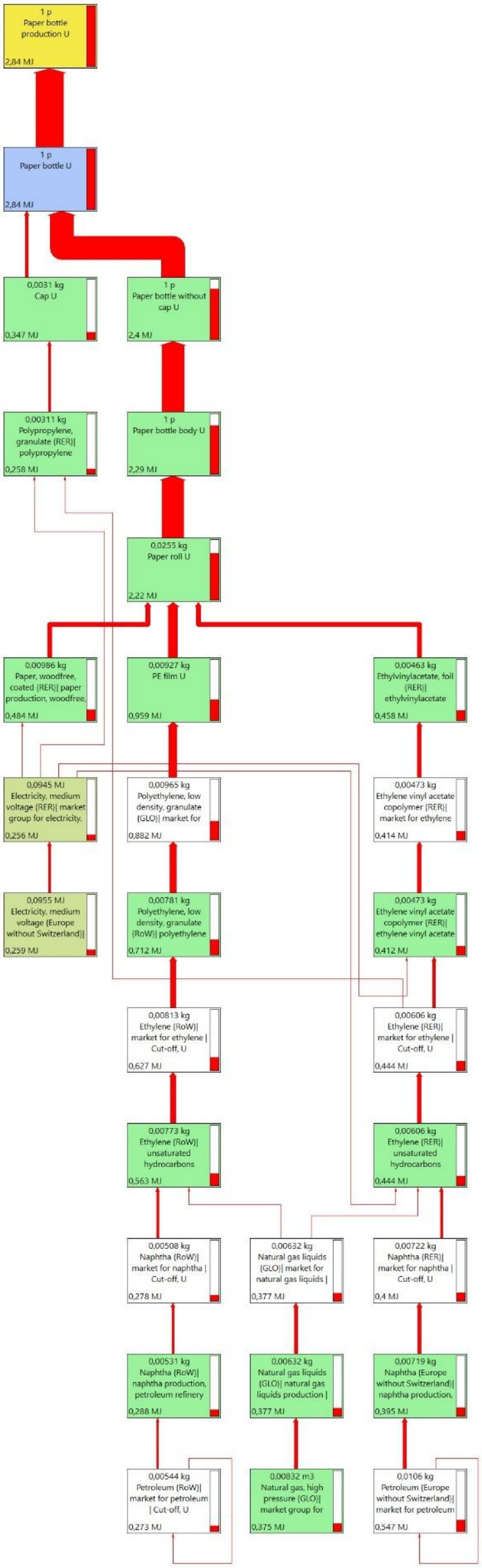


Figure 15 - CED total for paper bottle production

Figure 15 presents the cumulative values for different types of energy sources (non-renewable fossil, non-renewable nuclear, non-renewable biomass, renewable biomass, renewable wind, renewable solar, renewable geothermal, and renewable water). The results indicate that the highest energy consumption is attributed to the polyethylene protective film.

5.2.2 Vending machine

a) The Environmental Footprint (EF) method

The same framework used for the impact analysis of the vending machine is applied in this section to assess its production. This analysis evaluates the entire lifespan of the vending machine.

Table 24 - EF method total impact assessment for vending machine production

Damage Category	**Unit**	**Value for 1 Vending machine**
Acidification	mol H+ eq	1,43E+01
Climate change	kg CO2 eq	1,93E+03
Ecotoxicity, freshwater	CTUe	3,30E+04
Eutrophication, freshwater	kg P eq	1,40E+00
Eutrophication, marine	kg N eq	2,32E+00
Eutrophication, terrestrial	mol N eq	3,07E+01
Human toxicity, cancer	CTUh	2,71E-05
Human toxicity, non-cancer	CTUh	6,77E-05
Ionising radiation	kBq U-235 eq	1,52E+02
Land use	Pt	7,95E+03
Ozone depletion	kg CFC11 eq	6,86E-05
Particulate matter	disease inc.	1,48E-04
Photochemical ozone formation	kg NMVOC eq	7,42E+00
Resource use, fossils	MJ	2,29E+04
Resource use, minerals, and metals	kg Sb eq	2,78E-01
Water use	m3 depriv.	4,77E+02

Table 24 presents the results of the impact assessment for each damage category.

