The wear2wear^{TM} textile loop

Life Cycle Assessment

Report

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Contents

Summary

The wear2wear^{TM} production system consists of multiple companies working together along the textile supply chain. They have designed a system that produces a work-wear jacket based on Circular Economy (CE) principles. The Life Cycle Assessment (LCA) conducted in this study analyses this production system among a wide range of impact categories and compares it to a traditional, linear production system. The results show, that a thoughtful CE system design approach can result in significant lower environmental impacts than a linear production system. Additionally, the assessment illustrates the necessity of going beyond simple comparisons of one product to another when it comes to CE systems. CE products require a wider system analysis approach that takes into account multiple product systems that have interconnected material flows through reuse, remanufacture, and recycling practices.

1. Introduction

Today's economy is mostly of a linear nature. Products are often designed for a single lifetime only, whereupon they are mostly either incinerated or landfilled (Geissdoerfer, Savaget, Bocken, & Hultink, 2017). Opposite to this linear economy, the Circular Economy (CE) promises to create economic value while lowering environmental impacts of production through reducing resource consumption, reusing products, and recycling materials (Desing et al., 2020; Stahel, 2016). To fulfill this promise, common CE approaches include strategies to (1) close production loops of biological (organic) or technical (inorganic) cycles (2) extent the lifetime of products (3) use renewable energy for production and (4) integrate recycled and biodegradable materials (MacArthur, 2013). These approaches are inspiring companies around the globe to implement such CE strategies and design products and services in accordance. The textile sector is one of the industries that can extraordinary profit from those strategies, as of today approximately 73% of all textiles produced worldwide are either incinerated or landfilled, causing dramatic environmental consequences including greenhouse gas emissions (GHG), water scarcity, and land-use change (MacArthur, 2017).

The Swiss-based textile company Schoeller[1] started recently an initiative to introduce the CE approach in an innovative partnership called wear2wear[2]. This initiative is a common effort of renowned European companies that have committed to run their businesses in a sustainable and environmentally-friendly manner and for this, taken on the task of manufacturing new (functional) textiles solely from recyclable and single-origin materials. Each partner makes its individual contribution to close the textile loop. Depending on the field of application, such functional textiles need to meet high standards and requirements related to waterproofness, breathability, protection and comfort. In order to ensure that the raw material loop closes, these textiles need to be recycled at the end of their life cycle in order to manufacture new, upcycled apparel products. In addition, the entire textile production is performed according to the bluesign® system[3], thus ensures also a responsible processing of dyes and chemicals with an optimum use of energy and resources.

While this CE approach sounds promising in theory, it is far from obvious if it can make a significant contribution to the design of a more environmental-friendly and thus sustainable economy. Several limitations exist, that can prevent the environmental superiority of the CE approach (Korhonen, Honkasalo, & Seppälä, 2018). For example, a high percentage of recycled materials in a product could reduce the lifetime or reusing components of a product can result in more emissions due to additional transport needed for collecting products and bringing them back to the producer (Zink & Geyer, 2017). Hence, in order to cope with the uncertainty that comes along with applied and new CE strategies, Life Cycle Assessment (LCA) as a tool can be applied to systematically assess the environmental performance of products and derive conclusions which CE option is most suitable from an environmental point of view (Hauschild, Jeswiet, & Alting, 2005). For the wear2wear project, we applied LCA in order to consistently

[1] *https://www.schoeller-textiles.com/*

[2] *https://www.wear2wear.org/*

[3] *https://www.bluesign.com/*

analyze the entire life cycle of the wear2wear textile loop. The aim of this study is to understand the environmental effects of designing a textile with CE approaches and comparing it to a similar product, made of a traditional linear production process.

1.1 The wear2wear^{TM} loop

The wear2wear loop includes the steps illustrated in figure 1, which are described in the following.

Figure 1. The wear2wear production loop. (www.wear2wear.org, 2020).

In a first step (shown in light green in figure 1), fiber materials are produced out of recycled granulate as base material for the wear2wear textile loop. The granulate is a polyester polymer and is made out of polyethylen-terephthalat (PET) bottles.

In the second step, those fibers serve as the basis for the outer material of the 3-layered fabric while the membrane and lining is made of virgin polyester, which is partially produced with a pre-consumer waste content. The fabric is produced fluorocarbon-free and uses C-0 chemistry where possible to ensure water- and dirt-repellent properties. The membrane is highly breathable, wind- and waterproof but water vapor permeable, and regulates the climate. Used is a PTFE and PFC-free material. The lamination of the membranes, with polyester-based outer and lining materials, leads to single-origin polyester composites. By today, no mixed materials are used in the loop – e.g. no cotton/polyester blend that would be difficult to recycle – thus enabling a straightforward recycling process in which the garments can be melted down into one piece thanks to a uniform melting point of all the membranes and fabrics.

Third, the garment is designed on a recycling-based concept known as Design-to-Recycle and creates the basis for sustainable products. For the products, a selection of materials with the highest degree of purity, as well as a simplified design with a minimum amount of seams and trims is developed. This ensures that the individual components of the textiles can be separated with a technically-viable and cost-effective process once they are used. Apart from the integration of recyclable materials and ingredients, the focus is on already recycled materials to guarantee the upcycling character. An innovative sewing yarn known as textile screw is used for the seams to provide a sustainable solution to separate two different textiles from each other (here: the zipper from the fabric).

Forth, the garment is manufactured in a production facility within Europe to minimize transportation within the cycle and to the market. Thanks to a design with fewer seams and a selection of compatible ingredients, manufacturers are in a position to sustainably supply circular clothing and products that can be re-utilized as raw material components and resources after their life cycle.

Fifth, the garments are then sold or rented to a supplier. The latter is common in the field of Personal Protective Equipment. Customers rent protective garments for a certain period from their clothing supplier. The clothing supplier takes care of the laundry service during the use-phase and replaces garments by the end of their life cycles. The washing process of the garment can be done with water or CO_2. Contrary to washing with water and the necessary mechanical stress, CO_2 penetrates in the respective washing process the deep fibers and the membranes without damaging the properties of the textile.

Sixth, the garments are collected at the end of life (EoL). The used textiles are examined, cleaned, repaired, and sorted according to the material category. During the sorting process, apart from removing impurities, each piece of used clothing is analyzed in accordance with its wearability and marketability in order to determine the economic viability. The screening and sorting process is carried out either through the human eye or by using machine-controlled infrared spectroscopy. Through these steps, the industry partners ensure that the used textiles are optimally prepared for the subsequent recycling process.

Lastly, the recycler (i.e. the same company that makes the fibers from PET bottles in the first step) removes the zipper by dissolving the textile screw simply in hot water. The zipper can be used again in a new garment. Next, the remaining textile is shredded into small fragments or fiber structures, which are then turned into granulate through supplemental polymer melting processes. This granulate can again be used to make new fibers and the loop starts again at the second step. The polyester that has been lost in the recycling process is replaced by new granulate made from PET bottles.

