Technical University of Denmark

DTU 12772 Life Cycle Assessment

LCA Report G3.4

Case Study: Recycling Shower

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1 Executive Summary

This life cycle assessment (LCA) report examines the product LOOP shower from the company Flow Loop ApS, the commissioner of this LCA study. Compared to a regular shower the LOOP shower recycles large part of the bathing water and therefore has a smaller water and energy consumption. Since the main function for the LOOP shower is the same as the regular shower, both products are compared based on their main function identifying the environmental impact of each shower. In addition, a hot-spot analysis is conducted identifying the impact of each life cycle stage and the biggest contributors. Because the main purpose of the products is to provide bathing water, the functional unit (FU) is defined as *Delivering bathing water with a flow of 12 L/min and 38°C for 8 minutes in Denmark* containing exact specifications for comparing.

The system boundaries include every life cycle process covering the material extraction, transport to Flow Loop ApS and customer, production, use stage, and disposal. Excluded processes include any detergents used while showering, and fixed bathroom furniture such as ceramic tiles in the bathroom. The process tree consists of foreground and background processes. The foreground processes are based mainly on primary data. The background processes also include primary data like datasheets and measurements but uses secondary data such as data from internet research.

For conducting the LCA study several assumptions are made of which most regard the manufacturing stage and use stage. For the use stage district heat for water heating, showering duration and frequency, as well as number of people per apartment are the most impactful assumptions. The showering frequency and population per apartment also affect the manufacturing stage since they define the number of uses over shower lifetime. Based on the determined information, the environmental impact is calculated. The results indicate LOOP showers' global warming score as a bit more than half of the regular showers score. While for both showers the use stage represents the biggest contributor, the manufacturing stage of the LOOP shower shows also significant CO_2 emissions, whereas the regular shower is only dominated by the use stage. Especially the high contribution of the aluminium and the filter of the LOOP shower as part of the manufacturing impact are identified. Considering different impact categories, affecting human health and ecosystem quality, the LOOP shower has smaller impacts in the majority and in most important impact categories.

For considering the uncertainty of certain assumptions a sensitivity study was conducted. Longer shower duration, more frequent use, and higher water temperatures increase the environmental impact difference between the two product systems in favour of the LOOP shower. Additionally, heating the water with DK electricity mix shows similar results if the fraction of fossil energy increases. Besides a comparison of the products' sustainability, an absolute view on the sustainability was taken. It shows that both products are not absolute sustainable.

Based on the results, it is recommended to implement the LOOP shower in water intensive surroundings and to consider using recycled alumnium for the LOOP showerdue to its high impact contribution. Moreover, reusable filter can reduce the impact of the manufacturing stage.

2 Technical Summary

In this LCA study the object of investigation is a product called LOOP shower from the company Flow Loop ApS. The LOOP shower is a recycling shower, and it was compared to a regular shower which is used as a reference in this LCA. The LOOP shower recycles a large part of the bathing water through a treatment process which results in a significantly smaller water and energy consumption. For both product systems the whole life cycle from cradle to grave is evaluated in this LCA. Two goals for conducting this LCA were given by the company. The first is finding the most sensible ways to reduce the CO_2 impact of the LOOP shower. The second is identifying the break-even point after which the LOOP shower performs better than a regular shower in terms of CO_2 emissions. In order to meet these objectives, a comparative study between the two shower products and a hot-spot analysis of the LOOP shower is conducted.

The functional unit (FU) for this LCA is defined as *Delivering bathing water with a flow of 12 L/min and 38^oC for 8 minutes in Denmark.* The decision context for this study is the micro-level decision support, and therefore the attributional LCI modelling framework is applied in this LCA.

The main data source for this LCA is the commissioner, Flow Loop ApS. The company provided the data through component datasheets, a previous water and energy usage report, and their website. Additionally, a main primary data source is the weighting of the shower components and materials by the LCA team. The data for a regular shower was gathered from the internet through a company website. Regarding data quality it should be noted that the data for the LOOP shower is mainly high-quality primary data and therefore provides higher quality than for a regular shower. However, some of the data regarding the LOOP shower (transportation distances and detailed information about some components) were not gathered directly through the company and may not be of the same quality as the first-hand data. Ecoinvent database represents the main data source for the background processes. One of the main method assumptions is that all data has been specifically chosen for Denmark which is why there may be result usage limitations for countries outside Denmark. Another main assumption is that the SimaPro impact category Water availability for human health is not used in this LCA study because of misleading data in the Ecoinvent database, but rather calculated by hand for the use phase only. In the use stage district heat for water heating was assumed as well as shower time of 8 minutes and that four people are living in one apartment and using the shower on daily basis. In **Figure 1** a process tree of the LOOP shower is shown which gives an overview of all the processes that were taken into consideration in the data collection.

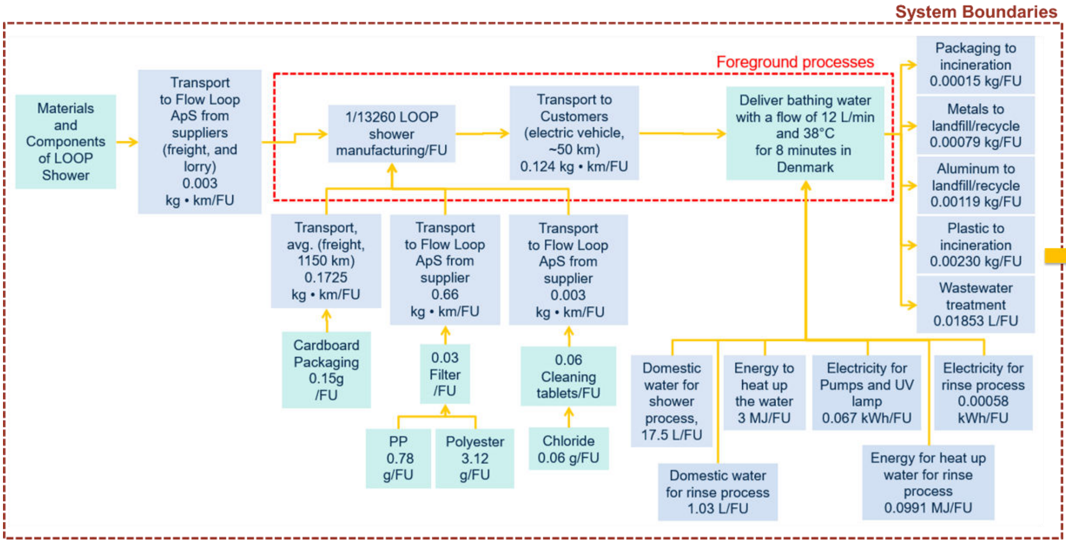

Figure 1. *LOOP shower process tree and system boundaries.*

The calculations of the global warming score with the Excel hand-calculations and in SimaPro software provide a similar picture. With 0.152 $kgCO_2eq/FU$ for the hand-calculations and 0.155 $kgCO_2eq/FU$ for the SimaPro calculations, the global warming score of the LOOP shower is significantly lower than that of a regular shower which has a score around 0.271 $kgCO_2eq/FU$ for the hand calculations and 0.275 $kgCO_2eq/FU$ for the SimaPro results. The main contributors in the SimaPro calculations for the LOOP shower are the heating of water in the use stage with 45% contribution, the manufacturing and raw materials with 31% contribution, and the use stage other than heating of the water with 14% contribution. The **Figure 2** of the normalized results shows a similar picture as the results of the global warming score.

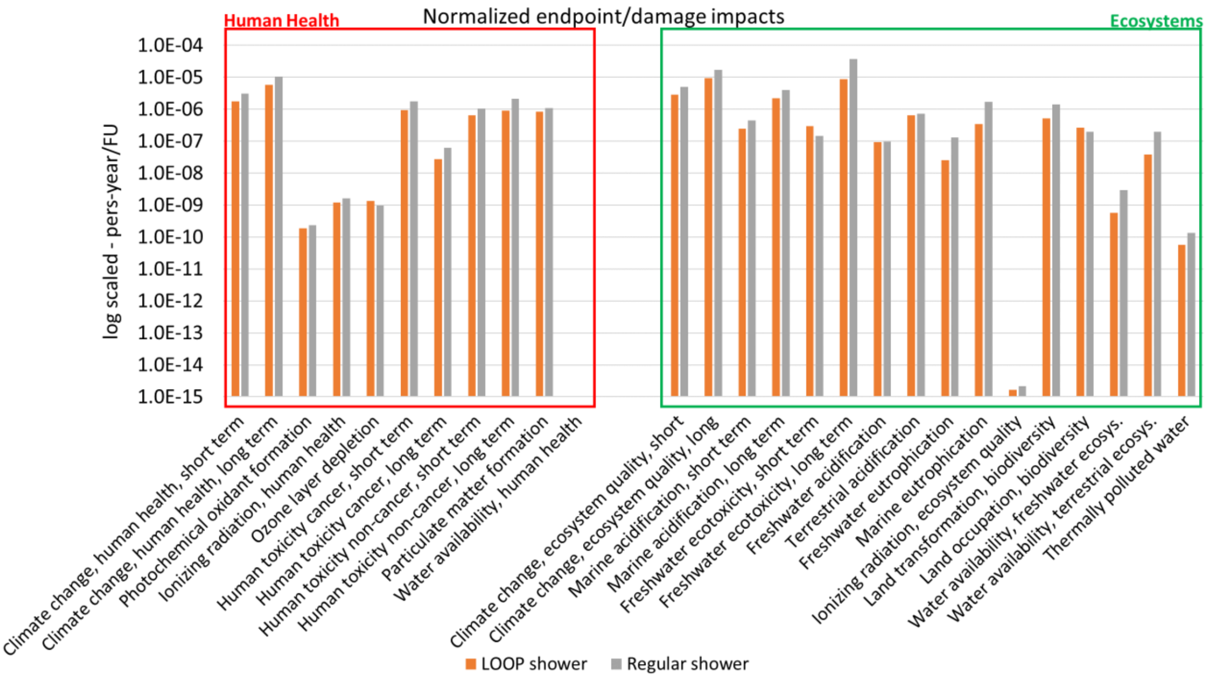

Figure 2. *Normalized endpoint results from SimaPro IMPACT World+ damage level method in pers-year/FU sorted into human health and ecosystem impact categories for the LOOP shower and a regular shower. Note: y-axis is log-scaled.*

The normalized endpoint results show that the impact categories *climate change short and long term* are contributing the most in the area of protection human health. For ecosystem the impact categories *climate change long term* and *freshwater ecotoxicity long term* have the highest impact.

For almost all impact categories the LOOP shower has a smaller impact than a regular shower. Only for *Ozone layer depletion* in human health and *Freshwater ecotoxicity (short term), Land occupation and biodiversity* in ecosystem quality are higher in impact for the LOOP shower than for a regular shower.

In the sensitivity study it was found out that in terms of global warming the LOOP shower is most sensitive to changes in shower duration and number of uses over product lifetime. Whereas the regular shower is significantly sensitive to the duration of the shower and especially to the heating method of the bathing water.

The calculations for the CO_2 break-even revealed that the LOOP shower outperforms the regular shower after 3133 uses. For this calculation the whole process of the shower has been considered, not just the use stage processes.

In total it can concluded based on the performed LCA including the normalization of results, sensitivity analysis, and absolute sustainability assessment that the LOOP shower is a more sustainable product than a regular shower. As always, there are some limitations to using LCA study results. As mentioned in the beginning, the study uses specific data for the Danish market and therefore results cannot easily be applied to another country. Secondly, the result are only applicable for the current state of the Flow Loop ApS company as the start-up is in a developing state and currently produces the LOOP showers by hand. The main takeaway from the results of this LCA is that Flow Loop ApS should focus on reducing the emissions of the product itself as they do not have any influence on how the bathing water is heated. For example, they could reduce the use of aluminium or use recycled aluminium instead of virgin one. Another way to reduce the carbon footprint of the product itself is to change the material of the microfilter or investigate if it can be safely used for longer than the Flow Loop ApS currently recommends. Furthermore, it is recommended for Flow Loop ApS to focus on users with higher water consumption as this reduces the overall emissions per FU.

3 Goal Definition

3.1 Intended Application

The intended application of this study is a comparative assertion of a recycling shower called LOOP shower and a regular shower. The environmental impact of both product systems is evaluated for the whole life cycle from cradle-to-grave.

3.2 Method Assumptions and Impact Limitations

There are some limitations in the study's usability for countries outside of Denmark since the data that has been used is specific to Denmark. For example, some of the processes used for modelling such as electricity mix have been picked to fit the Danish market. Also, the processes used (e.g., electricity mix) correspond to today's situation, and may no longer be valid years from now. Therefore, the study has limited representation of temporal and spatial variations. Nearly all possible impact categories will be taken into consideration in this study. One impact limitation is that the SimaPro Water Availability for Human Health impact cannot be used in this LCA study when using the IMPACT World+ method. This is because the Ecoinvent data is currently incorrect and is mixing extraction of water with consumption of water in the water turbine part of the metal working processes.

3.3 Reasons for Carrying Out the LCA Study and Decision Context

There are two main reasons for the execution of the LCA study. Firstly, it is the company's aim to find the most sensible ways to reduce the CO_2 impact of the LOOP shower. The second reason is to identify the break-even point, meaning the number of showers after the LOOP shower outperforms a regular shower in terms of the CO_2 emissions. The reasons for the LCA execution led to the decision context of the LCA study. It is likely that the company will use the results of this LCA to support their decision making in the future. However, due to the small scale of the studied product system, the decisions influenced by this LCA will not cause big structural changes in the systems that the product system interacts with. Therefore, the decision context for this study is Micro-Level Decision Support as it is defined in the LCA handbook by Hauschild et al. (2018, pp. 70-71).

3.4 Target Audience

The results of the LCA study are primarily destined for the company of the LOOP shower, so that they can be used internally for further development. The company has previously done some calculations regarding the carbon footprint of the LOOP shower but has not completed a full LCA. Therefore, they have some background knowledge about the assessment, but still require the help of external experts to make more informed decisions.

3.5 Comparative Assertions to be Disclosed to the Public

The study results are only intended to be used for internal use, so the comparative assertions will not be disclosed to the public.

3.6 Commissioner of the LCA Study and Other Influential Actors

The Commissioner of this LCA study is Flow Loop ApS, the company producing the LOOP shower.

4 Scope Definition

4.1 Deliverables

The deliverables will consist of a report describing and discussing a Life Cycle Assessment for the LOOP shower and a regular shower. The results will be based on a life cycle inventory with data on the environmental inputs and outputs associated with the two product systems. The impact assessment will include all impact categories (except limitations mentioned in 1.2) including water usage, energy consumption, carbon emissions etc. In addition, the assumptions made during the study and the potential impact of these assumptions on the results will be discussed. In the end, recommendations to the company will be provided, with suggestions for lowering the impact of the LOOP shower, including e.g., information on the current break-even point (CO_2) between a regular shower and the LOOP shower.

4.2 Product Description

The main product of this LCA is the LOOP shower, a water recycling shower produced by the company Flow Loop ApS (**Figure *3***). In contrast to a regular shower, the water used in the LOOP shower can be directly reused for showering again.

The process of the LOOP shower is as follows: The shower is turned on and the recycling mode is activated by pressing a button. After a few millimetres of water has collected on the floor, the water recycling starts. The water on the floor is sucked into the suction inlet by the pumps, and it gets filtered through a prefilter and a microfilter before getting disinfected by a UV lamp. The microfilter is changed once a month. After the used water has flowed through these processes, it flows through the shower head again and will be directly reused. Some fresh water is also added to the recycled water to maintain sufficient temperature.

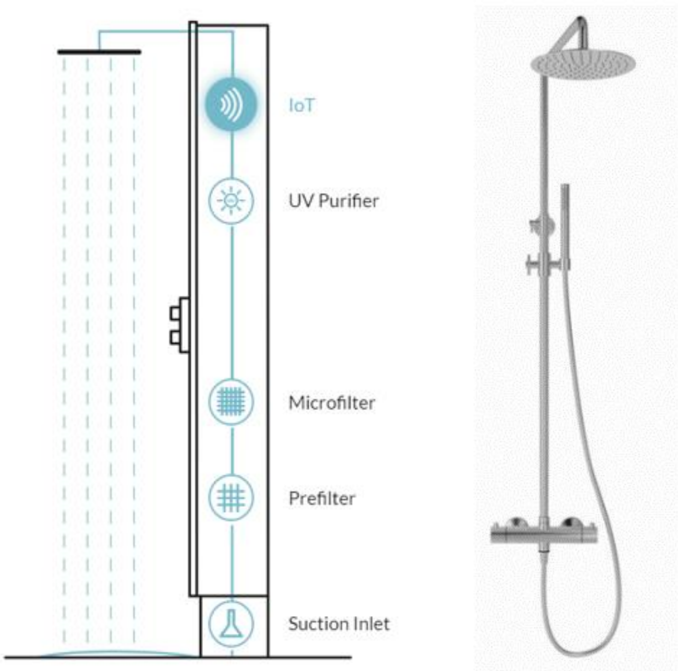

Figure 3. *Products of interest: LOOP shower (left) and regular shower (right). (Flow Loop ApS, 2023; Gulv & Flise Eksperten, 2023).*

Every two weeks the shower needs to go through a rinse process, and a cleaning tablet is added to purify the system. The rinse process works in a 3-3-3 cycle; the floor is first filled with water for 30 seconds after which the water is recirculated for 3 mins. Then, the shower is turned off to let the chemical sit and then the shower is run normally without the recycling mode for 3 more minutes. (Flow Loop ApS, 2023.)

The product on the right in **Figure *3*** was chosen as a reference shower to represent a regular shower in this LCA. It was chosen because it is able to reach the same flow rate as the LOOP shower, it has a hand shower, and it does not include any additional functionalities that the LOOP shower does not have (Gulv & Flise Eksperten, 2023.)

4.3 Function, Functional Unit and Reference Flows

To carry out a meaningful comparative LCA, the functions of the compared product systems need to be identified as either primary or secondary functions. In this study, the primary function of the two product systems is to provide bathing water for showering, while the secondary functions may include relaxation, maintaining good hygiene, being part of the interior design of the bathroom, or the ability to recycle and reuse the water and energy.

To ensure a representative functional unit (FU) for the systems to be evaluated, mandatory and positioning characteristics of the products must be defined. In this study, both showers have many mandatory characteristics such as safety and providing sufficient water flow. The safety parameter is a legally required property, so that the showers do not endanger the health of the user, e.g., by unregulated heating of the water or unregulated quality of the bathing water. Another mandatory feature is that the showers must be compatible with existing structures, such as household water outlets, and must be able to regulate water flow and temperature. Some positioning features that make the products more attractive to the customer and increase their value can be certain designs, including colour or shape, or different showerhead settings. In addition, the lifespan of a shower, the ease of use, and the energy and water consumption can vary between different shower products, providing different value to the customer.

Based on this defined information, the functional unit (FU) can be formed. The FU quantifies the performance of the product to be evaluated and serves as a reference unit for comparison and is therefore the same for both product systems (ISO 14044, 2006). The FU for this LCA is as follows,

- Delivering bathing water with a flow of 12 L/min and 38°C for 8 minutes in Denmark.

In the FU, the flow of 12 L/min, the water temperature of 38°C, and shower time of 8 min are based on a previous water and energy usage assessment report (Niras A/S, 2023). Referring to this functional unit, there are key environmental parameters used to calculate the reference flows (**Table 1**). For the quantity of the key environmental parameters, key assumptions are made and information from data sheets and reports of former analyzation of the LOOP shower are taken. The assumptions for the key environmental parameters or those which are used to calculate the key environmental parameters are stated in **Annex 1**. All assumptions that are made in the LCA study focus on Denmark as the Danish market is the only point of sale for the company for now. The influence of this assumption may result for example in a high percentage of renewable energy use in the modelling, because renewable sources are common in Denmark (Energinet, 2023).

