Assessing the impact of autoclaving versus purchasing new Plastic Flasks in a technological platform

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Executive Summary

The extensive use of single-use plastic flasks in laboratory settings presents significant environmental challenges, particularly in terms of plastic waste and greenhouse gas emissions. This study conducts a comparative Life Cycle Assessment (LCA) to evaluate the environmental impacts of single-use plastic flasks versus reusable flasks, focusing on their use within the EPFL SV-PTPSP platform. The analysis considers the entire life cycle, from raw material extraction to end-of-life treatment, and includes key processes such as production, transportation, washing, and autoclaving.

The results reveal that reusable flasks offer substantial environmental advantages over single-use flasks in terms of carbon footprint, fossil energy use, and ecosystem quality damage. However, the benefits are tempered by increased water consumption and resource use in cleaning and sterilization processes. Sensitivity analyses identify critical parameters, such as machine fill factor and energy source, as significant levers for improving environmental performance. Scenario analyses further highlight the potential of renewable energy integration to reduce environmental burdens.

This study concludes that transitioning to reusable flasks, alongside targeted optimizations in cleaning practices and integrating renewable energy sources, can significantly enhance sustainability in laboratory operations. These findings provide actionable recommendations for reducing environmental impacts in research laboratories, aligning with global sustainability goals.

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Contents

1 Introduction

The escalating global concern over plastic waste and its environmental ramifications has prompted various sectors to reassess their reliance on single-use plastics. Scientific laboratories, which have traditionally depended on disposable plastic equipment for convenience and sterility, are no exception. Laboratories contribute significantly to plastic waste generation, with estimates suggesting that the scientific sector produces millions of tons of plastic waste annually. This reality underscores the urgent need for sustainable practices within research environments.

At EPFL, the SV-PTPSP core technological platform specializes in the production and purification of proteins in mammalian cells, operating within a Biosafety Level 1 (BSL1) environment. A critical component of their operations involves the use of single-use plastic flasks for cell culture experiments made from high-density polyethylene (HDPE) and polycarbonate (PC) materials. Annually, the platform purchases over 1200 disposable plastic flasks. While these flasks offer convenience and ensure sterility, their single-use nature raises significant environmental and economic concerns.

Figure 1: Corning flasks [1]

The environmental issues associated with the extensive use of disposable plastic flasks are multifaceted. Firstly, the production of plastic flasks involves the consumption of non-renewable resources such as petroleum and natural gas. The manufacturing process emits greenhouse gases (GHGs), contributing to global warming and climate change. Secondly, the disposal of plastic flasks after a single use adds to the growing problem of plastic pollution. Plastics can take hundreds of years to degrade, and improper disposal can lead to environmental contamination, affecting wildlife and ecosystems.

One potential solution is the adoption of reusable flasks that can be sterilized through autoclaving. Autoclaving involves using pressurized steam at high temperatures to sterilize equipment, effectively eliminating microorganisms. Reusable flasks made from durable materials, can withstand multiple autoclave cycles before they degrade. By transitioning to reusable flasks, the platform could significantly reduce plastic waste generation and lower long-term costs associated with purchasing disposable equipment.

It is important to note that reusable flasks have a limited lifespan before they degrade. As they undergo repeated autoclaving cycles, their structural integrity and performance can diminish. This degradation can lead to issues such as contamination risks or failure to maintain the required experimental conditions, ultimately affecting the reliability of results. For example, initial attempts at using glass flasks at the SV-PTPSP platform revealed a significant decline in performance after just a few autoclaving cycles, resulting in failed experiments. This highlights the importance of carefully evaluating both the material durability and the practicality of adopting reusable flasks in a research environment.

Figure 2: Getinge 86-series washer [2]

Figure 3: FOB lab sterilizer (autoclaving machine) [3]

In addition to the challenges of flask durability, the environmental costs of autoclaving must also be considered to determine whether this approach represents a net improvement in sustainability. The autoclaving process consumes energy and water and may involve the use of detergents and other chemicals for cleaning. These inputs contribute to the overall environmental impact, potentially offsetting the benefits of reducing plastic waste.

These considerations underscore the importance of conducting a thorough Life Cycle Assessment to evaluate the environmental trade-offs between these two approaches. By assessing the complete life cycles of both single-use and reusable flasks, this study aims to provide data-driven insights to inform sustainable decision-making at the SV-PTPSP platform.

1.1 Objective of the study

In light of these considerations, this study aims to conduct a comprehensive Life Cycle Assessment (LCA) to evaluate the environmental impacts of autoclaving reusable flasks compared to the continued use of single-use plastic flasks at the SV-PTPSP platform. The assessment will consider the entire life cycle of the flasks, from the production of raw materials to end-of-life disposal, including the use phase involving autoclaving for reusable flasks.

1.2 Overview of similar studies

Some LCA study of the topic or related topics has already been performed. In fact, going over some of the findings helps us to understand the context of our current study and to specifically target questions that remain unanswered. To do so we have identified 4 studies (3 LCA's and one aggregate study on 18 LCA's) that have particular relevance for our own analysis. Namely, these studies focus on the laboratory environment and the life cycle of laboratory equipment.

Firstly, a 2022 LCA study of UCL's Bartlett department by Y. Cai provides useful insights that help motivate our analysis. This study assessed the department's overall emissions from 2018 to 2019, highlighting the main environmental contributors. While it grouped all lab procurements into a single category and did not focus solely on lab equipment, it showed that lab equipment and chemicals are major sources of greenhouse gas emissions, accounting for approximately 24% of the department's total emissions [4]. This finding underscores the importance of examining laboratory-specific impacts, which our study aims to address more directly.

Furthermore, an LCA study commissioned by lab equipment manufacturer Eppendorf and one published as part of Volume 1 of the journal *Advances in Sample Preparation* examine environmental performance of plastic lab containers and of sample preparation techniques respectively. The Eppendorf study finds that raw materials, distribution and end of life (EoL) contribute the most to CO2 emissions outside of the lab. Within the lab, it highlights procurement and EoL management of containers as the biggest levers for improvement. The second study supports these findings, further indicating that while washing reusable containers increases the environmental burden (primarily due to chemical usage), this impact is outweighed by the environmental benefits gained through reuse [5, 6].

Finally, an aggregate study on a total of 18 cradle-to-gate LCA's (5 additional LCA's were used specifically for disposal methods) was published in the *PLOS* journal, analyzing the use of life cycle assessments to guide reduction in the carbon footprint of single-use lab consumables. This paper is particularly relevant to our study as it assesses equipment of the same material (HDPE) within a very similar context. The paper highlights polymer and raw material production as the largest contributors to overall emissions, followed by end-of-life when incineration was the chosen disposal method. Additionally, it concludes that the most significant emission reductions can be achieved through circular supply chains, and identifies disposal choice of the equipment as one of the main levers on impact within the lab [7].

1.3 Gaps addressed by this study

In light of these findings, this study aims to provide further insights into the trade-offs involved specifically in choosing between single-use and multi-use containers of different materials and sizes within the scope of SV-PTPSP's research. It seeks to offer a comparative analysis of these trade-offs across the life cycle of each container type.

Additionally, this study is meant to take EPFL's specific context into account, namely the regulations and processes that dictate work within the SV-PTPSP lab. This means considering the local energy mix, the geographical context as well as the specific equipment and washing infrastructure available to the staff.

2 Project goals

As mentioned, this study specifically addresses the SV-PTPSP lab at EPFL and was commissioned by the lab as part of a broader EPFL initiative to evaluate the environmental impact across its labs and departments. The study aims to optimize the lab's sustainability performance by assessing and comparing the environmental impacts of single-use versus multi-use containers and flasks in lab operations.

The results of this study are intended to inform procurement and usage decisions regarding containers, helping to minimize environmental impact at the SV-PTPSP lab and, more generally, at EPFL. This information could guide the lab's sustainability practices, potentially influencing resource efficiency and waste reduction.

The primary audience for this study is decision-makers within EPFL, including lab managers and sustainability officers. However, it may also benefit other laboratories working under similar conditions, both in terms of scientific focus and geographic context.

As such, if the study finds significant differences between the two approaches (reuse vs. single-use), these findings may be used for comparative assertions disclosed to the public.

3 Function and functional unit

The primary function of the product systems under consideration is to provide sterile flask volume for the production and purification of proteins in mammalian cell cultures at the SV-PTPSP core technological platform of EPFL, Lausanne, in 2024. The flasks are critical to ensuring the sterility and efficiency of cell culture experiments conducted in a Biosafety Level 1 (BSL1) environment.

The product systems being compared are:

Single-use plastic flasks: Made from materials such as polycarbonate (PC), polypropylene (PP) and high-density polyethylene (HDPE), these flasks are designed for one-time use, ensuring sterility but contributing to significant plastic waste.

Reusable flasks: Made from durable materials capable of withstanding autoclaving cycles, these flasks can be sterilized and reused multiple times, reducing plastic waste but requiring energy and water for the autoclaving process.

While both systems serve the same primary function, their environmental impacts differ due to the single-use nature of plastic flasks versus the energy-intensive maintenance of reusable flasks. To ensure meaningful comparison, functional equivalence between the systems has been established by considering scalability and interchangeability across flask sizes and materials.

3.1 Functional Unit

The functional unit for this study is defined as:

The use of flasks sufficient to process ***25 L of a certain cell culture medium at EPFL SV-PTPSP in 2024****.*

This definition assumes that flasks of the same material are scalable and interchangeable for the experimental process. For example, the same culture volume could be achieved using one 4 L flask or two 2 L flasks. This allows for a direct comparison of systems while accounting for variations in flask size and usage frequency.

Key Assumptions

Scalability: Flasks of different volumes made from the same material can perform equivalent functions by scaling their usage appropriately.

Interchangeability: Experiments requiring a specific flask type can use alternative volumes without compromising functionality.

Material Grouping: Flasks of the same material are grouped for analysis to simplify comparisons across different product systems.

3.2 Limitations

The functional equivalence assumes that all flask sizes of the same material are equally suited to the cell culture process. Any material- or size-specific performance issues, such as sterility or structural integrity, are not explicitly considered in this functional unit but will be addressed in the broader LCA discussion.

4 Description of the product systems

This LCA study evaluates the environmental impacts of using single-use plastic flasks versus reusable flasks with autoclaving for protein production in a BSL1 lab setting at EPFL PTPSP. The functional unit (FU) for this analysis is defined as the "use of flasks sufficient to process 25 liters of cell culture medium in 2024." The process tree and system boundaries for each product system are designed to capture all relevant life cycle stages, from raw material extraction to end-of-life treatment.