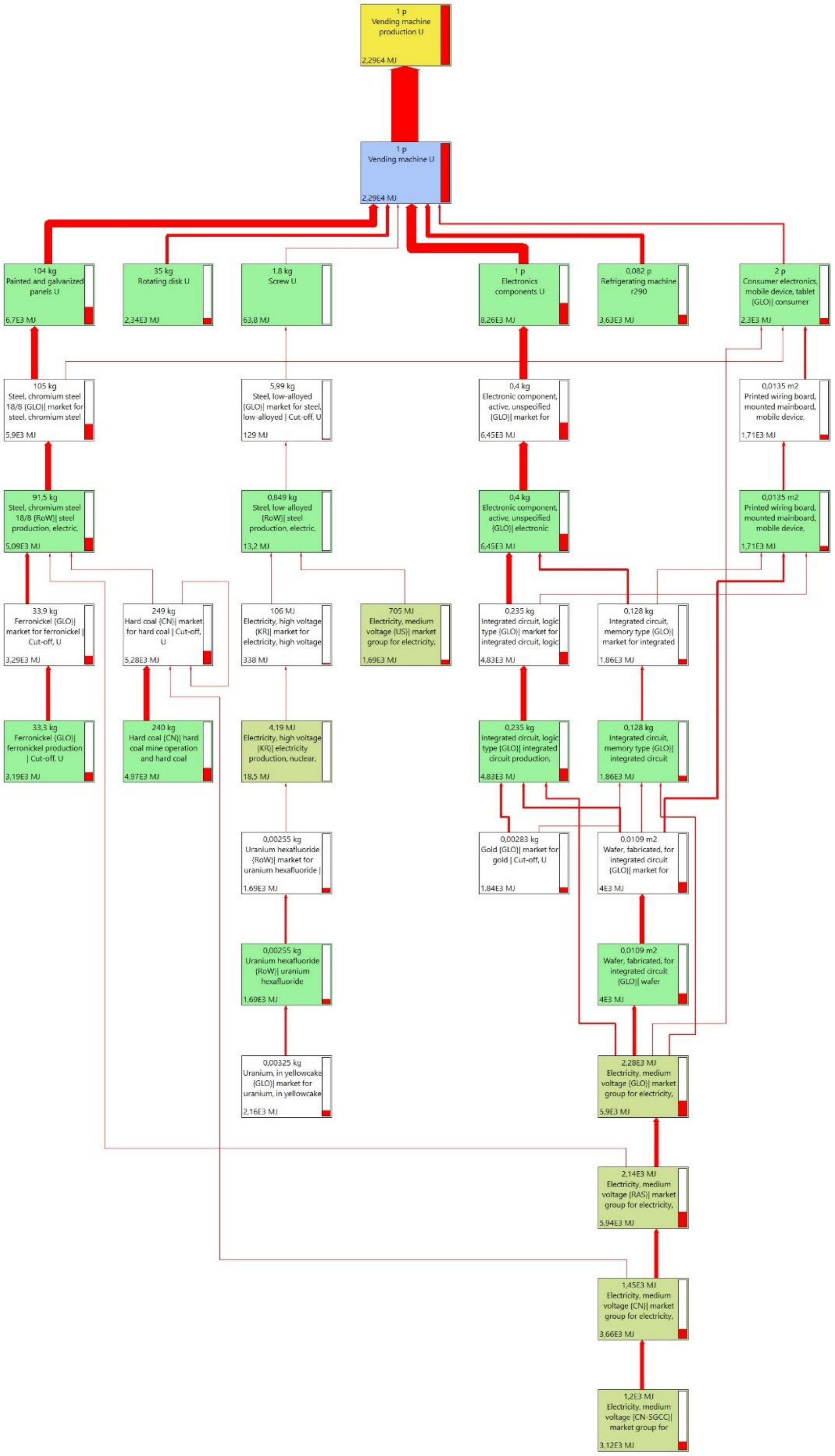


Figure 16 - EF method total for vending machine. Resource use, fossil

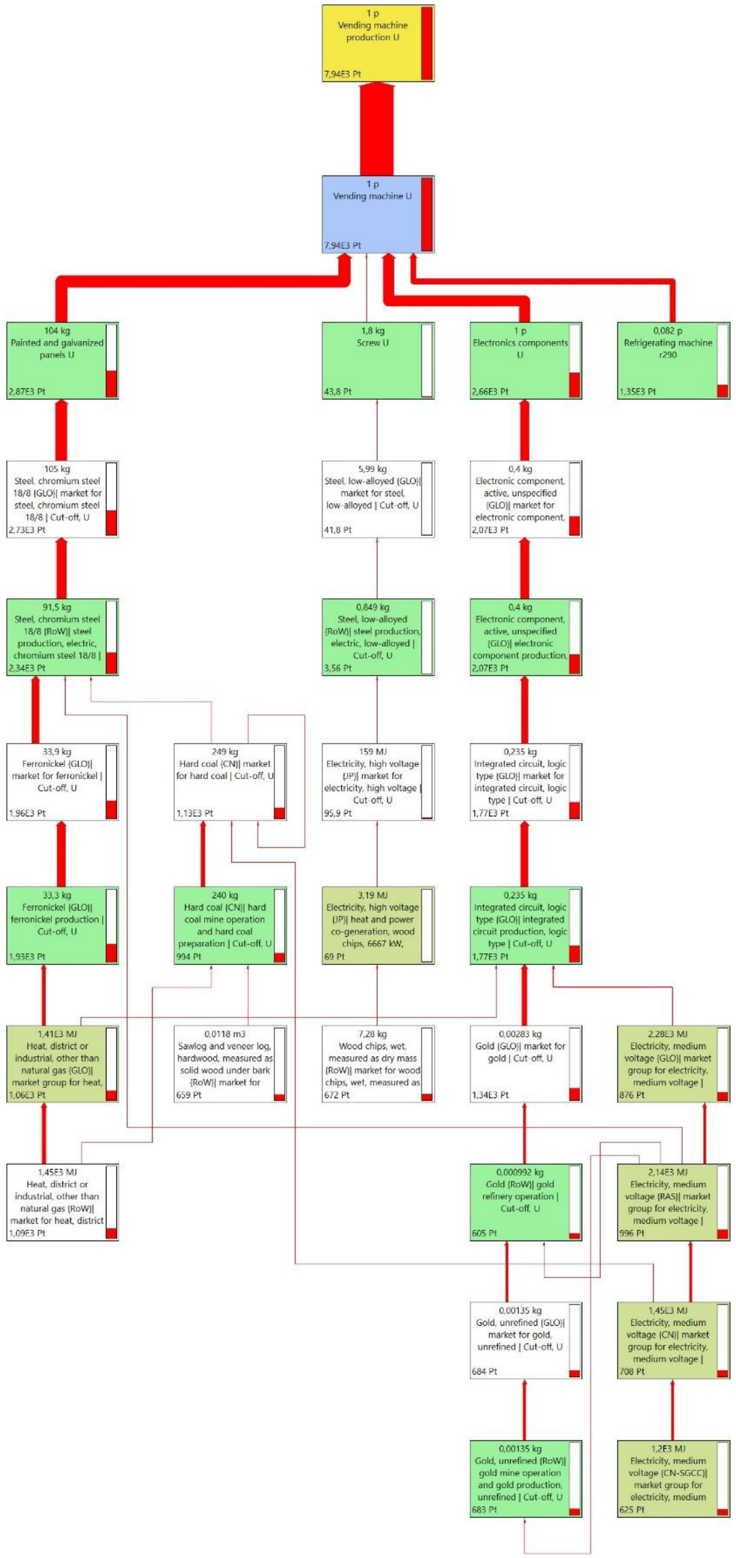


Figure 17 - EF method total for vending machine. Land use

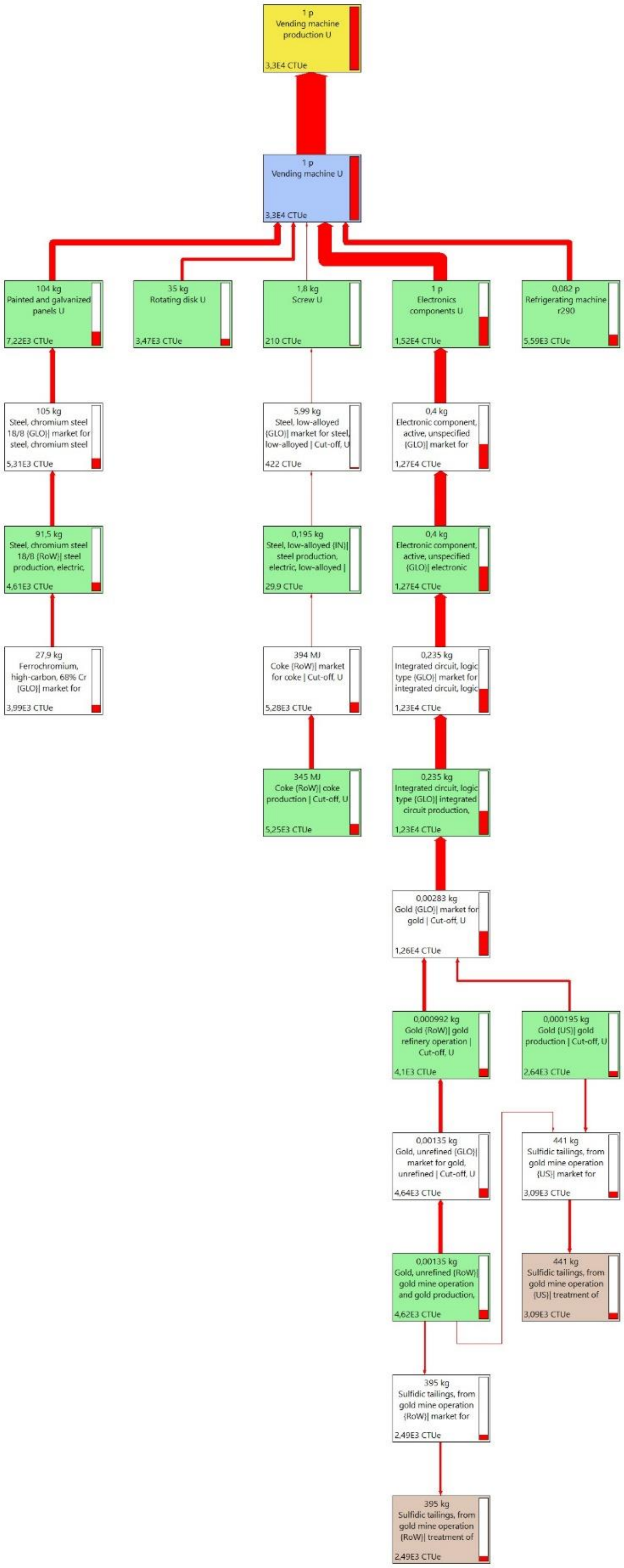


Figure 18 - EF method total for vending machine. Ecotoxicity, freshwater

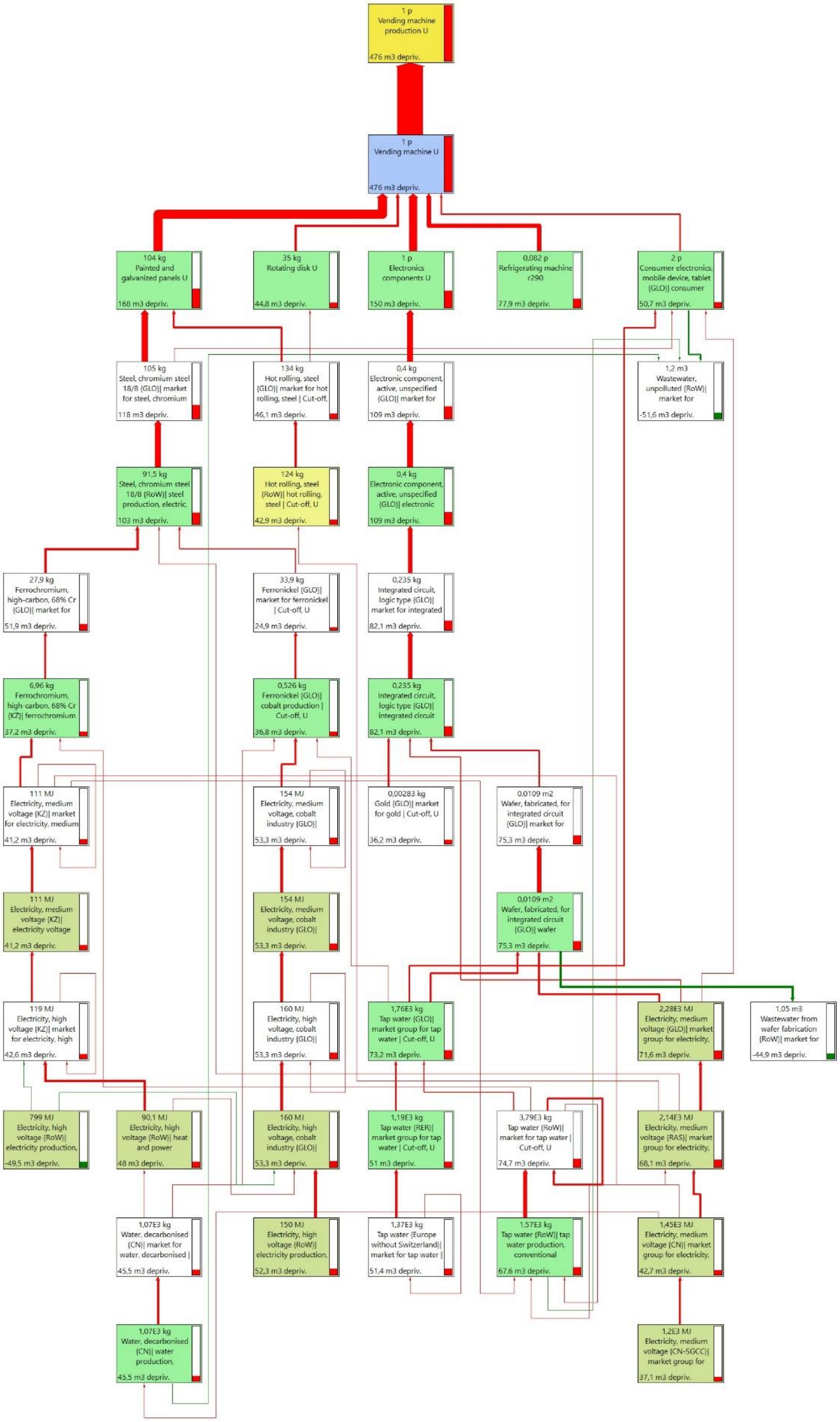


Figure 19 - EF method total for vending machine. Water use

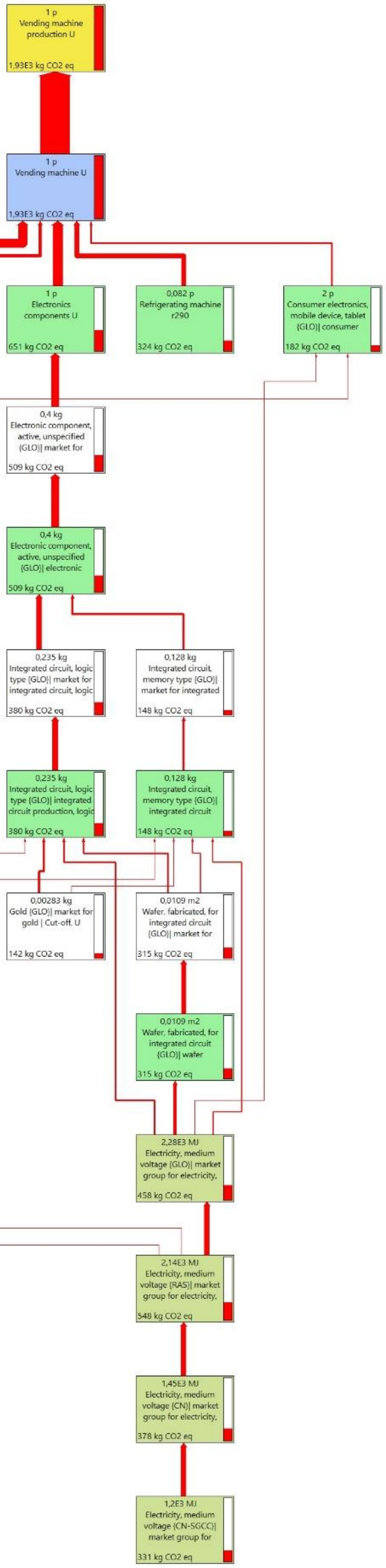


Figure 20 - EF method total for vending machine. Climate Change

The results for the damage categories are presented in Figure 16, Figure 17, Figure 18, Figure 19, Figure 20. In the first graph, Figure 16, which shows the fossil resource use impact, the electronic components and the steel panels stand out as the most significant contributors. For the electronic components, this is mainly due to the energy required for fabricating the wafer used in integrated circuits. For the steel panels, the impact is linked to ferronickel production and the mining of hard coal, both essential for steel production. Regarding land use, Figure 17, the same components remain the most impactful. For the electronic components, the production of gold and its refining process for use in integrated circuits play a major role. For steel production, ferronickel production is the main contributor, especially because of the heat required during the process. In the case of freshwater ecotoxicity, Figure 18, the main issue is gold mining, which releases sulfidic tailings. These tailings have a significant negative impact on water quality, in particular sulfidic tailings contain toxic materials that can leach into surrounding ecosystems, severely disrupting aquatic life. The water use impact is more complex. The Sankey diagram, Figure 19, illustrates both the output and input of water deprivation. The primary water use occurs during electricity production, and both the electronic components and steel panels are highly energy-intensive to manufacture. This means that a significant portion of the water footprint is indirectly tied to energy generation processes. Finally, in the Climate Change impact category, it is shown that producing a single vending machine results in the emission of 1927.61 kg of CO_2 equivalent. Most of these emissions are associated with the production of electronic components, particularly integrated circuits, and steel panels, where ferronickel production plays a major role. In conclusion, the components that most significantly influence the environmental impact of vending machine production are the electronic components. Despite their relatively low weight in the overall machine, they have a relevant impact compared to nearly all other components. This is primarily due to the materials used in their production, including rare metals and precious stones, such as gold, as well as the energy-intensive processes involved in manufacturing integrated circuits.

b) The single issue – IPCC 2021 method

By using the second method chosen to evaluate the environmental impact of the vending machine, namely the IPCC 2021 method, it was possible to obtain results for the overall case of the vending machine over its entire useful life and for the functional unit.

Table 25 - IPCC 2021 total for vending machine production

Impact Category	**Unit**	**Value for 1 Vending machine**
GWP100 - fossil	kg CO2-eq	1.927,61
GWP100 - biogenic	kg CO2-eq	3,74
GWP100 - land transformation	kg CO2-eq	2,85

As can be seen in Table 25, the greatest impact was obtained for the GWP – fossil category. Figure 21 presents the impacts of the components of the vending machine resulting from the sums of the impact categories listed in Table 25.

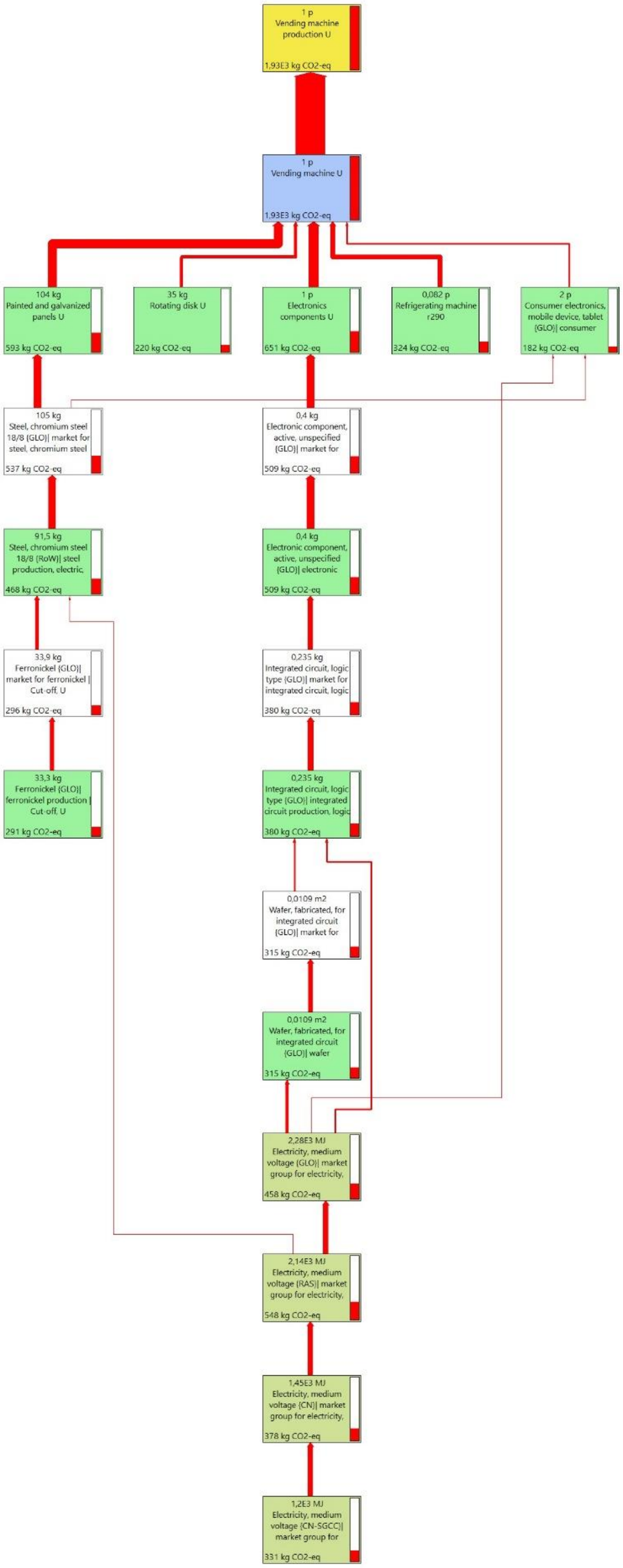


Figure 21- IPCC 2021 total for vending machine production

Figure 21 shows that, in addition to the contribution of electronic components and steel, aluminium, used for the Rotating disk, also appears among the most impactful materials, likely due to the high amount of energy required for its production.

c) The single issue – Cumulative Energy Demand method

By using the last method chosen to assess the energy consumption of the vending machine production, namely the CED method, it was possible to obtain results for the overall case of the vending machine over its entire useful life.

Table 26 - CED total for vending machine production

Impact Category	Unit	Value for 1 Vending machine
Non-renewable, fossil	MJ	22.017,46
Non-renewable, nuclear	MJ	2.414,89
Non-renewable, biomass	MJ	0,93
Renewable, biomass	MJ	510,42
Renewable, wind, solar, geothermal	MJ	561,95
Renewable, water	MJ	2.216,92

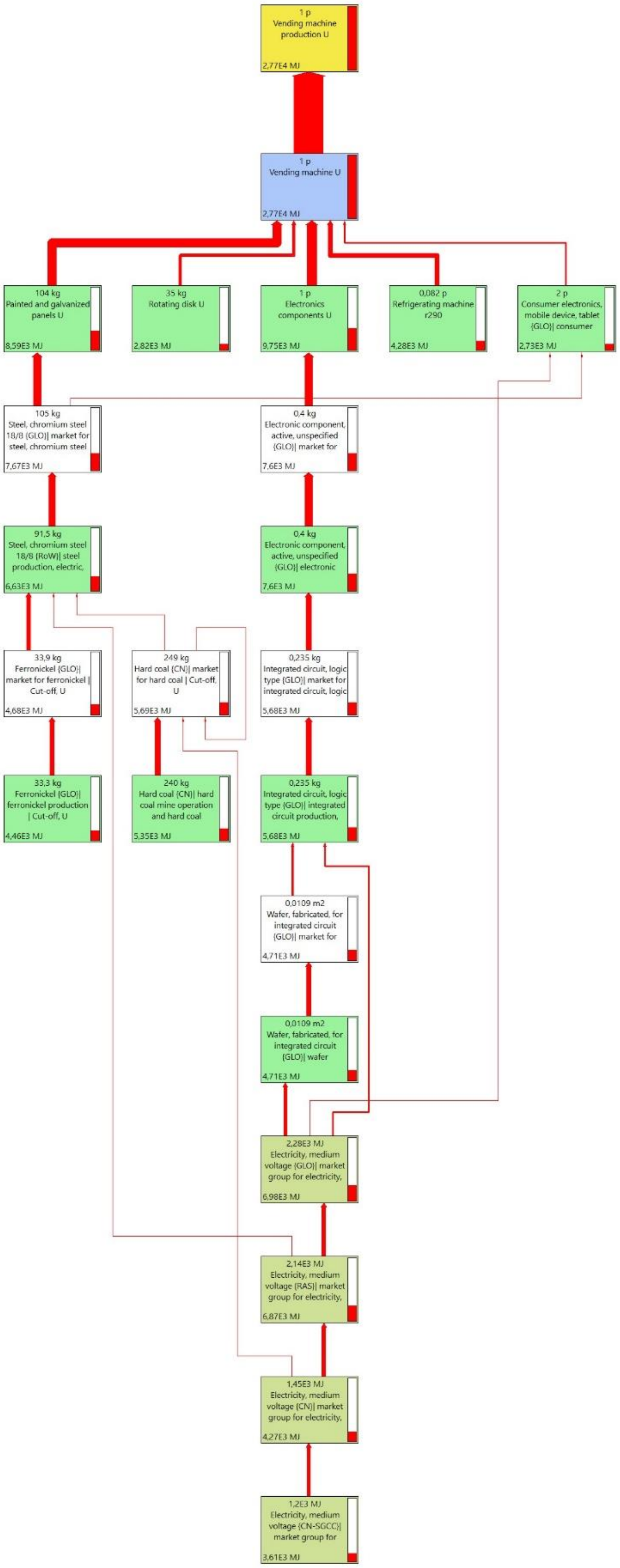


Figure 22 - CED total for vending machine production

Figure 22 presents the cumulative values for different types of energy sources (non-renewable fossil, non-renewable nuclear, non-renewable biomass, renewable biomass, renewable wind, renewable solar, renewable geothermal, and renewable water). The analysis indicates that the highest energy consumption is attributed to the electronic components, likely due to the extraction and manufacturing processes involved in their production. Additionally, it is important to note that the energy mix adopted during the production of the integrated circuit includes a significant contribution from CN-SGCC, which refers to the China State Grid Corporation. This entity operates as one of the largest electricity providers in China, influencing the energy sources utilized in industrial processes.