Table 1. *Key environmental parameters.*

• Lifespan of a shower • Recycling rate of the LOOP shower • Water savings of the LOOP shower • Frequency of filter change of the LOOP shower • Frequency of rinse process of the LOOP shower • Specific heat of water • Way of heating the water • Temperature of cold domestic water • Power of pumps • Power of UV lamp • Number of showers over the product lifetime • Temperature loss during recycling process of the LOOP shower • Rinse process data (temperature of water, water flow, duration)

These key assumptions and key environmental parameters mentioned above have been used to calculate the reference flows for both systems in

Table 2. These calculations have been categorized into required domestic water, energy for water heating, electricity, showers, and maintenance per FU. First, the calculations for the LOOP shower are based on the assumption that water is recycled for the whole showering process except the starting phase where water is collected on the floor. As 63% of the Danish households use district heating for water heating, this is counted as energy instead of electricity (Danish Energy Agency, 2015). The water consumption for both showers is calculated with the provided water flow and showering time. In addition, the water consumption of the LOOP shower takes into account the water savings calculated by the company. They measured that for a water flow of 12 L/min for 8 minutes, 17.5 L water are consumed (Niras A/S, 2023). Since the LOOP shower requires a rinsing process every two weeks, the water used for this process is also added. The energy and electricity used by the shower during the rinse process is calculated based on the information from the company that the UV lamp is on for the whole rinse process, and when in recirculation mode both pumps are on, and when in normal shower mode only the delivery pump is on. To provide more detailed information, the first 30 seconds when the water is pooling on the floor only one pump is active. Then, when the recirculating starts the two pumps are working for 3 minutes, and then the normal shower is active for 3 minutes with only one pump to finish up the rinsing.

The amount of energy needed to heat the water to 38ºC for a regular shower was calculated based on the information that 50% of the water coming in is cold and 50% is hot and they are mixed to find the optimal temperature (Niras A/S, 2023). The energy consumed by the LOOP shower is composed of the energy for heating the water during the showering process and the rinsing process (both heated to 38ºC), whereas for the regular shower only the energy for the showering process is required. However, for the LOOP shower less hot water is needed than for a regular shower because the water is constantly recycled back into the system and only a small amount of hot water is needed to keep up the temperature of 38°C. In addition, the LOOP shower requires electricity to pump up the water and to disinfect the recirculated water, again distinguishing between the rinse and the shower process. As shown earlier in the reference flow, the LOOP shower requires some maintenance, including rinsing (every 2 weeks, 1 tablet per rinse) and changing the microfilter (every 4 weeks). This information was used to calculate the number of filters and rinse tablets needed per FU. Additionally, the fraction of the actual shower itself used per FU for both product systems was also calculated based on the average number of showers taken per person in a week, the shower lifetime, and the number of people living in an apartment.

Table *2.* Reference flows of the LOOP shower and a regular shower.

Reference Flow	LOOP shower	Regular shower
Domestic Water	Shower process: $\mathbf{17.5\frac{L}{FU}}$ **(Niras A/S, 2023)**	$12\frac{L}{min}\times 8\,min = \mathbf{96\frac{L}{FU}}$
	Rinse process: $\frac{35L}{34\frac{showers}{rinse\ process}} = \mathbf{1.03\frac{L}{FU}}$	
Energy	$E_{total} = E_{shower,water} + E_{rinse,water} = \mathbf{3.204MJ}$	$\frac{\frac{96L}{2}\times 46°C \text{ x } 4.1876\frac{kJ}{kg\ °C}}{1000}$ $= \mathbf{9.25\frac{MJ}{FU}}$
	$E_{shower,water} = (5{,}18L\ \times 46°C + 7{,}14L\ \times (82°C - 15°C)) \times \frac{4.1876\frac{kJ}{kg\ °C}}{1000} = \mathbf{3\frac{MJ}{FU}}$	
	$E_{rinse,water} = (35L\ \times (38°C - 15°C)) \times \frac{4.1876\frac{kJ}{kg\ °C}}{1000} \times \frac{1}{34\frac{showers}{rinse\ process}} = \mathbf{0.0991\frac{MJ}{FU}}$	
Electricity	$El_{total} = El_{shower,equip.} + El_{rinse,equip} = \mathbf{0.07\frac{kWh}{FU}}$	-
	$El_{shower,equip.} = (2\ \times 240W + 25W)\ \times 8min = \mathbf{0.067\frac{kWh}{FU}}$	
	$E_{rinse,equip.} = ((240W + 25W)\ \times 3{,}5min + (2\ \times 250W + 25W) \times 3min) \times \frac{1}{34\frac{showers}{rinse\ process}} = \mathbf{0.0012\frac{kWh}{FU}}$	
Shower	$\frac{1\ shower}{\left(4.25\frac{showers}{week\ x\ person}\times 4\frac{person}{apartment}\times 52\frac{weeks}{year}\times 15\ years\right)} = \mathbf{\frac{1}{13260}\frac{shower}{FU}}$	$\mathbf{\frac{1}{13260}\frac{shower}{FU}}$ **(same calculation as for the LOOP Shower)**
Maintenance	$\frac{1\ Filter}{4.25\frac{showers}{week\ x\ person}\times 4\frac{weeks}{month}\times 4\frac{person}{apartment}} = \mathbf{0.0147\frac{Filter}{FU}}$	-
	$\frac{1\ Tabs}{4.25\frac{showers}{week\ x\ person}\times 2\frac{weeks}{month}\times 4\frac{person}{apartment}} = \mathbf{0.0294\frac{Tabs}{FU}}$	-

4.4 LCI Modelling Framework

The LCI modelling framework needs to align with the decision context determined in the goal definition (Hauschild et al., 2018, p. 88f). Therefore, based on the handbook recommendation this LCA study has an attributional modelling framework (Hausschild et al. 2018, p. 98). Following the handbook, the system expansion through the use of average processes was applied. Even though no elemental co-products could be identified in the product systems, the heat recovery through incineration of the plastics and the cardboard in the disposal stage was taken into account. If the product systems were to have some components that are reused, these would be shown in the modelling as avoided impact in the raw material stage.

4.5 System Process Tree, Boundaries, and Completeness Requirements

The process tree or flow chart is used to gain a clear overview of the different processes related to the product systems, and it displays the connections from reference flows up to existing database unit processes. The tree consists of foreground processes (specific to system) and background processes (not specific to system). The foreground and background processes are displayed in the process trees (**Figure 4 & 5**). The processes which are included in the foreground processes for the LOOP shower process tree (**Figure 5**) are the ones that the company contributes to themselves: the manufacturing of the LOOP shower, its transportation to the customer, and the service provided by the LOOP shower to the customer. All the processes inside the system boundaries which are not inside the foreground processes box are background processes and are ones that the company does not contribute to such as the extraction of the materials for the shower components.

According to ISO 14044 (2006), the system boundary is the set of criteria specifying which unit processes are part of a product system and ideally includes all the required processes from cradle to grave to fulfil the function (Jolliet et al., 2016). The system boundaries include the processes of shower production, transport, and use. As seen in the process trees (**Figure 4 & 5**), the LOOP shower has a greater number of components and therefore also raw materials needed for the shower production. That is why these processes are different and have been included in the boundaries. Also, as the water and energy consumption per functional unit are not the same between the two systems, water treatment, wastewater treatment, and energy supply are included in the system boundaries. Also, the emissions to soil, water, and air are included in the system boundaries, as shown in the process trees. Lastly, to consider differences in produced waste, the end-of-life processes (disposal method) are also to be included to the system. The factors that are excluded from the system boundaries are ones that are assumed to be equal between different systems. For example, some excluded processes are domestic cosmetics used while showering, and water and cleaning products used to clean the bathroom. Additionally, the other products used when showering such as a shower curtain or closet and ceramic tiles in the shower are also excluded from the system boundaries.

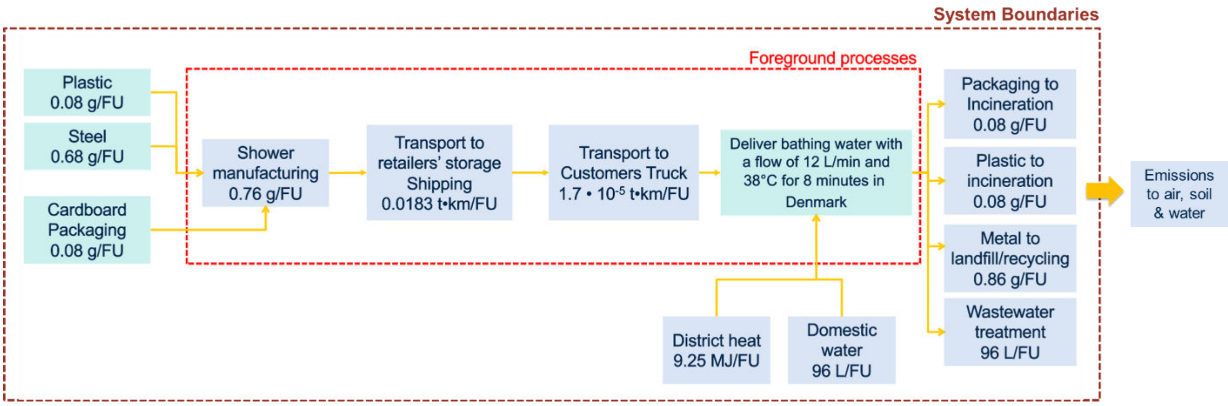

Figure 4. *Regular shower's process tree and system boundaries. The light blue boxes demonstrate all the materials needed per functional unit.*

A reduced process tree for the LOOP shower is displayed in **Figure 5.** A more detailed version of the process tree can be found in **Annex 2**.

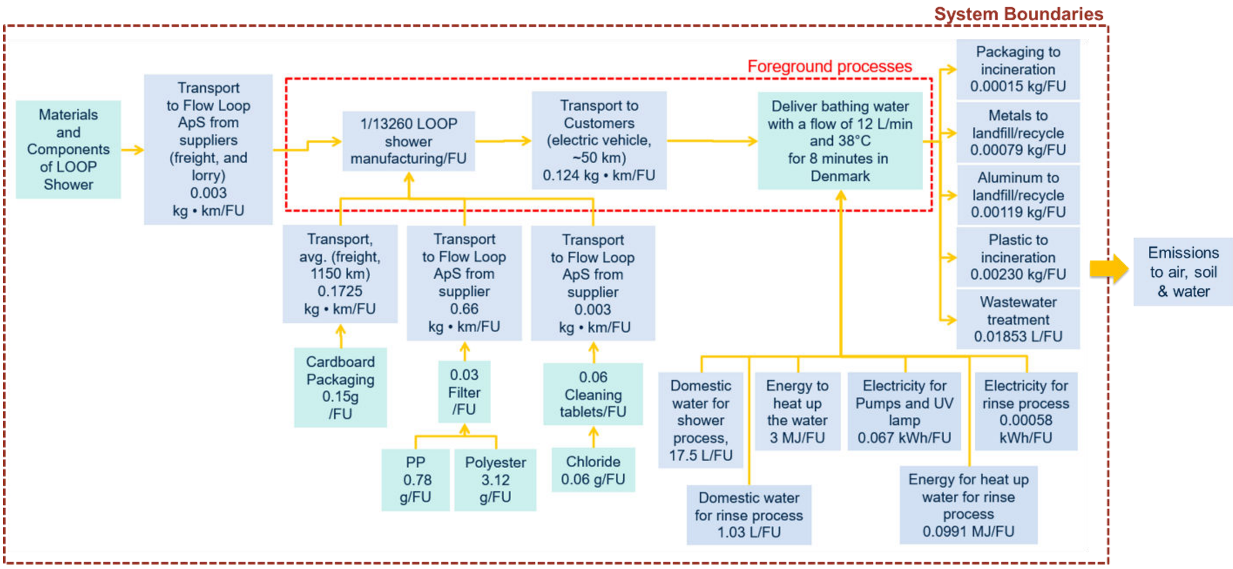

Figure 5. *LOOP shower process tree and system boundaries.*

4.6 Representativeness of LCI Data

The data regarding the foreground processes and some background processes has been collected first-hand from the Flow Loop ApS company. This primary data is the most accurate information available, however, it contains some justified assumptions (e.g., assumptions in the water and energy savings calculations carried out by the company) that have been traced and documented as best as possible. During the inventory analysis, almost all of the background processes were constructed from other than first-hand data sources, mostly from the Ecoinvent database within the SimaPro software. In terms of geographical representativeness, the data used in the study is specific to Denmark and Danish consumers and therefore the data does not represent a situation where the product is used in another country. The processes used e.g., electricity mix correspond to today's situation and might change over time, therefore affecting the temporal and technological representativeness of the data.

4.7 Basis for Impact Assessment

All impact categories (except limitations mentioned in 1.2) will be assessed in this LCA. However, there are some impact categories that are especially interesting, as the recycling shower requires a lot of components consisting of various materials compared to the regular shower yet uses less water and energy during the use stage because of its water recycling function. Therefore, the water use and energy consumption leading to emissions impacting global warming, fossil energy use and human respiratory health effects from air pollutants such as $PM_{2.5}$ from the upstream raw material extraction stage and transportation as well as the use stage are of special interest in this study. For the midpoint and endpoint impact calculations IMPACT World+ Endpoint method will be used. Additionally, normalization and weighing of results will be conducted.

4.8 Requirements for Comparative Studies

Special requirements are set in the ISO 14044 for comparative studies, to make sure that the systems can be compared fairly. Systems should have the same functional unit and equivalent methodological considerations e.g., performance, system boundary, data quality, and allocation procedures. The differences between these parameters should be identified and documented. (Hauschild et al., 2018, p. 113-114.)

The parameters have been kept as similar as possible for both product systems that are being compared in this study. However, more primary data has been collected for the LOOP shower regarding the shower components' materials compared to the regular shower. This is not surprising, as it was easier to gain access to the LOOP shower in real life since the company is also the commissioner of the LCA, whereas the regular shower was chosen based on internet research and was impossible to see in real life. Therefore, higher quality primary data has been used for some of the LOOP shower data.

4.9 Critical Review Needs

Critical reviews are conducted to prevent misuse and unsupported claims, help identify mistakes, find more justifiable assumptions, and improve the general quality of the LCA study. (Hauschild et al., 2018, p. 335). According to ISO 14044, a critical review is mandatory for LCA studies where "the results are intended to be used to support a comparative assertion intended to be disclosed to the public" (ISO 2006). The mandatory critical review can be performed only by a panel of interested parties including at least three LCA experts. (Hauschild et al., 2018, p. 339.)

A formal critical review is not needed in this case because the results are not intended to be disclosed to the public but are for the internal use of the company. Therefore, for the purposes of this LCA course, the reviewing is conducted by teacher assistants and the course professor who have signed the confidentiality agreement and are required not to disclose any confidential information. Furthermore, a version of the LCA reports that excludes all confidential information will be peer reviewed by other students participating in the LCA course.

5 Life Cycle Inventory Analysis

5.1 LCI Model at System Level

As mentioned previously, the detailed process tree for the Loop Shower can be found in the **Annex 2**. Compared to **Figure 5** this process tree provides all information about the materials and components that are part of the recycle shower as well as the transportation of them.

5.2 Data collection

The following described data collection is divided into the different life cycle stages. Because there was no data available for the disposal life cycle stages, this will be left out in this paragraph. In the **Annex 3** a full list with the collected data and the assumptions about the components and materials and the origin of manufacturing/supplier can be found.

To get a list of all different components and materials of the LOOP shower, an actual prototype was disassembled at the manufacturing site. After that, all the disassembled components were weighted to get exact values for each component using the scale in **Figure 6**.

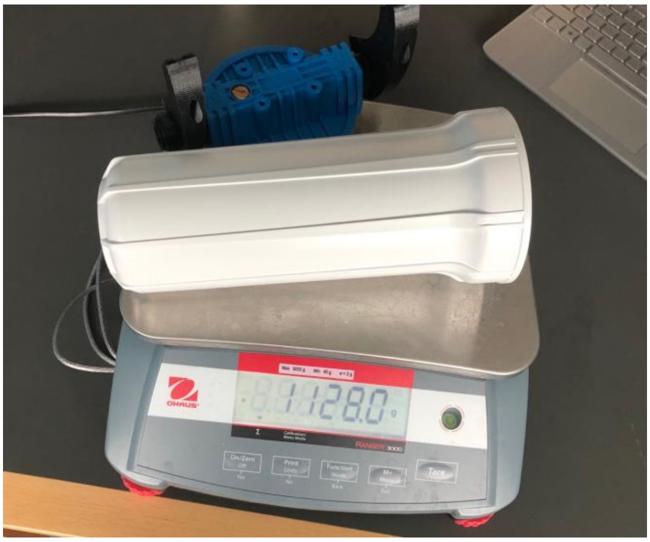

Figure 6. *Scale used for weighing the components.*

The data for the weight of the aluminium used for the LOOP shower cover and the frame, as well as the total weight of the shower was delivered by the contact person from the Flow Loop company. Most of the components' materials could be identified by looking at the supplier data sheets and billing list Excel information that was provided by the company. For the components that no data sheets were available, internet research was conducted. For the manufacturing and production of the LOOP shower and the components, the available data was provided by the company.

The data about the origin of the suppliers could also be gathered through the data sheets or through a deeper internet research about the supplier companies. After the data about the country of origin of the supplier was identified, the distance of transportation was found out. For countries of origin within Europe a transportation via truck was assumed and the distance was determined through a route calculation with Google Maps. For the starting point a city that is approximately in the middle of the supplier country and as the endpoint the location of Flow Loop ApS was chosen. For countries outside Europe the transportation via freight was assumed and the data about the distance of the transportation was gathered through a website (Fluent Cargo, 2023). The distances from country to another were calculated from port to port.

The data for the use stage of the LOOP shower was mainly provided by the company, the company's website, and a previous analysis report of the LOOP shower (Flow Loop ApS, 2023; Niras A/S, 2023). This included for example the technical properties, provided water flow, and details about the showering and rinsing processes. This report also provided data about the average showering habits in Denmark. Additional data was collected from data sheets of the different energy consuming components such as the UV lamp and pumps (Krausen Baltija, 2023; Xylem Inc., 2023).

In summary, most of the data was either provided by the company, their suppliers or was gathered trough own measuring, which present high quality sources. All other data sources (transportation distances and detailed information about components) have been carefully selected, but it should be noted that the quality may not be the same standard as primary first-hand data.

5.3 System Modelling Per Life Cycle Stage

In this section the system modelling will be presented in detail. The focus is set on collected data and its treatment as well as the major assumptions. For this purpose, the section is divided into two main sections: "LOOP shower" and "regular shower". Each of these sections consist of the following stages: materials/components, production, manufacturing, use, and disposal. The processes used in the hand-calculations and SimaPro model for the LOOP shower can be found in **Annex 4** and for the regular shower in **Annex 5**.

5.3.1 LOOP shower

Material/components stage: The gathered weights of the components were summed up and were compared to the total weight of the prototype. Because of a small weight gap between the sum of the weight of all components and the weight of the whole LOOP shower prototype, the weight of each component was scaled up. For this the relative weight discrepancy was used as the scale up factor. This constitutes the most important main assumption in this stage. For some components in the data sheets no detailed list of materials and/or amount of each material fraction for the component was given. For these components assumptions were made through internet research. For example, the materials of a power cord could be found in a former conducted LCA (Gallego-Schmid et al., 2023). In cases where the internet research was not successful, an educated guess was made by estimating the contributed weight of each material. For example, this was done for the two materials of the filter: polypropylene (PP) and polyester. As most of the filter was white polyester filter lining, it was assumed to be 80% of the whole filter and the smaller blue PP parts were assumed to cover the remaining 20%. Furthermore, the ingredients of the cleaning tablets are unknown. Therefore chloride, as it is a standard substance for purifying water (NOAH Chemicals, 2022), was assumed to be the main substance. In **Annex 1** a table of all minor and major assumptions of the materials and components is given.

Production stage: After all materials and their weights were gathered, the production of the components was taken into account. As there was limited data available about the production of the components, it was assumed that all products made of plastics were injection moulded since it is a common way of plastic production. Also, the additive manufactured plastic were considered to be made by injection moulding, as the Ecoinvent database does not cover additive manufacturing. The assembling of the thermostatic cartridge, the external power supply for the UV lamp, the thermostat housing and the power cord was neglected because of the lack of data.

Manufacturing stage: For the assembling of the whole LOOP shower, all components were transported to Flow Loop ApS. For some components no data about the country of origin was available, so an assumption was made for the transportation distance using the average distance of the known materials. The materials that were used for these components were also used for other components which used materials only coming from Europe. Therefore, the average distance of all European countries of origin were used as a distance for the components with an unknown origin.