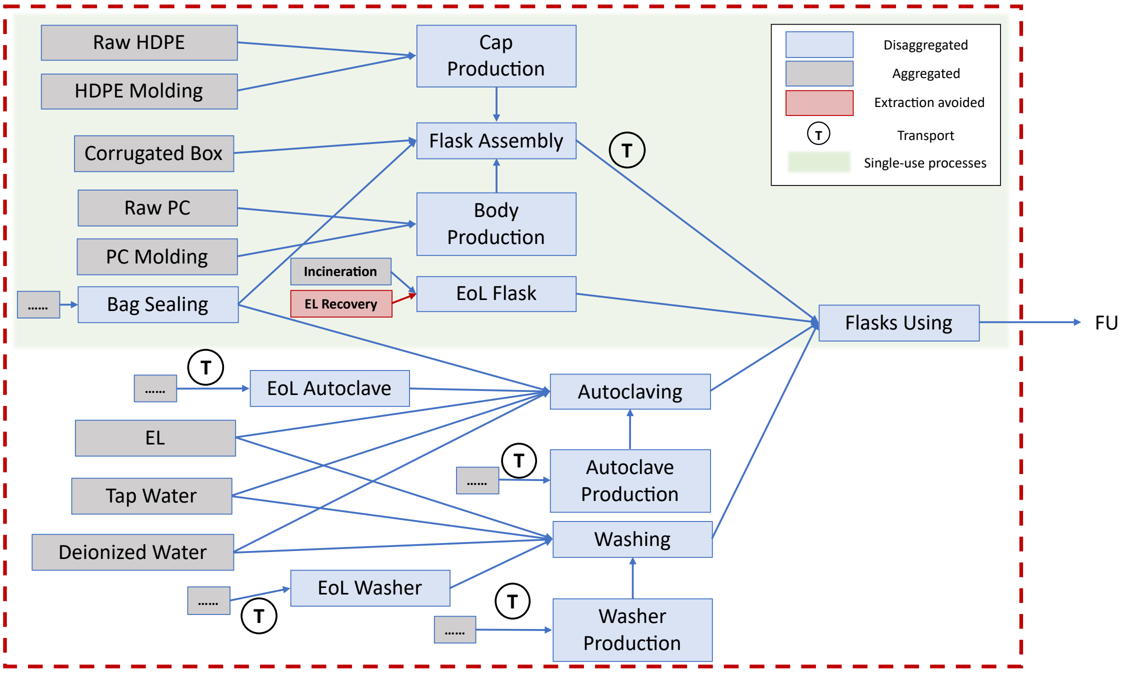


Figure 4: Process tree about the product systems

4.1 Process Tree Overview

The process tree, as shown in figure 4, includes two main product systems:

1. **Single-Use Plastic Flasks**: These flasks are manufactured from high-density polyethylene (HDPE) and polycarbonate (PC) materials or polypropylene (PP). They go through production stages including material extraction, molding, and assembly. Once used in the lab, these flasks are disposed of by incineration with energy recovery.

2. **Reusable Flasks with Autoclaving**: These flasks are sterilized and reused multiple times through autoclaving. This system includes additional processes like washing and autoclaving, which require inputs of electricity, tap water, and deionized water. At the end of their lifecycle, the reusable flasks are also disposed of through incineration with energy recovery.

4.2 System Boundaries and Process Classification

4.2.1 Foreground Processes (Gate-to-Gate)

These processes occur within the lab's operational boundaries and include flask usage, washing, and autoclaving. The impacts of these stages, such as energy and water consumption, are directly controlled by the lab and are thus categorized as gate-to-gate processes.

4.2.2 Background Processes (Cradle-to-Gate)

Background processes include the upstream activities of raw material extraction and flask production. These cradle-to-gate stages are outside the lab's direct control but are essential to the product systems being assessed. Examples include HDPE and PC production, molding, transport, and end-of-life processing.

The system boundary is set as cradle-to-grave to capture the entire lifecycle of both single-use and reusable flasks, ensuring a comprehensive assessment.

4.3 Inclusions and Exclusions

In the life cycle assessment of single-use and multi-use flasks, certain processes and resources are included or excluded to focus on the most impactful stages. Included are the production of flask components (cap and body), plastic packaging bags, and box materials. Plastic bags are used frequently to maintain sterility after each cleaning of reusable flasks, adding significantly to the environmental impact. The box material also contributes to the lifecycle footprint, especially during transportation. Additionally, the resources used for washing and autoclaving reusable flasks, such as water and electricity, are included due to their high consumption across multiple use cycles. Conversely, excluded processes include resources for initial flask assembly, as their impact is minimal compared to other stages, and on-campus maintenance and transportation, which are negligible. Furthermore, the energy and resources involved in manufacturing and maintaining the autoclaving and washing machines are excluded due to lack of specific data and the shared usage of these machines across various lab functions. These inclusions and exclusions ensure that the assessment focuses on the primary environmental impacts associated with each flask system.

4.4 End-of-Life (EoL) Treatment

For the end-of-life (EoL) treatment of flasks, incineration with energy recovery is utilized, allowing the energy generated from burning the flask materials to offset some of the system's energy demands. This is treated by introducing an end of life recycling: considering both waste disposal and the environmental credit from recovered energy. Rather than feeding energy directly back into the system, the recovered energy offsets the overall energy requirements, slightly reducing the environmental burden associated with energy use. This boundary expansion enables the LCA to capture the dual function of incineration, accurately reflecting the impact of energy recovery at the EoL stage.

5 Reference flows and key parameters

Definition: The Functional Unit (FU) is defined as the number of flasks required to process 25 liters of a specific cell culture medium at EPFL PTPSP in 2024.

For this analysis, the Corning 431144 flask (250 mL) was selected, which would require 100 experiments of 250 mL each per FU to process the total volume.

Single-Use Flask Requirement ($\mathbf{RF_{single}}$)

$$\mathrm{RF}_{\text{single}} = \frac{100 \text{ experiments/FU}}{1 \text{ experiment/flask}} = 100 \text{ flasks/FU}$$

Thus, for the single-use scenario, 100 flasks are required per FU.

Multiple-Use Flask Requirement ($\mathbf{RF_{multi}}$)

$$\mathrm{RF}_{\text{multi}} = \frac{100 \text{ experiments/FU}}{10 \text{ experiments/flask}} = 10 \text{ flasks/FU}$$

For the multiple-use scenario, only 10 flasks are required per FU. Empirical data from PTPSP lab suggests each flask can be reused for up to 10 experiments.

After defining the function unit, process tree and system boundaries, with data acquired in part 6, the key parameters about flask use and washing facility are calculated and shown in table 1 and table 2 respectively, the calculation processes are listed in appendix A .

Table 1: Reference flows and Key parameters (Flask)

Unit Process	**Unit**	**Key parameters**
PP for Cap Production	g/FU	- 830 g per FU for single-use scenario (100 caps per FU) - 83 g per FU for multiple-use scenario (10 caps per FU) - Material: Polypropylene (PP)
PC for Body Production	g/FU	- 4900 g per FU for single-use scenario (100 bodies per FU) - 490 g per FU for multiple-use scenario (10 bodies per FU) - Material: Polycarbonate (PC)
Electricity for Bag Sealing	kWh/FU	- 2.5 kWh per FU for single-use scenario (100 items) - 0.25 kWh per FU for multiple-use scenario (10 items) - Sealing energy requirement
Box Production	kg/FU	- 2.478 kg of cardboard per FU for single-use scenario (2 boxes for 100 flasks) - 0.2478 kg of cardboard per FU for multiple-use scenario (1/5 of a box for 10 flasks)
Bag Production (Paper)	g/FU	- 74.35 g per FU for single-use scenario (100 bags) - 74.35 g per FU for multiple-use scenario (10 bags) - Material: Paper (50% of bag composition)
Bag Production (HDPE)	g/FU	- 74.35 g per FU for single-use scenario (100 bags) - 74.35 g per FU for multiple-use scenario (10 bags) - Material: High-Density Polyethylene (HDPE, 50% of bag)
Distribution	tkm/FU	- 161.43 tkm per FU for single-use scenario (weight: 8.3567 kg per FU) - 44.58 tkm per FU for multiple-use scenario (weight: 2.3075 kg per FU) - Transportation path: 80% by sea/truck (China to Lausanne via Le Havre), 20% by air/truck, final disposal 11.5 km to incineration plant

6 Data sources and assumptions

6.1 Flask data

This study examines the performances of different flasks when used one or multiple times. The flasks presented below are produced in China, with the exception of the TPP model, that is

Table 2: Reference flows and Key parameters (Washer and Autoclave)

Unit Process	**Unit**	**Key parameters**
Electricity for Washing	kWh/FU	- 0.9375 kWh per FU (PTPSP allocation) - Washer model: Getinge S8666-7 - 32 flasks per cycle, 0.3125 cycles per FU - Total electricity: 3.125 kWh per FU
Tap Water for Washing	L/FU	- 9.375 L per FU (PTPSP allocation) - 31.25 L per FU total - 32 flasks per cycle, 0.3125 cycles per FU
Deionized Water for Washing	L/FU	- 2.8125 L per FU (PTPSP allocation) - 9.375 L per FU total - 32 flasks per cycle, 0.3125 cycles per FU
Electricity for Autoclaving	kWh/FU	- 0.4285 kWh per FU (PTPSP allocation) - Autoclave model: FOB3 TS - 28 flasks per cycle, 0.3571 cycles per FU - Total electricity: 1.4284 kWh per FU
Tap Water for Autoclaving	L/FU	- 6.9642 L per FU (PTPSP allocation) - 23.214 L per FU total - 28 flasks per cycle, 0.3571 cycles per FU
Deionized Water for Autoclaving	L/FU	- 3.2139 L per FU (PTPSP allocation) - 10.713 L per FU total - 28 flasks per cycle, 0.3571 cycles per FU
Washer Utilization per FU	cycles/FU	- 0.09375 cycles per FU - Contributes approximately 0.00625% of the washer's service life per FU
Autoclave Utilization per FU	cycles/FU	- 0.1071 cycles per FU - Contributes approximately 0.00714% of the autoclave's service life per FU

sourced from Switzerland directly. For given types of flasks, data on unit price, number of annual purchase, number of cleaning before disposal, maximum number of flasks per cleaning cycle in washer's chamber and autoclaving machine's chamber is provided by PTPSP's statistics, shown in table 3.

Table 3: Information about flasks used in PTPSP

Type	Unit Price/CHF	Annual purchase	Nb cleaning	Nb/Washer	Nb/Autoclave
Nest 786111	78.3	30	5∼8	12	6
Nest 787011	107.5	20	5∼8	4	6
Nest 785111	59.8	6	5∼8	16	11
Thompson 931116	125	45	0	4	6
Thompson 931114	48.3	20	0	12	6
Thompson 931113	57.6	25	0	16	16
Corning 430421	6.7	69	10	64	45
Corning 431144	8.32	60	10	32	28
Corning 431145	7.72	30	10	18	18
Corning 431147	17.25	100	10	18	18
TPP 87600	12.5	468	1	64	>100

Parameters of the flasks used in the lab are shown in table 4. The volume in the table corresponds to the nominal volume of each type of flask, raw materials used for manufacturing the body and cap are from the websites of producers[8, 9, 1, 10]. Data on mass, height and diameter is measured by group members in the lab.

Table 4: Parameters of flasks used in PTPSP

Type	Volume	Body material	m_{body}/g	Cap material	m_{cap}/g	Height/cm	⌀/cm
Nest 786111	3 L	PC	237.1	HDPE	19	24	17
Nest 787011	5 L	PC	367.1	HDPE	28.9	28	22
Nest 785111	2 L	PC	203.7	HDPE	19	20	15
Thompson 931116	5 L	PC	TBM	PTFE	TBM	N/A	N/A
Thompson 931114	2.8 L	PC	TBM	PTFE	TBM	N/A	N/A
Thompson 931113	1.6 L	PC	TBM	PTFE	TBM	N/A	N/A
Corning 430421	125 mL	PC	26.5	PP	7.7	12	7
Corning 431144	250 mL	PC	49	PP	8.3	14	9
Corning 431145	500 mL	PC	66	PP	9	16	11
Corning 431147	1000 mL	PC	113.1	PP	10.5	19	13
TPP 87600	600 mL	PP	98.5	PE	12.2	17	9

6.2 Washing facility data

Table 5 shows key data on the washer and autoclaving machine from the washing facility on EPFL campus, including average electricity usage, tap water usage, demineralized water usage and expected service life of the two machines. The total weight and effective chamber volume of them can be found in the manufacturers' website [2, 3].