6. USE STAGE

During the use phase, the system, consisting of the paper bottle, vending machine, and filters, utilizes water sourced directly from the aqueduct to produce the output of 0,55 litres of bottled water.

6.1 Inventory analysis

6.1.1 Filtration system

In the use phase, the water filtration process has been divided into two steps. The first step involves the use of a composite filter that employs pre-activated carbon through Integrated Membrane Pre-activated Carbon Technology (IMPACT) to filter water directly from the mains supply, Figure 23. After this initial filtration, the water undergoes further purification through a UV lamp. Subsequently, the water is cooled using the refrigeration unit, and then sanitized one final time with a second UV lamp. In this model, the filtration and sterilization systems have been categorized as ‘Composite Filter’ and ‘UV Lamps’. The processes used to model these components in SimaPro are detailed in Table 27.

Table 27 – Production of 1 unit of Composite filter

Product	Process	Calculation	Value	Unit of measurement
Composite Filter	*Polypropylene, granulate*	0,25	0,25	kg
	Injection moulding	0,25	0,25	kg
	Nylon 6	0,15/0,94	0,16	kg
	Extrusion of plastic sheets and thermoforming, inline	0,15/0,94	0,16	kg
	Activated carbon, granular	0,08	0,08	kg

Figure 23 - HF10 Drinking Water System [32]

Due to the lack of precise data on the composite filter materials and structure, several assumptions were made:

1. Polypropylene Cylinder: The filter includes a polypropylene cylinder with a lower section of larger diameter and an upper section with a 15% reduced diameter. The cylinder also has a 4 cm connector. According to the technical specifications, the total height of the cylinder is 35 cm, with a diameter of 10.2 cm. Assuming a density of 0.9 g/cm³, the total weight of the cylinder was calculated to be 0.25 kg.

2. Nylon Membrane: In addition to the polypropylene cylinder, the filter incorporates a nylon membrane. The membrane, which serves as a filtration barrier, is located at the base of the cylinder, where the pre-activated carbon block is inserted. Based on similar calculations and assuming a density of 1.15 g/cm³ and a thickness of 3 mm, the total weight of the nylon membrane was estimated to be 0.15 kg. The manufacturing process of Nylon involves a 6% waste rate.
3. Pre-Activated Carbon Block: The pre-activated carbon block was modelled as a generic block of activated carbon, due to the absence of specific data in the Ecoinvent database. The block was represented with an assumed packing density of 0.5 g/cm³, yielding a total weight of 0.08 kg.

For the UV Lamps, a pre-existing process from the Ecoinvent database, titled *'Ultraviolet Lamp'* was used. The system requires the use of two UV lamps.

During the use phase, the filters were scaled to the functional unit. Specifically, the Composite Filter has a maximum capacity of 11.000 litres, while the UV lamps need to be replaced once per year. Considering the number of daily dispensed volumes, 0,55 litres per serving, multiplied by the number of days in a year, the maximum number of dispenses that a single UV lamp can support was calculated.

6.1.2 Energy consumption

The energy consumption of the vending machine is categorized into three modes: fully active, active, and standby. In fully active mode, both the refrigerator and the rotating disk, responsible for the handling of the bottle, are operational. This mode consumes the most energy, but it is also the least frequent, as it is only activated during dispensing. In active mode, only the refrigerator compressor operates. For this analysis, it was assumed that, on average, the refrigerator is activated 10 times per day, remaining on for 30 minutes each time to reach the target temperature. The final mode is standby, during which the machine reduces its energy consumption to 30% of its nominal use. [33]

The nominal power is 0,7 kW, consistent with literature values [33]. Given a flow rate of 80 L/h and so a dispensing time of 24,8 seconds and the daily number of dispenses that is 13, the daily distribution of the different operating phases is presented Table 28.

Table 28 - Operational mode distribution during a typical day

Operational mode	Time [h/day]
Fully active	0,09
Active	5,00
Stand-by	18,91

By combining these assumptions with the developed calculations, it is possible to characterize the average daily energy consumption divided among the three phases. Subsequently, by dividing this value by the number of daily dispenses, the average energy consumption per dispense is determined and shown in Table 29.

Table 29 - Energy consumption of the vending machine

	Power [kW]	Power factor	Time [h/day]	Energy consumption [kWh/day]	Specific energy consumption [kWh/dispense]
Fully Active mode	0,7	0,8	0,09	0,05	0,004
Active mode	0,7	0,6	5,00	2,10	0,161
Standby	0,7	0,3	18,91	3,97	0,305
Total	0,7	0,57	24	6,12	0,47

6.1.3 Paper bottle

The company declares the paper bottle can be reused up to 10 times.

6.1.4 Vending machine

The manufacturer specifies the vending machine's operational lifespan to be eight years. In the absence of specific data, it was necessary to estimate the number of daily dispensations to determine the portion of the vending machine allocated to the functional unit, defined as 0,55 litres per dispensation. All reported data correspond to industry statistics for the year 2022. [34]

Given the following information:

1. Total number of vending machines in Italy: 835.360 units
2. Total number of dispensations: 3.944.831.374 units
3. Total water dispensations from vending machines: 564.344.955 units

It is possible to calculate the percentage of water dispensations relative to the total number of dispensations and assume this percentage is representative of the distribution of water-dispensing machines among the total number of vending machines. By dividing the total number of water dispensations by the number of water-dispensing machines, we can find the average annual number of bottles dispensed per machine, and subsequently, the average daily number of bottles dispensed per machine, assuming continuous operation throughout the year. This value is estimated to be 13 bottles per day.

To relate the vending machine analysis to the functional unit, we equate a single dispensation of 0,55 litres of bottled water to one bottle dispensed by the vending machine. Thus, over its operational lifespan, a vending machine can dispense:

$$Dispensation_{total} = Lifespan_{VM} * Dispensation_{daily} * 365 = 8 * 13 * 365 = 37.960$$

6.2 Impact assessment

a) The Environmental Footprint (EF) method

The following table shows the results of the damage category.

Table 30 - EF method total impact assessment for use stage

Damage Category	**Unit**	**Total**	**Main components**	**Active mode**	**Fully active mode**	**Stand-by**
Acidification	mol H+ eq	1,12E-03	4,22E-04	2,41E-04	5,96E-06	4,54E-04
Climate change	kg CO2 eq	0,23	0,06	0,06	1,42E-03	0,11
Ecotoxicity, freshwater	CTUe	1,44	0,92	0,18	4,41E-03	0,34
Eutrophication, freshwater	kg P eq	7,70E-05	3,99E-05	1,28E-05	3,16E-07	2,41E-05
Eutrophication, marine	kg N eq	1,77E-04	7,23E-05	3,60E-05	8,89E-07	6,78E-05
Eutrophication, terrestrial	mol N eq	2,06E-03	9,19E-04	3,93E-04	9,70E-06	7,40E-04
Human toxicity, cancer	CTUh	1,21E-09	7,78E-10	1,48E-10	3,65E-12	2,78E-10
Human toxicity, non-cancer	CTUh	6,67E-09	4,60E-09	7,14E-10	1,76E-11	1,34E-09
Ionising radiation	kBq U-235 eq	2,48E-02	4,96E-03	6,83E-03	1,69E-04	1,29E-02
Land use	Pt	1,38	0,40	0,34	0,01	0,63
Ozone depletion	kg CFC11 eq	5,91E-09	2,07E-09	1,32E-09	3,26E-11	2,49E-09
Particulate matter	disease inc.	8,14E-09	4,68E-09	1,19E-09	2,94E-11	2,24E-09
Photochemical ozone formation	kg NMVOC eq	7,37E-04	2,48E-04	1,68E-04	4,16E-06	3,17E-04
Resource use, fossils	MJ	3,51	0,84	0,92	0,02	1,73
Resource use, minerals and metals	kg Sb eq	9,49E-06	7,40E-06	7,17E-07	1,77E-08	1,35E-06
Water use	m3 depriv.	0,16	0,04	0,04	1,03E-03	0,08