2. Methodology

LCA represents the most comprehensive tool today able to obtain a full system perspective of the environmental impacts of any product or service. In this chapter, the chosen method and procedures are explained in detail.

2.1 Life Cycle Assessment

To record and assess the effects of human activities on the environment and the potential for optimization, LCA is the method of choice for most scientists, business and governments. Any holistic eco-assessment method needs to allow to systematically consider multiple environmental effects on water, land, and air along the entire value chain of a product or service and should go beyond a simple assessment of one impact category (e.g. CO_2 emission). A comprehensive LCA meets those needs by:

- Quantifying various environmental impacts
- Taking into account the entire life cycle
- Relying on high scientific standards
- Being transparent and accepted

Today, a standard for conducting a LCA exist, issued by the International Standards Organization (ISO, 2006). This ISO standard prescribes the procedure in four steps (see figure 2):

> *"defining goal and scope of the assessment, compiling an inventory of relevant inputs and outputs of a product system; evaluating the potential impacts associated with those inputs and outputs; interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study."*

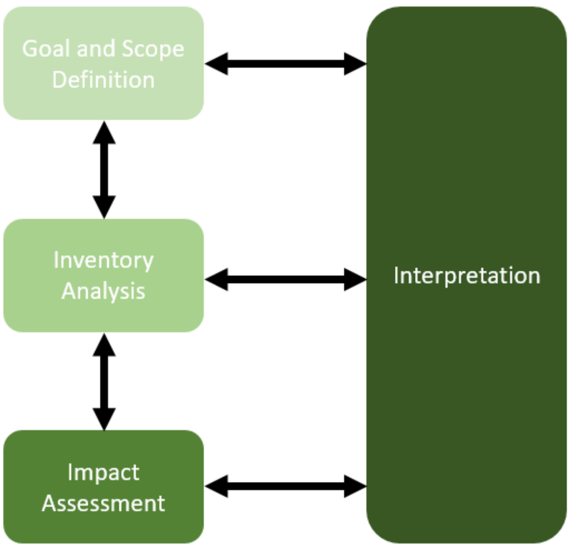

Figure 2. Life Cycle Assessment approach. (Own illustration, 2020).

In the following chapters, each LCA step is described in terms of the wear2wear garment.

2.1.1 Goal and Scope

The objective of the performed LCA study is to assess the environmental consequences of a closed loop production system (the wear2wear textile) in comparison to a traditional, linear production. Study object is a waterproof, breathable jacket made of recycled PET bottles, which is again recycled at the EoL. We compare this wear2wear garment to a linear produced product that has the exact same components and fulfills the same functionalities. The difference is that this product does not have the circular elements of the wear2wear textile. We do model the product of comparison in this way, in order to represent a classical, linear textile product (MacArthur, 2017) and to find out only the consequences of implementing circular elements.

The scope of the performed LCA study includes all lifecycle stages of the finished product from "cradle to grave" following the ISO standard 14040 and 14044 for LCA. As the central idea of the wear2wear project is to establish a closed loop production system, we could even speak of a "cradle to cradle" process here, as the EoL step is not an incineration (and thus final process step) but a recycling process that is the beginning of a (next) product life cycle.

Figure 3 illustrates the system boundaries of this study. They are identical for both the linear and circular product system except for the content of the processes *PES granulate* and *End-of-Life treatment*. The wear2wear system uses PET bottles as a resource and recycles the garment at the EoL, while the linear system uses virgin PES as a resource and has an incineration process at the EoL. We include all direct material and energy in- and outputs (up- and downstream) for all life cycle phases (dark boxes) from all partner companies in the wear2wear system as depicted in figure 3. The grey boxes are modeled based on generic data from the ecoinvent data. This is due to limited access to data from the corresponding sub-contractors. Furthermore, we include the transport between all production stages.

2.1.2 Inventory analysis

The *functional unit* – the measure of the service delivered by a product – is defined as *"the use of a three-layer-laminate jacket, repellent to water and permeable to heat and moisture for 4 years"*.

The product system of the wear2wear loop simply consists of all the steps necessary to produce the final garment including the use- and EoL phase. The garment is a black-colored, functional three-layer laminate jacket designed to have the following features:

- Water repelling
- Permeable to heat
- Permeable to moisture

We always assume size L for the garments. A natural fiber such as cotton is no option for the product to compare to, because natural fibers do not fulfill the features mentioned above. We have used two general data sources for this study. Mainly we collected case-specific unit process data from the partners of the wear2wear project. Secondly, we used data from the ecoinvent database for processes that are outside of the partner's direct access such as grid electricity mixes, chemical production, and transportation.