Table 5: Statistics on machines from the washing facility

Model	Washer Getinge S8666-7	Autoclave (sterilizer) FOB3 TS
Average electricity use (kWh/cycle)	10	4
Average tap water use (L/cycle)	100	65
Average demineralized water use (L/cycle)	30	30
Average service life (years)	20	20
Effective chamber volume (L)	316	36

From the similar LCA study on the autoclaving machine [11], the raw materials used for manufacturing the washer Getinge S8666-7 and the sterilizer FOB3-TS are estimated by downscaling and shown in table 6 .

Table 6: Raw materials usage of the machines (scaled from [11])

S/n	Material types	Washer: Mass (kg)	Sterilizer: Mass (kg)
1	Stainless Steel 316	246.9	132.6
2	Stainless Steel 304	70.6	37.9
3	Aluminum	3.3	1.8
4	Glass Wool	3.9	2.1
5	PTFE	9.7	5.2
6	Copper	0.7	0.4
7	Cast Iron	11.1	6.0
8	Electronic and control	3.9	2.1
Total weight		350	188

6.3 Assumptions

Bag sealing and packaging

- **Bag**: 50 % paper and 50 % HDPE. Since each flask is re-bagged after each sterilization, need 100 bags per FU. Assuming each re-bag is constructed from the same materials as the original packaging and transported from China to the lab in Switzerland.
- **Electricity for Bag Sealing**: 0.025 kWh per item, estimated based on typical energy requirements for heat sealing [12].
- **Flask Dimensions for Packaging**: 15 cm height and 10 cm diameter — Packaging size is adjusted to fit the flask dimensions and allow for sealing.
- **Cardboard Box for 50 Flasks**: 1.239 kg, estimated based on typical corrugated box size and density.
- **Packaging Material Density**: 700 kg/cm^3, typical corrugated box density.

Transportation Path (Flask)

- **80% by Sea and Truck**: About 80 % of deliveries to Switzerland are shipped by sea from the manufacturing site in China to Le Havre, France. From there, the flasks are transported by truck to Geneva, then to Lausanne (61 km from Geneva). This route covers approximately 21 588.21 km by sea and 742.93 km by truck. Sea freight is chosen for cost-effectiveness and its lower carbon footprint compared to air freight.
- **20% by Air and Truck**: To ensure flexibility and meet urgent demand, around 20 % of shipments are sent by air directly from China to Geneva, covering 7098.78 km by air, then trucked 61 km to Lausanne. Air freight is faster but has a higher environmental impact.
- **Disposal**: After use, flasks are incinerated, with an average transportation distance of 11.5 km from EPFL to the nearest incineration facility.

Cleaning

- **Neglecting Detergent Usage**: Detergent used in the washing process is ignored for this assessment.
- **Operation frequency**: Assume that each machine (washer and autoclave) completes 200 cycles per year (baseline scenario) throughout its 20-year service life.
- **Machine fill factor**: Since the chamber cannot be fully optimized due to flask arrangement (flasks placed upside down on nozzles), the effective capacity differs between washing and sterilization processes. In baseline scenario, machine fill factor is estimated as 50%.

6.4 Background processes

The background (cradle-to-grave) unit processes included in this project are shown in table 7, which comes from Ecoinvent databases [13].

Table 7: Cradle-to-grave data from Ecoinvent

Input	Provider
Electricity	market for electricity, low voltage | electricity, low voltage | cutoff, S - CH
Raw HDPE	market for polycarbonate | polycarbonate | cutoff, S - GLO
Moulding HDPE / PC	market for injection moulding | injection moulding | cutoff, S - GLO
Raw PC	market for polyethylene| polyethylene, high density, granulate | cutoff, S - GLO
Corrugated Box	market for corrugated board box | corrugated board box | cutoff, S - RoW
Tap Water	market for tap water | tap water | cutoff, S - CH
Deionized Water	market for water, deionized | water, deionized | cutoff, S - CH
Cast Iron	cast iron production | cast iron | Cutoff, S
Electronic and control	electronics production, for control units | electronics, for control units | Cutoff, S
Glass Wool	glass wool mat production | glass wool mat | Cutoff, S
Aluminum	market for sheet rolling, aluminium | sheet rolling, aluminium | Cutoff, S
Copper	market for sheet rolling, copper | sheet rolling, copper | Cutoff, S
Stainless Steel 304	market for steel, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, S
PTFE	market for tetrafluoroethylene | tetrafluoroethylene | Cutoff, S
Waste Water	market for wastewater, average | wastewater, average | Cutoff, S - CH

7 Impact assessment

The eight evaluated scenarios and their labels are:

- Single use of a Corning 43144 flask (label S-44, base scenario)
- Multiple use of a Corning 431144 flask (label M-44)
- Single use of a Corning 431145 flask (label S-45)
- Multiple use of a Corning 431145 flask (label M-45)
- Single use of a Nest 785111 flask (label S-N11)
- Multiple use of a Nest 785111 flask (label M-N11)
- Single use of a TPP 87600 flask (label S-T00)
- Multiple use of a TPP 87600 flask (label M-T00)

The aggregated damage level impact categories are evaluated using the IMPACT World+ footprint framework. The results of the impact assessment are presented in Tables 8 and 8. In order to be able to compare the scenarios between one another, an internal normalization for each category has been performed, and the results are graphically displayed in Figure 5. Additionally, the midpoint impact categories for Environmental quality and Human health are also presented in Figures 9 and 11 .

Table 8: Impact score categories and results according to IMPACT World+ (1/2)

Impact category	S-44	M-44	S-45	M-45	Unit
Carbon footprint	69.30	27.00	44.17	20.80	[kg CO_2 eq.]
Fossil and nuclear energy use	906.81	639.55	570.98	512.14	[MJ deprived]
Remaining Ecosystem quality damage	6.71	4.18	3.76	3.23	[PDF m^2 yr]
Remaining Human health damage	5.36E-05	3.06E-05	3.35E-05	2.41E-05	[DALY]
Water scarcity footprint	19.53	52.12	12.56	43.34	[m^3 world eq.]

For the different scenarios encountered in this work, the main processes can be divided into 5 categories:

Table 9: Impact score categories and results according to IMPACT World+ (2/2)

	S-N11	M-N11	S-T00	M-T00	Unit
Carbon footprint	36.11	15.9	27.1	15.36	[kg CO_2 eq.]
Fossil and nuclear energy use	463.67	314.94	559.25	331.71	[MJ deprived]
Remaining Ecosystem quality damage	4.25	2.31	2.74	1.7	[PDF m^2 yr]
Remaining Human health damage	2.87E-05	1.70E-05	1.61E-05	1.02E-05	[DALY]
Water scarcity footprint	10.27	22.62	10.46	9.86	[m^3 world eq.]

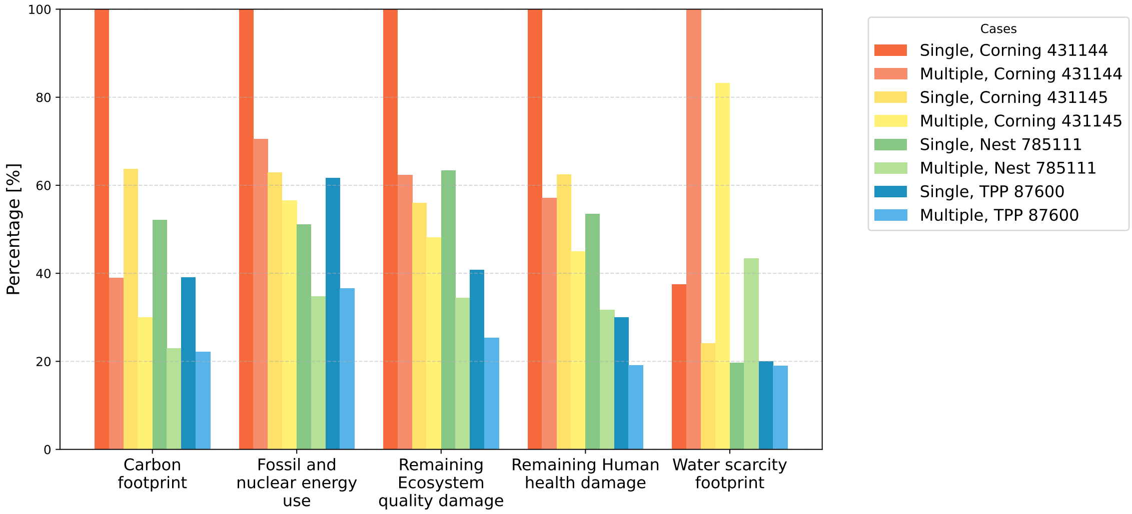


Figure 5: Normalized impact scores

1). Autoclaving process

2). End of Life

3). Assembly and production of the flask

4). Transport

5). Washing

In this section, the results for all the aggregated damage level impact categories are detailed with the contribution of each process and compared with one another.

7.1 Carbon footprint

The contribution for each process category are displayed in Figure 6.

As expected, reusing the flasks generates a lower carbon footprint. However, using the Corning 431144 flasks multiple times is roughly equivalent to a single use of the TPP 87600 flask type overall (27.0 against 27.1 [kg CO_2 eq.]). Among all scenarios, the carbon footprint of transport is minimal, ranging from 0.5 % (Multiple, Corning 431145) to 5.3 % (Single, Nest 78511) of the total impact, and is therefore not seen as an effective parameter for potential of improvement.

Another point of notice is the EoL impact for the TPP 87600. The impact is lower than the Corning 431144 but higher compared to other flasks. Furthermore, the EoL represents 38.7 % of its total carbon footprint, the highest fraction among all flasks. Looking at the properties of the different flasks, we can see that this is related to the material density of the TPP 87600

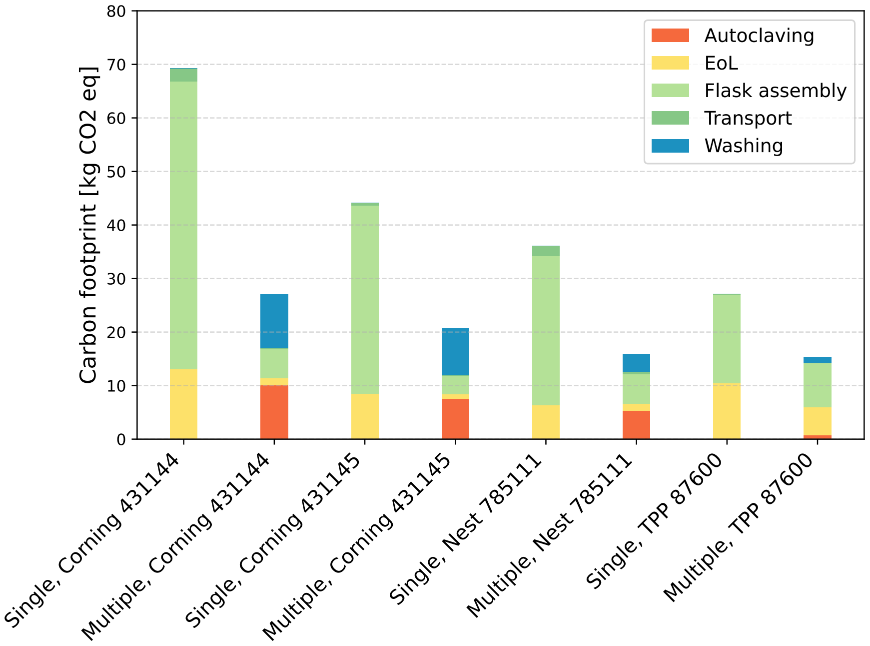


Figure 6: Carbon footprint by process category

(see Table 10). Because it has a higher material density than Corning 431145 and Nest 785111, there will be more material to incinerate for the same volume based on the functional unit.