In Table 30, the damage category impact assessment is presented

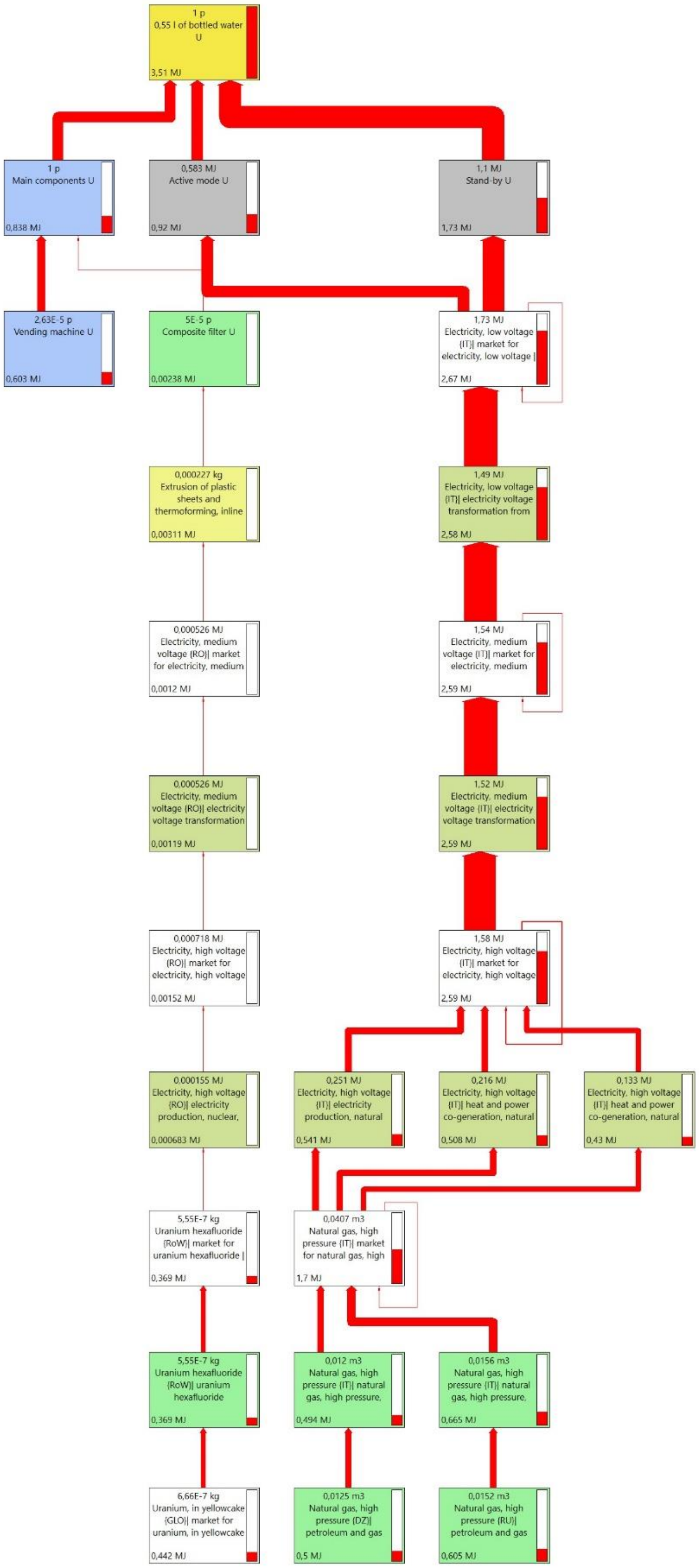


Figure 24 - EF method total for use stage. Resource use, fossil

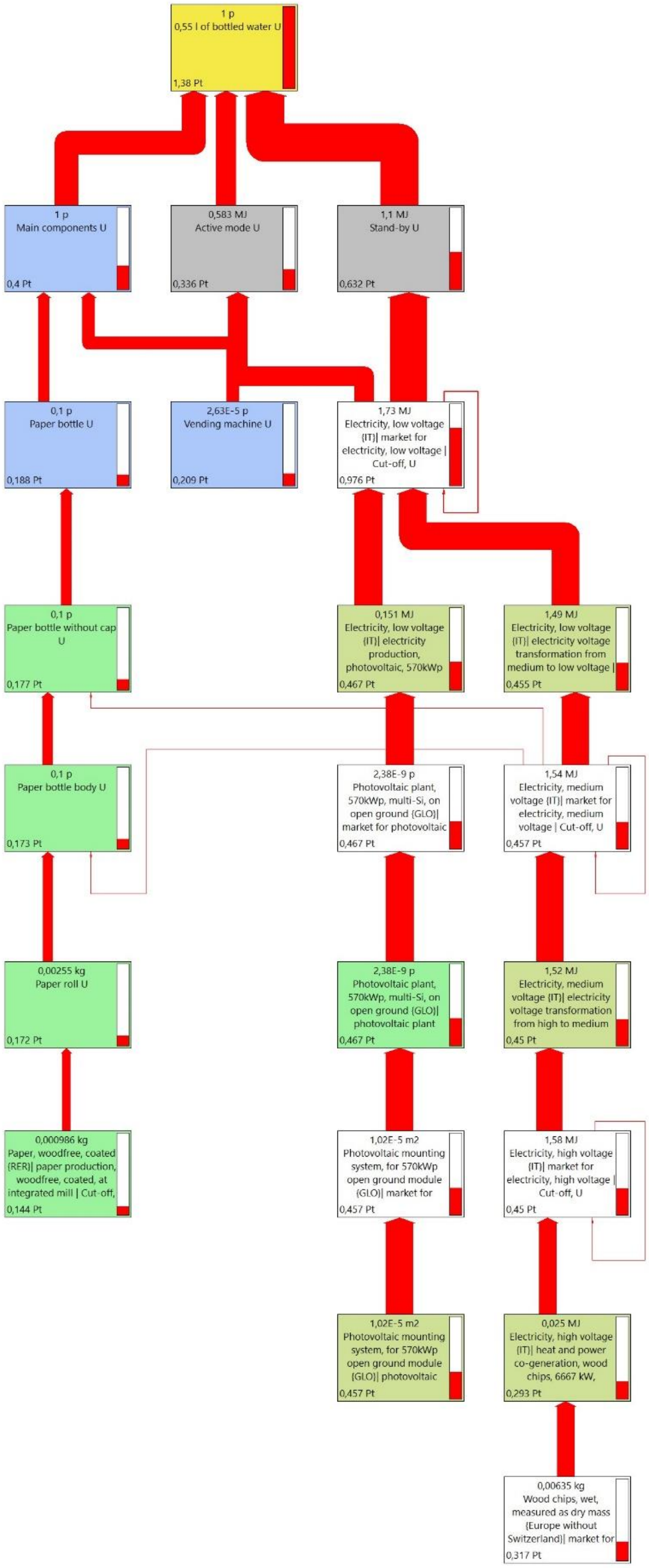


Figure 25 - EF method total for use stage. Land use

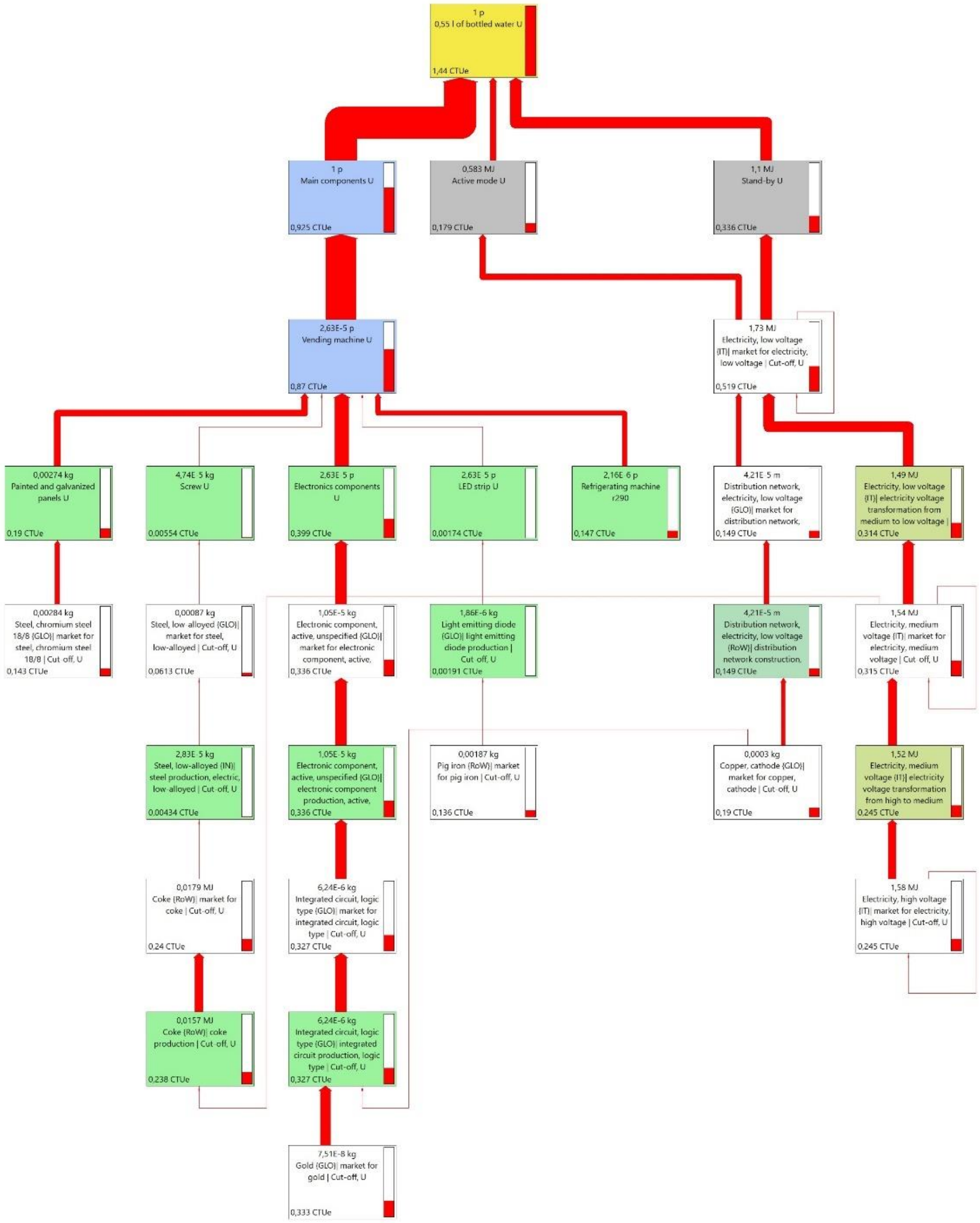


Figure 26 - EF method total for use stage. Ecotoxicity, freshwater

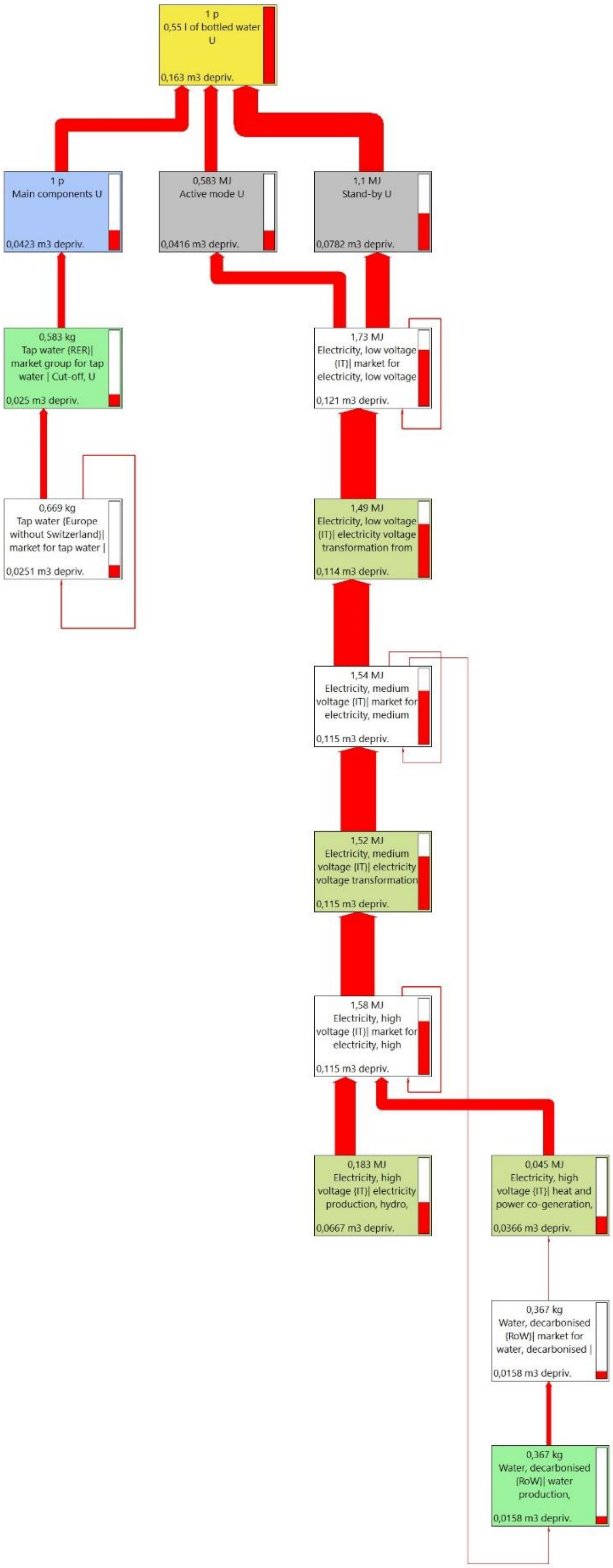


Figure 27 - EF method total for use stage. Water use

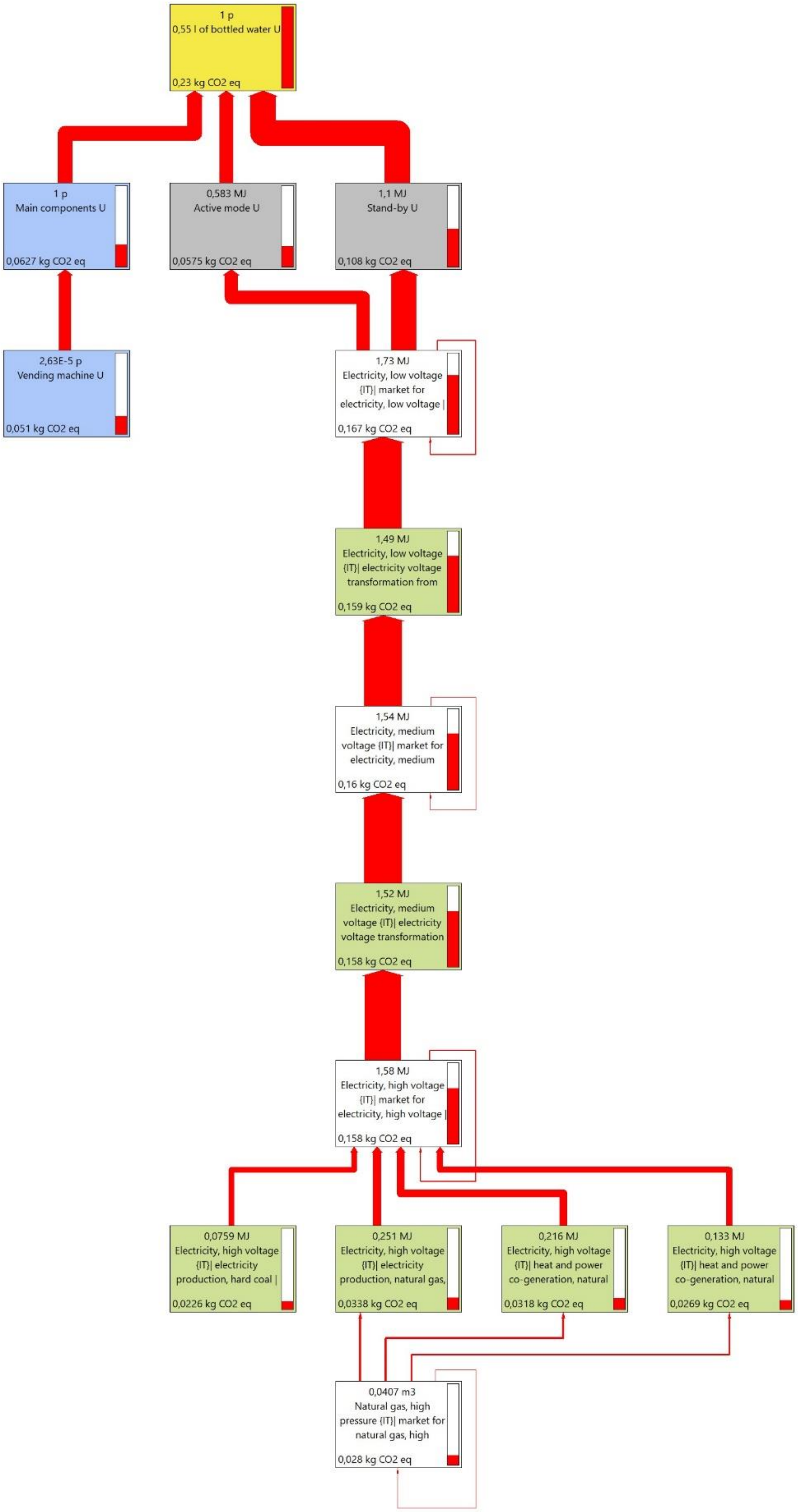


Figure 28 - EF method total for use stage. Climate Change

The result of the damage category are shown in Figure 24, Figure 25, Figure 26, Figure 27, Figure 28. In Figure 24, we can observe that the most significant contributor to the fossil resource use category is the energy consumption during active and stand-by modes. This is primarily due to the heavy reliance on fossil fuels in the Italian electricity mix, particularly natural gas. Regarding land use, Figure 25 , the largest impact is caused using photovoltaic parks, which are also part of the Italian energy mix. Another significant contributor is paper production. For the ecotoxicity impact category, Figure 26 , the greatest impact comes from the extraction and production chain of gold used in the electronic circuits inside the vending machine. In the water use category, Figure 27, the main contributors to water deprivation are electricity production, particularly from hydroelectric turbines and cogeneration systems. Another contributor to this impact is the tap water used by the vending machine to fill bottles, though this accounts for only 15% of the total water deprivation. Finally, in the climate change impact category, it is evident that the dispensing of 0.55 litres of bottled water results in the emission of 0.23 kg of CO_2 equivalent. Most of these emissions are linked to electricity use during stand-by mode. In conclusion, the energy mix, particularly its reliance on fossil fuels, plays a critical role in shaping the environmental impacts of vending machine operations.

b) The single issue – IPCC 2021 method

By using the IPCC 2021 method chosen to evaluate the environmental impact it was possible to obtain results in Table 31.