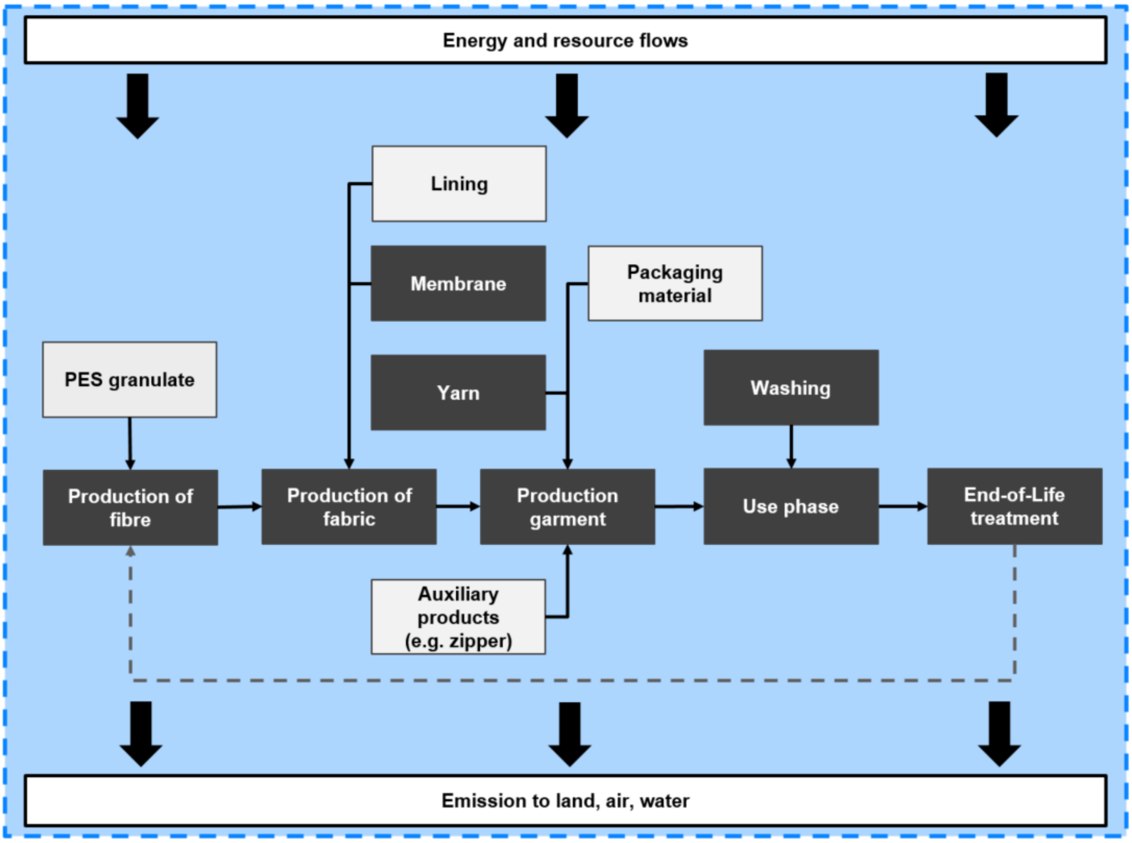

Figure 3. System boundaries in order to model the use of a three-layer-laminate jacket, repellent to water and permeable to heat and moisture for 4 years.

2.1.3 Allocation

The modeling of the wear2wear product system requires the application of allocation rules. The question of allocation in LCA arises when the product system under investigation uses/ delivers energy and material flows of/ for others product systems.

The wear2wear garment is made from recycled PET bottles. The production of those PET bottles have caused environmental impacts themselves. It can be debated, if the used bottles are considered waste and thus do not bear any environmental burden for the garment (so-called cut-off approach) or if a part of the burden are allocated to the garment. In the latter case, different approaches exist for allocating burden from recycled materials. The European Commission recommends in its Product Environmental Footprint (PEF) Guide, to use a 50/50 model for open loop recycling. This might be arbitrary for some industries, but it is consistent. For the wear2wear product system, it makes sense to allocate part of the environmental burden of the PET bottles to the garment, as PET bottles are in general a well-recycled product and cannot considered waste at the EoL. Thus, we choose the 50/50 rule as the default method in this study.

Since the allocation method may influence the outcomes of LCA, we perform a respective sensitivity analysis in this study (see section 4.3).

2.1.4 Impact assessment

Within the LCA procedure, the third step is then the assessment of the in- and outputs of the life cycle inventory (LCI) with regard to their effects on the environment. To determine those effects, all the in- and outputs of the product system must be translated to environmental impacts with the support of so-called characterization factors (CF). CF express how much a single unit of a determined substance contributes to a specific impact category. For example, how much one kg of CO_2 contributes to global warming. This characterization is done by weighting the individual substances against each other according to their potential for environmental impacts with regard to a lead substance. For example, greenhouse gases such as e.g. methane (CH_4) or nitrous oxides (N_2O) are translated into the corresponding amount of CO_2 having the same global warming potential and are expressed in kg CO_2-equivalent. CF exist for various impact categories and are constantly developed and updated. In this study, we use the European Environmental Footprint (EF) methodology, one of the most recent methods covering a range of different impact categories. In total, eleven impact categories are included in this study:

- Global warming potential, 100 years (GWP)

Influence on the climate due to the emission of climate-relevant substances such as carbon dioxide (CO_2), laughing gas (N_2O) or methane (CH_4) over a time horizon of 100 years.

- Ozone depletion potential, 100 years (ODP)

ODP quantifies the destructive effects on the stratospheric ozone layer over a time horizon of 100 years.

- Human toxicity (cancer effects)

Effect of emissions on human health expressed by the estimated increase in morbidity in the total human population per unit mass of a chemical emitted.

- Ecotoxicity

Effects of emissions on ecosystems expressed by an estimate of the potentially affected fraction of species (PAF) integrated over time and volume per unit mass of a chemical emitted (PAF m^3 year/ kg).

- Respiratory inorganics

Accounts for the adverse health effects on human health caused by particulate matter (PM) emissions such as NO_x, SO_x and NH_3.

- Ionizing radiation

Quantification of the impact of ionizing radiation on humans in comparison to Uranium 235.

- Photochemical ozone formation

Contribution to the formation of ozone (summer smog) due to the emission of substances such as hydrocarbons and nitrogen oxides.

- Acidification

Contribution to the acidification of soils and water, for example through nitrogen oxides and sulfur dioxide.

- Eutrophication

Change in the nutrient balance in soil and water through the introduction of compounds, which contain nitrogen and phosphorus.

- Land use

Related to the use and transformation of land by activities such as agriculture, mining and roads.

- Water scarcity

Relative available water remaining (AWARE) per area in a watershed after the demand of humans and aquatic ecosystems.

2.2 Assumptions and data quality

Due to the complexity of this study and the amount of data that is available to the involved companies, we make some general assumptions transparent in this study. First, we distinguish between case-specific unit process data (collected via project partner) and general data (mainly from "public" data sources and scientific literature). In general, the data quality of the production processes of the wear2wear project partner is very high. Up- and downstream manufacturing processes were modelled based on the LCA database ecoinvent[4]. The following table shows the most important assumptions that are applied in modelling the textile systems.

[4] *https://www.ecoinvent.org/*

	Assumption	*Explanation*	*Source*
Lifetime of the garment	4 years	Based on expert judgment	Schoeller
Allocation of PET bottle impacts	50%	Based on the PEF recommendation	PEF
Number of production loops with the same PES material	3	The PES material made from the PET bottle can be recycled three times, before the material does not meet the garment quality standard anymore	Weiske/ Schoeller
PET bottle origin	Bottles are locally supplied	Germany has an advanced PET bottle recycling system in place	Weiske
PET bottle sorting efficiency	75 %	Parts of the bottle cannot be used for the garment (unwanted color fraction, labels, non-PET material)	Shen, Worrell, and Patel (2010)
Dismantling of the wear2wear textile at the EoL	95 %	Based on expert judgment	Weiske
Input for the recycling process	High quality and pure PET bottles	For now, the recycler uses a mechanical recycling process. Thus, the PET bottles need to be of high quality (pure, transparent)	Weiske
Washing	3x in 4 years	-	CWS
Energy supply	Country specific energy grid mixes	Ecoinvent provides those datasets	Ecoinvent
Packaging	Only the packaging used for the final garment is considered	Other packaging material used in other stages of production are considered neglectable	Schoeller

Table 1. Data assumptions and their sources.

3. Life cycle inventory

In the life cycle inventory (LCI) quantitative statements are made about the product life cycle. For this purpose, the input data into the production system are collected. These include among others raw materials, auxiliary products, energy requirements, water, and transportation. The LCI analysis is a purely descriptive model without any evaluation. However, each LCI includes implicit assumptions that result from the previously defined system boundaries and allocation method.