Also note that because the body material of the TPP flask differs from that of the others (PE instead of PC), its footprint for production and assembly is lower, making it overall better for single use for this damage category. For instance for the Single use Nest 785111 the total results for the ”market for polycarbonate — polycarbonate — Cutoff, S” in the body production amount to 20.88 [kg CO_2 eq.], while for the TPP 87600 the ”market for polypropylene, granulate — polypropylene, granulate — Cutoff, S” process in the body production is 9.38 [kg CO_2 eq.], less than half of the production impact.

Table 10: Mass volume and densities of the different flasks

Flask	Total mass [g]	Volume [L]	Density [g/L]
Corning 431144	57.3	0.25	229.2
Corning 431145	75	0.5	150
Nest 785111	222.7	2	111.35
TPP 87600	110.7	0.6	184.5

7.2 Fossil and nuclear energy use

The contribution for each process category are displayed in Fig. 7.

Upon examination of the results, one can see that the TPP 87600 flask has a surprisingly large impact due to the production and assembly steps. The multiple use case is especially important in this impact category relatively to its role in the other categories. Similarly to its carbon footprint, this is due to the difference in material. For single use, the TPP 87600 has an impact of 337 [MJ deprived], in contrast to the 283.3 of the Nest 78111 flask (”market for polypropylene, granulate — polypropylene, granulate — Cutoff, S” and ”market for polycarbonate — polycarbonate — Cutoff, S” processes). This impact catergory is also the only one

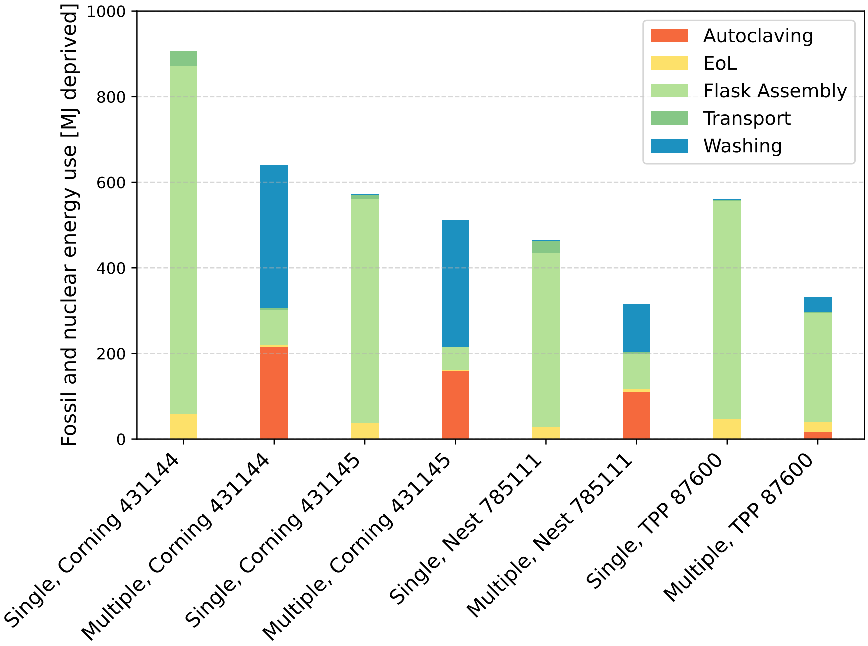


Figure 7: Fossil and nuclear energy use by process category

for which both TPP use cases rank second worse among all options. In fact, multiple use of Corning 431145 and Nest 785111 is better than single use of TPP, with Nest 785111 being the least energy intensive overall.

Despite this, the Single-use TPP 87600 flask still outperforms the multiple use of the Corning 431144 flask. This is because the washing and autoclaving processes require energy outweighing that required for the production of the TPP87600 flask. The impact of changing the energy source, away from fossil and nuclear, will be investigated in the sensitivity analysis section.

7.3 Remaining Ecosystem quality damage

The contribution for each process category are displayed in Figure 8.

Unlike the other impact categories, transport plays a significant role for the remaining ecosystem quality damages. Notably, it represents 13% of the impact contribution of the Corning 431144 flask (single-use), and even 16% of that of the Nest 785111 (single-use). Note that the Swiss-sourced TPP flask is not significantly affected by transport related impacts. Also note that the effect of transport is distributed over each use when using the flask multiple times and is thus negligible for the multiple-use cases of all flasks.

Again, as expected, washing and autoclaving are almost the sole contributors to the impact related to the multiple-use scenarios (except for TPP that is reused only once). This is due to the pollution of the water during the cleaning stages, which is showcased by the relative importance of freshwater ecotoxicity for the multiple-use scenario as described in Fig. 9 (roughly 30% of damage contribution for multiple-use, except TPP which is reused only once).

7.4 Remaining Human health damage

The contribution for each process category are displayed in Fig. 10. Furthermore, the relative midpoint impact categories for human health are shown in Fig. 11.

Fig. 11 shows that a lot of the impact on human health for the multiple use of the flasks comes from the water availability, which is in the 30 to 50 % range, depending on the flask.

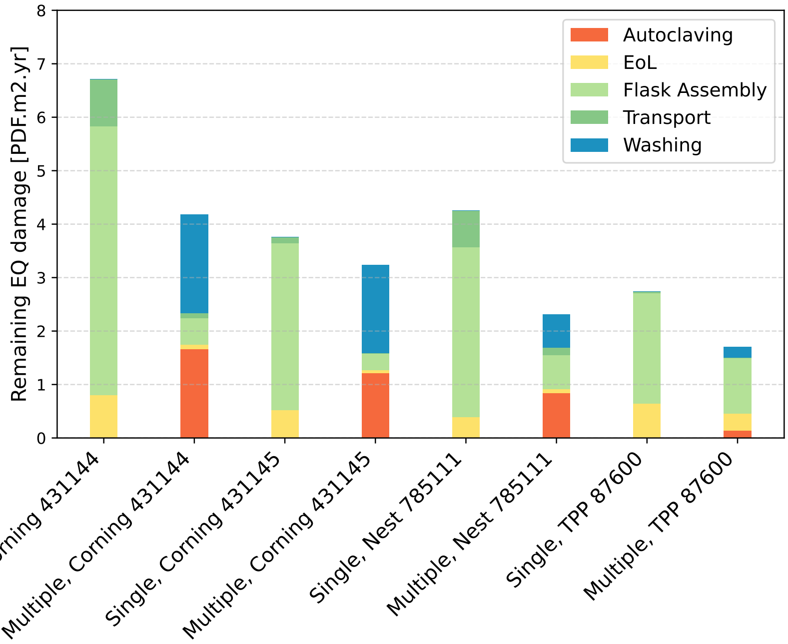


Figure 8: Remaining Ecosystem quality damage by process category

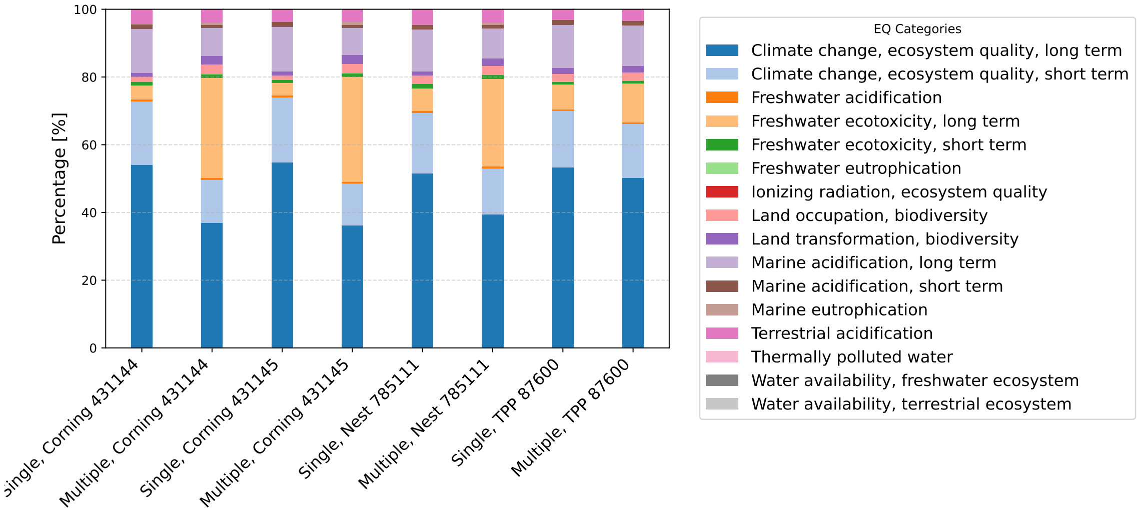


Figure 9: LCIA Damage Ecosystem Quality

Similarly, for the single use cases, the long term climate change impact plays a significant role, representing almost 50 % of the impact.

Similarly to other damage categories (e.g fossil and nuclear energy use), we see that using of the Corning 431144 flask multiple times is only significantly better when compared to the Single use of the same flask. It slightly improves compared to the single use of the Corning 431145, but both single and multiple use of the other flasks outperform it with respect to this indicator.

7.5 Water scarcity footprint

The contribution for each process category are displayed in Figure12.

As it could be expected the impact on water scarsity is higher for the product systems that require Autoclaving and washing (e.g. multiple use). In particular, with respect of this damage