Table 31 - IPCC 2021 total for use stage

Impact Category	**Unit**	**Total**	**Main components**	**Active mode**	**Fully active mode**	**Stand-by**
GWP100 - fossil	kg CO2-eq	2,29E-01	6,24E-02	5,72E-02	1,41E-03	1,08E-01
GWP100 - biogenic	kg CO2-eq	8,48E-04	1,69E-04	2,34E-04	5,77E-06	4,40E-04
GWP100 - land transformation	kg CO2-eq	1,23E-04	9,14E-05	1,09E-05	2,69E-07	2,05E-05

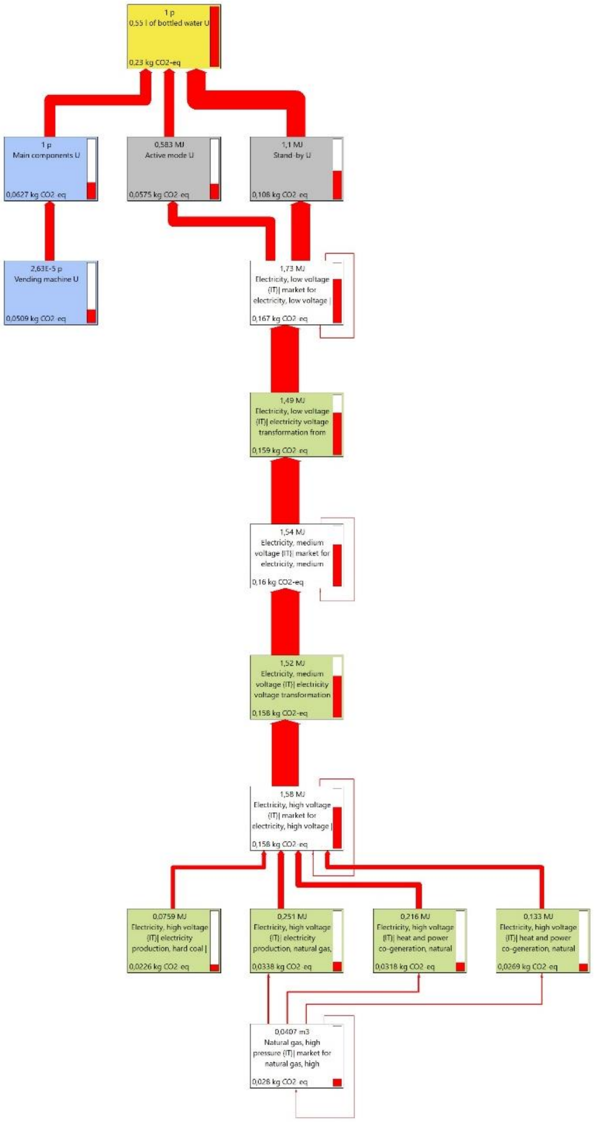


Figure 29 - IPCC 2021 total for use stage

Figure 29 illustrates the impacts resulting from the sum of the categories presented in Table 31. The primary contributor to the Climate Change impact is the operation of power plants highlighted in the green boxes (coal, direct natural gas, and cogeneration). These processes involve combustion, which is responsible for most emissions.

c) The single issue – Cumulative Energy Demand method

Using the most recent method selected to assess energy consumption in paper bottle production, namely the Cumulative Energy Demand (CED) method, the results are presented in Table 32.

Table 32 - CED total for use stage

Impact Category	Unit	Total	Main components	Active mode	Fully active mode	Stand-by
Non-renewable, fossil	MJ	8,14E-01	8,71E-01	2,15E-02	1,64E+00	8,14E-01
Non-renewable, nuclear	MJ	8,16E-02	1,27E-01	3,13E-03	2,39E-01	8,16E-02
Non-renewable, biomass	MJ	4,11E-05	9,66E-06	2,39E-07	1,82E-05	4,11E-05
Renewable, biomass	MJ	4,84E-02	2,89E-02	7,14E-04	5,45E-02	4,84E-02
Renewable, wind, solar, geothermal	MJ	1,93E-02	2,19E-01	5,41E-03	4,12E-01	1,93E-02

Figure 30 present the cumulative values for different types of energy sources (non-renewable fossil, non-renewable nuclear, non-renewable biomass, renewable biomass, renewable wind, renewable solar, renewable geothermal, and renewable water). The results indicate that the highest energy consumption is attributed to the energy use in stand-by mode.

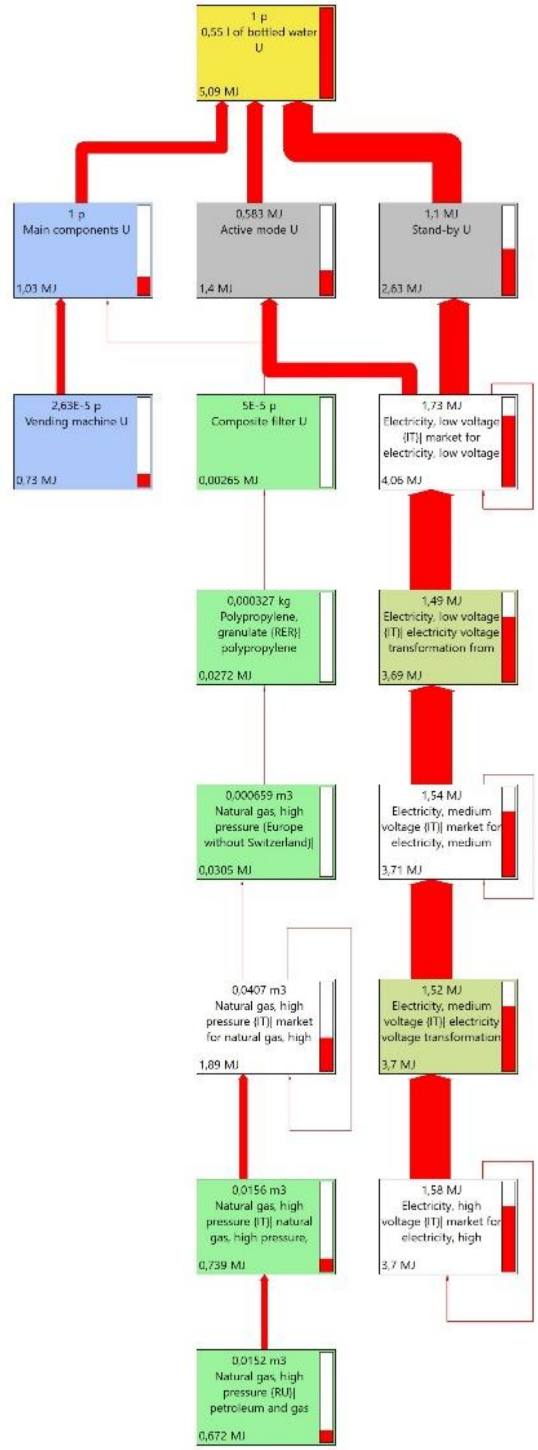
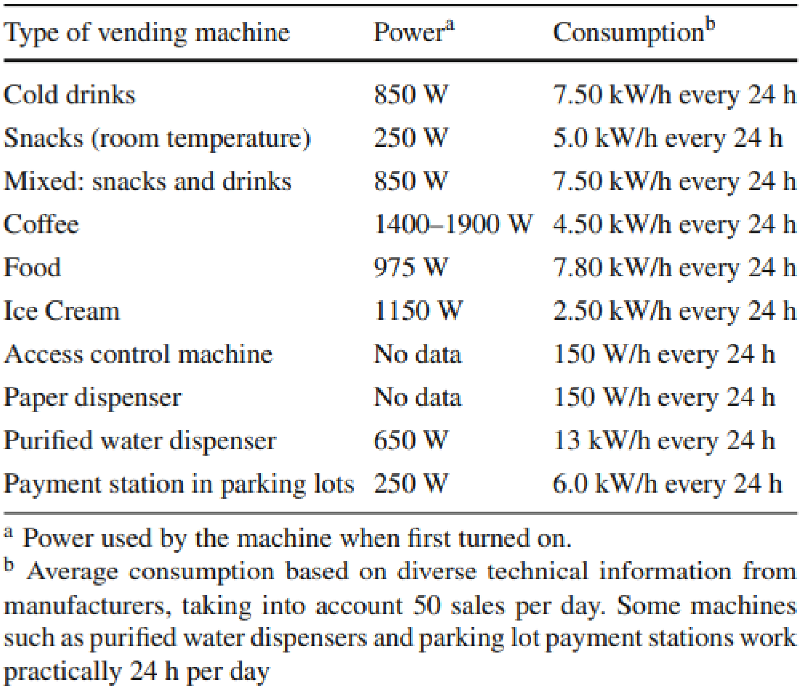


Figure 30 - CED total for use stage

7. INTERPRETATION

Precise data on the energy consumption of the vending machine are not available. Therefore, assumptions to build the reference scenario were made, and two alternative scenarios were analysed, to understand the influence of this assumption.

The first scenario uses data from a research paper [33], which provides average power and energy consumption values for 'Purified Water Dispensers' like the vending machine. These values are illustrated in Figure 31. Based on further assumptions, these data can be adapted to our case. By estimating a reasonable distribution of energy consumption across the machine different modes, specific consumption was calculated assuming a higher number of daily dispenses, 50 in total. This is a value taken as a reference within the study used as a source. Given a daily energy consumption of 13 kWh over 24 hours and 50 dispenses, the specific energy consumption per dispense is 0.26 kWh. The distribution of this consumption across the different phases is shown in Table 33.



Type of vending machine	Power[a]	Consumption[b]
Cold drinks	850 W	7.50 kW/h every 24 h
Snacks (room temperature)	250 W	5.0 kW/h every 24 h
Mixed: snacks and drinks	850 W	7.50 kW/h every 24 h
Coffee	1400–1900 W	4.50 kW/h every 24 h
Food	975 W	7.80 kW/h every 24 h
Ice Cream	1150 W	2.50 kW/h every 24 h
Access control machine	No data	150 W/h every 24 h
Paper dispenser	No data	150 W/h every 24 h
Purified water dispenser	650 W	13 kW/h every 24 h
Payment station in parking lots	250 W	6.0 kW/h every 24 h

[a] Power used by the machine when first turned on.

[b] Average consumption based on diverse technical information from manufacturers, taking into account 50 sales per day. Some machines such as purified water dispensers and parking lot payment stations work practically 24 h per day

Figure 31 - Potential data and electricity consumption of the most common vending machine in Mexico [33]

Table 33 - Energy consumption of the vending machine – scenario 1

	Mode distribution [%]	Energy consumption [kWh/day]	Specific energy consumption [kWh/dispense]
Fully Active mode	1%	0,03	0,002
Active mode	34%	1,16	0,089
Standby	65%	2,19	0,169
Total	100%	3,38	0,260

The second scenario considers consumption data reported by a competing company, which states that their vending machine consumes an average of 160 kWh per year, with an additional 18 kWh if equipped with a UV lamp filtration system [35].

Based on this information, the average annual consumption is divided by the average number of yearly dispenses (13 per day over 365 days) to determine the specific energy consumption per dispense. By applying the same distribution of consumption across the different modes, it is possible to characterize this scenario as well. The results are shown in Table 34.

Table 34 - Energy consumption of the vending machine – scenario 2

	Mode distribution [%]	Specific energy consumption [kWh/dispense]
Fully Active mode	1%	0,0003
Active mode	34%	0,0129
Standby	65%	0,0243
Total	100 %	0,0375

Table 35 shows the results of the damage category for scenario 1.

Table 35 - EF method total impact assessment for use stage – scenario 1

Damage Category	**Unit**	**Total**	**Main components**	**Active mode**	**Fully active mode**	**Stand-by**
Acidification	mol H+ eq	8,10E-04	4,22E-04	1,33E-04	2,98E-06	2,52E-04
Climate change	kg CO2 eq	0,15	0,06	0,03	7,10E-04	0,06
Ecotoxicity, freshwater	CTUe	1,21	0,92	0,1	2,21E-03	0,19
Eutrophication, freshwater	kg P eq	6,04E-05	3,99E-05	7,02E-06	1,58E-07	1,33E-05
Eutrophication, marine	kg N eq	1,30E-04	7,23E-05	1,98E-05	4,45E-07	3,76E-05
Eutrophication, terrestrial	mol N eq	1,55E-03	9,19E-04	2,16E-04	4,85E-06	4,10E-04
Human toxicity, cancer	CTUh	1,02E-09	7,78E-10	8,12E-11	1,83E-12	1,54E-10
Human toxicity, non-cancer	CTUh	5,74E-09	4,60E-09	3,92E-10	8,81E-12	7,45E-10
Ionising radiation	kBq U-235 eq	0,02	4,96E-03	3,75E-03	8,44E-05	7,13E-03
Land use	Pt	0,94	0,4	0,18	4,14E-03	0,35
Ozone depletion	kg CFC11 eq	4,19E-09	2,07E-09	7,26E-10	1,63E-11	1,38E-09
Particulate matter	disease inc.	6,59E-09	4,68E-09	6,54E-10	1,47E-11	1,24E-09
Photochemical ozone formation	kg NMVOC eq	5,18E-04	2,48E-04	9,25E-05	2,08E-06	1,76E-04
Resource use, fossils	MJ	2,31	0,84	0,51	0,01	0,96
Resource use, minerals and metals	kg Sb eq	8,55E-06	7,40E-06	3,94E-07	8,85E-09	7,48E-07
Water use	m3 depriv.	0,11	0,04	0,02	5,13E-04	0,04

As we can observe from the table, there are no substantial differences between the reference scenario and the first scenario. There is a slight reduction in the value of the damage categories for the second case. This is primarily because consumption between the two varies only slightly, demonstrating a similarity between the approach considered for the vending machine and the approach used in the previously cited report [33].

Table 36 shows the results of the damage category for scenario 2.

Table 36 - EF method total impact assessment for use stage – scenario 2

Damage Category	Unit	Total	Main components	Active mode	Fully active mode	Stand-by
Acidification	mol H+ eq	4,78E-04	4,22E-04	1,94E-05	4,47E-07	3,58E-05
Climate change	kg CO2 eq	0,08	0,06	4,61E-03	1,06E-04	8,52E-03
Ecotoxicity, freshwater	CTUe	0,97	0,92	0,01	3,31E-04	0,03
Eutrophication, freshwater	kg P eq	4,28E-05	3,99E-05	1,03E-06	2,37E-08	1,89E-06
Eutrophication, marine	kg N eq	8,05E-05	7,23E-05	2,89E-06	6,67E-08	5,34E-06
Eutrophication, terrestrial	mol N eq	1,01E-03	9,19E-04	3,15E-05	7,27E-07	5,82E-05
Human toxicity, cancer	CTUh	8,12E-10	7,78E-10	1,19E-11	2,74E-13	2,19E-11
Human toxicity, non-cancer	CTUh	4,76E-09	4,60E-09	5,73E-11	1,32E-12	1,06E-10
Ionising radiation	kBq U-235 eq	6,53E-03	4,96E-03	5,48E-04	1,27E-05	1,01E-03
Land use	Pt	0,48	0,40	0,03	6,22E-04	0,05
Ozone depletion	kg CFC11 eq	2,38E-09	2,07E-09	1,06E-10	2,45E-12	1,96E-10
Particulate matter	disease inc.	4,95E-09	4,68E-09	9,55E-11	2,20E-12	1,76E-10
Photochemical ozone formation	kg NMVOC eq	2,87E-04	2,48E-04	1,35E-05	3,12E-07	2,49E-05
Resource use, fossils	MJ	1,05	0,84	0,07	1,70E-03	0,14
Resource use, minerals, and metals	kg Sb eq	7,57E-06	7,40E-06	5,76E-08	1,33E-09	1,06E-07
Water use	m3 depriv.	0,05	0,04	3,33E-03	7,70E-05	6,16E-03

In scenario 2, we can observe that the difference from the reference is more pronounced, not so much in the total result, but rather in the distribution of contributions from the various processes.