3.1 Uniform data for both the circular and linear garment

As stated in the methodology chapter, we compare a circular with a linear produced garment. The garment itself is in both scenarios the same, i.e. it contains the exact same amount of materials (e.g. same amount of polyester). The specific components of one black garment size L are given in the table 2 below. Three elements vary between the two garments. First, the fibers that make up the outer material are made from PET bottles whereas the linear version utilizes virgin polyester. Secondly, the zipper is only removed and reused in the wear2wear system. And thirdly, the linear garment is incinerated completely and not recycled. The packaging of the garment (PE film) has been included (weight and material measured in the lab).

	Amount	*Unit*	*Material*	*Weight (g)*
Outer material	1.55	m^2	(partly recycled) PES	233
Membrane	1.55	m^2	Virgin PES	19.7
Lining	1.55	m^2	Virgin PES	47
Glue	1.55	m^2	PU	10.6
Zippers	-	-	PA	66
Yarn	400	m	PVA	3.3
Magnets	4	pieces	Ferrite	5
Shank	8	pieces	PA	2.4
Buttons	6	pieces	PA	3
Sum	**-**	**g**	**Mix**	**390**

Table 2. Components of the garment.

Furthermore, the transportation routes of both product systems are similar, as we assume the same supply chain and mode of transport. The only differences emerge due to the divergent input materials (PET bottles vs. virgin polyester) and EoL processes (recycling vs. incineration). The following table 3 gives an overview of the transport distances between each production facility and the type of transport. The distances are taken from Google Maps for all truck transport. For the ship distances, we use the website *www.ports.com*. Flight distances are provided by *www.distance.to*. The incinerator at the EoL (for the reference garment) is assumed to be locally stationed.

	Garment	*Type of transport*
Transport of PET bottles to fiber producer	100 km	*Truck*
Transport of fibers to fabric producer	500 km	*Truck*
Transport of membranes to fabric producer	400 km	*Truck*
Transport of lining to fabric producer	9'600 km	*Plane*
Transport of fabrics to garment manufacturer	2'500 km	*Truck*
Transport of zipper to garment manufacturer	50 km	*Truck*
Transport of garment to retailer	1'200 km	*Truck*
Transport to customer on average (one way)	1000 km	*Truck*
Transport of garment for washing during use-phase	200 km	*Truck*
Return of garments to recycling plant	1000 km	*Truck*

Table 3. Transport distances of each production process.

3.2 Specific data for the wear2wear™ garment

Two processes in the product system of the wear2wear garment are entirely different to the linear product system: the *resource extraction* and the *recycling* process.

The *resource extraction* process consists of (i) the collection of PET bottles and (ii) their processing to granulate. For the moment, the partner company responsible for this step uses a mechanical recycling process. Because the quality of the recycled granulate depends heavily on the purity of the waste stream, the recycler only uses high quality PET bottles where impurities are removed before entering recycling. This ensures that the recycled granulate has a similar quality as virgin material. For the recycling process itself, the main inputs are water, energy and the PET bottles. The material efficiency is 75% as some parts of the bottle cannot be utilized (e.g. bottle top, labels, colored fraction) and losses occur in the process (Shen et al., 2010). Note that only the outer material of the fabric is made from recycled PET bottles. The lining and membrane are still based on virgin PES material.

The *recycling* process of the wear2wear loop is the last process in the life cycle of the garment. It consists of two steps. First, the garment is dismantled (5% losses). Hereby, the yarn is dissolved in hot water and the zipper is removed, leaving just the fabric. In the second step, the fabric is shredded (95% efficiency) before it enters the polymer melting process. Water and electricity are the main inputs into the melting process together with the shredded fabric. The material efficiency of the melting process is 99%. Losses occur due to impurities (mostly PU glue) and the process efficiency.

3.3 Specific data for the linear production garment

The linear produced garment has two specific processes like the wear2wear garment. As explained in the methodology chapter, this garment is made of virgin PES as the standard market product in today's linear economy. Thus, the PES must be produced prior to the garment manufacturing. PES is made from the petroleum by-product alcohol and carboxyl acid (Ashby, 2012). They are combined by polymerization to monomers and stretched into long fibers. Detailed data about the production process of PES is available in the ecoinvent database.

The second specific process of the linear produced garment is again the EoL process. According to the EllenMacArthur Foundation, 85% the global material flow of clothing is either landfilled or incinerated at the EoL (MacArthur, 2017). We assume that our garment is incinerated in a modern municipal waste plant with energy recovery. This dataset is available in the ecoinvent database.

4. Results

In this chapter, we display the results based on the data we have collected from partner companies and the assumptions made in the previous part. For establishing the system model, we have made use of the LCA software SimaPro.

4.1 Comparison with the linear production system

The circular wear2wear system is given in figure 4 on the next page. Three production loops are illustrated with different colors. The blue cycle is the first production loop. Here, the PET bottles enter for the first time the system with 642.3 g. The efficiencies of each production step are given in the right lower corner of each box. The PET bottles are transformed into fibers, which are manufactured to a fabric by adding the lining, membrane, and polyurethane (PU) glue. Adding the auxiliary products, the fabric is assembled into a ready-to-wear garment. After the garment is delivered to the costumer, the retailer washes it in an industrial plant as a service. In the entire lifetime of the garment (four years), it is washing three times. After the use-phase, the zipper is dismantled for reuse in the second production loop (red boxes). The remaining fabric is shredded and the PES is re-granulated by a polymer melting process to enter the second loop. The entire second loop is similar to the first one, just without the zipper production (as it enters from the first cycle) and with only 147.2 g of newly produced PES from PET bottles (the amount needed to "fill up" for the lost PES in the first loop). At the EoL of the second loop, the garment is recycled again and the same amount of PES and the zipper are reused for a third production loop (green). The third loop is equal to the second one except the yellow marked box. That box represents the incineration process at the EoL after the third use-phase as the PES and the zipper are worn out and their quality is insufficient to meet the quality standard of the garment anymore. They must be disposed. Only the "fresh" PES that entered in the second and third loop can be recycled again.