Use stage: The water consumption was determined based on the assumption that 82% of water is saved for the defined parameter of showering at the rate of 12 L/min for 8 minutes. This implies the assumption that for the shower process the recycling function is active for the longest time possible and not turned off during the process. This percentage was calculated by the company and Niras. Furthermore, it is stated that the LOOP shower recycles at a rate of 10-11 L/min and the new mixed domestic water added to the flow is between 1-2 L/min. (Niras A/S, 2023.) For this LCA, 11 L/min of recycled water and 1 L/min of domestic water are assumed. In Denmark tap water comes from groundwater and the Ecoinvent process used for the bathing water is tap water production from disinfected underground water (Europe without Switzerland). For the wastewater the Ecoinvent process average wastewater treatment in Europe without Switzerland was chosen. Since the majority of Danish households use district heating for water heating (Danish Energy Agency, 2015), the energy calculations are based on this assumption. The temperature for the cold domestic water is assumed to be 15°C (Unified Water Label Association, 2023) and the temperature loss for the recycled water is assumed to be 4°C (Flow Loop ApS, 2023a). For the electricity, the process with the Danish electricity mix (later referred as DK electricity mix) in Ecoinvent was chosen. To calculate the required maintenance, the number of showers per week in an apartment in Denmark was calculated based on the assumption that 4 people live in an apartment and that the average weekly shower time in Denmark is 34 minutes (Niras A/S, 2023). Regarding the total lifetime of a shower, it was estimated that a shower is used for 15 years (Flow Loop ApS, 2023a).

Disposal: For the disposal of the LOOP shower no data is available except that the component materials are separated before they are disposed. This lack of data results from the fact, that Flow Loop ApS. is a relatively young company so a LOOP shower has not reached the end of its lifetime yet. Therefore, standard processes for Denmark are used in the modelling, such as incineration of mixed plastics and a mix of recycling and landfilling for the disposal of scrap metals. For the disposal of used metals, brass is counted as copper because disposal processes for brass were not found from the Ecoinvent database, and it is closest to copper from the available metals. Furthermore, the disposal methods used are based on the Swiss market. This assumption was made because this market is the closest to Denmark of the available options.

5.3.2 Regular Shower

Manufacturing (materials and processing): The regular shower materials and manufacturing was based on the information retrieved from the product website (Gulv & Flise Eksperten, 2023). The regular shower has a total weight of 10 kg made primary of stainless steel. The shower head is usually made of plastic that has been coated with a metallic finish. While it was not possible to find data upon the material distribution from the website, assumptions had to be made. From the total weight it was assumed that the steel would contribute to 9 kg, while the last 1 kg would be polypropylene plastics. Additionally, there was no information about the shower packaging, so 1 kg of cardboard was assumed. The shower is manufactured in China and transported to Denmark from Sweden (Gulv & Flise Eksperten, 2023; Zhuhai primy kitchen Co., Ltd., 2023). Thus, manufacturing processes included Ecoinvent rest of the world processes (RoW) of granulated polypropylene production to injection moulding, converter production of low-alloyed steel to metal working of average steel product manufacturing and solid bleached and unbleached board carton production.

Transport stage: The shower of 10 kg shower and 1 kg of packaging had to be transported 22000 km by global freight container ship from China to the supplier located in Sweden, Malmö. From the retailer's store to the customer in Denmark (assumed in Copenhagen), an average distance of 50 km transported by a larger truck (market for transport, freight lorry >32 metric ton, EURO 5) was assumed.

Use stage: Like the LOOP shower, showering water for the regular shower is also heated mostly with district heat in Denmark. For this the Ecoinvent process Heat, district or industrial, natural gas in Denmark is used as well. For the regular shower, the Ecoinvent process used for the bathing water is tap water production from disinfected underground water (Europe without Switzerland). Additionally, the same assumptions regarding the lifetime, the showers taken per week per apartment and the temperature of the cold domestic water and the temperature it needs to be heated to were made as they were for the LOOP shower.

Disposal stage: The disposal stage for the regular shower is largely unknown. Consequently, standard processes are applied. However, no Danish disposal processes exist in the database. The Danish waste disposal market has resemblance with the Swiss market, which is why disposal processes of waste are modelled from the Swiss market processes just like they have been with the LOOP shower. For the disposal of the steel, the process market for waste reinforced steel (CH), was used. Since the actual disposal processes are unknown, the market process was chosen as this considers a treatment mix including transportation, sorting, recycling, and final disposal. In Denmark, incineration is a plausible disposal process for plastics and cardboard. For the disposal of the 1 kg of plastic and 1 kg of cardboard packaging municipal incineration processes in Switzerland were used. The incineration would produce some energy, which would be regarded as avoided electricity. For these processes market for low voltage electricity in Denmark were used. Finally, the shower produces wastewater. For this process average wastewater treatment in Europe without Switzerland was chosen.

5.4 Calculated LCI Results

LCI results were calculated in SimaPro for both LOOP shower and regular shower. All the LCI results for the foreground and background systems are based on and available in existing LCI databases, in this case Ecoinvent. Tables detailing the unit processes used in SimaPro, that are behind the LCI results, are documented in **Annex 6**.

5.5 Basis for Sensitivity and Uncertainty Analyses

The parameters for the uncertainty and sensitivity analysis are shown in **Table 3** and include the values for the standard, low- and high-end scenarios. These parameters were chosen based on the contribution of the different life cycle stages and the uncertainty due to assumptions. The global warming potential results shown in **Figure 9** identify the use stage for both products as the highest contributor to CO_2 equivalent. Therefore, parameters were selected that have a high influence on the use stage. In addition to the above, one of the variables considered in the sensitivity analyses was the replacement of the virgin aluminium used in the production of the shower with recycled aluminium. This was done because the production of aluminium components was identified as one of the most significant processes in terms of the product's total emissions. In this analysis, the low-end and high-end scenarios were not applied, and no comparison was made with a regular shower, because there is no aluminium in it.

Table 3. *Parameters for sensitivity and uncertainty analysis including the low-end, default, and high-end scenarios.*

	Low-end	Default	High-end
Bathing water temperature	35°C	38°C	41°C
Shower duration	5.5 min	8 min	15 min
Heating method	Electricity, 100% photovoltaic (PV)	District heating	Electricity, DK electricity mix
Number of showers taken over shower lifetime	2.1 person per apartment (avg. Danish household) → 6962 showers	4 person per household (family) →13260 showers	10 showers per day (boarding school, sports facility etc.) → 54750 showers
Type of aluminium used as raw material	Virgin aluminium vs. recycled aluminium		

These parameters include the temperature of the shower, the duration of the shower, the way the water is heated, the number of showers taken, and the type of aluminium used as raw material for shower production. The water temperature is considered because the water temperature was an assumption made in the analysis report of the company (Niras A/S, 2023) and the temperature has a high uncertainty due to different showering habits. In addition, this parameter is expected to have a high influence on the results due to the large contribution of energy for water heating in the use stage. The length of a shower is the second parameter that is varied in a sensitivity analysis, as 8 minutes is an assumption made by the company (Niras A/S, 2023). For the low-end scenario, 5.5 min and for the high-end scenario, 15 min of showering time per shower are assumed, which we concluded from a survey as high and low showering times in Denmark (Energistyrelsen, 2022). The third parameter with a high degree of uncertainty is the way the bathing water is heated. Although the majority of the Danish population uses district heating for water heating, electricity shows an increasing trend and should therefore be considered (Danish Energy Agency, 2023). In the low-end scenario, the water is heated with 100% renewable energy from solar power, as this energy source has the lowest CO_2 emissions in the SimaPro software. In the high-end scenario, the DK electricity mix is used to heat the water with electricity. The number of showers taken during the lifetime of the shower product has also been calculated using a number of assumptions. However, in real life the number of showers used during the lifetime of the shower may be completely different. As a sensitivity analysis, a different number of showers taken per product lifetime should be used. The values for the low- and high-end scenarios are calculated based on the assumption in what kind of household and facility the showers are installed. Based on this, the lower end is represented by the average person per apartment in Denmark (Statistics Denmark, 2023). On the other side, the high-end encompasses a water-intensive frequent user scenario represented by a boarding school or a sports facility with estimated use of ten showers per day. As one of the biggest contributors to the overall emissions of the LOOP shower are the primary aluminium production and aluminium product manufacturing, it was also decided that a sensitivity study should be done on using recycled aluminium instead of virgin aluminium.

6 Life Cycle Impact Assessment

6.1 Energy Balance and Carbon Footprint

The hand-calculation results regarding non-renewable primary energy have been presented in the **Figure 7**. After that, the hand-calculation and SimaPro results are compared in **Figure 8** in terms of fossil CO_2 and in **Figure 9** in terms of the global warming score. All stack bars are grouped in such a way that the manufacturing stage includes both the production of the shower itself, but also the production of the more frequently changed microfilters. Transportation is presented as is. Use stage has been separated into *Use, heating of water* and *Use, other than heating of water,* of which the latter includes tap water, electricity, and cleaning tablet consumption during shower use. Also, the disposal stage has been separated into *Disposal, wastewater* and *Disposal, other than wastewater*, of which the latter includes disposal of the shower materials at the end of the life cycle and energy recovery from incineration of plastics and packaging cardboard.

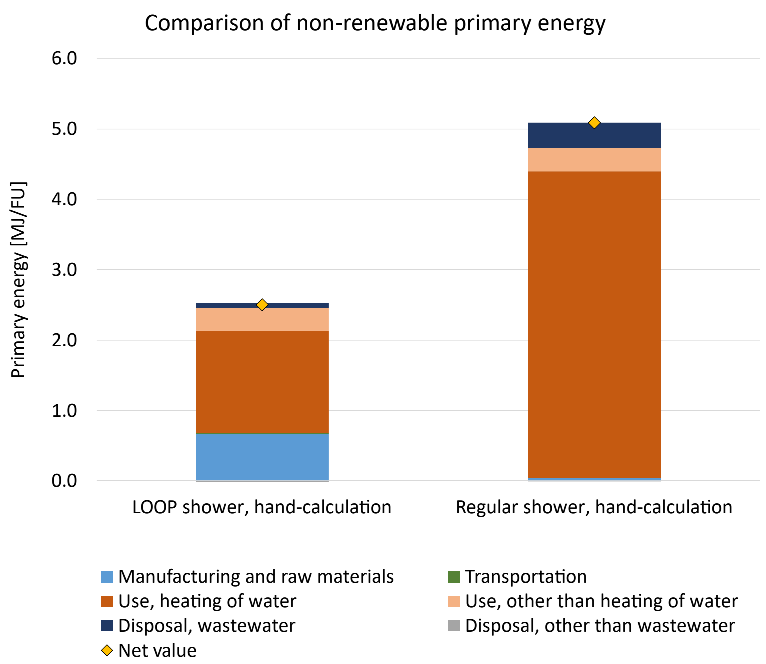

Figure 7. *Comparison stack bar for non-renewable primary energy.*

As seen in **Figure 7**, the total non-renewable primary energy consumption per FU of the LOOP shower is only slightly more than half of the total consumption of the regular shower. The primary energy consumption of the two showers is caused by slightly different life cycle stage. In the primary energy consumption of a regular shower, the heating of the bathing water is highlighted (86%) and, to small extent, also other components of the use stage (particularly electricity and tap water consumption) (7%), and wastewater treatment (7%). In the case of the LOOP shower, the primary energy consumption due to heating of bathing water is significantly smaller compared to regular shower, although it is still the largest component of the primary energy consumption (58%). It is also essential to note that the primary energy consumption of the LOOP shower is more affected by the manufacturing stage, its share being around 26%. The contribution of other components of the use stage (except heating of bathing water) is 13%.

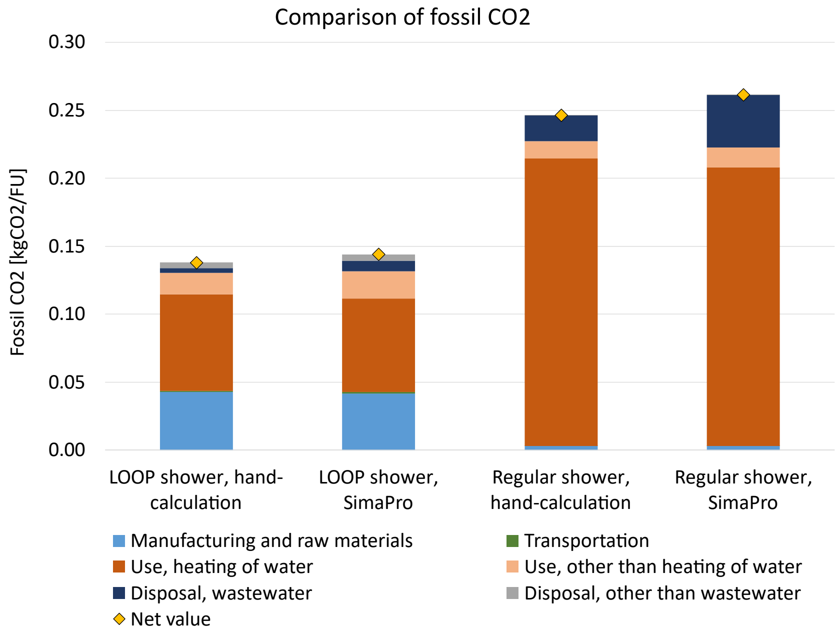

Figure 8. *Comparison stack bar of fossil CO_2.*

Figure 8 shows that the fossil CO_2 emissions of the LOOP shower are slightly more than half of the emissions of a regular shower. According to SimaPro results, the contribution of water heating is 78% for a regular shower and 48% for the LOOP shower. The second largest fossil CO_2 contributor for a regular shower is wastewater treatment (15%). Respectively, for the LOOP shower, it is manufacturing stage (29%). Regarding the LOOP shower, manufacturing is followed by *Use, other than heating of water*, whose share is 14%.

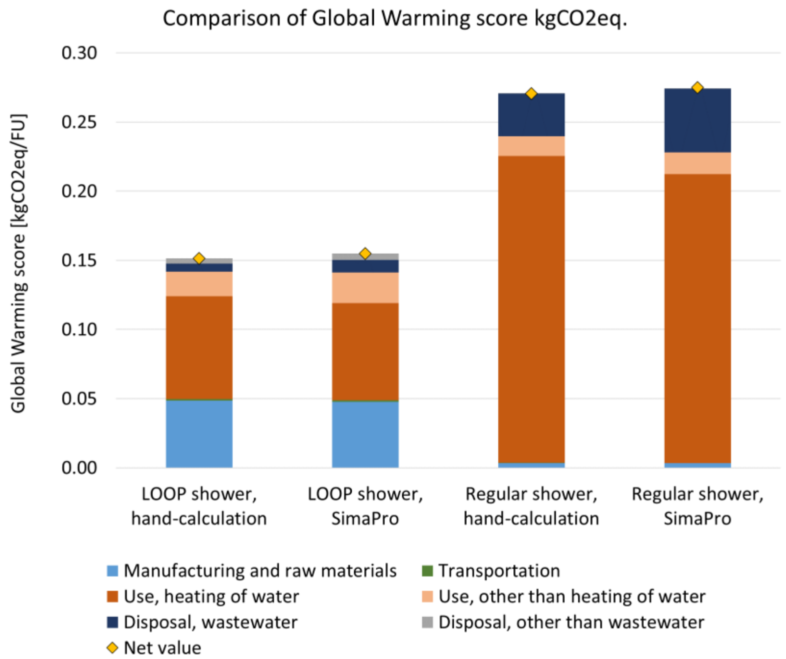

Figure 9. *Comparison stack bar of the Global Warming score (midpoint results).*

As seen in the midpoint stacked bar graph in **Figure 9**, the Global Warming score results follow a very similar trend to fossil CO_2 emissions. In SimaPro results, the main contributors of the LOOP shower use to CO_2 equivalent emissions are *Use, heating of water* (45%), *Manufacturing and raw materials* (31%), and *Use, other than heating of water* (14%). Respectively, for a regular shower the main contributors are *Use, heating of water* (76%), *Disposal, wastewater* (17%), and *Use, other than heating of water* (6%).

The viability of the energy balance and carbon footprint results was assessed by checking the gCO_2/MJ ratio of all the materials, material processing processes, transport, energy carriers (electricity and district heat), and end-of-life processes. End-of-life processes had, as expected, higher gCO_2/MJ ratios (4791 gCO_2/MJ for plastic incineration and 337 gCO_2/MJ for treatment of used cables), whereas all the other processes had ratios within range 12-85 gCO_2/MJ, majority of them being around 50-70 gCO_2/MJ, which indicates that the processes are valid. This can also be seen from **Figure 8** comparing primary energy and fossil CO_2. Similar shape and ratio of the stack bars indicate that the gCO_2/MJ ratio is as it should be.

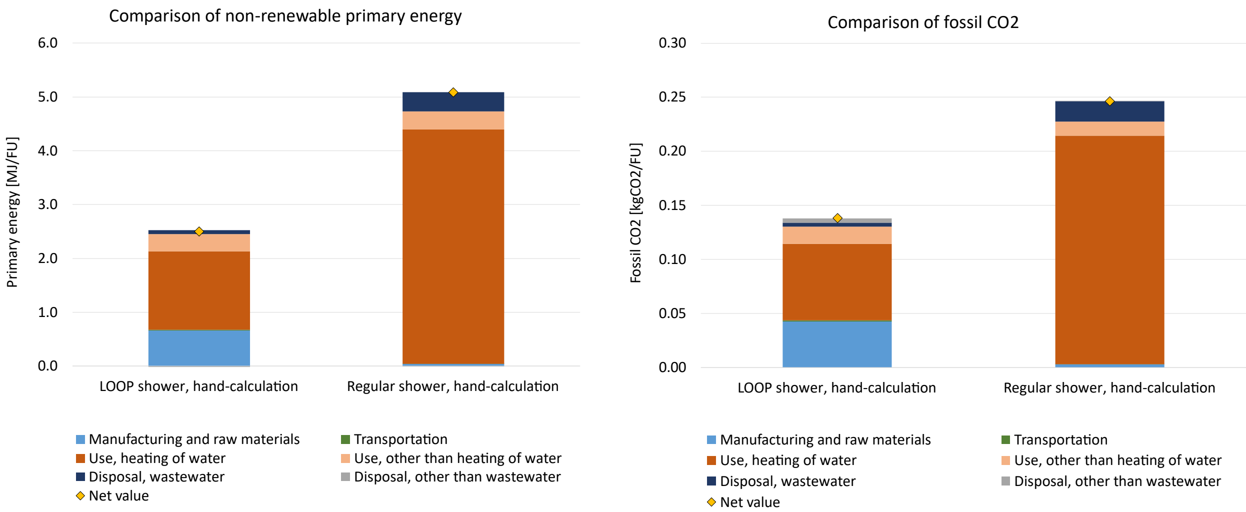

Figure 10. *Comparison of primary energy and fossil CO_2.*

6.2 Midpoint Impact Results

The tables below (**Table 4 & 5**) display midpoint impact results for a regular shower and the LOOP shower, which are the basis for the endpoint impact results. Water scarcity results should not be considered accurate (see section 5.3).