In the following figures are presented the Sankey diagrams for the Ecotoxicity, freshwater impact for scenario 1 and scenario 2.

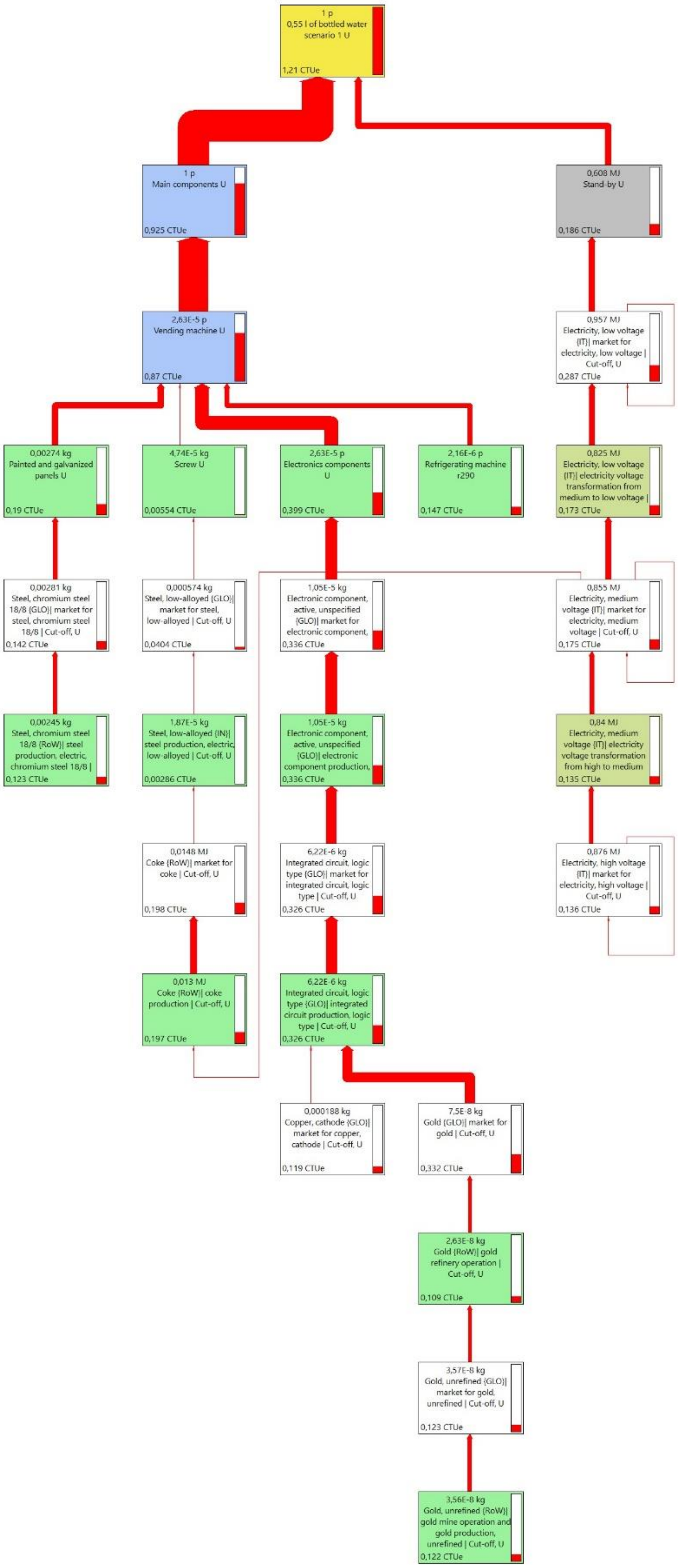


Figure 32 - EF method for use stage. Ecotoxicity, fresh water - scenario 1

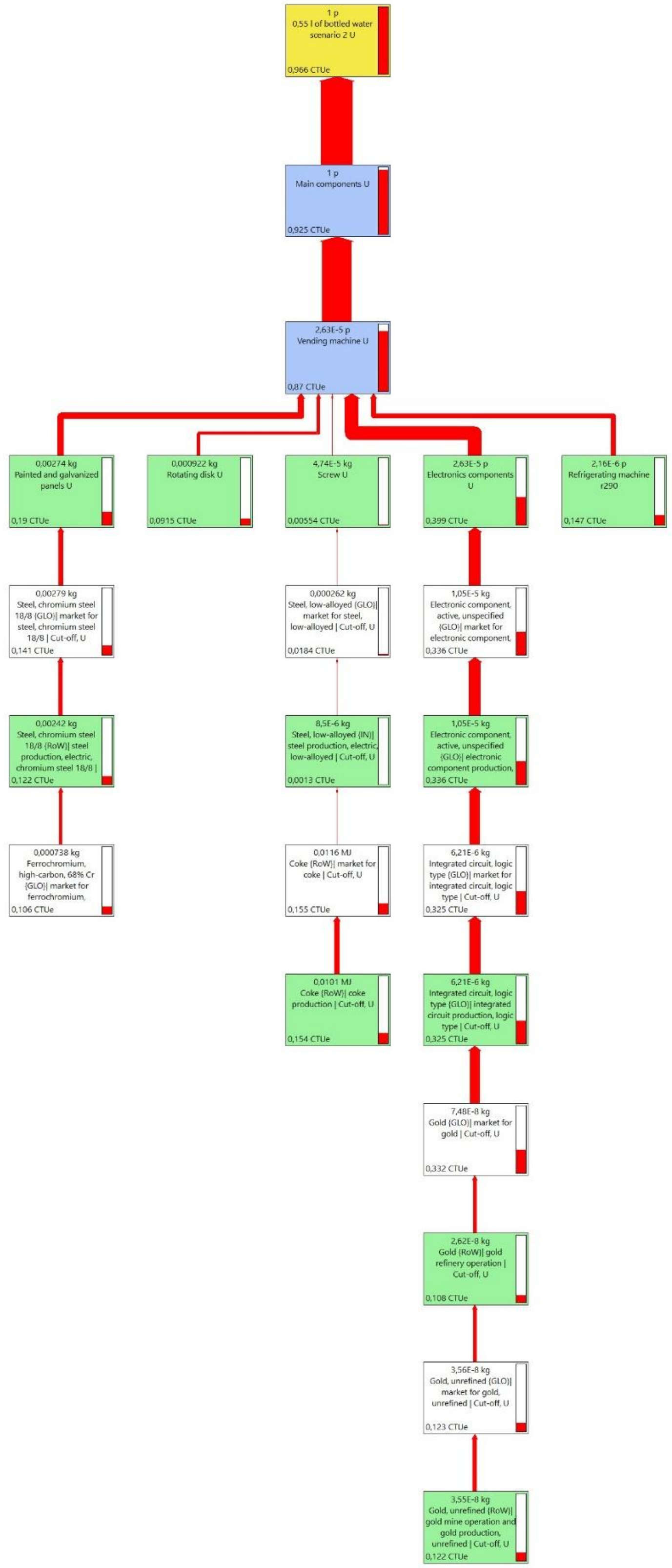


Figure 33 - EF method for use stage. Ecotoxicity, fresh water - scenario 2

As highlighted in the Sankey diagram, energy consumption during the active phase is notably absent from all damage category graphs, while energy consumption in the stand-by mode contributes only marginally. This can be attributed to the vending machine very low overall energy use. A further observation is that, unlike the electricity consumed during the stand-by and active phases, the energy associated with the fully active phase does not appear in the results. This is primarily due to the limited duration of time the vending machine spends in full operation. Since the machine remains in active mode only briefly, its contribution to the overall energy impact is negligible compared to phases with sustained energy consumption, such as stand-by. This emphasizes the importance in the implementation of an efficient design, where the consumption in stand-by mode is minimized, ensuring that the environmental impact remains low during typical use.

In Table 37 and Table 38 are presented the result obtained with the IPCC method for scenario 1 and scenario 2.

Table 37 - IPCC 2021 total for use stage – scenario 1

Impact Category	**Unit**	**Total**	**Main components**	**Active mode**	**Fully active mode**	**Stand-by**
GWP100 - fossil	kg CO2-eq	1,54E-01	6,24E-02	3,14E-02	7,07E-04	5,97E-02
GWP100 - biogenic	kg CO2-eq	5,44E-04	1,69E-04	1,28E-04	2,89E-06	2,44E-04
GWP100 - land transformation	kg CO2-eq	1,09E-04	9,14E-05	5,98E-06	1,34E-07	1,13E-05

Table 38- IPCC 2021 total for use stage - scenario 2

Impact Category	**Unit**	**Total**	**Main components**	**Active mode**	**Fully active mode**	**Stand-by**
GWP100 - fossil	kg CO2-eq	7,56E-02	6,24E-02	4,59E-03	1,06E-04	8,48E-03
GWP100 - biogenic	kg CO2-eq	2,22E-04	1,69E-04	1,88E-05	4,33E-07	3,46E-05
GWP100 - land transformation	kg CO2-eq	9,39E-05	9,14E-05	8,73E-07	2,01E-08	1,61E-06