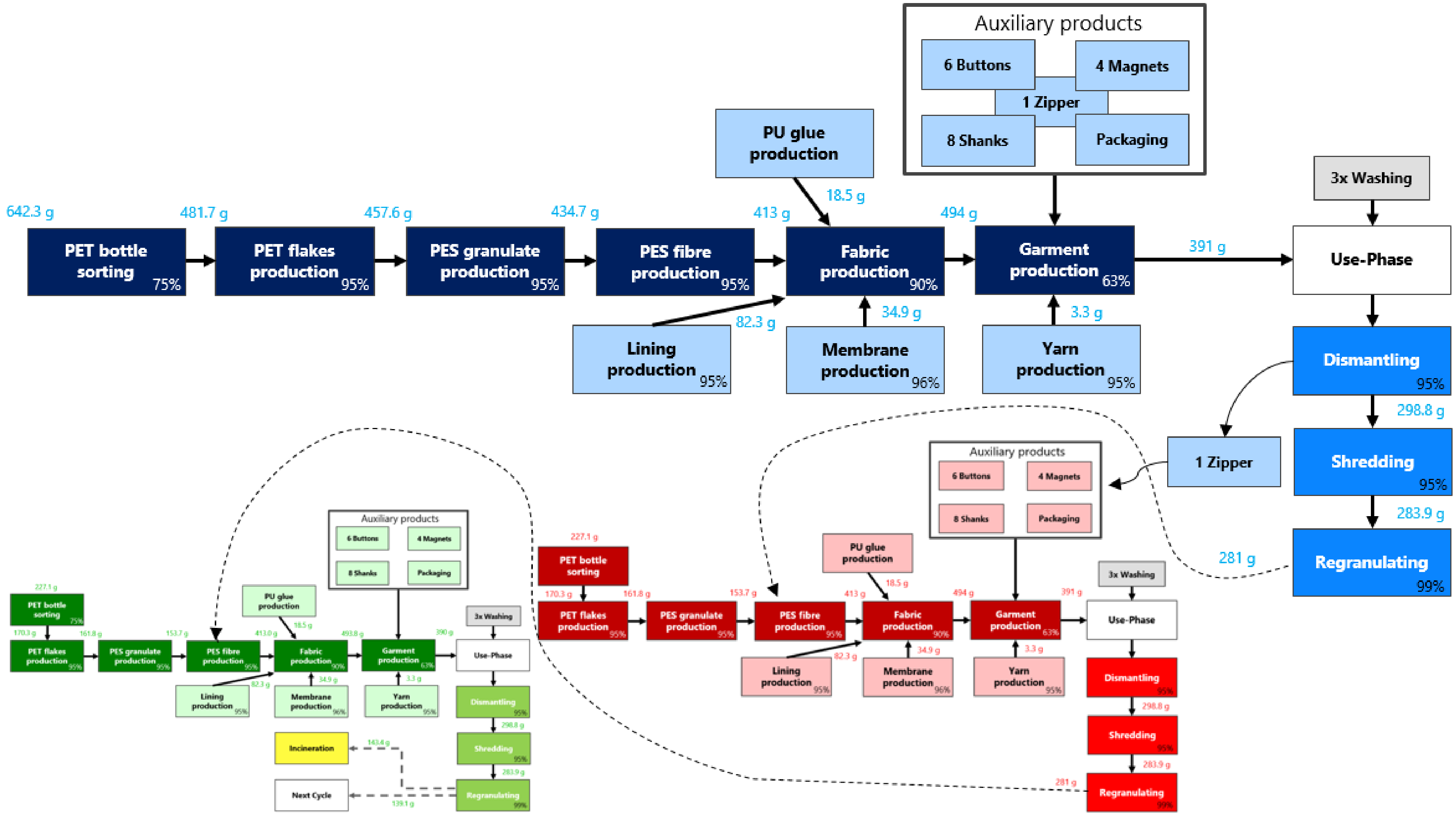

Figure 4. The wear2wear system divided into three production loops.

For comparison, the linear garment has the same components as the wear2wear garment and is produced in the same way. Therefore, the system shown in figure 5 is very similar to the wear2wear system above. The differences are marked by red circles, namely the different primary input material (not PET bottles but virgin PES), the non-reuse of the zipper, and the incineration process at the EoL.

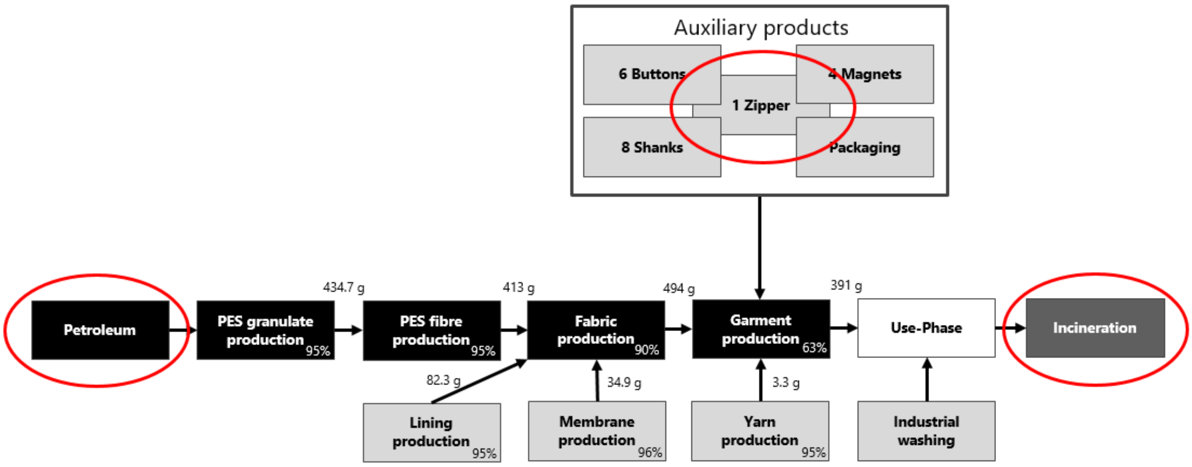

Figure 5. The linear production system with the three main differences to the wear2wear system marked by red circles.

Due to the interconnectedness of the wear2wear system, we cannot simply compare the circular and linear product systems. Instead, we compare the average impacts of the three wear2wear production loops to one linear production system. In this way, we are able to capture the differences of the wear2wear production loops. This leads to the results in figure 6 below. Among all eleven impact categories, the wear2wear system scores lower in comparison to the linear garment, ranging from -25% for GWP to more than -50% for the effects on human health and water use.