Table 4. *Regular shower midpoint impact results from IMPACT World+ Midpoint method.*

Impact category	Unit/FU	Total	Tap water	Production (rest)	Heating of bathing water	Transport total	Disposal	Wastewater treatment
Climate change, short term	$kgCO_2eq$	2.77E-01	1.57E-02	3.35E-03	2.10E-01	1.75E-04	1.30E-04	4.73E-02
Climate change, long term	$kgCO_2eq$	2.71E-01	1.51E-02	3.06E-03	2.08E-01	1.73E-04	1.33E-04	4.42E-02
Fossil and nu-clear energy use	MJ deprived	5.34E+00	3.45E-01	4.27E-02	4.38E+00	2.40E-03	-6.81E-04	5.69E-01
Mineral resources use	kg deprived	2.07E-02	1.48E-04	7.53E-04	3.88E-04	2.68E-06	-3.52E-08	1.94E-02
Photochemical oxidant formation	Kg NMVOC eq	4.45E-04	3.69E-05	1.21E-05	1.71E-04	3.97E-06	4.51E-07	2.21E-04
Ozone layer depletion	kgCFC-11eq	1.96E-08	9.67E-10	1.90E-10	1.46E-08	3.68E-11	8.59E-12	3.78E-09
Freshwater ecotoxicity	CTUe	6.32E+02	4.86E+00	1.71E+00	8.89E-01	9.80E-03	-2.86E-02	6.25E+02
Human toxicity cancer	CTUh	1.17E-08	1.92E-10	5.26E-10	3.16E-10	2.41E-12	7.42E-14	1.07E-08
Human toxicity non-cancer	CTUh	8.62E-08	1.65E-09	3.36E-10	1.14E-09	5.51E-12	-8.80E-12	8.31E-08
Freshwater acidification	$kgSO_2eq$	1.19E-09	1.66E-10	2.67E-11	1.92E-10	1.03E-11	1.60E-13	7.99E-10
Terrestrial acidification	$kgSO_2eq$	1.10E-06	1.34E-07	2.20E-08	1.66E-07	8.43E-09	1.45E-10	7.69E-07
Freshwater eutrophication	$kgPO_4eq$	1.11E-04	4.52E-08	3.87E-08	6.92E-08	5.79E-09	1.23E-09	1.11E-04
Marine eutrophication	kgNeq	1.36E-03	7.59E-07	3.91E-07	3.07E-06	7.62E-08	8.57E-09	1.36E-03
Particulate matter formation	$kgPM_{2.5}eq$	6.66E-05	4.66E-06	1.83E-06	3.73E-06	1.79E-07	3.48E-08	5.61E-05
Ionizing radiation	Bq C-14eq	5.53E-01	2.87E-01	8.41E-03	1.55E-02	9.67E-04	-7.11E-04	2.42E-01
Land transformation, biodiversity	m^2yr arable	5.45E-05	2.29E-06	6.28E-07	7.18E-06	2.92E-08	-4.59E-10	4.44E-05
Land occupation, biodiversity	m^2yr arable	2.73E-03	3.91E-04	8.88E-05	1.05E-04	7.52E-07	-1.07E-05	2.16E-03
Water scarcity	m^3 world eq	4.45E-01	3.94E+00	7.33E-04	3.24E-02	4.10E-06	-8.50E-06	-3.53E+00

Table 5. *LOOP shower midpoint impact results from IMPACT World+ Midpoint method.*

Impact category	Unit	Total	Aluminium	Production (rest)	Filter	Cleaning tablet	Tap water	Heating bathing water	Electricity	Transport total	Disposal	Waste water treatment
Climate change, short term	kgCO_2eq	1.57E-01	2.65E-02	1.41E-02	1.29E-02	1.45E-04	3.03E-03	7.04E-02	1.92E-02	8.74E-04	8.49E-04	9.14E-03
Climate change, long term	kgCO_2eq	1.51E-01	2.47E-02	1.30E-02	1.21E-02	1.38E-04	2.92E-03	6.96E-02	1.84E-02	8.60E-04	8.67E-04	8.54E-03
Fossil and nuclear energy use	MJ deprived	2.58E+00	2.53E-01	1.98E-01	1.90E-01	2.99E-03	6.65E-02	1.47E+00	2.88E-01	1.33E-02	-6.54E-03	1.10E-01
Mineral resources use	kg deprived	5.27E-03	9.09E-05	6.60E-04	4.07E-04	3.01E-06	2.85E-05	1.30E-04	1.89E-04	1.55E-05	-1.36E-06	3.75E-03
Photo-chemical oxidant formation	kg NMVOC eq	3.51E-04	8.58E-05	5.89E-05	4.50E-05	3.90E-07	7.13E-06	5.71E-05	4.32E-05	1.05E-05	-4.42E-07	4.26E-05
Ozone layer depletion	kg CFC-11 eq	3.47E-08	8.42E-10	1.71E-09	2.56E-08	1.03E-11	1.87E-10	4.89E-09	5.71E-10	1.93E-10	2.02E-12	7.29E-10
Fresh water ecotoxicity	CTUe	1.51E+02	7.19E+00	1.34E+01	1.77E+00	5.20E-02	9.39E-01	2.98E-01	6.87E+00	1.01E-01	-9.75E-02	1.21E+02
Human toxicity cancer	CTUh	6.11E-09	1.49E-09	1.79E-09	1.98E-10	1.67E-11	3.70E-11	1.06E-10	3.87E-10	1.60E-11	-4.98E-13	2.06E-09
Human toxicity non-cancer	CTUh	4.17E-08	4.46E-09	1.68E-08	7.98E-10	2.13E-11	3.18E-10	3.81E-10	2.79E-09	6.36E-11	-4.37E-11	1.60E-08
Freshwater acidification	kgSO_2eq	1.14E-09	3.33E-10	2.98E-10	9.78E-11	2.97E-12	3.20E-11	6.42E-11	1.35E-10	2.39E-11	-2.42E-12	1.54E-10
Terrestrial acidification	kgSO_2eq	9.58E-07	2.68E-07	2.40E-07	8.34E-08	2.36E-09	2.58E-08	5.56E-08	1.16E-07	1.98E-08	-2.07E-09	1.49E-07
Freshwater eutrophication	kgPO_4eq	2.23E-05	9.31E-08	3.39E-07	2.45E-07	2.28E-09	8.73E-09	2.32E-08	7.89E-08	3.02E-08	-4.49E-10	2.14E-05
Marine eutrophication	kg N eq	2.70E-04	1.57E-06	2.18E-06	1.55E-06	1.20E-08	1.47E-07	1.03E-06	1.04E-06	1.92E-07	-5.92E-09	2.62E-04
Particulate matter formation	kg$PM_{2.5}$eq	5.14E-05	1.79E-05	1.12E-05	4.09E-06	6.88E-08	9.00E-07	1.25E-06	4.52E-06	6.28E-07	-5.29E-08	1.08E-05
Ionizing radiation	Bq C-14 eq	4.18E-01	2.12E-02	4.65E-02	3.06E-02	2.25E-03	5.53E-02	5.18E-03	2.08E-01	5.51E-03	-5.17E-03	4.68E-02
Land transformation, biodiversity	m^2 yr arable	2.05E-05	2.39E-06	3.29E-06	1.13E-06	1.83E-08	4.42E-07	2.41E-06	2.05E-06	1.93E-07	-2.92E-08	8.57E-06
Land occupation, biodiversity	m^2 yr arable	3.77E-03	2.51E-04	4.31E-04	2.41E-04	3.63E-06	7.54E-05	3.51E-05	2.34E-03	1.74E-05	-5.97E-05	4.16E-04
Water scarcity	m^3 world eq	1.06E-01	2.90E-03	5.95E-03	4.06E-03	2.60E-04	7.60E-01	1.09E-02	2.65E-03	4.67E-05	-2.86E-05	-6.81E-01

Figure 11 shows the contributions to the total impact on the midpoint impact category particulate matter formation that affects the human health for both the LOOP and regular shower. The impact in stated in kg $PM_{2.5}$ equivalent, meaning the equivalent impact of particles less or equal than 2.5 µm in aerodynamic diameter. Overall, the regular shower can be identified as the product with the higher impact in this impact category. For the LOOP shower, the manufacturing stage including the extraction of the raw material is the biggest contributor to this impact category accounting for around 60% of the total impact. The second biggest contributor is the use stage and the wastewater treatment. Furthermore, it can be concluded that heating the water has a negligible fraction and the highest contributors in the use stage are the filter and the electricity with similar fractions. The impact from the regular shower on the other side is dominated by wastewater treatment processes accounting for around 85% of the impact. Since the LOOP shower recycles most of the used water, less wastewater needs to be treated afterwards and therefore explains the results.

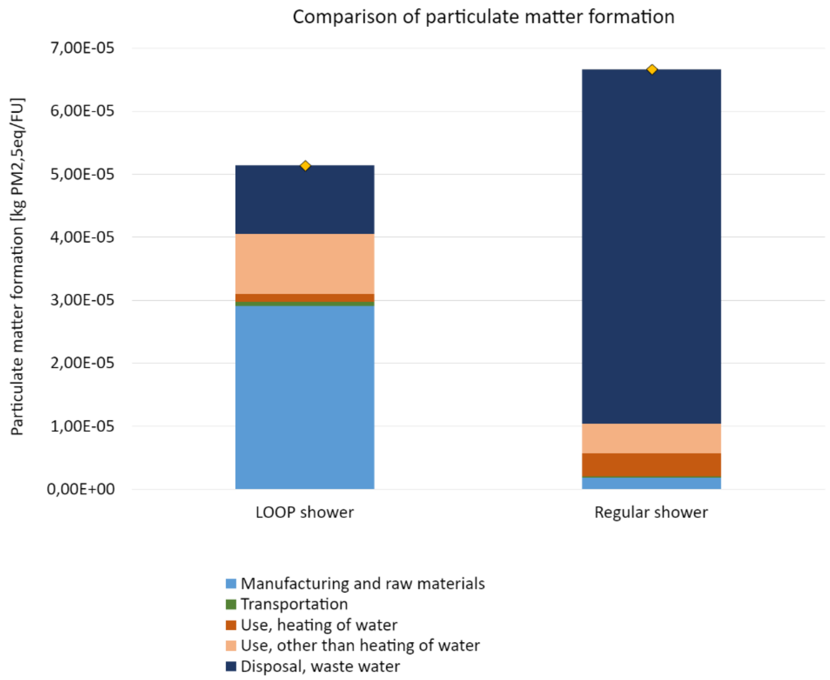

Figure 11. *Comparison stack bar of particulate matter formation (midpoint results)*

Another midpoint result is shown in **Figure 9**, which shows the climate change impact of the LOOP shower and the regular shower in kg CO_2eq. A detailed description of the climate change results can be found in Section 6.1.

6.3 Normalized Results

The graph in **Figure 12** below displays the normalized endpoint impact results. The graph is in log scale so that the impact values can be compared more easily. Normalized results are based on the damage scores exported from SimaPro in DALY/FU and PDF-m^2-yr/FU for human health- and ecosystem quality impact categories, respectively. DALY refers to Disability-Adjusted Life Years and PDF to Potentially Disappeared Fraction of species due to environmental pressures. From SimaPro IMPACT World+ method the normalization factor was determined to be 13.7 pers-yr/DALY for human health and 0.000101 pers-yr/PDF-m^2-yr for ecosystem quality, respectively. From SimaPro ReCiPe 2016 (H) method the normalization factor was determined to be 41.7 pers-yr/DALY, 676 pers-yr/species-yr and $3.57 \cdot 10^{-5}$ pers-yr/USD2013 for human health, ecosystem quality, and resources, respectively.

Although all other impact categories were included in this study, the SimaPro Water availability human health and water availability freshwater ecosystems had to be excluded because of problems in the database processes. For these two impact categories, the Ecoinvent database used in SimaPro is mixing extraction of water with consumption of water in the water turbine part of the metal working processes for aluminium and steel. The water turbine in the metal working process is being used to create electricity. In reality, the water that passes through the turbine is given back to nature, but Ecoinvent calculates it as consumed. Additionally, under the impact categories, the wastewater treatment process is contributing negatively to the overall impact based on that it is released back into nature. This is not realistic in Denmark. Danish drinking water comes from groundwater, and therefore when wastewater is released to nature (e.g., rivers), the quality of the water is not as high as when it was extracted. Consequently, for water availability human health the impact of wastewater treatment should not be subtracted in the overall impact category. Furthermore, in Denmark a lot of wastewater is discharged to the fjords and the sea. In this case, all the freshwater is lost. Therefore, the results from SimaPro of water availability- human health and freshwater ecosystems for this LCA cannot be used and Ecoinvent data needs to be updated.

In order to still include these missing impact categories in this LCA study, the results have been calculated by hand. It is assumed that all the water used is during the use-stage of the lifecycle. Thus, water used during production and disposal are neglected. Either way, most water is probably used during the use stage of a shower, which is why other water consumptions could be considered negligible in addition to no water recovery from wastewater treatment, due to loss of water quality in the Danish supply. Thus, the Water availability, human health and Water availability freshwater ecosystems was calculated based on only the use stage water consumption of 18.5 L for the LOOP shower and 96 L regular shower. In SimaPro, for Water availability, human health in Denmark a midpoint to damage factor of 0 DALY/m^3 water was found. Consequently, the normalized impact is zero for both the LOOP and regular shower. This indicates that there is no water scarcity in Denmark. In SimaPro, for Water availability, freshwater ecosystems in Denmark a midpoint to damage factor of 0.000306 PDF-m^2-yr/m^3 water was found. Using the already mentioned normalization factor of IMPACT World+, the normalized impact of Water availability, freshwater ecosystems was determined.

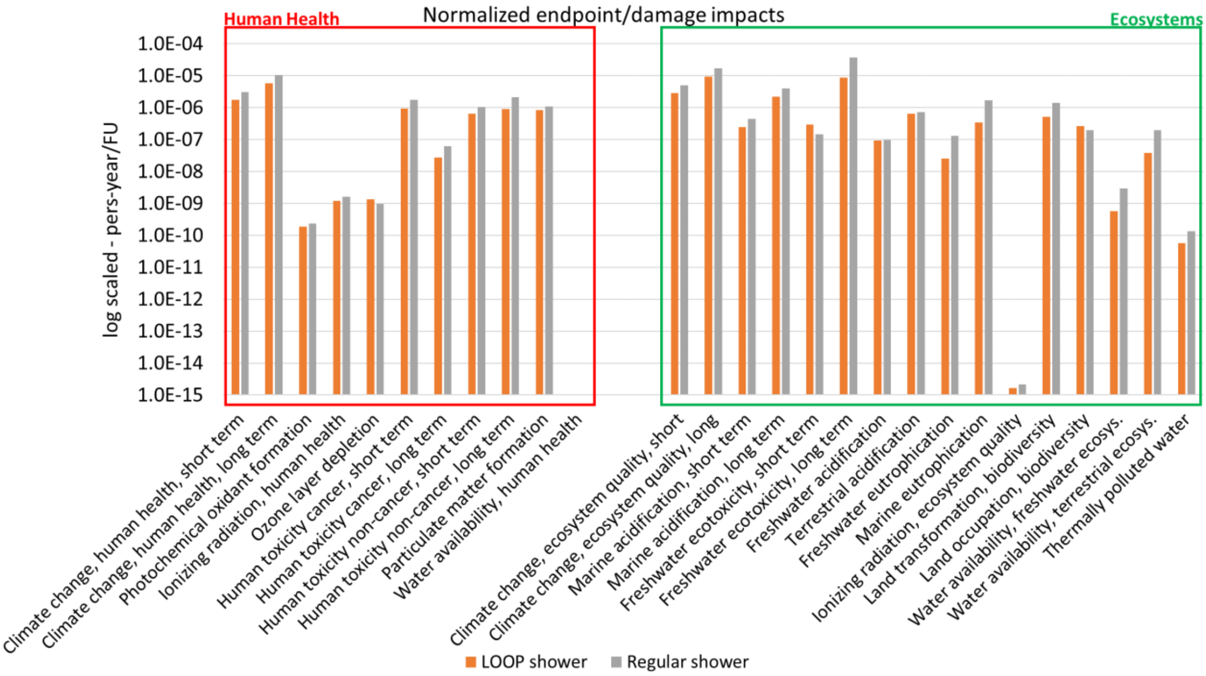

Figure 12. *Normalized endpoint results from SimaPro IMPACT World+ damage level method in pers-year/FU sorted into human health and ecosystem impact categories for the LOOP shower and a regular shower. Note: y-axis is log-scaled.*

In **Figure 12**, it can be seen that compared to the regular shower the LOOP shower has smaller impacts in nine of ten impact categories affecting human health. The only impact category where the LOOP shower has a slightly higher impact, is Ozone layer depletion. Very significant differences and high impacts in categories affecting human health can be identified in Climate-change short and long-term where the LOOP shower outperforms the regular shower considering the log-scale. These conclusions can be made because of the log-scale which helps to not overinterpret small differences among scenarios (Hauschild, Rosenbaum, & Irving Olsen, 2018, p. 118). Water availability human health has impacts of 0 pers-yr/FU for both the LOOP shower and the regular shower due to the already explained midpoint to impact damage factor from SimaPro of 0 DALY/m^3 deprived water, as there is no water scarcity in Denmark. This could change a lot depending on the geography of the study.

Additionally, when examining the impacts on the ecosystem quality the overall picture shows that the LOOP shower has lower impacts in nearly every impact category except ecotoxicity short term and Land occupation. Climate change affecting the ecosystem on long and short term, Ecotoxicity long term, Marine eutrophication, Land occupation, Biodiversity, and Water availability in freshwater and terrestrial ecosystems are examples for impact categories where the LOOP showers show significantly lower impacts. For the last three mentioned impact categories, in **Figure 15** it becomes clear that higher water consumption of the regular shower explains these results. It can be seen, that either the wastewater or the tap water is by far the dominant contributor. Regarding the impact of climate change to both human health and ecosystem quality, the contribution figure indicates that the higher impacts of the regular shower are primarily attributed to the heating of bathing water from district heat production, with smaller contributions from wastewater treatment and tap water extraction.

To make sure that the conclusion is not only based on one LCIA method, the ReCiPe 2016 Endpoint (H) method has been used as well found in **Figure 13**. Rrom now on it will be referred to as just ReCiPe or ReCiPe method. However, same problems with water consumption in the ReCiPe method were identified, which is why same calculations made by hand in the IMPACT World+ method had to be applied. For Water consumption - Human health and Aquatic ecosystems in Denmark the midpoint to damage factor was found to be 0 DALY/m^3 or species-yr/m^3. This leads to the same conclusion derived from IMPACT World+ method results. For Water Consumption, Terrestial ecosystems in Denmark the midpoint to damage factor was found to be $1.56 \cdot 10^{-9}$ species-yr/m^3 water. By using the already mentioned normalization factor of ReCiPe, the normalized impact of Water Consumption, Terrestrial ecosystems was determined and is found in **Figure 13**.

Before comparison between these two methods, it should be noted that the methods use different wording for many of the same impact categories, while both methods feature something not included in the other.

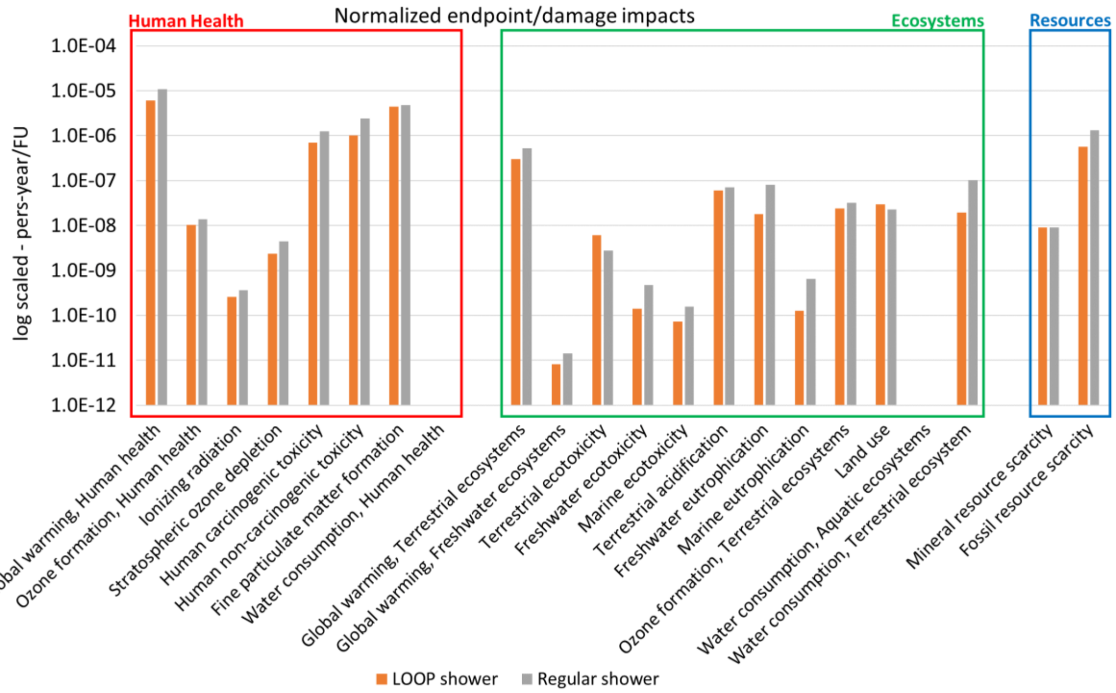

Figure *13. Normalized endpoint results from ReCiPe 2016 (H) damage level method in pers-year/FU sorted into human health and ecosystem impact categories for the LOOP shower and a regular shower. Note: y-axis is log-scaled.*

For the comparison of human health impact categories between the ReCiPe- and IMPACT World+ method featuring long- and short-term impact categories, both the long- and short-term impact categories are compared with the equivalent impact category in ReCiPe. If IMPACT World+ only features one impact category, this is compared to the equivalent impact category in ReCiPe.