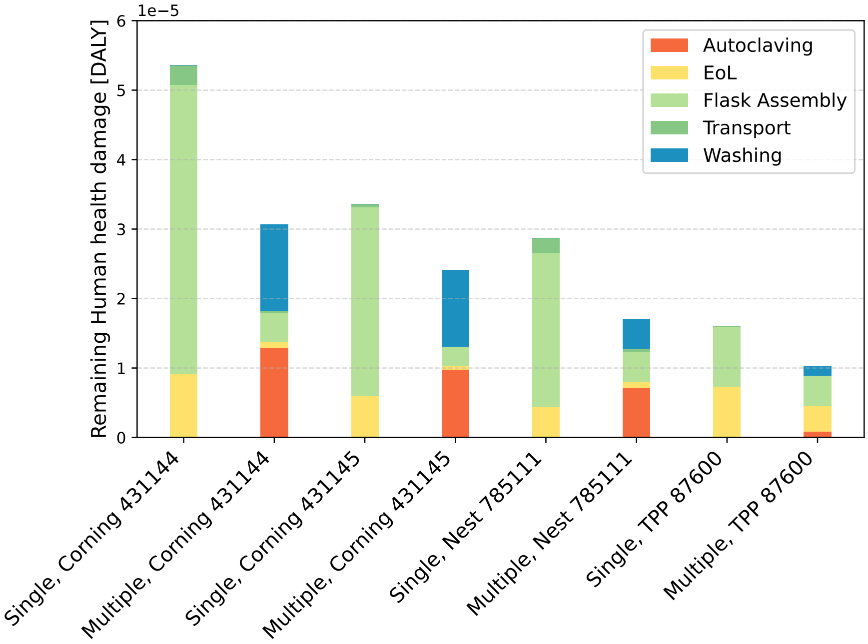


Figure 10: Remaining Human health damage by process category

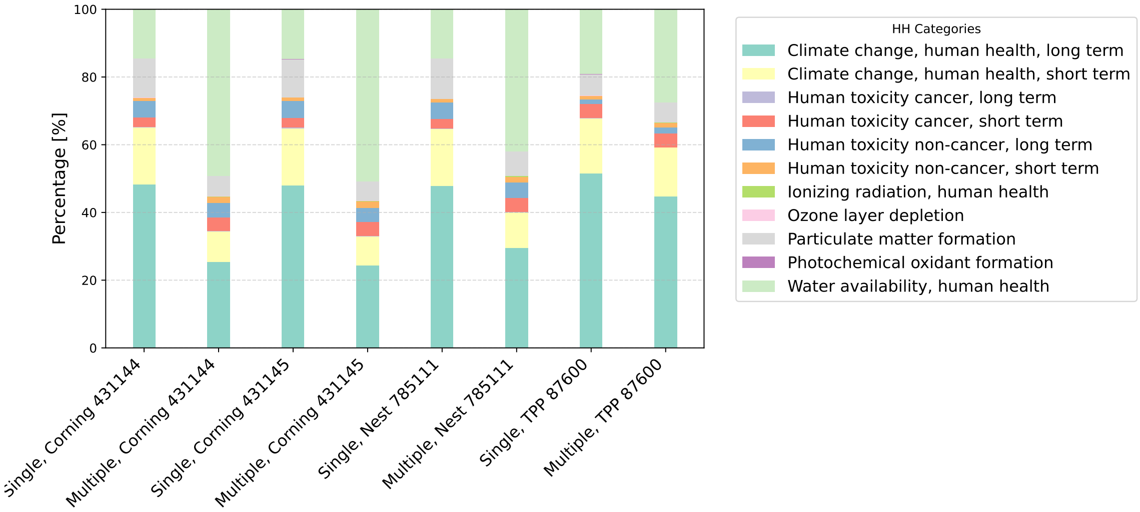


Figure 11: LCIA Damage Human Health

category, the multiple use of the Corning 431144 and 431145 should be avoided as it impacts are more than twofold compared to the worst-performing single use flask. However, the multiple use of the Nest 78511 is comparable with the single use of the Corning 431144 flask, so it is a viable option, if one considers the other damage impact categories.

Finally, and more interestingly, the multiple use of the TPP 87600 has an impact comparable,and slightly lower, than all the single-use flasks. This goes to show that the improvement (reduction in Assembly and EoL impacts) due to the reusing of the flask is compensated by the increased use of water that is a consequence of the washing and Autoclaving processes. A potential improvement to minimize use of water could be to improve the fill factor of the machine. This path will be explored in the sensitivity analysis

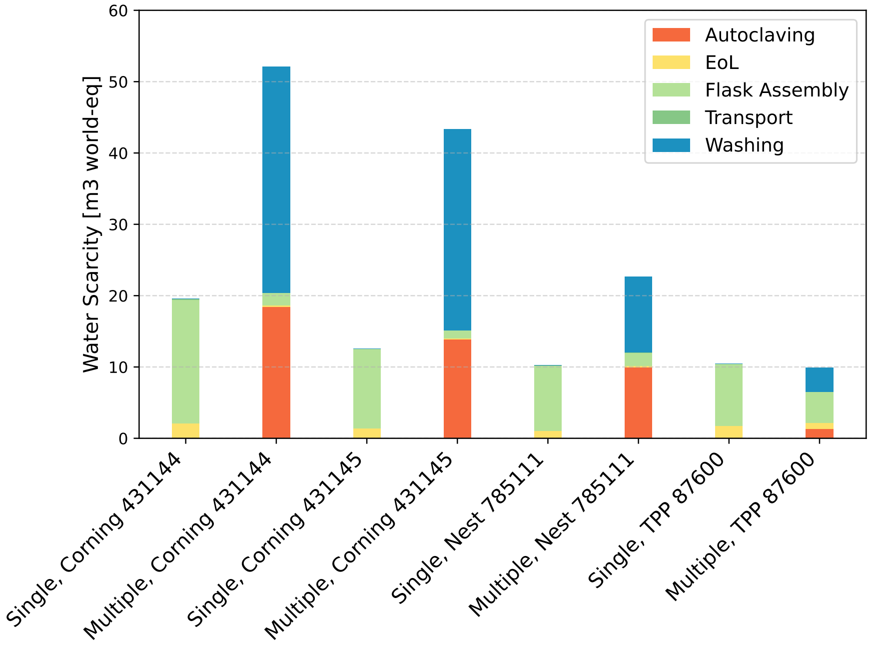


Figure 12: Water scarcity footprint by process category

8 Sensitivity Analysis

8.1 Analysis of Key Input Parameters

The sensitivity analysis was conducted to determine how changes in key input parameters influence the environmental performance of the Corning Flask 431144 during its use phase. The analysis specifically evaluated the sensitivity of five key environmental indicators: Carbon Footprint, Fossil and Nuclear Energy Use, Remaining Ecosystem Quality Damage, Remaining Human Health Damage, and Water Scarcity Footprint.

To achieve this, a 10% increase was applied independently to each global parameter, while keeping all other inputs constant. This systematic approach allowed us to identify which parameters contribute most significantly to the environmental impacts and highlight potential hotspots for performance improvement.

Among the parameters tested, three parameters emerged as the most significant influencers of the results: Machine Annual Cycle (+10%), Mass Body Corning (+10%), and MFF (Ratio of filled machine) (+10%). The results of these changes are summarized in Figure 13, which compares the percentage changes across all five indicators.

8.1.1 Key Findings

The MFF parameter (+10%) had the largest influence on multiple indicators, showcasing its critical role in energy consumption and resource impacts. Specifically, it resulted in a −8.46% reduction in Water Scarcity Footprint, followed by −7.35% in Fossil and Nuclear Energy Use, and −7.19% in Remaining Human Health Damage. This significant reduction indicates that the energy-related parameters, particularly those associated with machine energy consumption during washing or autoclaving, dominate the environmental performance in the use phase. These findings suggest that optimizing machine energy use or transitioning to more energy-efficient systems could drastically reduce environmental burdens.

The Machine Annual Cycle (+10%) parameter also demonstrated notable effects on environmental indicators. Increasing the machine cycle load by 10% resulted in a −2.86% reduction

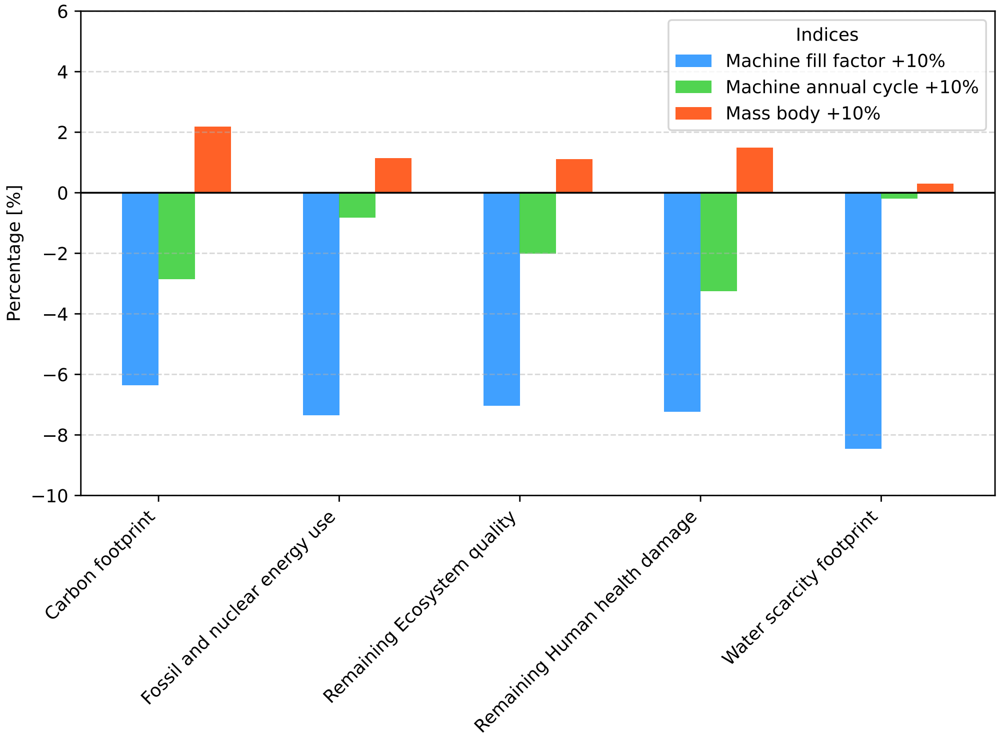


Figure 13: Percentage changes in environmental indicators for key parameters.

in Carbon Footprint and a −3.27% decrease in Remaining Human Health Damage. These results highlight the importance of optimizing machine operation cycles to improve resource and energy efficiency. While the magnitude of change was lower compared to MFF, the impact remains significant and actionable. This parameter indicates the sensitivity of environmental results to machine use frequency and highlights it as a key operational lever for improvement.

In contrast, the Mass Body Corning (+10%) parameter displayed a smaller but positive influence on environmental indicators, increasing the Carbon Footprint by +2.19% and Fossil and Nuclear Energy Use by +1.14%. The positive change suggests that heavier materials and mass components contribute directly to higher energy demands, particularly in production and transport phases. While the influence of this parameter is less significant than energy-related ones, it emphasizes the role of material efficiency and weight reduction as a secondary strategy for improving environmental performance.

8.1.2 Conclusion

Overall, the sensitivity analysis revealed that energy-related parameters such as MFF and Machine Annual Cycle are the dominant drivers of environmental impacts in the use phase. These parameters significantly affect indicators such as Water Scarcity Footprint, Fossil and Nuclear Energy Use, and Carbon Footprint. Addressing these energy-related parameters, for instance, through process optimization, energy-efficient equipment, or renewable energy sources, presents the greatest opportunity for reducing environmental burdens. Meanwhile, material mass, although less impactful, still warrants attention, particularly for reducing production and transportation-related impacts.

In summary, this sensitivity analysis highlights the following key findings:

- **Energy Consumption (MFF +10%)**: The most critical driver, particularly for Water Scarcity and Fossil Energy Use.

- **Machine Operations (Machine Annual Cycle +10%)**: Substantial influence on Carbon Footprint and Human Health Damage.
- **Material Efficiency (Mass Body Corning +10%)**: Plays a secondary role but remains relevant for improving environmental performance.

Additional sensitivity results for other parameters, such as transport distances and waste processes, are included in Appendix D. These analyses further support the conclusion that energy optimization is the most effective lever for enhancing sustainability outcomes during the use phase of Corning Flask 431144.

8.2 Scenario Analyses - PV vs Baseline Scenario

With increasing emphasis on global sustainability goals, laboratories are under growing scrutiny for their environmental performance, particularly regarding energy use. Solar photovoltaic (PV) energy has emerged as a key solution for laboratory sustainability as it provides a low-carbon, renewable alternative to conventional electricity. By integrating PV energy, laboratories can significantly reduce their environmental burden during operations. This study compares a **PV scenario** with a **baseline scenario** to assess potential improvements.

PV electricity generates significantly lower carbon emissions during production compared to traditional grid electricity, particularly in regions reliant on fossil fuels. Replacing grid electricity during cleaning and sterilization processes can effectively reduce the system's carbon footprint. Fossil and nuclear energy consumption, which are major contributors to environmental impacts in the baseline scenario, are also significantly reduced by introducing PV energy. Additionally, PV energy has lower water consumption compared to grid electricity, which relies heavily on water for cooling during power generation. Given that EPFL already operates its own PV power system, the adoption of solar energy is technically feasible and aligns with EPFL's long-term campus sustainability goals.