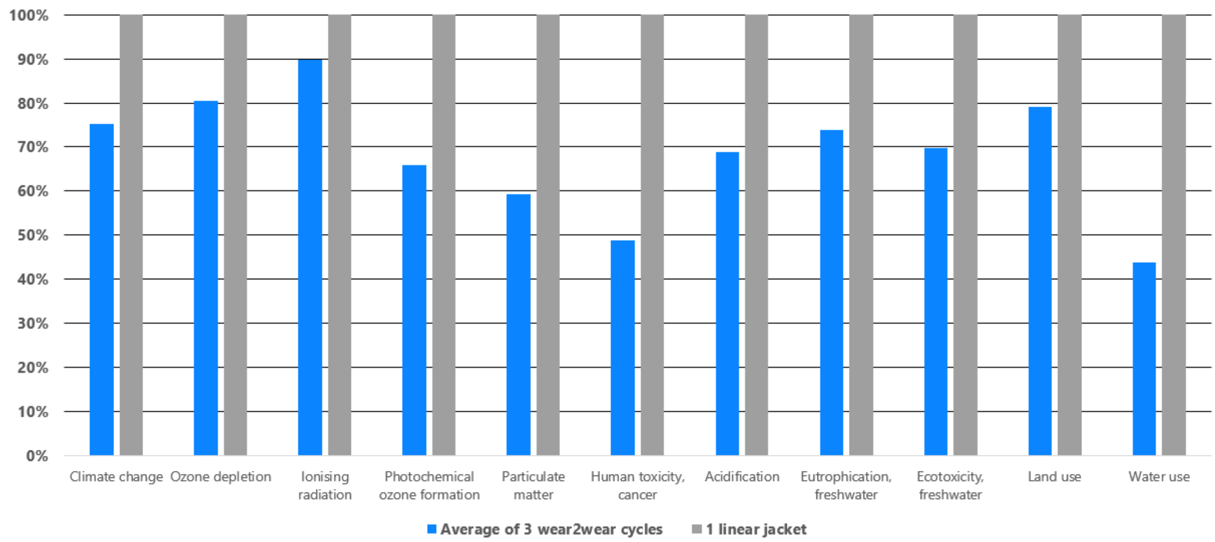

Figure 6. Impact assessment comparison between circular and linear garment.

The main reasons why the wear2wear system performs better is exemplified by the climate change impact category. Figure 7 shows the GHG emissions divided into the five categories energy use, material production, transportation, washing, EoL. While the wear2wear system shows slightly higher GHG emissions for energy use (due to increased energy demand for recycling) and transportation (due to longer routes for returning the garment to the recycler), it has significant smaller GHG emissions in the categories material production (because less primary production is needed) and EoL (due to recycling activities).

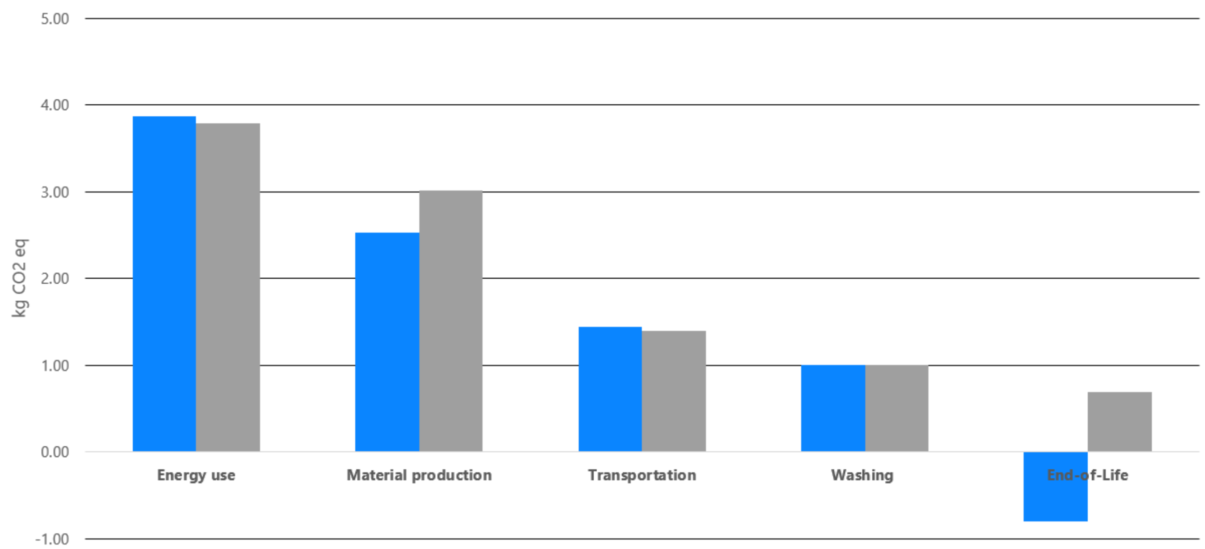

Figure 7. Comparison of GHG emissions between circular (blue) and linear garment (grey) divided into five categories.

4.2 Analysis of the wear2wear™ system

Due to the interconnectedness of the wear2wear system, we included all three production loops in our analysis as explained before. Those three production loops vary in their structure and impacts generated. This is highlighted with figure 8, where the relative impacts of each production loop for the eleven impact categories is shown. The colors corresponds to those in figure 3 (blue: first loop; red: second loop; green: third loop). The first loop scores highest in 8 out of 11 categories. The reason is that the first loop requires PET bottles as an input (which do not enter the system burden free) and the production of the zipper. Opposite, the second loop reuses the zipper from the first loop and recycles the PES material so less PET bottles are required. The third loop also reuses the zipper and PES material, but it does not include a full recycling of the fabric at the EoL, because the PES from the first loop is worn out and cannot be recycled completely (only the PES that is made from PET bottles in the second and third loop). Thus, the second loop scores in all categories the lowest as it has all three elements that contribute to a lower impact: reuse of zipper, input of recycled PES, recycling at the EoL.

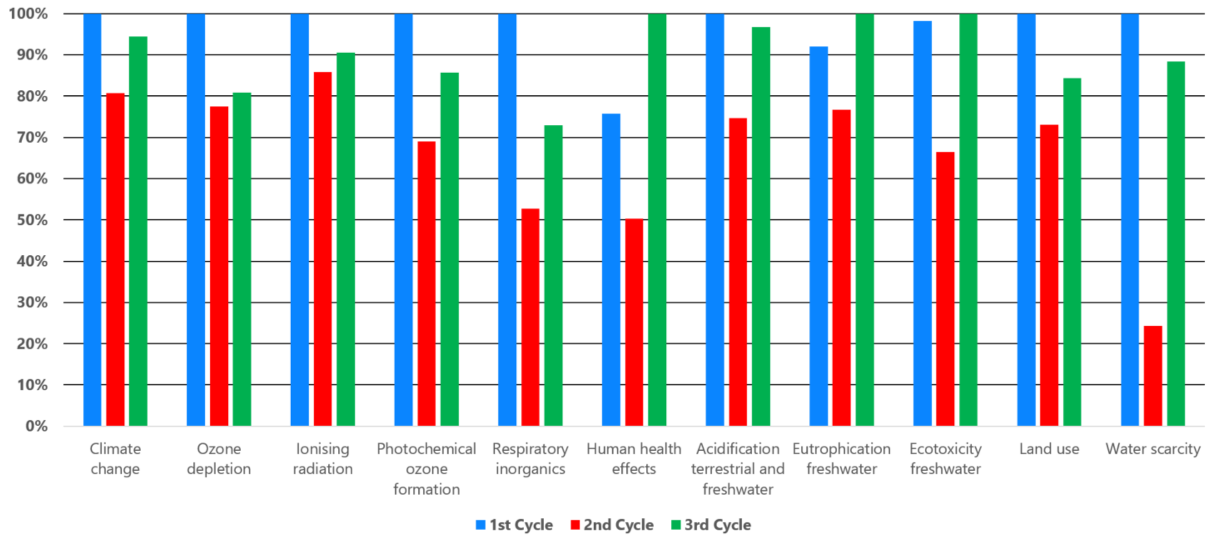

Figure 8. Comparison of the three wear2wear production loops.