By comparing **Figure 12** and **Figure 13** the ReCiPe method gives close to the same result as IMPACT World+ for Global Warming scores, with comparable order of magnitudes, especially between Global warming human health in ReCiPe and Climate change human health long term in IMPACT World+. For Ozone formation human health in ReCiPe equivalent to Photochemical oxidant formation in IMPACT World+, the regular shower still has a higher impact, but the values vary where ReCiPe yields an approximate 2 orders of magnitude higher impact than IMPACT World+. For Ionizing radiation the trend is also the same, however ReCiPe yields around 1 order of magnitude lower impacts than IMPACT World+. For Stratospheric ozone depletion equivalent to ozone layer depletion the LOOP shower impact are comparable, though the impact of the regular shower is around 1 order of magnitude higher in the ReCiPe method. Interestingly, this shifts around the impact score of the systems, with the regular shower in ReCiPe having the higher impact. Human Carcinogenic toxicity equivalent to human toxicity cancer is in the same order of magnitude compared to the short term IMPACT World+ category, but roughly 1 order of magnitude higher in ReCiPe than IMPACT World+ long term. For human Non-carcinogenic toxicity in ReCiPe equivalent to Human toxicity non-cancer in IMPACT World+ the values are in the same order of magnitude for both short term and long term. Additionally, the lon-term impact value in IMPACT World+ is very close to the human carcinogenic toxicity impact value in ReCiPe. For fine particulate matter formation, ReCiPe yields approximately 1 order of magnitude higher impacts than IMPACT World+. Finally for human health, the water availability are zero in both methods due to the hand calculations described earlier. Generally, for the human health results the only notable change is the stratospheric or ozone layer depletion results varying both in order of magnitude and the LOOP shower having a lower impact than the regular shower in ReCiPe and vice versa in IMPACT World+. Else orders of magnitude across impact categories are comparable between the two methods, and the general conclusion that the LOOP shower outperforms the regular shower still holds across the human health impact categories.

For the comparison of ecosystem quality impacts between IMPACT World+ and ReCiPe the methods have a handful of comparable impact categories. The same comparison method used in the human health impact category comparison applies for the ecosystem quality impact category comparison between the two methods. Climate change ecosystem quality in IMPACT World+ might not be directly comparable to the global warming- terrestrial- and freshwater ecosystems in ReCiPe, and these comparisons should be critically viewed.

By comparing **Figure 12** and **Figure 13** for global warming terrestrial ecosystems in ReCiPe to climate change short- and long-term in IMPACT World+, ReCiPe yields around 1 and 2 orders of magnitude lower impact values, respectively. For global warming freshwater ecosystems in ReCiPe compared to climate change short- and long-term in IMPACT World+, ReCiPe yields 6 orders of magnitude lower impacts than IMPACT World+ in both cases of short- and long-term. However, as mentioned above, this comparison is not reliable as the impact categories are not equivalent to each other. Other than that, in ReCiPe the global warming ecosystem scores for the LOOP shower are notably smaller than the regular shower considering the log scaled results, making the same conclusion as IMPACT World+. Freshwater ecotoxicity in ReCiPe is comparable to the freshwater ecotoxicity short- and long-term of IMPACT World+. Here there are higher differences between the methods. ReCiPe yields around 3 and 2 orders of magnitude lower results for the Loop- and regular shower, respectively, when compared to Ecotoxicity freshwater short-term in IMPACT World+ and around 5 orders of magnitude lower impacts when compared to long term IMPACT World+ for both the LOOP- and regular shower. Additionally, the ReCiPe Freshwater ecotoxicity shows the same trend as the IMPACT World+ long term Freshwater ecotoxicity with the regular shower having significantly higher impact than the LOOP shower. One noteworthy observation, in contrast to IMPACT World+, is that with ReCiPe Freshwater ecotoxicity does not seem to be an important impact category. For Terrestrial acidification ReCiPe yields 1 order of magnitude lower impacts. For Freshwater eutrophication ReCiPe yields comparable values with the same order of magnitude as found in IMPACT World+. For Marine eutrophication ReCiPe yields different values with 3 orders of magnitude lower impacts than found in IMPACT World+. Land use in ReCiPe does not have a direct equivalent impact category in IMPACT World+, but are compared with Land transformation biodiversity and Land occupation biodiversity, respectively. For Land use and Land transformation ReCiPe yields around a 1 and 2 order of magnitude lower impact for the LOOP- and regular shower. For Land use and Land occupation, ReCiPe yields 1 order of magnitude lower impacts than IMPACT World+. Even though these impact categories are not directly equivalent, they compare fairly well between the two methods. Land occupation in IMPACT World+ and Land use in ReCiPe compare the best, demonstrating in both methods, that the LOOP shower has the higher impact, whereas when taking Land transformation into account the opposite is found. Finally for ecosystem quality impact categories, the hand calculated Water consumption terrestrial ecosystem in ReCiPe can be compared with the Water availability terrestrial ecosystem in IMPACT World+. These values compare well having the same order of magnitude, which strengthens the assumption that most of the water is used in the use stage of the shower lifetime.

Generally, ecosystem quality impact categories vary more between the used methods. This emphasizes the high uncertainties coupled to the final impact results, as they are not only dependent on the assumptions made, but also the methods used. Though, the impact values differ, the trend is mostly the same across the compared impact categories, supporting the narrative that the LOOP shower has a smaller environmental impact than the regular shower.

The ReCiPe method additionally features the resource impact categories Mineral resource scarcity and Fossil resource scarcity as seen in **Figure 13**. The impact for the LOOP shower is comparable to the regular shower in Mineral resource scarcity, but notably smaller in the Fossil resource scarcity impact category.

6.4 Weighted Results

The weighted endpoint results per impact category as well as the total weighted impact score for both the LOOP shower and regular shower is shown in **Figure 14**. The unit of the weighted damage is Euro per FU and is calculated from the damage score results exported from SimaPro with the IMPACT World+ method and weighting factors based on the economic approach. This approach considers how much people are willing to pay to avoid certain emissions or damages. (Jolliet et al., 2016). The weighting factor is a value as described by Weidema (2009) of 74000 EUR/DALY and 0.14 EUR/PDF-m^2-yr (1400 EUR/BAHY = 0.14 EUR/PDF-m^2-yr (BAHY - Biodiversity Adjusted Hectare Years)) for human health and ecosystem quality, respectively.

Figure 14. *Weighted endpoint results from SimaPro IMPACT World+ damage level method in Euro/FU sorted into human health and ecosystem impact categories for the LOOP shower and a regular shower. Note: y-axis is log-scaled.*

The total weighted results for both shower products can be seen at the very right of the diagram in **Figure 14** and conclude that the LOOP shower has overall smaller damages. Taking a closer look at the impact categories relating to human health a higher damage of the regular shower to all high weighted impact categories (prioritized importance) including Climate change in short and long, Human toxicity cancer and Particulate matter formation can be identified. The only category affecting human health where the LOOP shower performs worse than the regular shower is the impact category Ozone layer depletion. Because the weighted results are generally lower than the other categories and the difference is not significantly high, this does not change the overall results.

The impacts categories relating to ecosystem quality that are weighting the most are short- and long-term impacts of Climate change and Freshwater ecotoxicity (**Figure 14**). In all these impact categories, the LOOP shower outperforms the regular shower with less damages. Especially a very high difference can be seen in the impact category Freshwater ecotoxicity. This result can be explained by taking a closer look at the contribution figure (**Figure 15)** where the wastewater treatment dominates the impact. Since the LOOP shower has a significantly lower water consumption, the large difference in the impact makes sense.

According to **Figure 14**, for both the LOOP- and regular shower, Climate change human health long term is the most important impact category contributing 33% and 28% respectively to the total weighted impact score of the showers. Considering all climate change impact categories in both human health and ecosystem quality, they contribute 61% and 52% to the total weighted impact score for the LOOP- and regular shower, respectively. For the LOOP shower, according to the IMPACT World+ weighted impact results, the Freshwater ecotoxicity is the third most important impact category contributing 13% to the total impact. However, as mentioned in section 6.3 the impact of the Freshwater ecotoxicity impact category is small according to the ReCiPe method, while global warming impacts are consistently the high contributors. In all of these most important impact categories, the LOOP shower is performing better than the regular shower.

7 Interpretation

This section continues to elaborate on the results from the previous section and goes into more detail about them.

7.1 Significant Issues

7.1.1 Process contribution analysis

The graph in **Figure 15** and **Figure 16** displays the contribution of the shower lifetime processes for each endpoint impact category. The impact categories have been summed up to equal 100% to highlight their contribution to the whole.

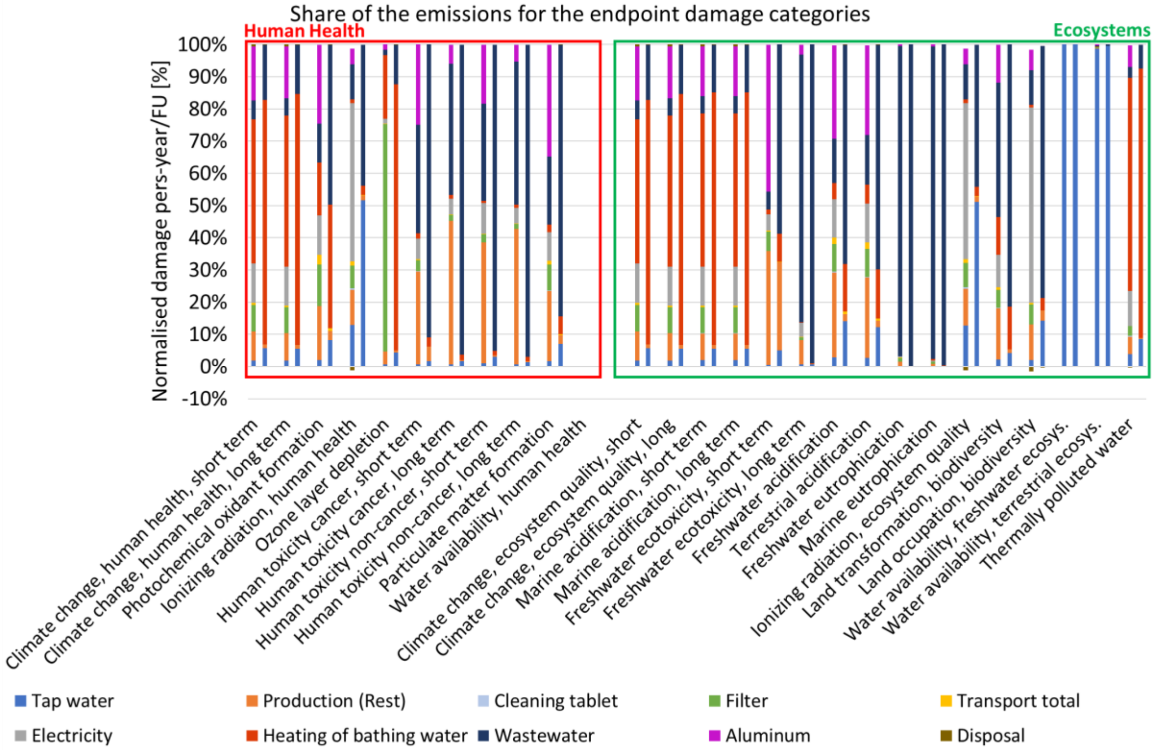

Figure 15. *Differentiated contribution of different life cycle processes for each endpoint impact category summing up to 100% based on the normalized IMPACT World+ results. Under each impact category the LOOP shower is the left bar and regular shower is the right bar.*

Generally, from **Figure 15** in the case of the LOOP shower the heating of bathing water, the wastewater treatment and the aluminium play significant roles in many impact categories, along with contributions from the filter and electricity consumption. For the regular shower, also the heating of bathing water and wastewater treatment are the primary contributors across most impact categories, and, in a few cases, tap water extraction. Production (rest) reporting all other materials and components than the aluminium also plays a significant role across many impact categories, and especially for all the Human toxicity cancer and non-cancer impact categories. For almost all impact categories the disposal of the LOOP and regular shower contributes to less than 1% and less than 2% for all impact categories. The cleaning tablet contributes less than 1% to all impact categories and can be considered negligible. Transportation also has small contributions all less or equal to 3%. Water availability human health is not displayed in **Figure 15**, as these values were zero as mentioned earlier. Water availability freshwater ecosystems numbers are only based on the used tap water from reasons already explained (see 5.3).

Taking a closer look at the impact categories that were pointed out in the normalized endpoint results we can see that for the Ozone layer depletion which was the only category in human health where the LOOP shower has a slightly higher impact the biggest contributors between the two showers differentiates. For the regular shower the biggest contributor in this category is the heating of bathing water, while for the LOOP shower it is the filter. For impact categories in the ecosystem quality the most interesting impact category from the categories where the LOOP shower as higher impacts as the regular shower is the Land occupation. The biggest contributor in this category is for the LOOP shower the used electricity and for the regular shower the wastewater treatment. Another interesting category in ecosystem quality is the freshwater ecotoxicity (short term) where the biggest part for the LOOP shower is the Aluminium whereas for the regular shower it is the wastewater treatment.

Again, for quality control, the ReCiPe 2016 endpoint (H) method results with differentiated contribution have been included in **Figure 16**.

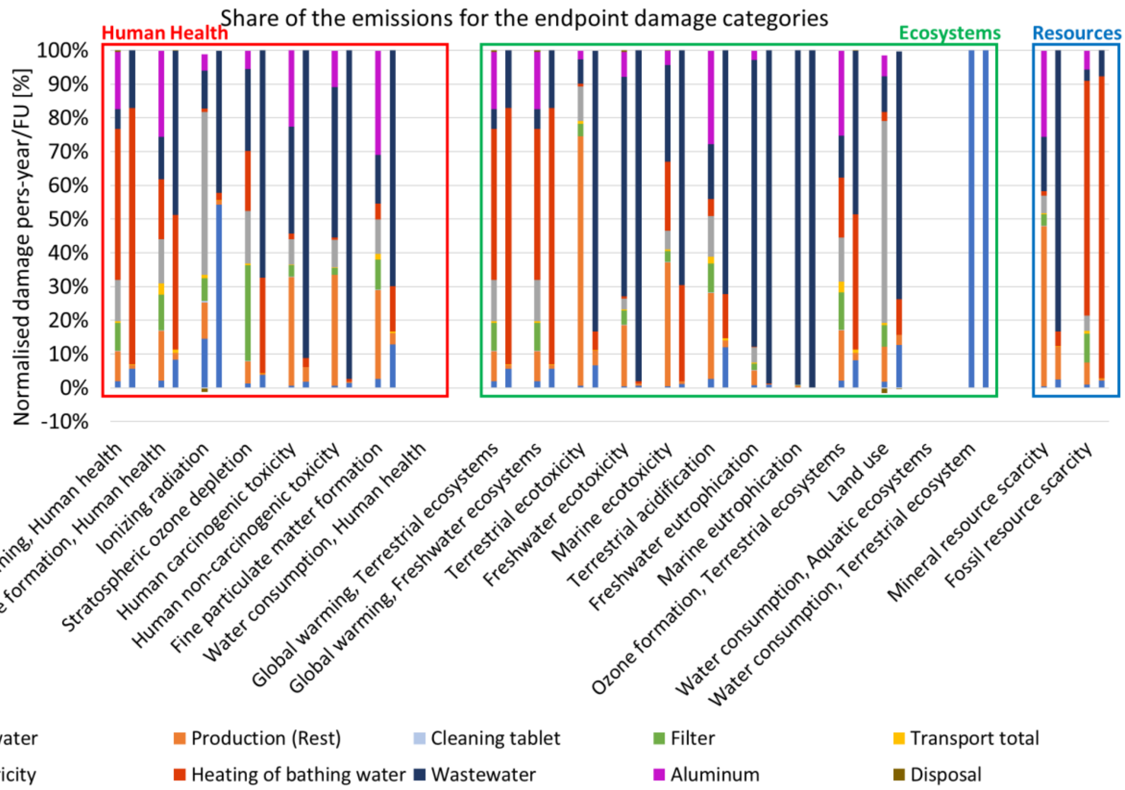

Figure 16. *Differentiated contribution of different life cycle processes for each endpoint impact category summing up to 100% based on the normalized ReCiPe 2016 (H) results. Under each impact category the LOOP shower is the left bar and regular shower is the right bar.*

As seen in **Figure 16,** the disposal of the LOOP and regular shower contributes to less than 1% for all impact categories. The cleaning tablet contributes to less than 1% for all impact categories and transportation has comparable low impact with all but Fine particulate matter formation, Ozone formation for both human health and terrestrial ecosystems and Terrestrial acidification contributing less than 1%. However, for the mentioned impact categories transportation contribution is still low at less than 4%. Therefore, there is no changes in the smaller contribution processes from ReCiPe to IMPACT World+.

When comparing **Figure 15** and **Figure 16** for all human health impact categories with exception of Stratospheric ozone depletion/ozone layer depletion the contributions of the different processes are very comparable, showing the same picture between methods. The major difference is the filter contribution in the Ozone layer depletion impact category between the two methods. In ReCiPe the filter still has the highest contribution by around 30%, however it is substantially lower than the contribution in IMPACT World+ of approximately 70%. In ReCiPe this makes the contribution in receding order of wastewater treatment, the heating of bathing water and the electricity consumption of the LOOP shower more important for the Ozone layer depletion impact category.

For the ecosystem quality impact categories by comparison of **Figure 15** and **Figure 16** all the ReCiPe global warming categories compares well to the IMPACT World+ short- and long-term climate change categories. The ReCiPe Freshwater ecotoxicity is in good comparison to the long term Freshwater ecotoxicity in IMPACT World+. Terrestrial acidification also has good contribution comparison between the methods. For Freshwater eutrophication ReCiPe attributes a little lower contribution to wastewater treatment in the LOOP shower giving electricity consumption of the LOOP shower and the Production (Rest) a slightly bigger contribution. Marine eutrophication compares well across methods. Land use in ReCiPe compares really well with the Land occupation in IMPACT World+, as was found in section 6.3. Finally, the hand calculated Water consumption terrestrial ecosystem in ReCiPe has a very good comparison to the SimaPro IMPACT World+ Water availability terrestrial ecosystem, further reinforcing the validity of the assumptions made. Generally, even though the different methods yielded some different impact category values, the contribution of the different processes towards the impact remains more or less the same. The methods support the same narrative in the contribution analysis.

Finally, ReCiPe includes resource impact categories. For mineral resource scarcity the production of the LOOP shower has the highest contribution, while for the regular shower it is the wastewater treatment contributing most. For fossil resource scarcity the heating of the bathing water is by far the biggest contributor, explaining why the LOOP shower outperforms the regular shower in this impact category.

7.1.2 Hot-spot Analysis

The hot-spot analysis determines which processes have the most impact in the product system's life cycle. Based on the SimaPro model results and hand-calculations, the processes contributing the most to the LOOP shower's total CO_2 fossil and carbon footprint (CO_2 equivalent) are listed in the table below (**Table 6**). The processes with 3% or less contribution have not been considered as hot spots. All the processes used in modelling the LOOP shower can be seen in **Annex 4** inventory table.

Table 6. *Hot-spot processes for the LOOP shower.*

Process	Ecoinvent process name(s)	Contribution to total carbon footprint (CO_2eq.)	Contribution to total fossil CO_2
Heating water for showering and rinse processes (district heating)	Heat and power co-generation, natural gas, combined cycle power plant, 400 MW electrical, DK, Cut-off S	45%	48%
Primary aluminium production and aluminium product manufacturing	Aluminium production, primary, ingot (RoW), Cut-off S; Metal working, average for aluminium product manufacturing (RoW), Cut-off S	20%	18%
Electricity for shower and rinse processes	Electricity, low voltage (DK), market for, Cut-off S	12%	12%
Wastewater treatment	Treatment of wastewater, average, capacity 1E9l/year (Europe without Switzerland), Cut-off S	6%	5%
Microfilter (changed every 4 weeks)	Textile production, nonwoven polyester, needle-punched (RoW), Cut-off S; Injection moulding (RoW), Cut-off S	5%	5%

7.2 Sensitivity and Uncertainty Analysis

The sensitivity studies were done using SimaPro and only the CO_2 equivalent was taken into consideration in the comparisons. This decision was based upon the arguments given in section 6.4. Here it was found that climate change impacts are by far the most important in both the IMPACT World+ and ReCiPe method. In IMPACT World+, the impact category Freshwater ecotoxicity also was found important, which was in contrast to ReCiPe. It was therefore found relevant to make the analysis upon the most important impact categories, which also was consistent in both LCIA methods. For all scenarios, the default values of the parameters that were not varied are applied. This means for example that the default number of four people in a household stays the same for the duration of shower, energy source for heating bathing water, and bathing water temperature sensitivity studies. Since varying a parameter result in different values of the unit processes, the SimaPro input data was adjusted to include the new values for the unit processes (**Table 7**). An explanation of the sensitivity scenarios is described in paragraph 5.5 and displayed in **Table 3**.