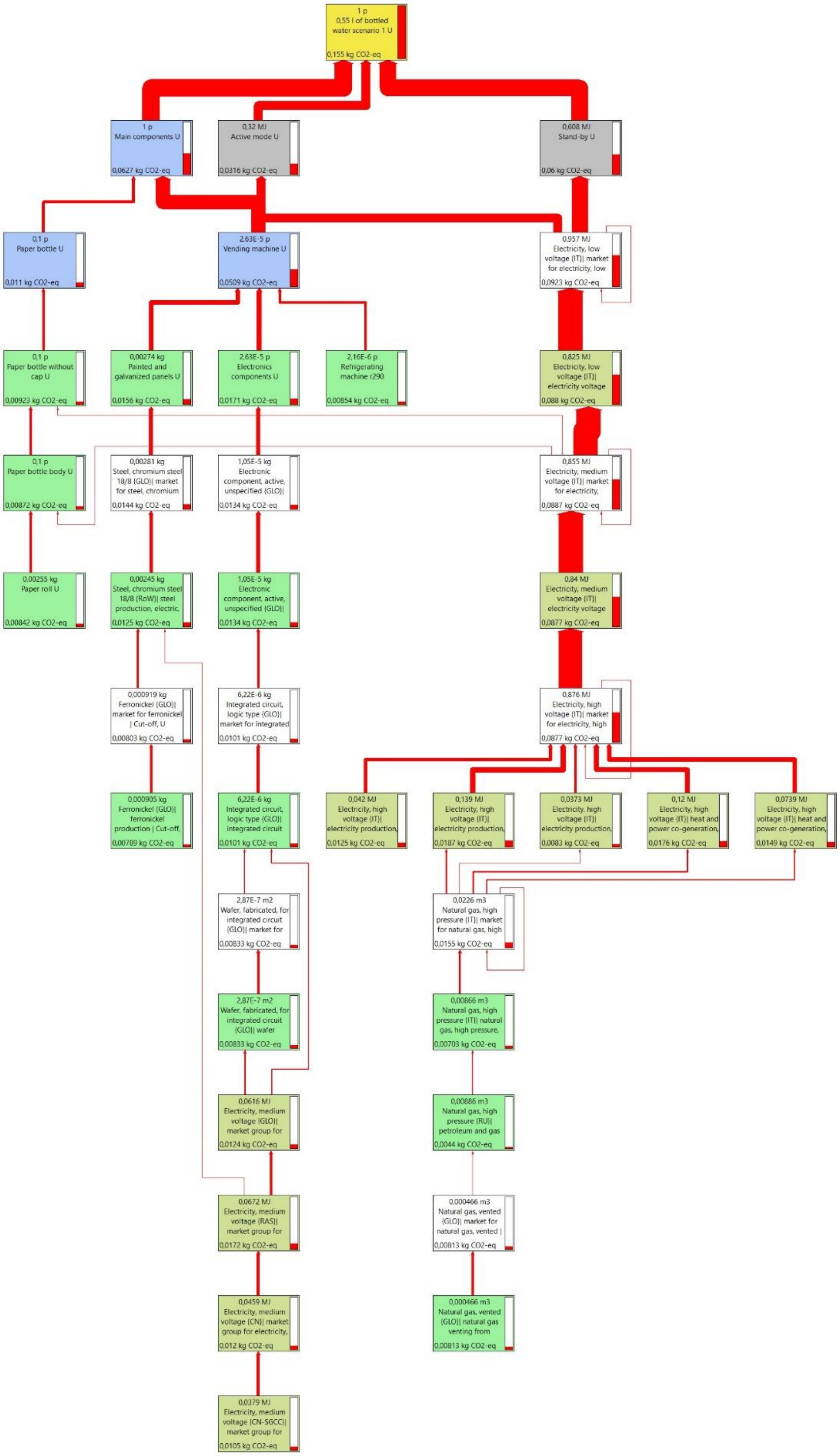


Figure 34 - IPCC 2021 total for use stage - scenario 1

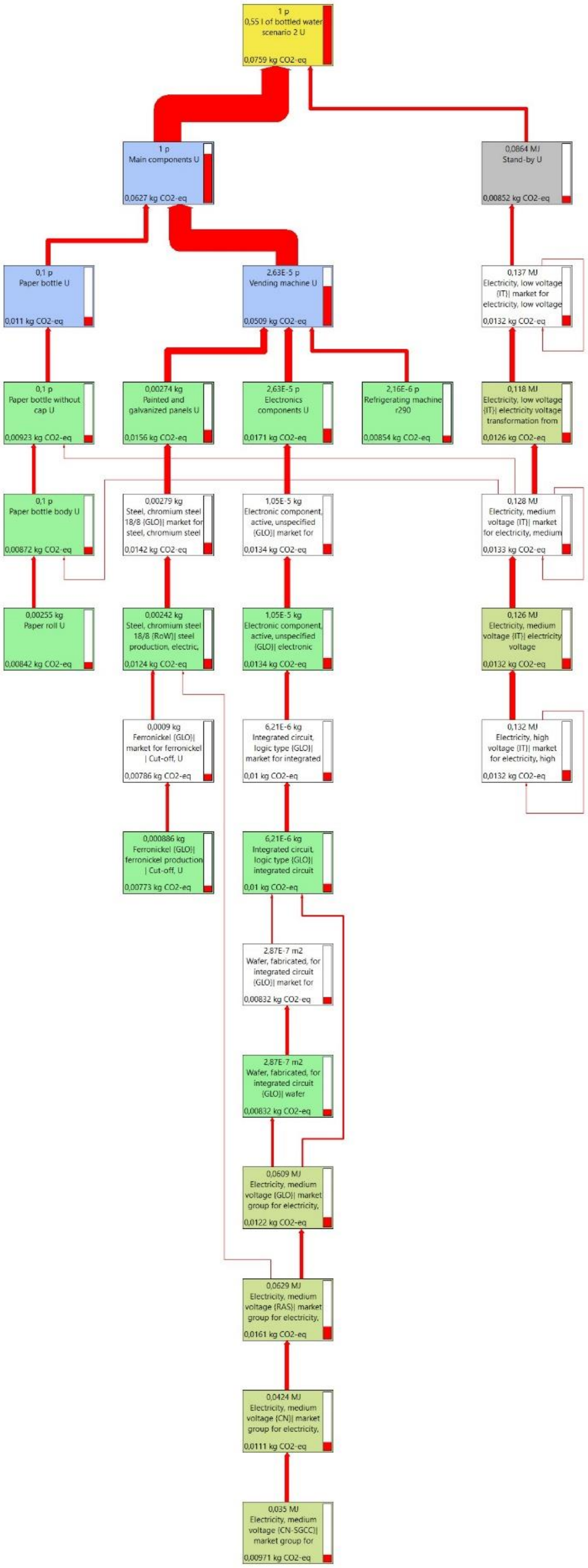


Figure 35 - IPCC 2021 total for use stage - scenario 2

The results obtained using the IPCC method confirm that Scenario 2 presents a lower Climate Change impact compared to Scenario 1 and the case analysed in Chapter 6. This demonstrates how essential a detailed analysis of consumption is in providing a complete picture of the impacts associated with the dispensing of 0,55 litres of bottled water.

In Table 39 and Table 40 are presented the result obtained with the CED method for scenario 1 and scenario 2.

Table 39 - CED total for use stage – scenario 1

Impact Category	Unit	Total	Main components	Active mode	Fully active mode	Stand-by
Non-renewable, fossil	MJ	2,21E+00	8,14E-01	4,79E-01	1,08E-02	9,09E-01
Non-renewable, nuclear	MJ	2,85E-01	8,16E-02	6,96E-02	1,56E-03	1,32E-01
Non-renewable, biomass	MJ	5,66E-05	4,11E-05	5,31E-06	1,19E-07	1,01E-05
Renewable, biomass	MJ	9,48E-02	4,84E-02	1,59E-02	3,57E-04	3,02E-02
Renewable, wind, solar, geothermal	MJ	3,71E-01	1,93E-02	1,20E-01	2,70E-03	2,28E-01

Table 40 - CED total for use stage – scenario 2

Impact Category	Unit	Total	Main components	Active mode	Fully active mode	Stand-by
Non-renewable, fossil	MJ	1,01E+00	8,14E-01	6,99E-02	1,61E-03	1,29E-01
Non-renewable, nuclear	MJ	1,11E-01	8,16E-02	1,02E-02	2,35E-04	1,88E-02

Impact Category	Unit	Total	Main components	Active mode	Fully active mode	Stand-by
Non-renewable, biomass	MJ	4,33E-05	4,11E-05	7,75E-07	1,79E-08	1,43E-06
Renewable, biomass	MJ	5,50E-02	4,84E-02	2,32E-03	5,36E-05	4,29E-03
Renewable, wind, solar, geothermal	MJ	6,97E-02	1,93E-02	1,76E-02	4,05E-04	3,24E-02

From the Sankey diagram in Figure 36 and Figure 37, it can be observed that, for Scenario 1, the electricity used during both the active and stand-by phases represents a significant portion of the total energy consumption. However, in Scenario 2, both energy uses are secondary when compared to the energy required to produce the main components of the vending machine and the bottle. This further emphasizes the importance of conducting a thorough analysis of energy consumption when studying these products.

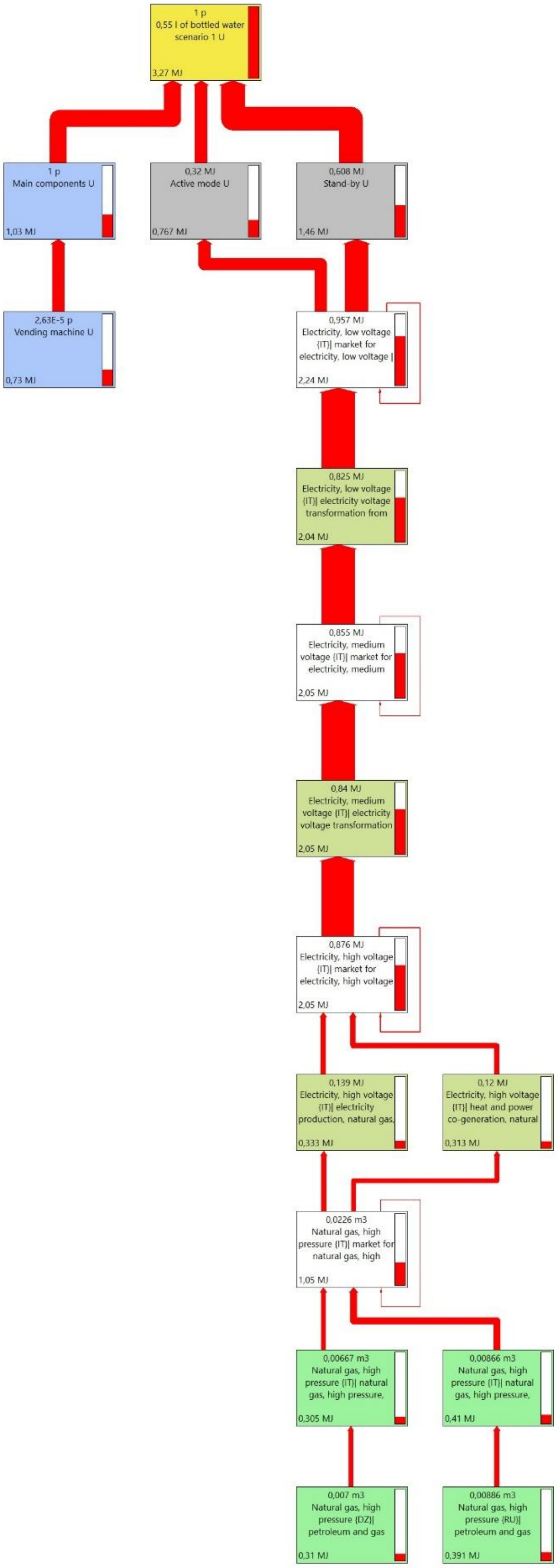


Figure 36 - CED total for use stage - scenario 1

Figure 37 - CED total for use stage - scenario 2

7.1 Optimizing Waste Reduction

This section involves analysing a design improvement to evaluate the effectiveness of waste reduction strategies in minimizing environmental impacts. Two scenarios are examined: one in which waste is reduced by 50% and another where waste is reduced by 25%. The analysis focuses on how these reductions in material waste during the cutting phase affect overall resource consumption and ecological footprint. By comparing these two cases, the aim is to determine the most effective approach for enhancing sustainability in the production process.

Table 41 – Normalized result for impact categories with the waste factor reduction

Damage Category	**Paper bottle production**	**Paper bottle production 0,5**	**Paper bottle production 0,25**
Acidification	100%	69%	61%
Climate change	100%	70%	62%
Ecotoxicity, freshwater	100%	69%	61%
Eutrophication, freshwater	100%	69%	61%
Eutrophication, marine	100%	70%	62%
Eutrophication, terrestrial	100%	70%	62%
Human toxicity, cancer	100%	74%	67%
Human toxicity, non-cancer	100%	70%	63%
Ionising radiation	100%	75%	68%
Land use	100%	65%	55%
Ozone depletion	100%	73%	66%
Particulate matter	100%	67%	59%
Photochemical ozone formation	100%	70%	62%
Resource use, fossils	100%	70%	63%
Resource use, minerals, and metals	100%	69%	60%
Water use	100%	67%	59%

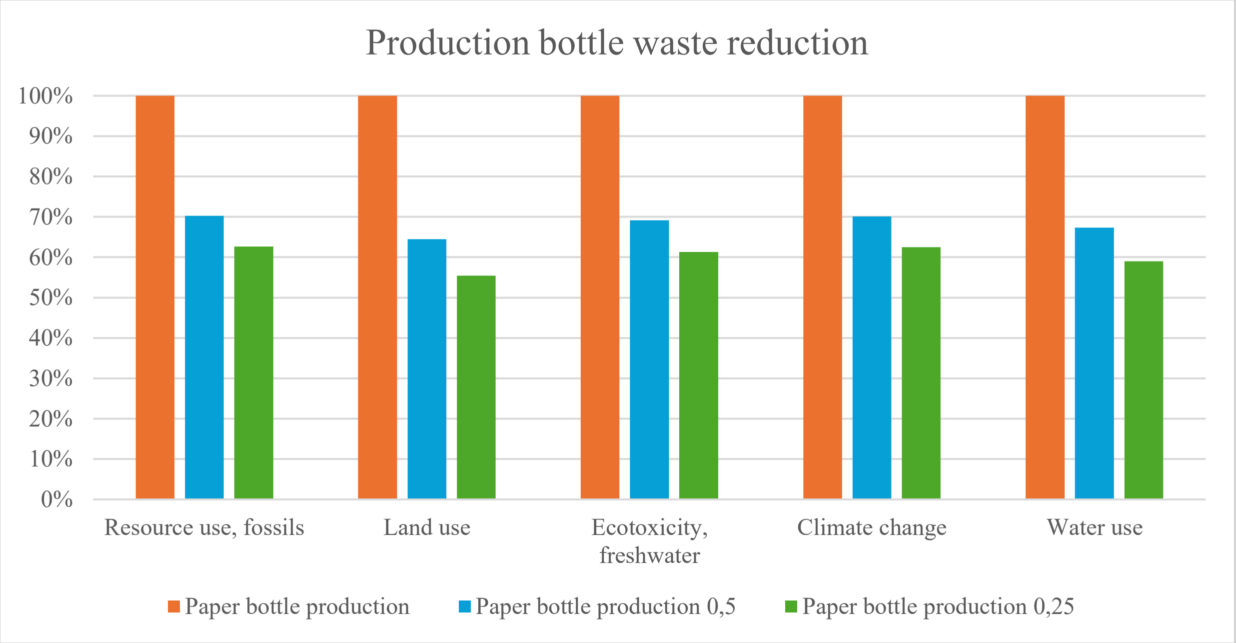


Figure 38 - Comparison between waste reduction scenarios

As shown in Figure 38, in scenarios where waste reduction is present, the production of paper bottles consistently demonstrates lower values across all environmental impact categories. This reduction is particularly significant in terms of resource use, land use, and freshwater consumption, especially in the case of a 50% reduction.

7.2 Consumption Reduction Strategies

In this section, the reduction in energy consumption is analysed to evaluate its potential impact on mitigating effects across various damage categories. The assumptions regarding consumption reduction are outlined in Table 42. The decision was made to apply reductions exclusively to the standby phase, as this phase presents the highest degree of uncertainty. By focusing on standby, the analysis aims to gain a clearer understanding of system behaviour and assess the extent to which uncertainties in this data affect the results. This approach provides insights into the reliability of consumption data and helps to identify the specific influence of standby variations on overall system performance.

Table 42 - Assumption in consumption reduction strategies

Case	**Assumption**
Bottled water (case 1)	Initial case
Bottled water_1	Reduction of stand-by power factor by 10%
Bottled water_2	Reduction of stand-by power factor by 20%
Bottled water_3	Reduction of stand-by power factor by 1/3
Bottled water_4	Reduction of stand-by power factor by 2/3

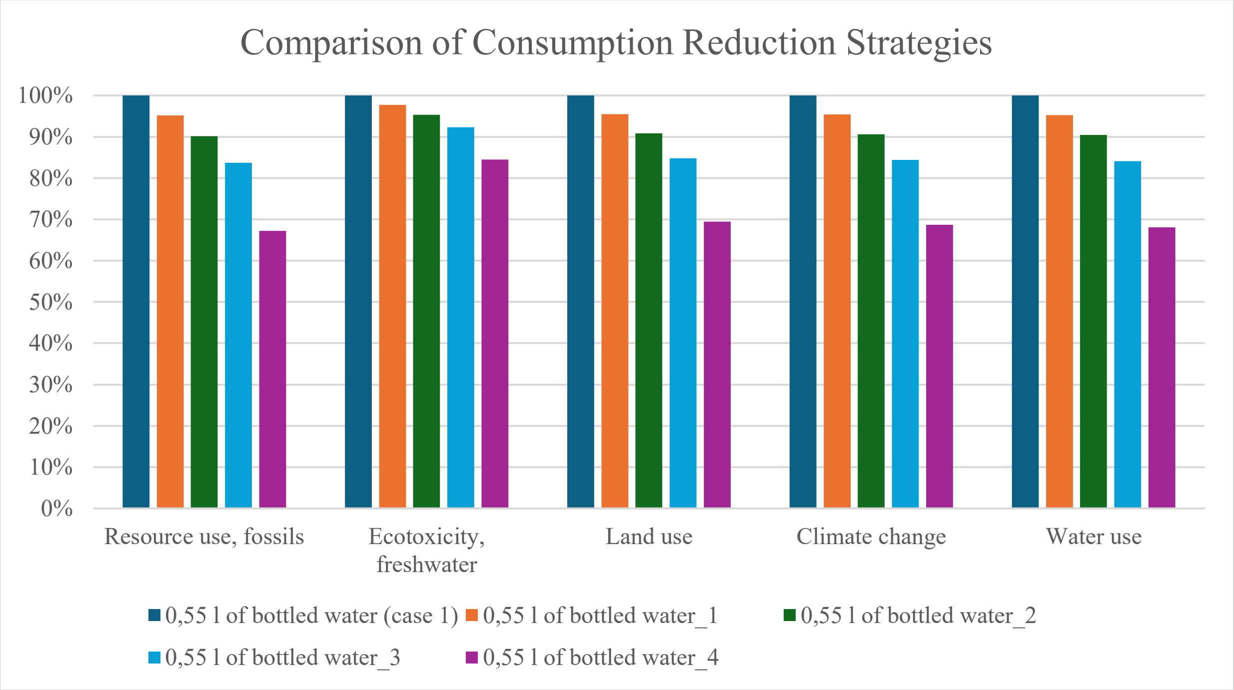


Figure 39 - Comparison between consumption reduction scenarios

The graph in Figure 39 shows a comparison between different scenarios where electricity consumption during standby mode is reduced. As can be seen, the most significant reduction occurs in the 'Resource Use, Fossil' impact category, due to its strong sensitivity to electricity consumption. For all other impact categories, the reduction is marginal.