Furthermore, we have analyzed the first production loop (blue) more deeply to get an understanding, how the overall impacts per category are composed of. We have divided the overall impacts of each category into five activities as shown in figure 9. As the results show, the activities of energy use, material production, and transportation dominate the graph.

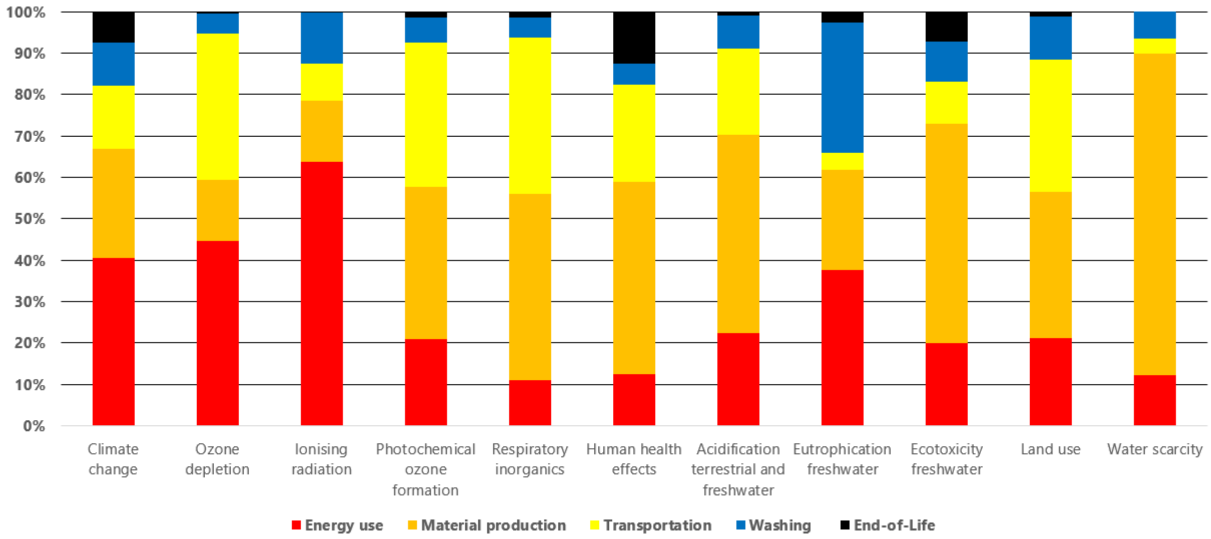

Figure 9. Impacts per category divided into activities.

4.3 Sensitivity analysis

A sensitivity analysis is used to check the robustness of the results and their sensitivity to variations in assumptions and data uncertainties. Two sensitivity analysis have been established in the frame of this study here – (i) the allocation method of the PET bottle production impacts, and (ii) the number of cycles possible for the wear2wear garment.

PET bottle allocation. Instead of having a 50% allocation of the bottle production impacts, the bottles were now entering the wear2wear system burden free. The results show, that the changes per impact category are less than 1% on average. The impacts generated by the bottle production are, compared to the overall impacts of the wear2wear system, insignificant and changing the allocation method does not significantly influence the results.

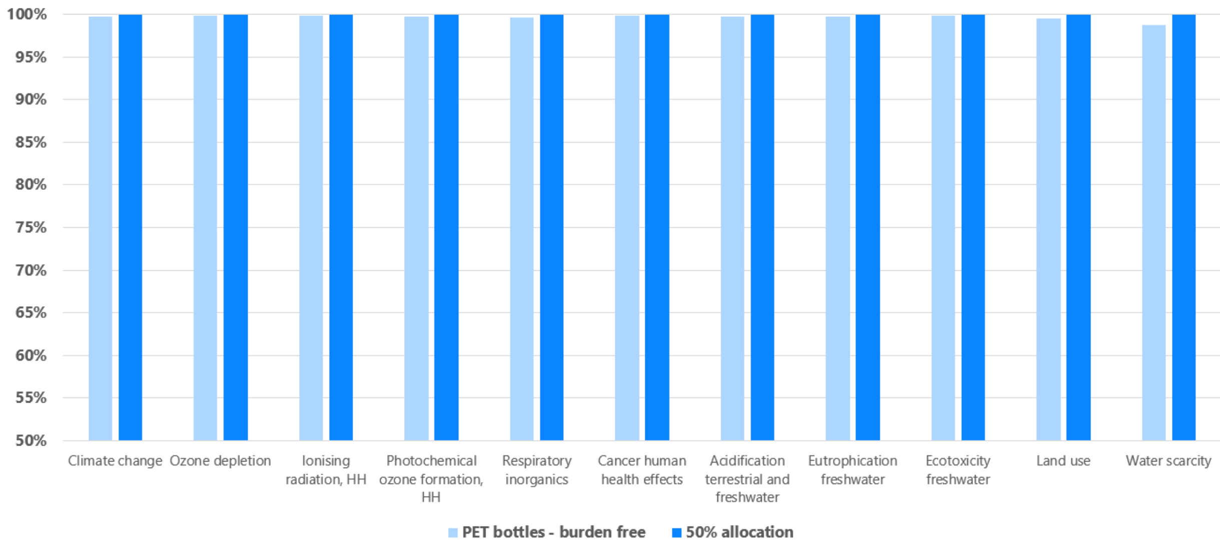

Figure 10. Impact differences of overall wear2wear system when PET bottles come burden free or with a 50% allocation. Own illustration (2020).

Number of loops with same PES material. We deviate the number of loops that are possible with the same PES in two scenarios: In one scenario, we assumed that only two loops are possible and in another, that four can be done with the same PES. The results are given in the following figure 11. On average, the impacts increase by 9.3% for the entire wear2wear system, if only two loops are possible with the same PES. If the PES lasts for four instead of three loops, the impacts on average decrease by 3.7%.