Table 7. *Values for changed unit processes for the applied sensitivity scenarios.*

<table>
<tr><th></th><th>Low-end</th><th>High-end</th></tr>
<tr><td>Bathing water temperature</td><td>Energy required for heating water:
• Regular shower: 8.04 MJ
• LOOP shower: 2.91 MJ</td><td>Energy required for heating water:
• Regular shower: 10.45 MJ
• LOOP shower: 3.09 MJ</td></tr>
<tr><td>Shower duration</td><td>Water required for bathing:
• Regular shower: 66 L
• LOOP shower: 15 L
Energy required for heating water:
• Regular shower: 6.36 MJ
• LOOP shower: 2.3 MJ

Electricity (only LOOP shower):
• LOOP shower: 0.046 kWh</td><td>Water required for bathing:
• Regular shower: 180 L
• LOOP shower: 24.5 L
Energy required for heating water:
• Regular shower: 17.34 MJ
• LOOP shower: 4.96 MJ

Electricity (only LOOP shower):
• LOOP shower: 0.126 kWh</td></tr>
<tr><td>Energy source for heating bathing water</td><td colspan="2">Electricity for water heating (not including electricity for LOOP shower use):
• Regular shower: 2.57 kWh
• LOOP shower:
  ○ Bathing water: 0.83 kWh
  ○ Rinsing process: 0.028 kWh</td></tr>
<tr><td>Number of showers taken over shower lifetime</td><td>Rinsing process:
• Heating water: 0.1889 MJ
• Electricity: 0.0023 kWh
• Tap water: 0.35L
• Cleaning tablets: 1/17.85 units
Microfiltering:
• Filter: 1/35.7 units</td><td>Rinsing process:
• Heating water: 0.0337 MJ
• Electricity: 0.0002 kWh
• Tap water: 0.35L
• Cleaning tablets: 1/100 units
Microfiltering:
• Filter: 1/200 units</td></tr>
<tr><td>Type of aluminium used as raw material</td><td colspan="2">Virgin aluminium:
• Manufacturing raw materials: 100% virgin aluminium (of total weight of aluminium in the product)
• Disposal, other than wastewater: 100% scrap aluminium

Recycled aluminium (further explanations in section 7.3.5):
• Manufacturing and raw materials: 80% virgin aluminium, 20% recycled aluminium
• Disposal: 80% aluminium recycled, 80% avoided virgin aluminium</td></tr>
</table>

7.2.1 Bathing Water Temperature

Figure 17 shows that the absolute global warming potential of the LOOP shower remains almost the same for the low and high scenarios, whose differences can be negligible. Nevertheless, an increase in the bathing water temperature for the LOOP shower results in a very small increase in the global warming score. On the contrary, the regular shower shows higher differences for the global warming potential of both sensitivity scenarios compared to the default one. Based on these results, it can be concluded that the difference in CO_2eq emissions for both products become smaller as the shower temperature decreases and becomes larger as the temperature increases. These results make sense because of the functionality of the LOOP shower. Since the LOOP shower requires significantly less water to be heated due to its recycling function, the temperature change does not have much impact on the energy required. The regular shower, on the other hand, requires much more heated water, depending on the scenario. Although the impact of the LOOP shower remains unchanged, scenarios with higher bathing temperatures show that the LOOP shower is even more preferable in terms of CO_2eq emissions. In addition, it is important to note that the results show that the LOOP shower has lower CO_2eq emissions in every water temperature scenario and can therefore be classified as the better product regarding these emissions. The water temperature only affects the use stage (heating of water) of the products, where the sensitivity changes take place.

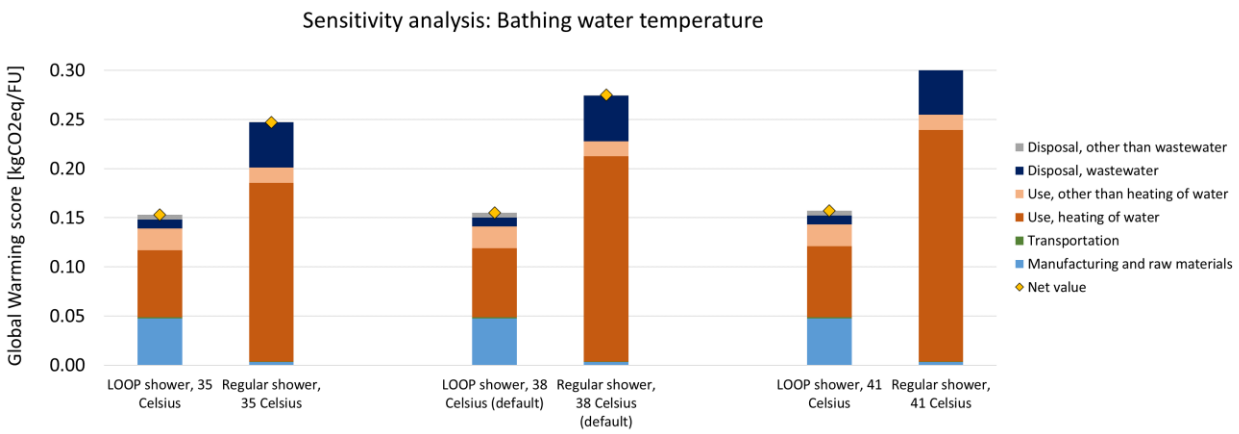

Figure 17. The *effect of the bathing water temperature on the Global Warming scores of the two showers.*

7.2.2 Shower Duration

The effects of varying the shower duration are shown in **Figure 18**. When looking at the low-end scenario (shower of 5.5 minutes), the Global warming scores of both products are very close together, whereas for the high-end scenario (15 minutes) the score is much higher for the regular shower than for the LOOP shower. Because of the very high increase compared to the LOOP shower, the regular shower is at 5.5 min still worse regarding emissions than LOOP shower at 8 min. The same applies for the regular shower at 8 min compared to the LOOP shower at 15 min. It can be said that the variation in the shower duration has the biggest impact on the use stage for heating the water that is used more, but also the impact of wastewater disposal goes up for the regular shower significantly. Regarding regular shower, in total 84 L water is consumed more in the high-end scenario compared to default scenario, whilst for the

LOOP shower only 7 L is consumed more compared to default scenario. To sum up, the LOOP shower has lower global warming score for all scenarios and is significantly better for long showering. The biggest difference occurs indeed in the high-end scenario where the global warming score of the regular shower is 2.3 times higher than of the LOOP shower.

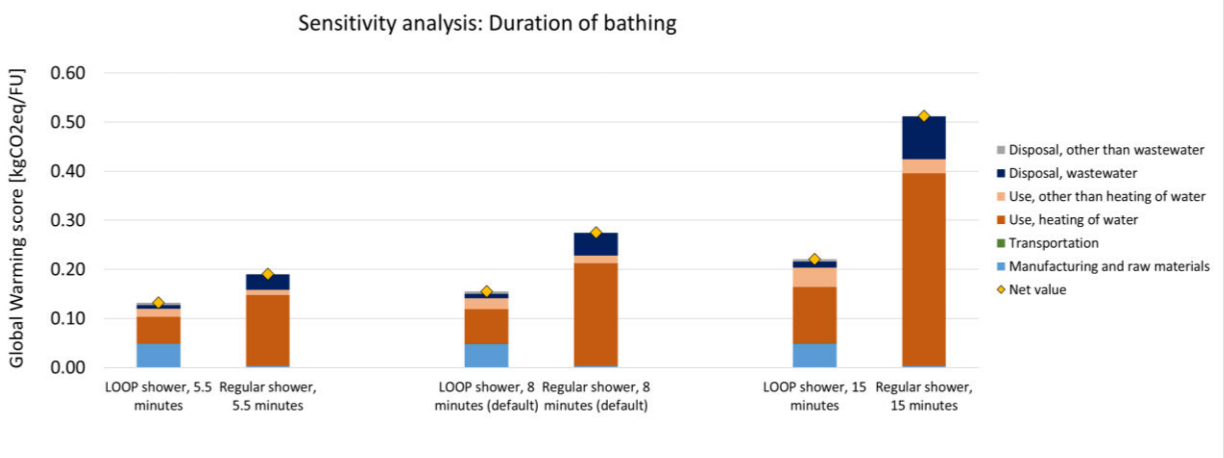

Figure 18. *The effect of the duration of bathing on the Global Warming scores of the two showers.*

7.2.3 Heating Method

Starting from the comparison of the default scenario to the low-end one shows that heating up the bathing water with electricity that is generated by 100% photovoltaic does not result in significant differences for neither product compared to district heating. In **Figure 19** can be seen that using PV electricity result in a very small decrease of the global warming score of both products. This can also be seen by the comparison of the product. While in the district heating scenario the global warming impact of the regular shower is 1.8 times higher than of the LOOP shower, the impact difference amounts up to 1.7 in favour of the LOOP shower. Therefore, this sensitivity scenario does not result in changes of the order. Nevertheless, heating up the bathing water with electricity generated with the DK electricity mix leads to significantly higher GHG emissions compared to district heating. Although, both products have higher emissions in the high-end scenario, the emission increase of the regular shower is much higher than for the LOOP shower. While the LOOP shower has 2.1 higher CO_2eq emissions in the high-end scenario compared to the default one, the regular shower emits 2.9 times as much. This leads to the results, that in the high-end scenario, the regular shower emits 2.4 times more CO_2eq emissions than the LOOP shower. Hence, the LOOP shower becomes even better when comparing it to the regular shower. Based on these results it can be concluded that changing the district heat to electricity for water heating, does not affect the order of the two products in terms of GHG emissions. Moreover, it can be seen that by using partly fossil based electricity, the LOOP shower becomes better when comparing it to a regular shower.

Since in some countries the fossil fraction in the electricity mix is higher, the difference between regular and LOOP shower will increase even more. The difference between the scenarios is only due to an increase in the use stage of the emissions by heating the water. Therefore, the ratios of the life cycle stages vary and only for the LOOP shower significant differences between the life cycle stage ratios can be seen due to the high carbon intensive manufacturing. If the water is heated with 100% renewable energy, as in the low-end scenario, manufacturing accounts for 32% of the total CO_2eq emissions. This is only one percent higher than using district heating, where manufacturing accounts for 31%. If, on the other hand, the DK electricity mix is used to produce the electricity, manufacturing in this scenario is responsible for only 15% of the total CO_2eq emissions of the whole product. This is around half as much as in the district heating scenario. Nevertheless, it can be seen in the figure that no scenario changes the ranking of contribution of the life cycle phases, meaning that the use stage still accounts for most of the CO_2eq emissions in each scenario.

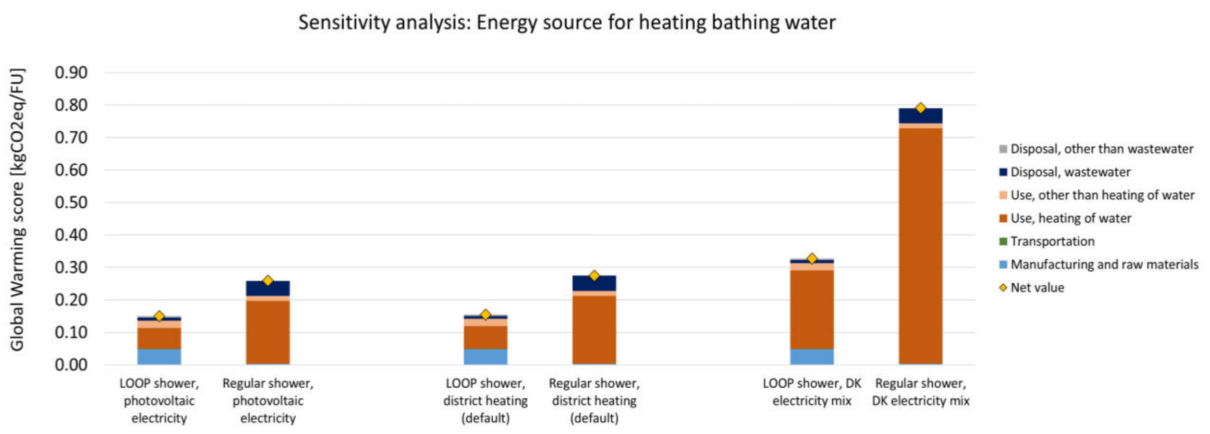

Figure 19. *The effect of the energy source for heating bathing water on the Global Warming scores of the two showers.*

7.2.4 Number of Showers Taken Over Product Lifetime

The global warming score for different scenarios regarding number of showers taken over product lifetime is shown in **Figure 20**. When looking at the graph, several things stand out. Firstly, the global warming score of the regular shower stays approximately the same (around 0.27-0.28 $kgCO_2eq/FU$). Only a very small increase when decreasing number of showers can be seen. The reason for this is that decreasing the number of showers over product lifetime increases only the emissions per FU related to manufacturing of the shower. At the same time the global warming score for the LOOP shower increases significantly when reducing the number of uses over product lifetime. Again, the reason lays in the increasing fraction of the manufacturing per FU. In the low-end scenario, the fraction of the manufacturing is around 11% and increases in the default scenario to 31%. In the high-end scenario, the manufacturing takes up nearly half (44%) of the global warming score per FU. Lastly, it is to mention that the LOOP shower has lower global warming scores for all scenarios compared to the regular shower.

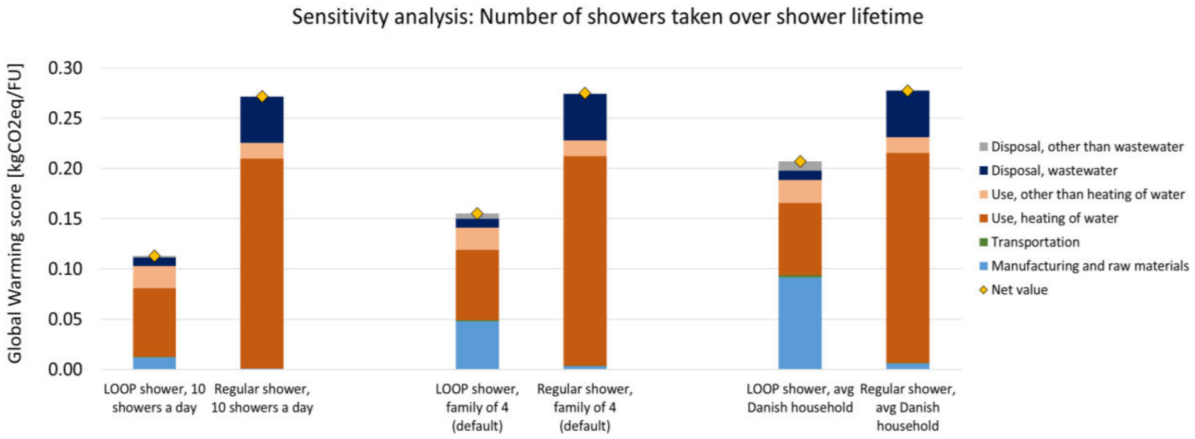

Figure 20. *The effect of the number of showers taken over shower lifetime on the Global Warming scores of the two showers.*

7.2.5 Type of aluminium used as raw material

A slightly different sensitivity study from other sensitivity analyses was also conducted to assess how using recycled aluminium affects the total emissions of the LOOP shower. The same analysis could not be done for the regular shower, because it does not contain alumin-ium. However, the regular shower in its default scenario was used as a benchmark also in this study.

As instructed in this course, formulas based on the Circular Footprint Formula (Zampori & Pant, 2019, p. 65) were used to calculate the effect of using recycled material on the product lifetime emissions. The used formulas for the calculations were:

- Input: $E_v + R_1 \times 0.2 \times (E_{rec} - E_v)$
- Output: $R_2 \times 0.8 \times (E_{rec} - E_v)$

where R_1=R_2=1 (R_1 = fraction of recycled materials used as input, R_2 = fraction material recycling as output),

E_v = emissions and resources consumed caused by the acquisition and pre-processing of virgin material,

E_{rec} = specific emissions and resources consumed (per functional unit) arising from the recycling process of the recycled (reused) material, including collection, sorting, and transportation process (Zampori & Pant, 2019, S. 65)

The equations presented above mean that the benefits of recycled aluminium can only be fully obtained when 1) recycled aluminium is used as raw material and 2) used aluminium is recycled at the end of the product's life cycle. The input equation contains an assumption that only 20% of the input is actually recycled aluminium whereas 80% is virgin because the global supply of recycled aluminium is too small compared to the demand (Frees, 2008; Zampori & Pant, 2019, S. 66-67). In the output equation, on the other hand, it is assumed that 80% of the used aluminium ends up in recycling and can be deducted from the product's emissions in the disposal stage as avoided virgin aluminium. This action grants a bonus to the product in question from recycling used aluminium to meet the global demand.

The global warming score for the recycled aluminium scenario, the virgin aluminium scenario, and default scenario of a regular shower are shown in **Figure 21**. The results show that using recycled aluminium instead of virgin aluminium in the LOOP shower production decreases the net emissions by 16%. Due to the used formulas, this change can mostly be seen under *Disposal, other than wastewater* category. However, also the emissions related to the manufacturing decrease by 9%. Compared to the regular shower in its default scenario, the emissions of LOOP shower per FU are 44% lower when using virgin aluminium and 53% lower when using recycled aluminium.

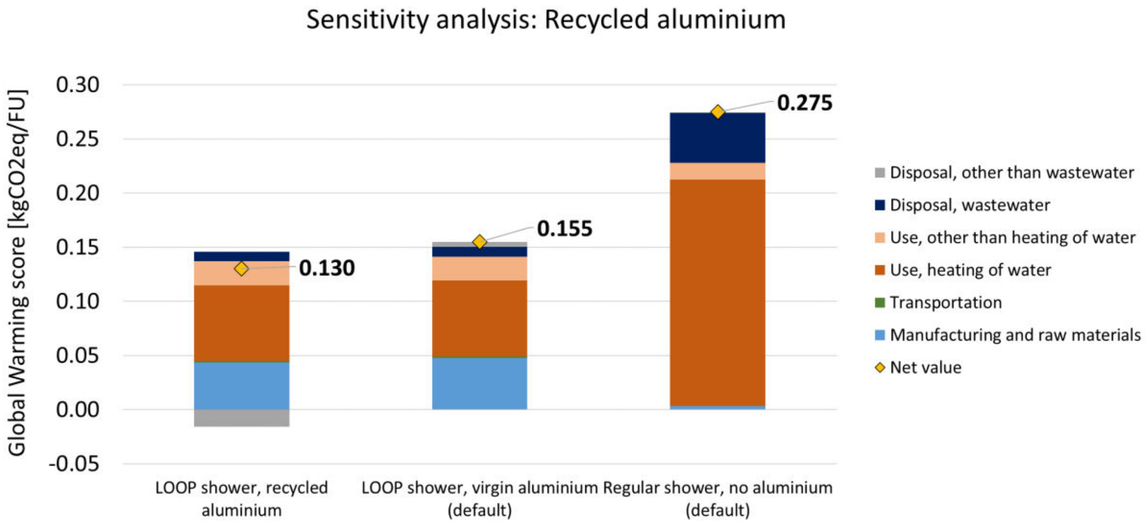

Figure 21. *The effect of using recycled aluminium instead of virgin aluminium in the LOOP shower production on the Global Warming score.*

7.2.6 Sensitivity and Uncertainty Analysis Summary

From the results of all the sensitivity analyses, it can be concluded that the global warming score of the LOOP shower is sensitive to changes in different parameters than the regular shower. This can also be seen from **Table 8**. As proposed by Jolliet et. al (2016) the criteria for significant differences in CO2 is considered when the results change for more than 10%. Therefore, the low and high end scenarios for the LOOP shower for the water temperature and number of uses over life time are significant sensitive. However, for the heating method, the LOOP shower is only significant sensitive for the high-end scenario. Furthermore, the results of the LOOP shower are the most sensitive to changes inthe heating method for the high-end scenario (+111%). The . A regular shower, on the other hand, is significantly sensitive to the duration of the shower and water temperature just like the LOOP shower, but especially to the heating method of the bathing water. The highest sensitivity is again produced by the high-end scenarios (heating method +188% and shower duration +86%). These results are of high importance and tell about the magnitude of the uncertainty of the entire LCA results. However, it is important to note that these results only show trends in sensitivity, since not every parameter is changed by the same amount.

Table 8. *Net value comparison of low-end and high-end scenarios to default scenario.*

Net value comparison to default scenario (100%)		
LOOP shower		
Changed parameter	***Low-end***	***High-end***
Bathing water temperature	*99 %*	*101 %*
Shower duration	*85 %*	*143 %*
Heating method	*97 %*	*211 %*
Number of uses over product lifetime	*73 %*	*134 %*
Regular shower		
Bathing water temperature	*90 %*	*110 %*
Shower duration	*69 %*	*186 %*
Heating method	*94 %*	*288 %*
Number of uses over product lifetime	*99 %*	*101 %*

7.3 CO_2 Break-even Analysis

In **Figure 22** the break-even point in terms of CO_2 equivalent emissions for the LOOP shower compared to the regular shower is shown. The whole process of the shower from cradle-to-gate has been considered in this calculation, not just the use stage processes. The break-even point in this case states the number of showers that must be taken until the LOOP shower is better than a regular shower in terms of greenhouse gas emissions, which are indicated in CO_2 equivalent. To calculate the break-even point, the fixed CO_2eq and variable CO_2 were determined. The fixed CO_2 emissions are independent from the number of showers used and are mainly represented by the material, production, manufacturing, and disposal stage. The variable CO_2 emissions are emitted every time a shower is taken and are therefore emissions from the use stage.