8.2.1 Scenario Setup

In the baseline scenario, electricity for the cleaning and sterilization stages is sourced from the market grid electricity, represented by the flow *"market for electricity, low voltage."* In the PV scenario, the electricity source is replaced by PV power, using the flow *"electricity production, photovoltaic, 3kWp slanted-roof installation, ribbon-Si, panel, mounted."*

To evaluate the environmental impacts of these scenarios, we applied the **IMPACT World+ method** within the life cycle assessment framework. This method provides a comprehensive evaluation across multiple impact categories, including climate change, fossil and nuclear energy use, ecosystem quality, human health damage, and water scarcity. The analysis specifically focuses on the Corning 431144 Erlenmeyer flask during the cleaning and sterilization stages. This flask serves as the functional unit (FU) for comparing environmental impacts between the baseline and PV scenarios.

8.2.2 Results Analysis

The carbon footprint in the baseline scenario is **27.00 kg CO_2-eq**, while in the PV scenario, it is reduced to **23.84 kg CO_2-eq**, a decrease of approximately 12%. The life-cycle carbon emissions of PV electricity are significantly lower than conventional grid electricity.

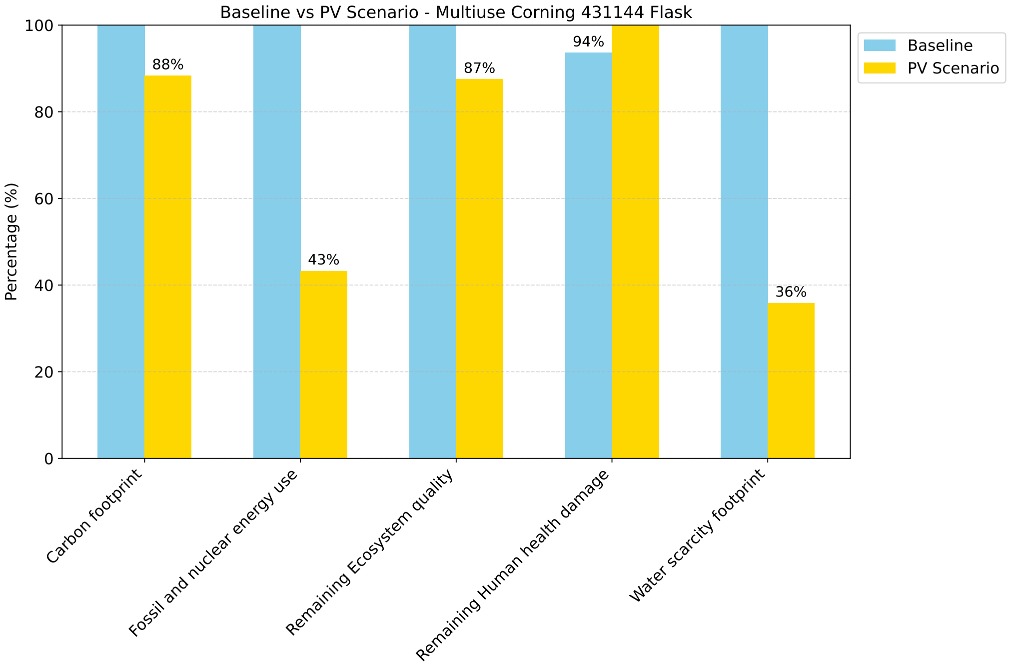


Figure 14: Comparison of Baseline and PV Scenarios

Fossil and nuclear energy consumption drops from **639.42 MJ deprived** in the baseline scenario to **276.49 MJ deprived** in the PV scenario, a reduction of 57%. The use of PV power effectively reduces dependence on non-renewable energy sources.

For ecosystem quality, the baseline scenario measures **4.18 PDF·m^2·yr**, while the PV scenario reduces this to **3.66 PDF·m^2·yr**, an approximate 13% decrease. This demonstrates that PV energy has a smaller impact on ecosystem damage compared to grid electricity.

Human health damage, expressed in **DALY**, increases slightly from **3.06E-05** in the baseline to **3.27E-05** in the PV scenario, an increase of approximately 7%. This small rise is likely due to the resource extraction and manufacturing processes involved in PV electricity production. However, the overall impact remains minimal and acceptable.

Water scarcity footprint is significantly improved, with the baseline scenario measuring **52.13 m^3 world-eq** and the PV scenario reducing this to **18.67 m^3 world-eq**, a 64% decrease. PV electricity requires significantly less water compared to conventional grid power, particularly in cooling processes during generation.

The PV scenario demonstrates clear environmental advantages by reducing the carbon footprint, fossil and nuclear energy consumption, and water scarcity impacts. Although human health damage increases slightly, the magnitude of change is minimal and acceptable. With EPFL's existing PV infrastructure, the transition to PV electricity is both technically feasible and aligns with the institution's sustainability strategy. This shift can significantly contribute to reducing the environmental burden of laboratory operations.

9 Uncertainties and limits of the study

9.1 Uncertainties and limitations

9.1.1 Limitation of Functional Unit Definition

The functional unit in this study is defined as the "number of flasks required to process 25 L of cell culture medium." While this definition is practical for comparing flask systems, it introduces potential limitations. For instance, equating a 2.5 L flask to 10×250 mL flasks may hold true in industrial contexts due to scalability, but such assumptions may not reflect operational realities in research laboratories. Consequently, this functional unit might overestimate the environmental advantages of larger flasks, as their benefits are dependent on specific usage patterns. This limitation should be carefully documented to avoid overgeneralization.

9.1.2 Uncertainty in Flask Production and Transportation

The environmental impact of flask production and transportation stages is influenced by both known and uncertain factors:

- Flask production: While parameters like volume, material, fabrication site, and initial sterilization are well-defined, uncertainties remain regarding the production of raw materials, fabrication processes, and initial sterilization impacts.
- Transportation: Known aspects include approximate distances traveled, but uncertainties arise from shipping modes (e.g., air, train, or cargo vessels) and packaging materials used, both of which affect environmental outcomes.

9.1.3 Uncertainty in Cleaning and Sterilization

This study reveals that multi-use flasks generally outperform single-use flasks in terms of environmental impact. However, this advantage is contingent upon the efficiency of cleaning and sterilization processes, represented by the Maximum Flask Factor (MFF), which measures equipment loading efficiency:

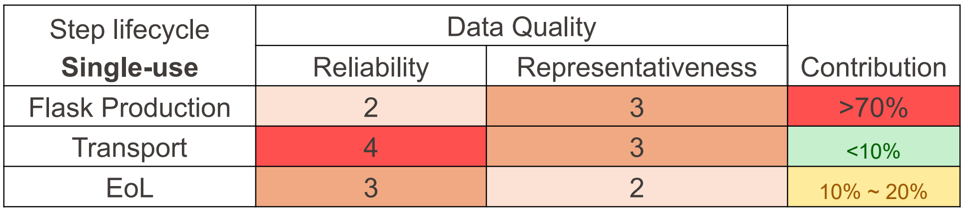
- Low MFF: Underloaded sterilization cycles increase per-flask energy and water consumption, reducing environmental efficiency;
- High MFF: Fully loaded sterilization cycles maximize resource efficiency, making multi-use flasks more sustainable.

Additionally, the environmental impacts of equipment maintenance and detergent use are excluded from the analysis, which could understate the resource demands of cleaning processes, although the impact is considered relatively small with respect to water and electricity use in each washing cycle. This exclusion should be addressed in future iterations for a more comprehensive evaluation.

9.2 Data quality

An assessment of data quality reveals key insights into the reliability and representativeness of lifecycle stages for single-use and multiple-use flasks, the results are summarized in figure 15 and 16.

The evaluation underlines the significance of improving the data quality of flask production process for single use flasks as well as the cleaning process for multiple use flasks.



Step lifecycle **Single-use**	Data Quality		Contribution
	Reliability	Representativeness	
Flask Production	2	3	>70%
Transport	4	3	<10%
EoL	3	2	10% ~ 20%

Figure 15: Evaluation of Data Quality related contribution analysis of single use flasks

Step lifecycle **Multiple-use**	Data Quality		Contribution
	Reliability	Representativeness	
Flask Production	2	3	10% ~ 20%
Washing	2	3	20% ~ 40%
Autoclaving	2	3	20% ~ 40%
Transport	4	3	< 3%
EoL	3	2	<10 %

Figure 16: Evaluation of Data Quality related contribution analysis of multiple use flasks

10 Recommendations

Based on the findings of this Life Cycle Assessment, the following recommendations are made regarding the use of flasks:

10.1 Transition to Multiple-Use Flasks where Feasible

The findings of the LCA strongly support the adoption of multiple-use flasks as the default option for most laboratory applications within SV-PTPSP and similar labs. This conclusion is based on their consistently lower environmental impacts compared to single-use flasks in key categories, including:

- **Carbon Footprint:** Across types, multi-use flasks reduce emissions by about 50-60% on average, which is especially impactful for smaller flask types (Corning 431144 for example)
- **Fossil Energy Use:** Multi-use flasks have consistently lower energy consumption relative to the functional unit when compared to their single-use counterpart.
- **Ecosystem Quality:** Lower impacts are observed due to reduced material extraction and waste generation, as well as reduced transport impact.

10.2 Key Actions for a Successful Implementation

1. **Maximize Flask Lifespan:** To fully realize the environmental benefits, reusable flasks must be utilized to their maximum designed reuse cycles. Proper handling and maintenance protocols should be implemented to prevent premature wear and contamination risks.
2. **Optimize Washing and Autoclaving Processes:** Because Water Scarcity impact is the main drawback for multi-use flasks, the impact should be properly addressed by increasing the machine fill factor to minimize per-flask water and energy use. Additionally, though it is not within the scope of the study, investigating and adopting water reuse systems could help address water scarcity impacts.

3. **Selective Use of Single-Use Flasks:** Reserve single-use flasks for specialized applications. In such cases, choose materials with lower overall impacts, such as polypropylene.
4. **Monitor and Review Performance:** Conduct periodic evaluations of flask reusability, water use efficiency, and overall environmental impact to ensure the lab meets the desired sustainability objectives.

11 Conclusion

This LCA has comprehensively evaluated the environmental impacts of single-use and multiple-use flasks used in laboratory operations at the SV-PTPSP lab, providing actionable insights into the trade-offs between these two systems. The study conclusively shows that transitioning to reusable flasks offers substantial benefits, including:

- An average 50% reduction of carbon footprint.
- A significant reduction of energy use, especially for locally sourced polypropylene flasks (close to 50% reduction).
- Lower impacts on ecosystem quality through reduced material extraction and waste generation.

However, the environmental benefits of reusable flasks are tempered by increased water use during cleaning and autoclaving processes. These drawbacks can be mitigated through operational optimizations such as improving machine fill factors, enhancing water efficiency, and integrating renewable energy sources like photovoltaics.

In conclusion, adopting reusable flasks, combined with targeted process optimizations, represents a viable pathway to enhancing sustainability in laboratory operations. These insights provide a valuable foundation for EPFL and similar research platforms to make informed decisions that align with global sustainability goals.