7.3 Renewable Energy Mix Scenario

In this section, we explore a scenario where the current energy mix is entirely replaced by a nearly 100% renewable energy mix. This transition aims to eliminate dependency on fossil fuels and significantly reduce environmental impacts. By shifting to renewable sources such as solar, wind, and hydropower, this scenario envisions not only a decrease in greenhouse gas emissions but also improvements in resource sustainability and energy security. The analysis will focus on the potential benefits and challenges associated with achieving a fully renewable energy mix.

This scenario builds upon the considerations discussed in the use phase chapter regarding consumption and entirely replaces the electricity source from the Italian energy mix with a nearly 100% renewable energy mix, maintaining the same distribution as the Italian energy mix [36].

Composition:

- 39% photovoltaic
- 19% wind
- 33% hydroelectric
- 8% from the Italian mix.

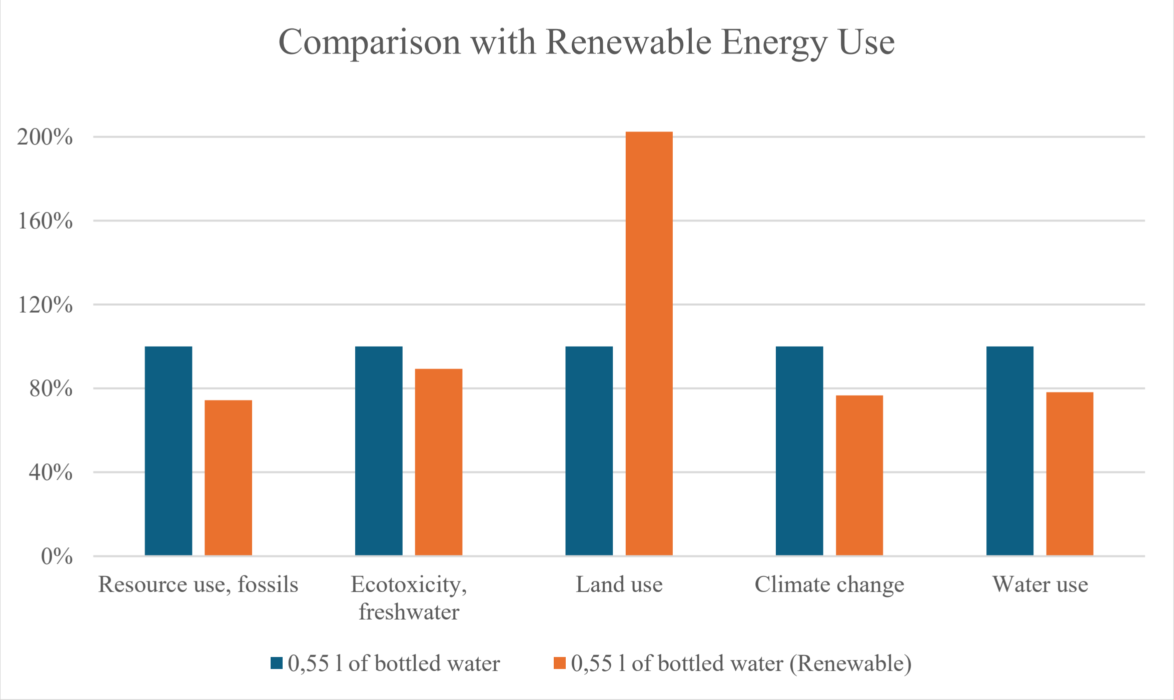


Figure 40 - Comparison with the Renewable Energy Use

As shown in Figure 40 comparing the results for the damage categories analysed throughout this study, the Resource Use, Fossil category decreases. However, the impact associated with Land Use rises, likely because of the infrastructure required for the installation of photovoltaic panels, wind turbines, and hydroelectric plants. The Climate Change impact, which might have been expected to show the most significant change, does not decrease substantially. This is unexpected, as one would anticipate at least a 50% reduction, given that more than 60% of the previous impact was attributed to the electricity consumed. This suggests that using a nearly 100% renewable energy mix does not lead to a significant reduction in CO_2 emissions in this case.

8. COMPARISON WITH SINGLE USE PLASTIC BOTTLE

To compare the paper bottle analyzed in this study with its alternative, a single-use plastic bottle, Environmental Product Declarations (EPDs) were used. EPDs provide standardized, independently verified reports on the environmental impact of a product throughout its lifecycle. They serve as reliable benchmarks in environmental assessments as they adhere to ISO standards and offer consistent, transparent data. In this case, using EPDs allows for an objective comparison by providing a clear view of each bottle environmental impacts under similar parameters.

To ensure comparability between the two cases, it was essential to align their functional units. The paper bottle, when filled, has a capacity of 0,55 liters of water, while a typical single-use plastic bottle holds 0,5 liters. To make the impacts comparable, a scaling factor of 0,5/0,55 was applied to the impact data of the paper bottle. The analysis was then repeated following the same methodology used in the Environmental Product Declaration (EPD) for the commercial single-use plastic bottle, specifically employing the EPD 2018 method.

For the single-use plastic bottle, multiple EPDs have been published, all of which include end-of-life analysis. However, since this study excludes end-of-life impacts, these were also excluded from the analysis of the plastic bottle to maintain consistency.[37]

Figure 41 represents the system boundaries of the life cycle assessment in the EPD considered for the comparison.

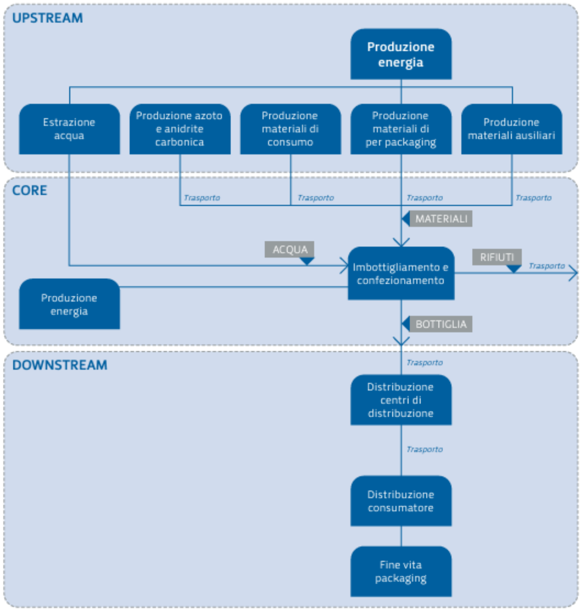


Figure 41 - Flow diagram of the processes included in the life cycle of the single use plastic bottle analysed in the EPD. The dashed line represents the system boundary under examination [37]

In parallel with the analysis of the paper bottle examined in this thesis and the results obtained from the EPD of a single-use plastic bottle taken as a reference, a third option was included in the comparison to better align with the case studied in this work. This additional scenario, labelled *"Plastic Bottle,"* follows the same steps for the production and transportation of the bottle but substitutes the paper body with plastic. The plastic component is modelled using a typical processing method for PET bottle production. The process used in SimaPro to model this option is detailed in Table 43.

Table 43 – Production of 1 Plastic Bottle

Product	Process	Calculation	Value	Unit of measurement
Plastic bottle	*Polyethylene terephthalate, granulate, bottle grade*	13/1000	0,013	kg
	Stretch blow moulding	13/1000	0,013	kg

Table 44 shows the results for the Global Warming impact across the three scenarios analysed. As the table illustrates, the two implemented scenarios, Plastic Bottle and Paper Bottle, are more like each other, and so more comparable. This similarity is primarily due to the use of the same approach for defining the system boundaries. In contrast, the case analysed through the EPD follows a different set of system boundaries. In any case the reduction of the Global Warming impact in the case of paper bottle is also due to its multiple possible reutilizations.

Table 44 – Global Warming comparison between EPD, single-use plastic bottle and filled paper bottle

	EPD	**Plastic bottle**	**Paper bottle**
Global Warming [kg $CO_{2,\,eq}$]	0,35	0,098	0,011

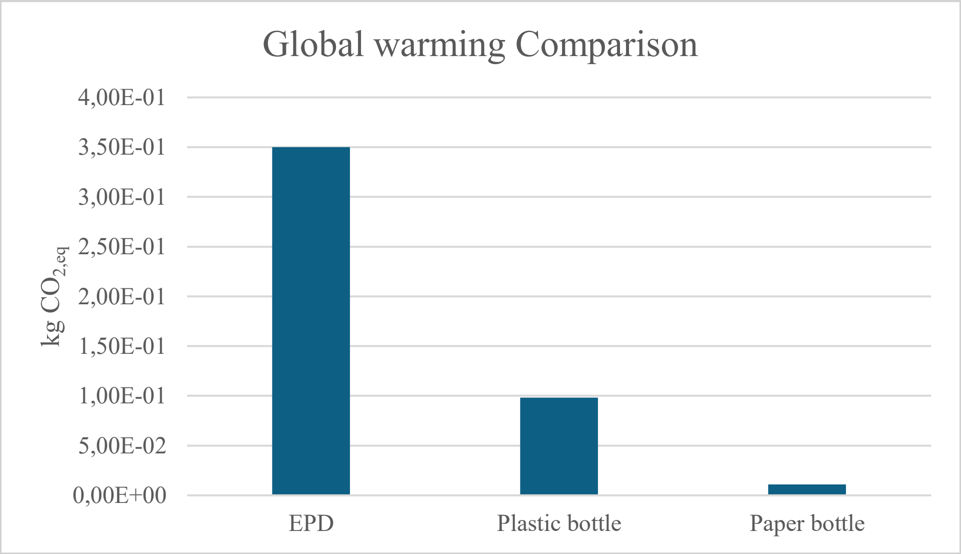


Figure 42 - Global warming comparison between EPD, single-use plastic bottle and filled paper bottle.

In conclusion, as shown in Figure 42 and in Table 44, the ‘Global Warming’ impact is significantly lower for the filled paper bottle. This reduction stems not only from the potential for reuse of the paper bottle but also from differences in the water sourcing processes considered in each analysis. Specifically, the environmental analysis of the plastic bottle includes the entire supply chain impact associated with bottling water at its source, which encompasses extraction, transportation, and processing stages.

In contrast, the paper bottle analysis assumes that water is sourced directly from the municipal supply. This approach eliminates the extensive logistical and processing operations required for traditional bottled water, significantly reducing associated greenhouse gas emissions. Consequently, the environmental impact of the paper bottle appears notably lower, emphasizing how both material selection and supply chain design play a critical role in determining the Global Warming Potential in life cycle assessments.

However, the analysis has certain limitations. The paper bottle requires a dedicated filtration system and vending machine for filling. When the entire system is accounted for, the equivalent CO_2 emissions are estimated at 0,23 kg of CO_2 equivalent per dispense. Although this remains lower than the 0,35 kg associated with the single-use plastic bottle, a more detailed and system-level analysis would be necessary for a fully robust comparison.

9. CONCLUSIONS

This thesis has presented a comprehensive Life Cycle Assessment (LCA) of an innovative vending machine system designed to dispense oligomineral water in reusable paper bottles. The primary objective was to evaluate the environmental impact of the system across its production and use phases, focusing on material consumption, emissions, and energy use, to identify opportunities for reducing the system environmental footprint. Life Cycle Assessment (LCA) is a standardized methodological framework that evaluates the environmental impact of a product, process, or system throughout its entire lifecycle, encompassing stages such as raw material extraction, production, transportation, use. By systematically assessing factors like energy consumption, resource use, and emissions at each stage, LCA provides a holistic understanding of the environmental burdens associated with the vending machine system. Within this study, the LCA methodology allowed for a detailed examination of the innovative system production and operational phases, offering insights into its overall environmental footprint.

This study demonstrates that this innovative solution offers a sustainable alternative to single-use plastic bottles, aligning with European Union sustainability goals and advancing the transition toward a circular economy. The findings reveal that leveraging municipal water sources combined with reusable paper bottles can significantly reduce the environmental footprint compared to traditional plastic bottled water. By minimizing dependence on long supply chains, the system reduces greenhouse gas emissions associated with material extraction, single-use production, and transportation. Additionally, the paper bottles, designed for up to ten reuses, shift the consumption paradigm from disposability to reuse, which is essential for addressing waste generation.

Despite these advantages, the calculations in this analysis are subject to the limitations posed by various assumptions, which introduce a degree of uncertainty. Assumptions on machine operational modes, power use distribution, daily number of dispenses and component specifications, while necessary, may differ from actual field conditions. Additionally, hypothetical dimensions of the LED strip, the spacing between LEDs, and material estimates for specific machine parts were adopted due to lack of precise data. The exclusion of routine maintenance activities and parts replacement, other than filters, means that the assessment does not fully capture the machine lifecycle impact. These assumptions, although methodologically sound, suggest that a refined study with more detailed empirical data would yield an even more precise evaluation of the system environmental footprint.

A further recommendation involves transitioning the vending machines to renewable energy sources such as solar or wind power. While the machines are relatively energy efficient, relying on renewables would drastically lower their carbon footprint, especially during the use phase, making the system even more sustainable.

In conclusion, this thesis confirms that integrating reusable paper bottles with a vending machine system offers a compelling solution to reduce the environmental footprint of bottled water consumption. Through resource efficiency, waste minimization, and emissions reductions, this model supports European directives on plastic reduction and sustainable development. The implementation of this system on a larger scale has the potential to significantly decrease single-use plastic waste, foster responsible water consumption habits, and contribute meaningfully to a circular economy. By addressing the identified limitations, such as improving bottle production efficiency and incorporating renewable energy, the sustainability of this system can be further enhanced, paving the way for a scalable and impactful solution to contribute to facing global environmental challenges.

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