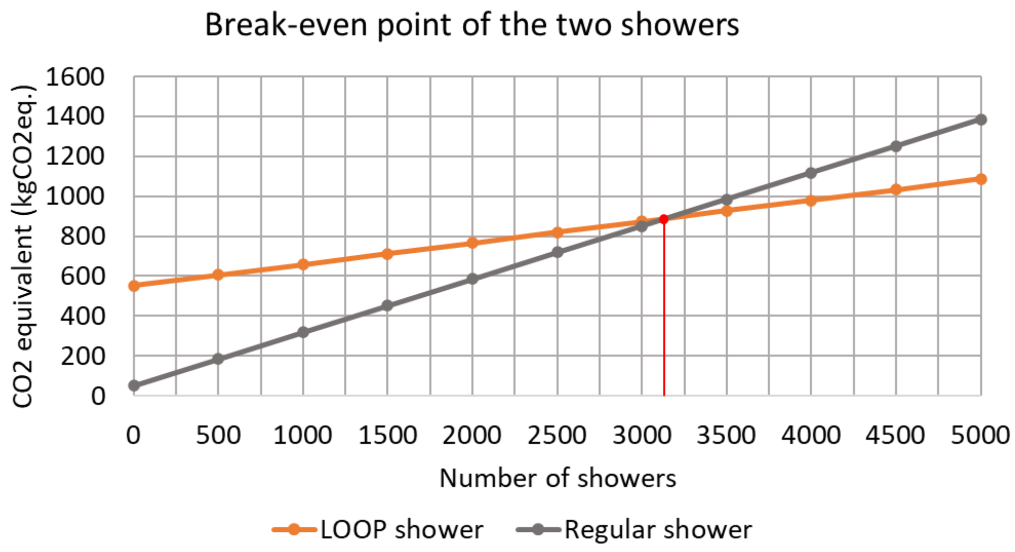

Figure 22. *Break-even point of the LOOP shower and a regular shower.*

The calculations resulted in a break-even point at 3133 showers. Under the assumption that one person showers 4.25 times per week, this number is reached after approximately 3.5 years for the default scenario with 4 people per household. For 2.1 people per household (average Danish household) 3133 showers have been taken after approximately 6.7 years. For the high-end scenario with 10 showers per day, the break-even point is reached after 0.85 years (around 10 months).

7.4 Completeness and Consistency Checks

Consistency of the SimaPro calculations and hand-calculations were checked by means of the percentage difference of the obtained values (**Tables 9 and 10**). Overall, there are no significant differences in the net values of the CO_2 equivalent and fossil CO_2. The biggest differences occur in wastewater treatment emissions between hand-calculations and SimaPro calculations. The reason for this error is different emission data behind the same wastewater treatment process between hand-calculation spreadsheet and SimaPro. This means that different version of the Ecoinvent database has been used in the calculations. The results obtained from SimaPro are based on more recent data, and thus, SimaPro results should be used whenever possible. For the same reason, the *Use, other than heating of water* results differ, although the difference is smaller. The DK electricity mix process included in *Use, other than heating of water* has been updated and therefore gives different results between hand-calculations and SimaPro. It is also important to note that although there are 9-18% differences in the results of *Disposal, other than wastewater* and *Transport*ation, these stages do not play a big role in the carbon footprint of either shower, so they can be neglected.

Table 9. *Hand-calculations compared to SimaPro in terms of GHG CO_2 equivalent.*

	Hand-calculations compared to SimaPro in terms of GHG CO_2 equivalent	
	LOOP shower	*Regular shower*
Manufacturing and raw materials	*2 %*	*3 %*
Transportation	*-11 %*	*16 %*
Use, heating of water	*6 %*	*6 %*
Use, other than heating of water	*-20 %*	*-8 %*
Disposal, wastewater	*-34 %*	*-34 %*
Disposal, other than wastewater	*-20 %*	*-12 %*
Net value	***-2 %***	***-2 %***

Table *10.* *Hand-calculations compared to SimaPro in terms of fossil CO_2.*

	Hand-calculations compared to SimaPro in terms of fossil CO_2	
	LOOP shower	*Regular shower*
Manufacturing and raw materials	*3 %*	*1 %*
Transportation	*-16 %*	*9 %*
Use, heating of water	*3 %*	*3 %*
Use, other than heating of water	*-21 %*	*-10 %*
Disposal, wastewater	*-52 %*	*-52 %*
Disposal, other than wastewater	*-18 %*	*-12 %*
Net value	***-4 %***	***-6 %***

7.5 Absolute Sustainability

The normal LCA process in this study supports the relative assessment of sustainability and enables one to conclude if a product is more sustainable compared to another product. However, to know whether a product is sustainable or not in an absolute sense, an absolute sustainability assessment needs to be done. This assessment creates a boundary for what is sustainable, by using the planetary boundaries and how much can be allowed per capita (carbon footprint/person).

When determining the absolute sustainability of a product system, the sustainable boundary assigned to one FU (kgCO_2eq/FU) needs to be calculated. For this the Absolute Environmental Sustainability Assessment (AESA) is used. As the first step of the AESA the life cycle environmental impact per FU is calculated. Then the environmental carrying capacities (planetary boundary) are calculated and allocation is done for the FU.

One of the allocation methods used for this study is the economic allocation, which considers the price of the shower product itself as well as the Danish price of the wastewater, raw water, and the heat used during the shower use stage. The heating water cost was 2.55 DKK/FU (Gregsen, & Patursson, 2023), the raw water/wastewater cost 3.71 DKK/FU (Hofor, 2022), and the purchase cost of the product 0.45 DKK/FU (Gulv & Flise Eksperten, 2023). Therefore, in total the cost per FU is 6.71 DKK/FU. For this study, the default of a 4-person family and the regular shower product system are used to set up the economic allocation. The price of the regular shower is used rather than the LOOP shower because it is the more conventional scenario from the two and is closer to what most people are using in Denmark now. The reference shower simply represents a proxy of what is the value of taking a shower. Based on the economic allocation method, the sustainable boundary assigned to one FU is 0.007 kgCO_2eq.

The second allocation method used in this study is the Grandfathering method, which does not allocate emissions based on price but instead allocates the carbon emissions proportionally according to emissions at a particular base year. For this study, the total carbon footprint emissions in Denmark from the year 2019 were used to calculate the annual consumption-based emissions per person (kgCO_2eq/pers/yr). Then this value is used to calculate the reduction factor to reach planetary boundary. The reference shower emissions are divided by this reduction factor to allocate the sustainable boundary for one FU. Based on the Grandfathering allocation method the sustainable boundary assigned to one FU is 0.009 kgCO_2eq.

The **Table 11** below shows the absolute sustainability calculation results for the two different allocation methods: Economic Allocation and Grandfathering. Two methods are used because the calculation includes a lot of uncertainty. The results are based on the absolute sustainability exceedance ratio which is calculated by dividing the global warming score [kgCO_2eq/FU] by the sustainable boundary assigned to one functional unit [kgCO_2eq/FU]. The sustainable boundary assigned to one FU is higher for the grandfathering method than the economic allocation method which means that more emissions have been allowed per FU. This shows in the results as a higher exceedance ratio in the Economic Allocation results than the Grandfathering results. The absolute sustainability assessment was done for all LOOP shower sensitivity study scenarios (see section 7.3). As seen from the table results, all scenarios' global warming score, or carbon footprint, exceeds the respective sustainable boundary assigned to one FU and are colored red. Therefore, none of the scenarios meet the absolute sustainability requirements. When looking at both allocation method results, it seems like the best (most sustainable) scenario is the one where the default LOOP shower parameters are the same but the number of people using the shower per day has been increased (10 showers per day). The worst (least sustainable) scenario is the high-end scenario with LOOP shower using DK electricity mix. It should be noted that the regular shower using DK electricity mix still has a higher global warming score than the LOOP shower and would therefore be the least sustainable if the regular shower's sensitivity analysis would be shown as well (see **Figure 19).** It is advised that the LOOP shower is used by multiple people per day to bring down the overall CO_2eq impact of the shower per FU.

Table 11. *Absolute sustainability calculation results.*

Scenarios	**Global Warming score** [kgCO_2eq/FU]	**Economic allocation** [exceedance ratio]	**Grandfathering** [exceedance ratio]
Regular shower (reference system) 8 min shower, family of 4, district heating, 38°C	0.275	41.89	29.05
LOOP shower (default system) 8 min shower, family of 4, district heating, 38°C	0.155	23.61	16.37
LOOP shower sensitivity analysis scenarios			
Bathing water heating: **100% PV electricity** (low-end)	0.150	22.85	15.85
Bathing water heating: **DK electricity mix** (high-end)	0.327	**49.81**	**34.54**
Bathing water temperature: **35°C** (low-end)	0.153	23.30	16.16
Bathing water temperature: **41°C** (high-end)	0.157	23.91	16.59
Length of shower: **5.5 min** (low-end)	0.132	20.11	13.94
Length of shower: **15 min** (high-end)	0.221	33.66	23.35
Number of people in household: **2.1 people** (low-end)	0.207	31.53	21.87
Number of showers taken per day: **10 (boarding school, sports facility, etc.)** (high-end)	0.113	**17.21**	**11.94**
Different material: **Recycled aluminium**	0.130	19.80	13.73

8 Conclusions

Based on the performed LCA, it can be concluded from the normalization of results, sensitivity analysis, and absolute sustainability assessment that the LOOP shower is a more sustainable product than a regular shower. This is despite LOOP shower being a significantly more complex product in terms of manufacturing (more materials, transportation, and complicated production) than a regular shower. The main reason for the regular shower being less sustainable is that it uses much more water and requires more heating in the use stage. Although the LOOP shower is more sustainable than the regular shower in a relative sense, neither of the products are absolute sustainable.

The most important impact categories for the LOOP shower were found from the IMPACT World+ weighted results to be Climate change human health long-term contributing 33% to the total weighted impact score. Considering all human health and ecosystem quality climate change impact categories, they contributed above 60% to the total weighted impact score of the LOOP shower. The IMPACT World+ ecosystem quality impact category Freshwater ecotoxicity long term was also found to be important. Climate change impacts was found to be consistently important from the LCIA ReCiPe 2016 (H) method, while the Freshwater ecotoxicity impact was found to be negligible. The ReCiPe method did not change general conclusions regarding which product is more sustainable but did change the order of magnitude of the different impact category results. This emphasizes that the results are highly dependent on used methods and limitations.

8.1 Limitations

As with all LCAs, there can be some limitations for the usability of the study results. In this study, there are some spatial and temporal limitations because the study has been done for Danish users and uses data specific to the Danish market and corresponding to today's situation. Therefore, the results cannot be expanded to compare the product's impact in a different country or in different time. For example, the impact of water availability will change drastically based on geographical and temporal scale.

Additionally, the Flow Loop ApS company is a startup and is currently producing the LOOP showers by hand at their small manufacturing facilities in Denmark but have plans of upscaling the business. The LCA study has been done considering the current situation, and if the company were to scale up the production, the results are not applicable. Therefore, these results cannot be directly applied to a scale-up situation.

When using the LOOP shower, the consumer can choose whether they want the system in recycling mode or not. In this study it was assumed that the consumer uses the recycling feature as much as possible. Therefore, the results will be affected based on how often the consumer uses the recycling feature. For example, if the consumer decides to shower without using the recycling feature at all, this will affect the results negatively as more water and heating will be required.

Furthermore, any LCA result may vary from case to case and study to study, as the results are based on a lot of assumptions and choices (e.g., modelling processes). A more refined dataset could reduce the number of needed assumptions and thus lead to more certain results. However, the results of this case study are notably limited by the collected data and are therefore based upon several assumptions.

8.2 Recommendations

The carbon footprint of the LOOP shower mainly consists of the heating of bathing water and manufacturing and raw material extraction. The possibility of Flow Loop influencing the way the bathing water is heated is very small, so focusing on reducing the carbon footprint of the product itself is recommended especially if the recycling function of the LOOP shower cannot be further enhanced to reduce the hot water consumption and the produced wastewater. A less effective, but not insignificant way to reduce the emissions in the use stage would be to reduce the electricity consumption of the LOOP shower during showering.

As found in the hot-spot analysis, in reducing the LOOP shower's carbon footprint resulting from manufacturing and raw material extraction, it is worth focusing on reducing the use of aluminium or switching to recycled aluminium if this is not already the case. Also, Flow Loop ApS could influence the recycling of LOOP shower materials at the end of the product lifetime, which could be a potential way to make reductions in emissions per shower. The disposal stage already has a contribution of less than 1% across impact categories, however, potentially it would significantly reduce the production and manufacturing stage impact of the shower with reused or recycled materials. Regarding the microfilter, it is worth investigating alternative materials (e.g., reusable filter material) or investigating whether the current filter can be safely used longer than the current recommendations state. Additionally, as seen by the sensitivity study of the frequent user case (boarding school, sports facility case, etc.), it is recommended that Flow Loop targets to intensive water users since this significantly brings the overall emissions per FU down. Similar effect can be achieved by increasing LOOP shower’s effective lifetime meaning that the number of showers taken over shower lifetime increases.

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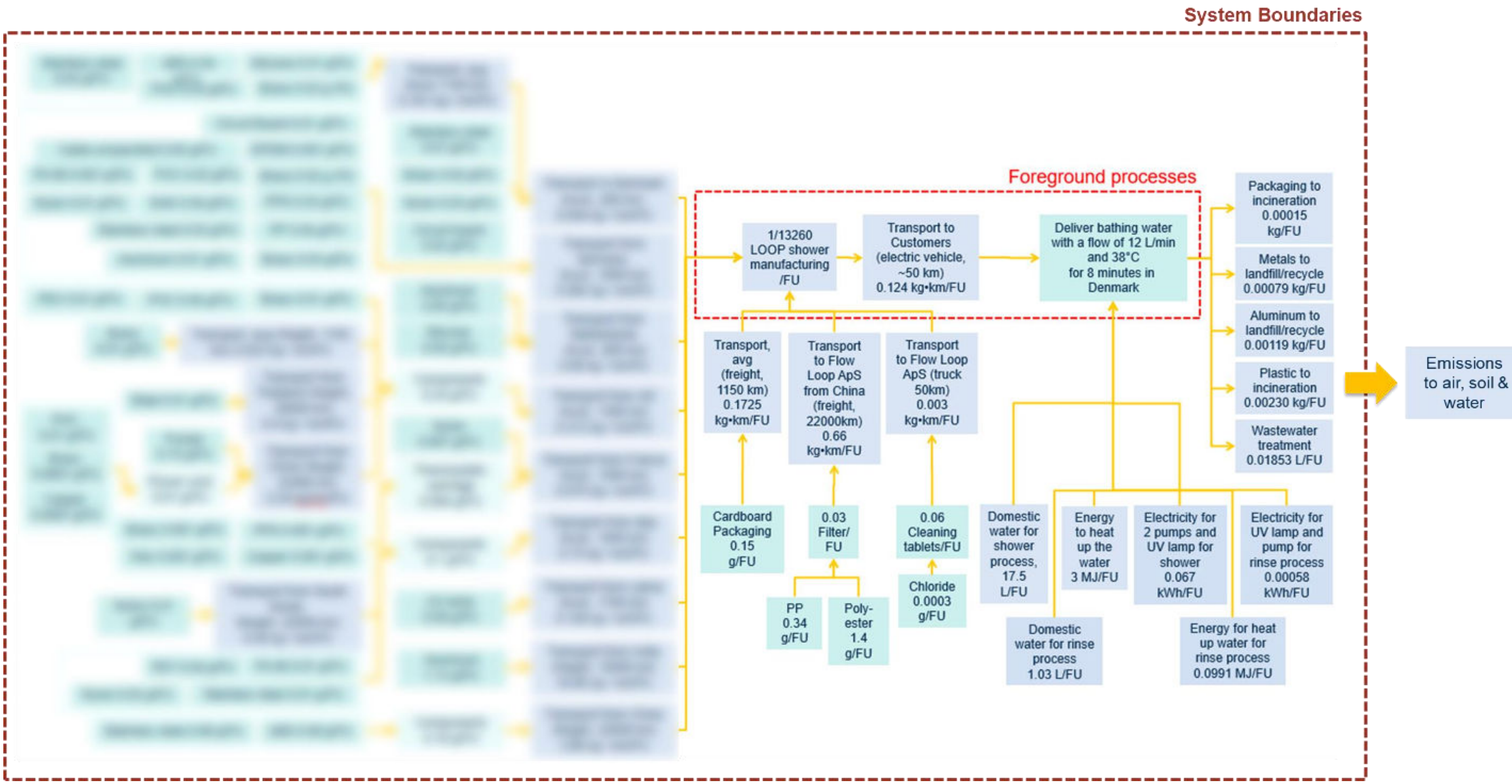
Annexes

Annex 1. Assumptions use stage.

Assumption	Quantity	Source	Explanation
Water flow	12 L/min	-	-
Water temperature	38°C	-	-
Lifespan of a shower	15 years	Flow Loop ApS, 2023a	-
Recycling rate of the LOOP shower	11 L/min	NIRAS A/S & Flow Loop ApS., 2023	-
Water consumption at water flow of 12 L/min for 8 minutes	17.5 L	NIRAS A/S & Flow Loop ApS., 2023	-
Average weekly showering time in Denmark	34 min/week	Energistyrelsen, 2022	-
Consumed water per week per person	408 L	-	Showering 34 min per week at a flow of 12 L/min
Number of showers per person per week	4.25 showers/week	-	$\frac{408\ L}{8\ min \times 12\ \frac{L}{min}}$
Number of showers over shower lifetime per person	3315 showers	-	$4.25\ \frac{showers}{week} \times 52\ \frac{weeks}{year} \times 15\ years$
Avg. population in one apartment	2.1 persons	Statistics Denmark, 2023	-
Number of showers over shower lifetime per apartment (family of 4)	13260 showers	-	$4\ \frac{person}{apartment} \times 3315\ \frac{showers}{person}$
Number of showers over shower	6962 showers	-	$2.1\ \frac{person}{apartment} \times 3315\ \frac{showers}{person}$

lifetime per apartment (avg. Danish household)			
Filter change frequency for a family of 4	Every 4 weeks or every 200 showers (whichever comes first) → 68 showers per filter	Flow Loop	$4{,}25 \frac{showers}{week\ and\ person} \times 4\ weeks\ x\ 4 \frac{person}{aparment}$
Rinse process frequency	Every 2 weeks or 100 showers (whichever comes first) → 34 showers per rinse process	Flow Loop	$4{,}25 \frac{showers}{week\ and\ person} \times 2\ weeks\ x\ 4 \frac{person}{aparment}$
Specific heat of water	4.1876 kJ/kg * °C	-	-
Method of heating water	50:50 cold and hot domestic water (non-recycling process)	NIRAS A/S & Flow Loop ApS., 2023	-
Temperature of cold domestic water	15°C	Unified Water Label Association, 2023	-
Power of pump	240 W	Xylem Inc., 2023	-
Power of UV lamp	25 W	Krausen Baltija, 2023	-
Temperature loss of recycled water	4°C	Flow Loop (measured)	-

Annex 2. Process tree LOOP shower (non-confidential)

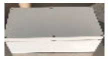


Annex 3. Weighted LOOP shower materials and components (confidential).