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A Appendix: Calculations

A.1 Flask Production Flow Calculations

A.1.1 Single-Use Scenario (100 flasks per FU)

1. **PP for Cap Production**:

$$\text{PP mass for cap production (single-use)} = \left(\frac{100\text{ caps}}{\text{FU}}\right) \cdot 8.3\text{ g/cap} = 830\text{ g/FU}$$

2. **PC for Body Production**:

$$\text{PC mass for body production (single-use)} = \left(\frac{100\text{ bodies}}{\text{FU}}\right) \cdot 49\text{ g/body} = 4900\text{ g/FU}$$

3. **Electricity for Bag Sealing**:

$$\text{Electricity for bag sealing (single-use)} = \left(\frac{100\text{ items}}{\text{FU}}\right) \cdot 0.025\text{ kWh/item} = 2.5\text{ kWh/FU}$$

4. **Box Production** (Calculation of Cardboard Mass for 50 Flasks):
   - **Box Dimensions**: 40 cm (length) x 30 cm (width) x 25 cm (height)
   - **Thickness**: 0.3 cm
   - **Density**: 700 kg/m^3
   - **Surface Area**:

$$2 \times (40 \times 30 + 40 \times 25 + 30 \times 25) = 5900\,\text{cm}^2 = 0.59\,\text{m}^2$$

   - **Volume**:

$$0.59\,\text{m}^2 \times 0.003\,\text{m} = 0.00177\,\text{m}^3$$

   - **Mass**:

$$0.00177\,\text{m}^3 \times 700\,\text{kg/m}^3 = 1.239\,\text{kg}$$

   - **Mass of Cardboard for Single-Use**:

$$\text{Cardboard box mass (single-use)} = \left(\frac{2\text{ boxes}}{\text{FU}}\right) \cdot 1.239\,\text{kg/box} = 2.478\,\text{kg/FU}$$

5. **Bag Production for Packaging** (Calculation of Packaging Material Density):
   - **Total Bag Mass** (based on measured weight): Assume a total bag mass of 3.77 g for a small bag.
   - **Bag Area**: For a bag with a length of 20 cm and width of 16 cm:

$$\text{Area} = 20 \times 16 = 320\,\text{cm}^2$$

   - **Density per Unit Area**:

$$\text{Density per unit area} = \frac{\text{Bag Mass}}{\text{Bag Area}} = \frac{3.77\,\text{g}}{320\,\text{cm}^2} = 0.011805\,\text{g/cm}^2$$

- **Total Mass for Packaging per Flask**:

$$126\,\mathrm{cm}^2 \times 0.011805\,\mathrm{g/cm}^2 = 1.487\,\mathrm{g}$$

- **Paper (50%)**:

$$1.487\,\mathrm{g} \times 0.5 = 0.7435\,\mathrm{g}$$

- **HDPE (50%)**:

$$1.487\,\mathrm{g} \times 0.5 = 0.7435\,\mathrm{g}$$

- **Total Bag Material for 100 Flasks**:
  - **Paper**: $100 \times 0.7435 = 74.35\,\mathrm{g/FU}$
  - **HDPE**: $100 \times 0.7435 = 74.35\,\mathrm{g/FU}$

6. **Distribution (Transportation)**:

$$\left[\frac{5.73\,\mathrm{kg} + 2.478\,\mathrm{kg}\ (\mathrm{box}) + 0.1487\,\mathrm{kg}\ (\mathrm{bags})}{\mathrm{FU}} \cdot \frac{1\,\mathrm{t}}{1000\,\mathrm{kg}}\right]$$

$$\cdot\,[0.8 \times (21,588.21 + 681.93 + 61) + 0.2 \times (7,098.78 + 61) + 11.5]\ \mathrm{km}$$

- Calculated Value:

$$0.0083567\,\mathrm{t/FU} \cdot 19,308.368\,\mathrm{km} = 161.43\,\mathrm{tkm/FU}$$

A.1.2 Multiple-Use Scenario (10 flasks per FU)

1. **PP for Cap Production**:

$$\text{PP mass for cap production (multiple-use)} = \left(\frac{10\ \text{caps}}{\text{FU}}\right) \cdot 8.3\ \text{g/cap} = 83\ \text{g/FU}$$

2. **PC for Body Production**:

$$\text{PC mass for body production (multiple-use)} = \left(\frac{10\ \text{bodies}}{\text{FU}}\right) \cdot 49\ \text{g/body} = 490\ \text{g/FU}$$

3. **Electricity for Bag Sealing**:

$$\text{Electricity for bag sealing (multiple-use)} = \left(\frac{10\ \text{items}}{\text{FU}}\right) \cdot 0.025\ \text{kWh/item} = 0.25\ \text{kWh/FU}$$

4. **Box Production**:

$$\text{Cardboard box mass (multiple-use)} = \left(\frac{1}{5}\ \text{box/FU}\right) \cdot 1.239\,\mathrm{kg/box} = 0.2478\,\mathrm{kg/FU}$$

5. **Bag Production for Packaging**: - Since each flask is re-bagged after each sterilization, we need **100 bags per FU**.
- Total Mass for Packaging per Flask:

$$1.487\,\mathrm{g}$$

- Paper (50%):

$$0.7435\,\mathrm{g}$$

- HDPE (50%):

$$0.7435\,\text{g}$$

- **Total Bag Material for 100 Bags**: Assuming each re-bag is constructed from the same materials as the original packaging and transported from China to the lab in Switzerland, the distribution calculation requires modification to account for the transportation of these additional bags.

- **Paper**: $100 \times 0.7435 = 74.35\,\text{g/FU}$
- **HDPE**: $100 \times 0.7435 = 74.35\,\text{g/FU}$

6. **Distribution (Transportation)**: - Calculation:

$$\left[\frac{0.573\,\text{kg} + 0.2478\,\text{kg (box)} + 1.487\,\text{kg (bags)}}{\text{FU}} \cdot \frac{1\,\text{t}}{1000\,\text{kg}}\right]$$

$$\cdot 19,308.368\,\text{km} = 44.58\,\text{tkm/FU}$$

A.2 Calculations for Washer and Autoclave Resource Usage

With the new per-cycle capacities for washing and sterilization, the resource allocation for each functional unit (FU) can be recalculated.

A.2.1 Multiple-Use Flask Requirement

- **Functional Unit (FU)**: 10 flasks per FU, with each flask reused 10 times (100 experiments per FU).
- **Washer (32 flasks per cycle)**: Each washing cycle can handle 32 flasks, so 1 cycle can cover 3.2 FUs.
- **Autoclave (28 flasks per cycle)**: Each sterilization cycle can handle 28 flasks, so 1 cycle can cover 2.8 FUs.

Thus, to clean and sterilize 10 flasks per FU:

- Washing cycles required per FU: $\frac{10}{32} = 0.3125$ cycles/FU
- Sterilization cycles required per FU: $\frac{10}{28} = 0.3571$ cycles/FU

A.2.2 Resource Allocation Per FU

Using the above cycle requirements, we can allocate resources for washing and sterilizing each FU as follows:

1. **Electricity for Washing**:

$$\text{Electricity per FU} = 0.3125\,\text{cycles/FU} \times 10\,\text{kWh/cycle} = 3.125\,\text{kWh/FU}$$

Allocated to PTPSP:

$$\text{PTPSP Allocation} = 3.125\,\text{kWh/FU} \times 0.3 = 0.9375\,\text{kWh/FU}$$

2. **Tap Water for Washing**:

   $$\text{Tap Water per FU} = 0.3125\,\text{cycles/FU} \times 100\,\text{L/cycle} = 31.25\,\text{L/FU}$$

   Allocated to PTPSP:

   $$\text{PTPSP Allocation} = 31.25\,\text{L/FU} \times 0.3 = 9.375\,\text{L/FU}$$

3. **Deionized Water for Washing**:

   $$\text{Deionized Water per FU} = 0.3125\,\text{cycles/FU} \times 30\,\text{L/cycle} = 9.375\,\text{L/FU}$$

   Allocated to PTPSP:

   $$\text{PTPSP Allocation} = 9.375\,\text{L/FU} \times 0.3 = 2.8125\,\text{L/FU}$$

4. **Electricity for Autoclaving**:

   $$\text{Electricity per FU} = 0.3571\,\text{cycles/FU} \times 4\,\text{kWh/cycle} = 1.4284\,\text{kWh/FU}$$

   Allocated to PTPSP:

   $$\text{PTPSP Allocation} = 1.4284\,\text{kWh/FU} \times 0.3 = 0.4285\,\text{kWh/FU}$$

5. **Tap Water for Autoclaving**:

   $$\text{Tap Water per FU} = 0.3571\,\text{cycles/FU} \times 65\,\text{L/cycle} = 23.214\,\text{L/FU}$$

   Allocated to PTPSP:

   $$\text{PTPSP Allocation} = 23.214\,\text{L/FU} \times 0.3 = 6.9642\,\text{L/FU}$$

6. **Deionized Water for Autoclaving**:

   $$\text{Deionized Water per FU} = 0.3571\,\text{cycles/FU} \times 30\,\text{L/cycle} = 10.713\,\text{L/FU}$$

   Allocated to PTPSP:

   $$\text{PTPSP Allocation} = 10.713\,\text{L/FU} \times 0.3 = 3.2139\,\text{L/FU}$$

A.3 Machine Resource Consumption Per Cleaning and Sterilization Cycle

1. **Machine Service Life**:
   - Each machine (washer and autoclave) operates for **20 years**, with an estimated **250 cycles per year**.
   - **Total operational cycles over 20 years**:

     $$20\,\text{years} \times 250\,\text{cycles/year} = 5000\,\text{cycles}$$

   - This is the total cycle capacity for each machine over its service life.
2. **PTPSP Allocation**:

- PTPSP utilizes **30% of the total service life** for both the washer and autoclave.
- Therefore, the effective cycle allocation for PTPSP over 20 years is:

$$5000\,\text{cycles} \times 0.3 = 1500\,\text{cycles}$$

- This means that PTPSP has access to 1500 cycles on each machine over its service life.

3. **Cycle Requirements per FU**:
   - For each functional unit (FU) in the multiple-use scenario:
     - **Washer cycles per FU**:

$$\text{Washer cycles per FU} = \frac{10\,\text{flasks/FU}}{32\,\text{flasks/cycle}} = 0.3125\,\text{cycles/FU}$$

     - **Autoclave cycles per FU**:

$$\text{Autoclave cycles per FU} = \frac{10\,\text{flasks/FU}}{28\,\text{flasks/cycle}} = 0.3571\,\text{cycles/FU}$$

4. **PTPSP Utilization per FU**:
   - Given PTPSP only uses 30% of each machine's total cycles, we calculate the **PTPSP-specific cycle usage per FU**:
     - **Washer utilization per FU**:

$$\text{Washer utilization per FU} = 0.3125\,\text{cycles/FU} \times 0.3 = 0.09375\,\text{cycles/FU}$$

     - **Autoclave utilization per FU**:

$$\text{Autoclave utilization per FU} = 0.3571\,\text{cycles/FU} \times 0.3 = 0.1071\,\text{cycles/FU}$$

5. **Percentage of Service Life Used per FU**:
   - To determine the contribution of each FU to the total service life (in percentage terms), we divide the PTPSP-specific cycle usage per FU by the total PTPSP cycle allocation:
     - **Washer**:

$$\text{\% of Washer service life per FU} = \frac{0.09375\,\text{cycles/FU}}{1500\,\text{cycles}} \times 100 = 0.00625\%\,\text{life/FU}$$

     - **Autoclave**:

$$\text{\% of Autoclave service life per FU} = \frac{0.1071\,\text{cycles/FU}}{1500\,\text{cycles}} \times 100 = 0.00714\%\,\text{life/FU}$$

B Appendix: LCIA results

All results of LCIA can be reached via this link (with EPFL internal access) : LCIA results

C Appendix: Damage indicators

Name	Unit	S-44	M-44	S-45	M-45	S-N11	M-N11	S-T00	M-T00
Climate change, EQ, long term	PDF.m2.yr	36.813	14.164	23.317	10.902	19.175	8.288	15.621	8.771
Climate change, EQ, short term	PDF.m2.yr	12.700	4.850	8.103	3.734	6.619	2.869	4.890	2.767
Climate change, HH, long term	DALY	1.68E-04	6.44E-05	1.06E-04	4.96E-05	8.73E-05	3.77E-05	7.11E-05	3.99E-05
Climate change, HH, short term	DALY	5.87E-05	2.24E-05	3.74E-05	1.73E-05	3.06E-05	1.33E-05	2.26E-05	1.28E-05
Climate change, long term	kg CO2 eq (long)	62.827	25.593	39.885	19.768	32.756	14.892	25.822	14.647
Climate change, short term	kg CO2 eq (short)	71.779	27.421	45.798	21.108	37.412	16.222	27.633	15.639
Fossil and nuclear energy use	MJ deprived	906.815	639.545	570.982	512.139	463.673	314.944	559.251	331.711
Freshwater acidification	PDF.m2.yr	0.44808	0.21868	0.24235	0.16768	0.25265	0.12474	0.13663	0.08398
Freshwater acidification	kg SO2 eq	0.19530	0.09439	0.10526	0.07227	0.11037	0.05402	0.05935	0.03642
Freshwater ecotoxicity	CTUe	6167.67	20244.29	3557.67	16680.89	5139.47	9818.62	4193.23	3745.74
Freshwater ecotoxicity, long term	PDF.m2.yr	2.811	11.316	1.616	9.347	2.436	5.433	2.174	2.013
Freshwater ecotoxicity, short term	PDF.m2.yr	0.68609	0.38488	0.39688	0.29716	0.51951	0.24260	0.21852	0.13732
Freshwater eutrophication	PDF.m2.yr	0.01344	0.02251	0.00825	0.01844	0.00816	0.01098	0.00502	0.00432
Freshwater eutrophication	kg PO4 P-lim eq	0.00371	0.00621	0.00228	0.00509	0.00225	0.00303	0.00139	0.00119
Human toxicity cancer	CTUh	9.10E-07	9.25E-07	5.88E-07	7.47E-07	4.61E-07	4.70E-07	5.02E-07	3.21E-07
Human toxicity cancer, long term	DALY	6.09E-07	3.47E-07	3.99E-07	2.77E-07	3.22E-07	1.93E-07	6.32E-08	5.57E-08
Human toxicity cancer, short term	DALY	9.86E-06	1.03E-05	6.36E-06	8.31E-06	4.98E-06	5.21E-06	5.71E-06	3.63E-06
Human toxicity non-cancer	CTUh	7.49E-06	5.61E-06	4.89E-06	4.51E-06	4.01E-06	2.97E-06	1.26E-06	1.04E-06
Human toxicity non-cancer, long term	DALY	1.68E-05	1.06E-05	1.11E-05	8.49E-06	8.89E-06	5.81E-06	1.83E-06	1.66E-06
Human toxicity non-cancer, short term	DALY	3.41E-06	4.54E-06	2.12E-06	3.70E-06	1.92E-06	2.20E-06	1.57E-06	1.16E-06
Ionizing radiation, ecosystem quality	PDF.m2.yr	4.44E-09	3.58E-08	2.56E-09	3.00E-08	2.33E-09	1.48E-08	4.23E-09	5.40E-09
Ionizing radiation, human health	DALY	5.30E-08	5.37E-07	3.18E-08	4.52E-07	2.59E-08	2.21E-07	6.34E-08	8.11E-08
Ionizing radiations	Bq C-14 eq	252.61	2557.51	151.32	2150.85	123.16	1050.72	301.73	385.97
Land occupation, biodiversity	PDF.m2.yr	1.01430	1.08465	0.57019	0.83518	0.88499	0.54447	0.66935	0.44052
Land occupation, biodiversity	m2 arable land eq .yr	1.54123	1.64812	0.86641	1.26905	1.34474	0.82733	1.01708	0.66937
Land transformation, biodiversity	m2 arable land eq	0.00492	0.00609	0.00278	0.00492	0.00299	0.00299	0.00309	0.00205
Land transformation, biodiversity	PDF.m2.yr	0.78327	0.97007	0.44196	0.78373	0.47639	0.47575	0.49172	0.32570
Marine acidification, long term	PDF.m2.yr	8.84866	3.16577	5.60488	2.42492	4.60823	1.87597	3.75770	2.09140
Marine acidification, short term	PDF.m2.yr	0.96114	0.34419	0.60875	0.26366	0.50074	0.20394	0.40824	0.22724
Marine eutrophication	PDF.m2.yr	0.04504	0.28560	0.02287	0.23754	0.02918	0.13107	0.01788	0.03252
Marine eutrophication	kg N N-lim eq	0.00515	0.03264	0.00261	0.02715	0.00334	0.01498	0.00204	0.00372
Mineral resources use	kg deprived	0.24572	1.36426	0.13734	1.10795	0.14601	0.67990	0.22228	0.21407
Ozone layer depletion	kg CFC-11 eq	1.59E-05	9.92E-05	1.04E-05	8.05E-05	8.45E-06	5.06E-05	2.40E-06	8.38E-06
Ozone layer depletion	DALY	7.80E-09	2.92E-07	4.55E-09	2.38E-07	4.39E-09	1.47E-07	5.92E-09	2.44E-08
Particulate matter formation	kg PM2.5 eq	0.0335	0.0125	0.0209	0.0095	0.0181	0.0076	0.0073	0.0044
Particulate matter formation	DALY	4.02E-05	1.50E-05	2.50E-05	1.14E-05	2.18E-05	9.18E-06	8.73E-06	5.33E-06
Photochemical oxidant formation	kg NMVOC eq	0.1921	0.0749	0.1008	0.0555	0.1121	0.0461	0.0644	0.0373
Photochemical oxidant formation	DALY	7.33E-09	2.89E-09	3.83E-09	2.14E-09	4.29E-09	1.78E-09	2.48E-09	1.44E-09
Terrestrial acidification	PDF.m2.yr	2.937	1.446	1.577	1.108	1.672	0.826	0.900	0.554
Terrestrial acidification	kg SO2 eq	0.2046	0.1009	0.1099	0.0774	0.1165	0.0576	0.0628	0.0386
Thermally polluted water	PDF.m2.yr	7.18E-05	1.41E-04	4.56E-05	1.17E-04	3.48E-05	6.15E-05	4.99E-05	3.74E-05
Water availability, freshwater ecosystem	PDF.m2.yr	1.39E-04	3.72E-04	8.96E-05	3.09E-04	7.32E-05	1.61E-04	7.46E-05	7.03E-05
Water availability, human health	DALY	5.05E-05	1.24E-04	3.25E-05	1.03E-04	2.64E-05	5.33E-05	2.65E-05	2.44E-05
Water availability, terrestrial ecosystem	PDF.m2.yr	0.0012	0.0166	0.0007	0.0139	0.0008	0.0075	0.0008	0.0018
Water scarcity	m3 world-eq	19.531	52.119	12.562	43.335	10.267	22.621	10.462	9.862

D Appendix: Sensitivity analysis results

Category (+10 %)	Name	Result	Unit	Δ Value	% change
Baseline Results	Carbon footprint	26.996	kg CO2 eq	/	/
	Fossil and nuclear energy use	639.545	MJ deprived	/	/
	Remaining EQ damage	4.178	PDF.m2.yr	/	/
	Remaining HH damage	3.06E-05	DALY	/	/
	Water scarcity footprint	52.119	m3 world-eq	/	/
Dist transport sea	Carbon footprint	27.028	kg CO2 eq	-0.033	0.121
	Fossil and nuclear energy use	639.991	MJ deprived	-0.446	0.070
	Remaining EQ damage	4.193	PDF.m2.yr	-0.015	0.349
	Remaining HH damage	3.07E-05	DALY	-4.44E-08	0.145
	Water scarcity footprint	52.120	m3 world-eq	-0.001	0.002
Dist transport truck	Carbon footprint	27.013	kg CO2 eq	-0.017	0.063
	Fossil and nuclear energy use	639.826	MJ deprived	-0.281	0.044
	Remaining EQ damage	4.182	PDF.m2.yr	-0.003	0.080
	Remaining HH damage	3.06E-05	DALY	-1.31E-08	0.043
	Water scarcity footprint	52.120	m3 world-eq	-0.001	0.002
Dist transport waste	Carbon footprint	26.997	kg CO2 eq	-0.001	0.003
	Fossil and nuclear energy use	639.557	MJ deprived	-0.012	0.002
	Remaining EQ damage	4.178	PDF.m2.yr	0.000	0.003
	Remaining HH damage	3.06E-05	DALY	-1.18E-09	0.004
	Water scarcity footprint	52.119	m3 world-eq	0.000	0.000
Machine annual cycle	Carbon footprint	26.225	kg CO2 eq	0.771	-2.856
	Fossil and nuclear energy use	634.325	MJ deprived	5.220	-0.816
	Remaining EQ damage	4.094	PDF.m2.yr	0.084	-2.007
	Remaining HH damage	2.96E-05	DALY	9.93E-07	-3.240
	Water scarcity footprint	52.018	m3 world-eq	0.101	-0.194
Mass sterilizer	Carbon footprint	27.023	kg CO2 eq	-0.027	0.101
	Fossil and nuclear energy use	639.700	MJ deprived	-0.155	0.024
	Remaining EQ damage	4.182	PDF.m2.yr	-0.004	0.101
	Remaining HH damage	3.06E-05	DALY	-1.57E-08	0.051
	Water scarcity footprint	52.121	m3 world-eq	-0.002	0.004
Mass body	Carbon footprint	27.586	kg CO2 eq	-0.590	2.186
	Fossil and nuclear energy use	646.819	MJ deprived	-7.274	1.137
	Remaining EQ damage	4.224	PDF.m2.yr	-0.046	1.104
	Remaining HH damage	3.11E-05	DALY	-4.55E-07	1.490
	Water scarcity footprint	52.278	m3 world-eq	-0.159	0.305
Mass box	Carbon footprint	27.019	kg CO2 eq	-0.023	0.086
	Fossil and nuclear energy use	639.877	MJ deprived	-0.332	0.052
	Remaining EQ damage	4.189	PDF.m2.yr	-0.010	0.251
	Remaining HH damage	3.07E-05	DALY	-2.47E-08	0.081
	Water scarcity footprint	52.128	m3 world-eq	-0.009	0.017
Mass cap	Carbon footprint	27.047	kg CO2 eq	-0.051	0.188
	Fossil and nuclear energy use	640.532	MJ deprived	-0.987	0.154
	Remaining EQ damage	4.184	PDF.m2.yr	-0.005	0.128
	Remaining HH damage	3.07E-05	DALY	-3.34E-08	0.109
	Water scarcity footprint	52.134	m3 world-eq	-0.015	0.030
Mass sterile bag	Carbon footprint	27.097	kg CO2 eq	-0.102	0.376
	Fossil and nuclear energy use	641.724	MJ deprived	-2.179	0.341
	Remaining EQ damage	4.204	PDF.m2.yr	-0.025	0.609
	Remaining HH damage	3.07E-05	DALY	-7.20E-08	0.235
	Water scarcity footprint	52.183	m3 world-eq	-0.064	0.123
Mass washer	Carbon footprint	27.040	kg CO2 eq	-0.044	0.164
	Fossil and nuclear energy use	639.797	MJ deprived	-0.252	0.039
	Remaining EQ damage	4.185	PDF.m2.yr	-0.007	0.165
	Remaining HH damage	3.07E-05	DALY	-2.54E-08	0.083
	Water scarcity footprint	52.122	m3 world-eq	-0.004	0.007
MFF	Carbon footprint	25.279	kg CO2 eq	1.717	-6.361
	Fossil and nuclear energy use	592.555	MJ deprived	46.991	-7.348
	Remaining EQ damage	3.885	PDF.m2.yr	0.294	-7.026
	Remaining HH damage	2.84E-05	DALY	2.21E-06	-7.230
	Water scarcity footprint	47.710	m3 world-eq	4.409	-8.459