Photo of the weighted component	Component desciption/name	Component website	Materials based on data sheets/websites	Weight for one component (kg)	Number of components in one shower	Total weight in one shower (kg)	Supplier (na=not available)	Supplier country (na=not available)	Manufacturer (na=not available)	Manufacturing country (na=not available)	Estimated material fractions IF multiple materials	Amount of each material (kg)	Corrected amount of each material (kg)	Material/component used in the LCA	Assumptions
															
															
															
															
															
															
															
															
															
															
															

Legend

Information in the cell includes assumptions

Photo of the weighted component	Component desciption/name	Component website	Materials based on data sheets/websites	Weight for one component (kg)	Number of components in one shower	Total weight in one shower (kg)	Supplier (na=not available)	Supplier country (na=not available)	Manufacturer (na=not available)	Manufacturing country (na=not available)	Estimated material fractions IF multiple materials	Amount of each material (kg)	Corrected amount of each material (kg)	Material/component used in the LCA	Assumptions
															
															
															
															
															
															
															
															
															
															
															

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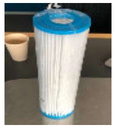
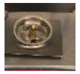
															
															
															
															
															
															

Photo of the weighted component	Component desciption/name	Component website	Materials based on data sheets/websites	Weight for one component (kg)	Number of components in one shower	Total weight in one shower (kg)	Supplier (na=not available)	Supplier country (na=not available)	Manufacturer (na=not available)	Manufacturing country (na=not available)	Estimated material fractions IF multiple materials	Amount of each material (kg)	Corrected amount of each material (kg)	Material/component used in the LCA	Assumptions
															
															
															
	S														
	S														
															
															
															
															
	M														
	P														
											Total	33,4	33,9	kg	

Weighted components in total	**33,4**	**kg**
Total weight of the Loop shower	**33,9**	**kg**
Weight missing	**0,5**	**kg**
Correction factor	**1,02**	**-**
Packaging (cardboard)	2,0	kg

Annex 4. Inventory table of Ecoinvent processes for the LOOP shower.

Process #	**Component/ material/process**	**Ecoinvent process**	**Region code**
Manufacturing (Materials + Processing)			
17429	Stainless Steel	steel production, chromium steel 18/8, hot rolled	RER
146	ABS	acrylonitrile-butadiene-styrene copolymer production	RoW
16436	PVC	polyvinylchloride production, suspension polymerisation	RER
17112	Silicone	silicone product production	RER
904	Brass	brass production	RoW
15471	Nylon	nylon 6-6 production	RER
16576	Circuit board	printed wiring board production, through-hole mounted, unspecified, Pb free	GLO
17429	Stainless Steel	steel production, chromium steel 18/8, hot rolled	RER
904	Brass	brass production	RoW
17714	EPDM	synthetic rubber production	RER
15471	Nylon	nylon 6-6 production	RER
327	Aluminium	aluminium production, primary, ingot	RoW
16576	Circuit board	printed wiring board production, through-hole mounted, unspecified, Pb free	GLO
16389	PPS	polyphenylene sulfide production	GLO
16436	PVC	polyvinylchloride production, suspension polymerisation	RER
16391	PP	polypropylene production, granulate	RER
17515	SAN	styrene-acrylonitrile copolymer production	RER
904	Brass	brass production	RoW
5701	PA 66 glass fibre	glass fibre reinforced plastic production, polyamide, injection moulded	RER
17429	Stainless Steel	steel production, chromium steel 18/8, hot rolled	RER
995	Cable	cable production, unspecified	GLO
17112	Silicone	silicone product production	RER
327	Aluminium	aluminium production, primary, ingot	RoW
16436	PVC	polyvinylchloride production, suspension polymerisation	RER
16346	PEX	polyethylene production, high density, granulate	RER
904	Brass	brass production	RoW
17430	Steel	steel production, converter, low-alloyed	RoW
14474b	Pumps	market for water pump, 240W	GLO
146	ABS	acrylonitrile-butadiene-styrene copolymer production	RoW
904	Brass	brass production	RoW
2009	Copper	copper production, cathode, solvent extraction, and electrowinning process	GLO
16436	PVC	polyvinylchloride production, suspension polymerisation	RER
17429	Stainless steel	steel production, chromium steel 18/8, hot rolled	RER
904	Brass	brass production	RoW
15804	Wax	paraffin production	RER
2009	Copper	copper production, cathode, solvent extraction, and electrowinning process	GLO
16389	PPS	polyphenylene sulfide production	GLO

15471	Nylon	nylon 6-6 production	RER
15471	Nylon	nylon 6-6 production	RER
5701	PA 66 glass fibre	glass fibre reinforced plastic production, polyamide, injection moulded	RER
16359	PET	polyethylene terephthalate production, granulate, amorphous	RER
17429	Stainless Steel	steel production, chromium steel 18/8, hot rolled	RER
15471	Nylon	nylon 6-6 production	RER
20673	UV Lamp	ultraviolet lamp production, for water disinfection	GLO
327	Aluminium	aluminium production, primary, ingot	RoW
7164	Shower manufacturing, plastics	injection moulding	RER
14806	Shower manufacturing, copper	metal working, average for copper product manufacturing	RoW
1099	Shower manufacturing, brass	casting, brass	RoW
14810	Shower manufacturing, steel	metal working, average for steel product manufacturing	RoW
14802	Shower manufacturing, aluminium	metal working, average for aluminium product manufacturing	RoW
2029	Packaging Cardboard	corrugated board box production	RER
17821	Filter manufacturing, polyester	textile production, nonwoven polyester, needle-punched	RoW
7163	Filter manufacturing, PP	Injection moulding	RoW
16391	PP for filter	polypropylene production, granulate	RER
Transportation			
18094	Transportation truck, average distance	market for transport, freight, lorry >32 metric ton, EURO5	RER
18094	Transportation truck Denmark	market for transport, freight, lorry >32 metric ton, EURO5	RER
18094	Transportation truck Germany	market for transport, freight, lorry >32 metric ton, EURO5	RER
18094	Transportation truck Netherlands	market for transport, freight, lorry >32 metric ton, EURO5	RER
18094	Transportation truck UK	market for transport, freight, lorry >32 metric ton, EURO5	RER
18094	Transportation truck France	market for transport, freight, lorry >32 metric ton, EURO5	RER
18094	Transportation truck Italy	market for transport, freight, lorry >32 metric ton, EURO5	RER
18094	Transportation truck Latvia	market for transport, freight, lorry >32 metric ton, EURO5	RER
18150	Transportation freight India	transport, freight, sea, container ship	GLO
18150	Transportation freight China	transport, freight, sea, container ship	GLO
18150	Transportation freight Thailand	transport, freight, sea, container ship	GLO
18150	Transportation freight South Korea	transport, freight, sea, container ship	GLO
18150	Transportation of pumps from China	transport, freight, sea, container ship	GLO
18150	Transportation of filters from China	transport, freight, sea, container ship	GLO

18027	Transport to customer from Flow Loop	transport, freight, light commercial vehicle	Europe without Switzerland
18094	Transportation of cleaning tablets to Flow Loop, truck	market for transport, freight, lorry >32 metric ton, EURO5	RER
		Use stage	
17772	Tap water for shower process	tap water production, underground water with disinfection	Europe without Switzerland
6281	Heat for bathing water	heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical	DK
9708	Electricity for shower process	market for electricity, low voltage	DK
17772	Tap water for rinse process	tap water production, underground water with disinfection	Europe without Switzerland
6281	Heat for rinse process	heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical	DK
9708	Electricity for rinse process	market for electricity, low voltage	DK
1332	Cleaning tabs	chlorine dioxide production	RER
		Disposal	
20583	Wastewater from shower process	treatment of wastewater, average, wastewater treatment	Europe without Switzerland
20583	Wastewater from rinse process	treatment of wastewater, average, wastewater treatment	Europe without Switzerland
12611	Aluminium treatment mix (recycling and landfill)	market for scrap aluminium	Europe without Switzerland
12619	Steel treatment mix (recycling and landfill)	market for scrap steel	Europe without Switzerland
12614	Copper and brass treatment mix (recycling and landfill)	market for scrap copper	Europe without Switzerland
20237	Mixed plastics from shower and filter to incineration	treatment of waste plastic, mixture, municipal incineration	CH
9708	Energy recovery from plastic incineration	market for electricity, low voltage	DK
20184	Cardboard packaging incineration	treatment of waste paperboard, municipal incineration	CH
9708	Energy recovery from cardboard incineration	market for electricity, low voltage	DK
19990	Electrical components to waste treatment	treatment of waste electric and electronic equipment, shredding	GLO
19772	Used cables to waste treatment	treatment of used cable	GLO

Annex 5. Inventory table of Ecoinvent processes for a regular shower.

Process #	Component/ material/process	Ecoinvent process	Region code
Manufacturing (Materials + Processing)			
17430	Steel production	steel production, converter, low-alloyed	RoW
16390	Plastic production	polypropylene production, granulate	RoW
7163	Shower manufacturing plastic	injection moulding	RoW
14810	Shower manufacturing metal (steel)	metal working, average for steel product manufacturing	RoW
2029	Cardboard for packaging	corrugated board box production	RER
Transportation			
18150	Transport to retailer freight	transport, freight, sea, container ship	GLO
18094	Transport to costumer truck	transport, freight, lorry >32 metric ton, EURO5	RER
Use stage			
6281	Electricity hot water	heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical	DK
17772	Bathing water	tap water production, underground water with disinfection	Europe without Switzerland
Disposal			
20583	Wastewater treatment	treatment of wastewater, average, wastewater treatment	Europe without Switzerland
12619	Steel treatment mix recycled and landfill	market for scrap steel	Europe without Switzerland
20237	Plastic to incineration	treatment of waste plastic, mixture, municipal incineration	CH
9708	Energy recovery from plastic incineration	market for electricity, low voltage	DK
20184	Cardboard packaging incineration	treatment of waste paperboard, municipal incineration	CH
9708	Energy recovery from cardboard incineration	market for electricity, low voltage	DK

Annex 6. Unit processes in SimaPro (confidential).

Loop shower use per FU configuration

Name	Status	Comment
Loop shower use per FU (family of 4)	None	

Materials/Assemblies	Amount	Unit	Comment
Tap water {Europe without Switzerland}| tap water production, underground water with disinfection | Cut-off, S	17,5	kg	Showering water
Tap water {Europe without Switzerland}| tap water production, underground water with disinfection | Cut-off, S	1,03	kg	Rinse process water
Add			

Processes	Amount	Unit	Comment
Loop shower	1/13260 = 7,54E-5	p	
Cleaning tablet	1/34 = 0,0294	p	
Filter	1/68 = 0,0147	p	
Transport, freight, light commercial vehicle {Europe without Switzerland}| processing | Cut-off, S	0,000257936	tkm	Transport of Loop Shower to customer/FU
Electricity, low voltage {DK}| market for | Cut-off, S	0,067	kWh	Electricity for showering/FU
Heat, district or industrial, natural gas {DK}| heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical | Cut-off, S	3	MJ	Heating water for showering/FU
Heat, district or industrial, natural gas {DK}| heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical | Cut-off, S	0,0991	MJ	Heating water for rinse process/FU
Electricity, low voltage {DK}| market for | Cut-off, S	0,00058	kWh	Electricity for rinse process/FU
Wastewater per FU (family of 4)	1	p	
Add			

Loop shower configuration

Outputs to technosphere: Products and co-products	Amount	Unit	Comment
Loop shower	1	p	
Add			

Outputs to technosphere: Avoided products	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Add							

Inputs

Inputs from nature	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Add								

Inputs from technosphere: materials/fuels	Amount	Unit	Comment
Steel, chromium steel 18/8, hot rolled {RER}| production | Cut-off, S		kg	
Acrylonitrile-butadiene-styrene copolymer {RoW}| production | Cut-off, S		kg	
Polyvinylchloride, suspension polymerised {RER}| polyvinylchloride production, suspension polymerisation | Cut-off, S		kg	
Silicone product {RER}| production | Cut-off, S		kg	
Brass {RoW}| production | Cut-off, S		kg	
Nylon 6-6 {RER}| production | Cut-off, S		kg	
Printed wiring board, through-hole mounted, unspecified, Pb free {GLO}| production | Cut-off, S		kg	
Synthetic rubber {RER}| production | Cut-off, S		kg	
Aluminium, primary, ingot {RoW}| market for | Cut-off, S		kg	
Polyphenylene sulfide {GLO}| production | Cut-off, S		kg	
Polypropylene, granulate {RER}| production | Cut-off, S		kg	
Styrene-acrylonitrile copolymer {RER}| production | Cut-off, S		kg	
Glass fibre reinforced plastic, polyamide, injection moulded {RER}| production | Cut-off, S		kg	
Cable, unspecified {GLO}| production | Cut-off, S		kg	
Polyethylene, high density, granulate {RER}| production | Cut-off, S		kg	
Steel, low-alloyed {RoW}| steel production, converter, low-alloyed | Cut-off, S		kg	
Water pump, 22kW {GLO}| market for water pump, 22kW | Cut-off, S		p	
Copper, cathode {GLO}| copper production, cathode, solvent extraction and electrowinning process | Cut-off, S		kg	
Paraffin {RER}| production | Cut-off, S		kg	
Polyethylene terephthalate, granulate, amorphous {RER}| production | Cut-off, S		kg	
Ultraviolet lamp {GLO}| ultraviolet lamp production, for water desinfection | Cut-off, S		p	
Injection moulding {RER}| processing | Cut-off, S		kg	

Metal working, average for aluminium product manufacturing {RoW}| processing | Cut-off, S		kg		
Corrugated board box {RER}| production | Cut-off, S		kg		
Transport, freight, lorry >32 metric ton, EURO5 {RER}| transport, freight, lorry >32 metric ton, EURO5 | Cut-off, S		tkm		
Transport, freight, lorry >32 metric ton, EURO5 {RER}| transport, freight, lorry >32 metric ton, EURO5 | Cut-off, S		tkm		
Transport, freight, lorry >32 metric ton, EURO5 {RER}| transport, freight, lorry >32 metric ton, EURO5 | Cut-off, S		tkm		
Transport, freight, lorry >32 metric ton, EURO5 {RER}| transport, freight, lorry >32 metric ton, EURO5 | Cut-off, S		tkm		
Transport, freight, lorry >32 metric ton, EURO5 {RER}| transport, freight, lorry >32 metric ton, EURO5 | Cut-off, S		tkm		
Transport, freight, lorry >32 metric ton, EURO5 {RER}| transport, freight, lorry >32 metric ton, EURO5 | Cut-off, S		tkm		
Transport, freight, lorry >32 metric ton, EURO5 {RER}| transport, freight, lorry >32 metric ton, EURO5 | Cut-off, S		tkm		
Transport, freight, lorry >32 metric ton, EURO5 {RER}| transport, freight, lorry >32 metric ton, EURO5 | Cut-off, S		tkm		
Transport, freight, sea, container ship {GLO}| transport, freight, sea, container ship | Cut-off, S		tkm		
Transport, freight, sea, container ship {GLO}| transport, freight, sea, container ship | Cut-off, S		tkm		
Transport, freight, sea, container ship {GLO}| transport, freight, sea, container ship | Cut-off, S		tkm		
Transport, freight, sea, container ship {GLO}| transport, freight, sea, container ship | Cut-off, S		tkm		
Transport, freight, sea, container ship {GLO}| transport, freight, sea, container ship | Cut-off, S		tkm		
Metal working, average for steel product manufacturing {RoW}| processing | Cut-off, S		kg		
Metal working, average for copper product manufacturing {RoW}| processing | Cut-off, S		kg		
Casting, brass {RoW}| processing | Cut-off, S		kg		
Electricity, low voltage {DK}| market for | Cut-off, S		kWh		
Electricity, low voltage {DK}| market for | Cut-off, S		kWh		
Add				

Filter configuration

Outputs to technosphere: Products and co-products	Amount	Unit	Comment
Filter	1	p	
Add			

Outputs to technosphere: Avoided products	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Add							

Inputs

Inputs from nature	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Add								

Inputs from technosphere: materials/fuels	Amount	Unit	Comment
Polypropylene, granulate {RER}| production | Cut-off, S		kg	
Transport, freight, sea, container ship {GLO}| transport, freight, sea, container ship | Cut-off, S		tkm	
Injection moulding {RoW}| processing | Cut-off, S		kg	
Textile, nonwoven polyester {RoW}| textile production, nonwoven polyester, needle-punched | Cut-off, S		kg	
Add			

Outputs to technosphere: Waste and emissions to treatment	Amount	Unit
Waste plastic, mixture {CH}| treatment of, municipal incineration | Cut-off, S		kg
Add		

Cleaning tablet configuration

Outputs to technosphere: Products and co-products	Amount	Unit	Comment
Cleaning tablet	1	p	
Add			

Outputs to technosphere: Avoided products	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Add							

Inputs

Inputs from nature	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Add								

Inputs from technosphere: materials/fuels	Amount	Unit	Comment
Transport, freight, lorry >32 metric ton, EURO5 {RER}| transport, freight, lorry >32 metric ton, EURO5 | Cut-off, S		tkm	Transport from manufacturing to Flow Loop
Chlorine dioxide {RER}| production | Cut-off, S		g	
Add			

Wastewater per FU configuration for Loop shower

Outputs to technosphere: Products and co-products	Amount	Unit	Comment
Wastewater per FU (family of 4)	1	p	

Add

Outputs to technosphere: Avoided products	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment

Add

Inputs

Inputs from nature	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment

Add

Inputs from technosphere: materials/fuels	Amount	Unit	Comment

Add

Inputs from technosphere: electricity/heat	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment

Add

Outputs

Emissions to air	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment

Add

Emissions to water	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment

Add

Emissions to soil	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment

Add

Final waste flows	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment

Add

Non material emissions	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment

Add

Social issues	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment

Add

Economic issues	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment

Add

Outputs to technosphere: Waste and emissions to treatment	Amount	Unit	Comment
Wastewater, average {Europe without Switzerland}| treatment of wastewater, average, capacity 1E9l/year | Cut-off, S	0,0175	m3	Bathing water
Wastewater, average {Europe without Switzerland}| treatment of wastewater, average, capacity 1E9l/year | Cut-off, S	0,00103	m3	Rinsing water

Add

Regular shower use per FU configuration

Name	Status	Comment
Regular shower use per FU (family of 4)	None	

Materials/Assemblies	Amount	Unit	Comment
Tap water {Europe without Switzerland}| tap water production, underground water with disinfection | Cut-off, S	96	kg	
Add			

Processes	Amount	Unit	Comment
Regular Shower	1/13260 = 7,54E-5	p	
Heat, district or industrial, natural gas {DK}| heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical | Cut-off, S	9,25	MJ	
Wastewater per FU	1	p	
Add			

Regular shower configuration

Outputs to technosphere: Products and co-products	Amount	Unit	Allocation %	Comment
Regular Shower	1	p	100 %	
Add				

Outputs to technosphere: Avoided products	Amount	Unit	Comment
Electricity, low voltage {DK}| market for | Cut-off, S	1*18*0,25/3,6 = 1,25	kWh	Energy recovery from cardboard incineration
Electricity, low voltage {DK}| market for | Cut-off, S	1*42,5*0,25/3,6 = 2,95	kWh	Energy recovery from plastic incineration
Add			

Inputs

Inputs from nature	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Add								

Inputs from technosphere: materials/fuels	Amount	Unit	Comment
Steel, low-alloyed {RoW}| steel production, converter, low-alloyed | Cut-off, S		kg	
Polypropylene, granulate {RoW}| production | Cut-off, S		kg	
Injection moulding {RoW}| processing | Cut-off, S		kg	
Metal working, average for steel product manufacturing {RoW}| processing | Cut-off, S		kg	
Corrugated board box {RER}| production | Cut-off, S		kg	
Transport, freight, sea, container ship {GLO}| transport, freight, sea, container ship | Cut-off, S		tkm	Transport from manufacturer to Denmark
Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport, freight, lorry >32 metric ton, EURO5 | Cut-off, S		tkm	Transport within Denmark to customer
Add			

Outputs to technosphere: Waste and emissions to treatment	Amount	Unit	Max	Comment
Waste reinforcement steel {CH}| market for waste reinforcement steel | Cut-off, S		kg		
Waste plastic, mixture {CH}| treatment of, municipal incineration | Cut-off, S		kg		
Waste paperboard {CH}| treatment of, municipal incineration | Cut-off, S		kg		

Wastewater per FU configuration for regular shower

Outputs to technosphere: Products and co-products	Amount	Unit	Allocation %	Comment
Wastewater per FU	1	p	100 %	
Add				

Outputs to technosphere: Avoided products	Amount	Unit	Comment
Add			

Inputs

Inputs from nature	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Add								

Inputs from technosphere: materials/fuels	Amount	Unit	Comment
Add			

Inputs from technosphere: electricity/heat	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Add							

Outputs

Emissions to air	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Add								

Emissions to water	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Add								

Emissions to soil	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Add								

Final waste flows	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Add								

Non material emissions	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Add								

Social issues	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Add								

Economic issues	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Add								

Outputs to technosphere: Waste and emissions to treatment	Amount	Unit	Max	Comment
Wastewater, average {Europe without Switzerland}| treatment of wastewater, average, capacity 1E9l/year | Cut-off, S	96/1000 = 0,096	m3		
Add				