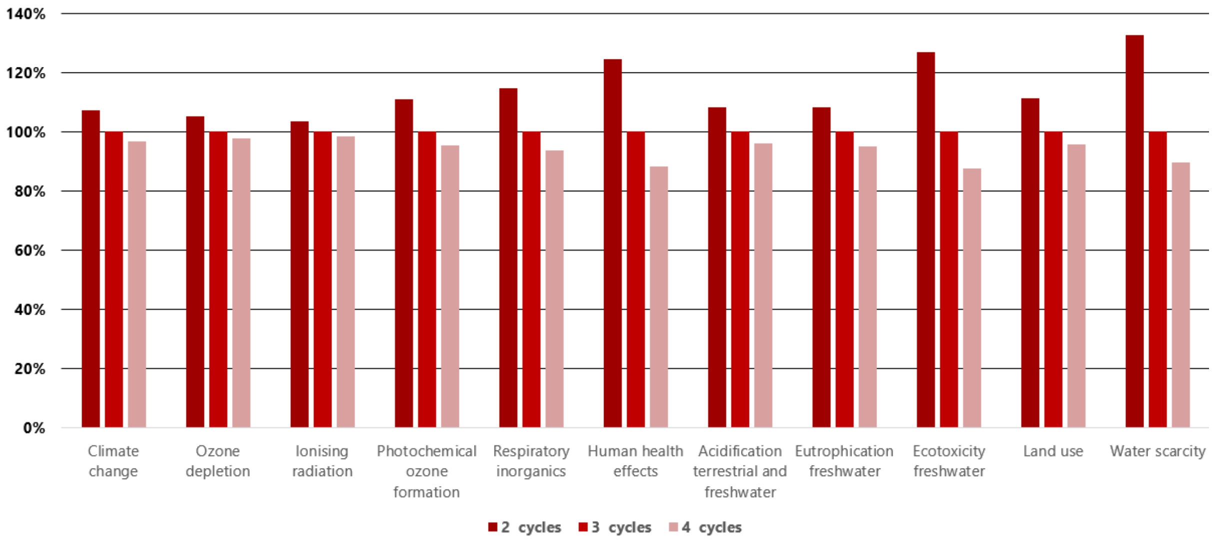

Figure 11. Impact differences of overall wear2wear system when the number of production loops utilizing the same PES de- and increases. Own illustration (2020).

Therefore, it can be concluded here, that the number of loops utilizing the same PES again, has especially an influence if this number decreases. The partner companies should monitor this parameter of the production system closely. How the PES reacts if the recycling process moves from a mechanical to a chemical process should also be subject to further studies.

4.4 Outlook – Unlimited loops with virgin PES material

The wear2wear production system is still under development and the partner companies involved are still experimenting along the supply chain. Especially the recycling scheme might be subject to major changes. Different options are still discussed to keep the quality of the PES high. One option is to inject virgin PES instead of recycled PET from the second loop on (red part in figure 12). This improves the overall quality of the resulting PES allowing to extent the number of possible loops considerably. We have therefore adjusted the wear2wear system as shown in figure 12.

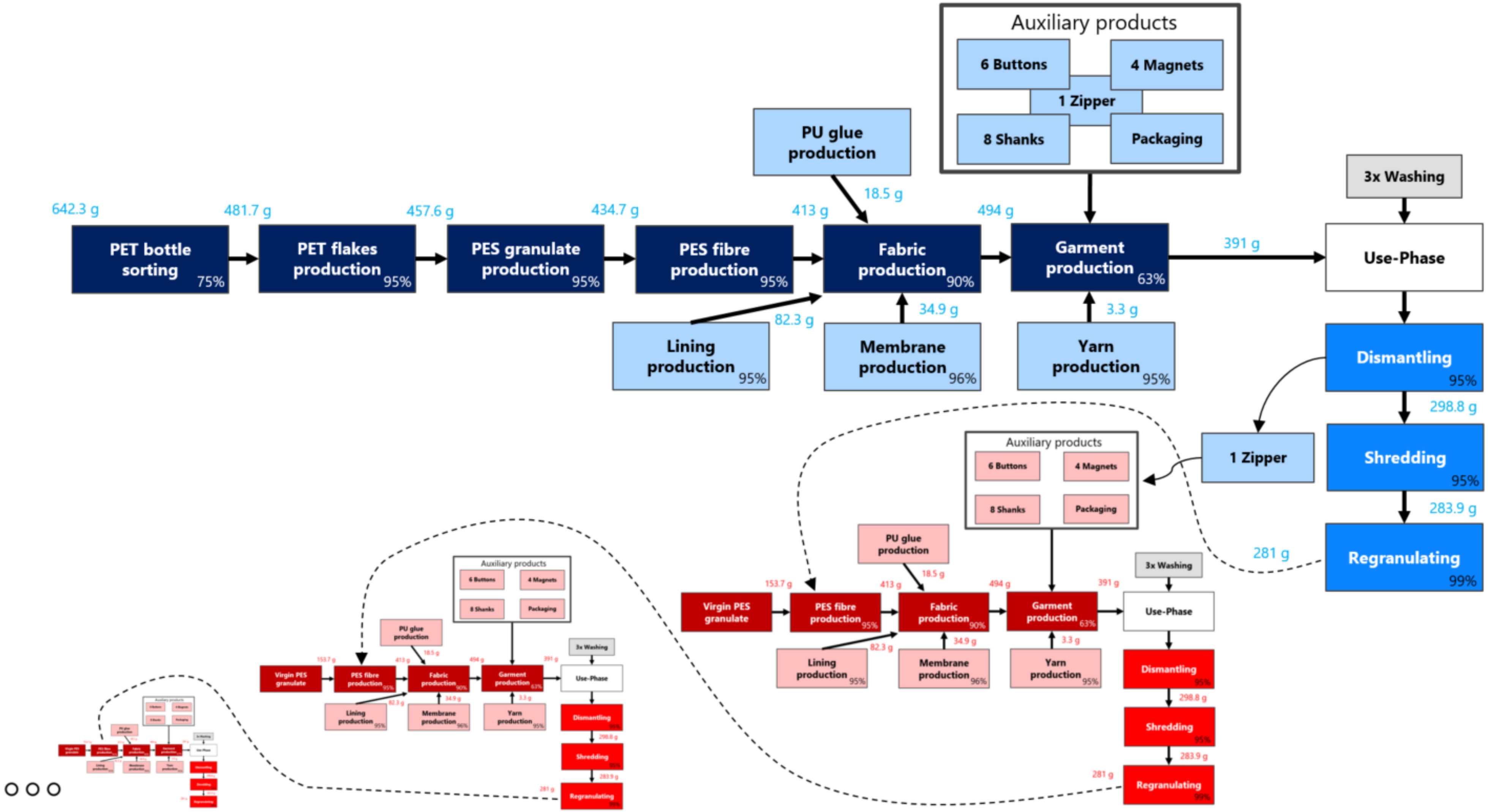

Figure 12. Unlimited wear2wear loops due to virgin polyester input starting from the second (red) loop.

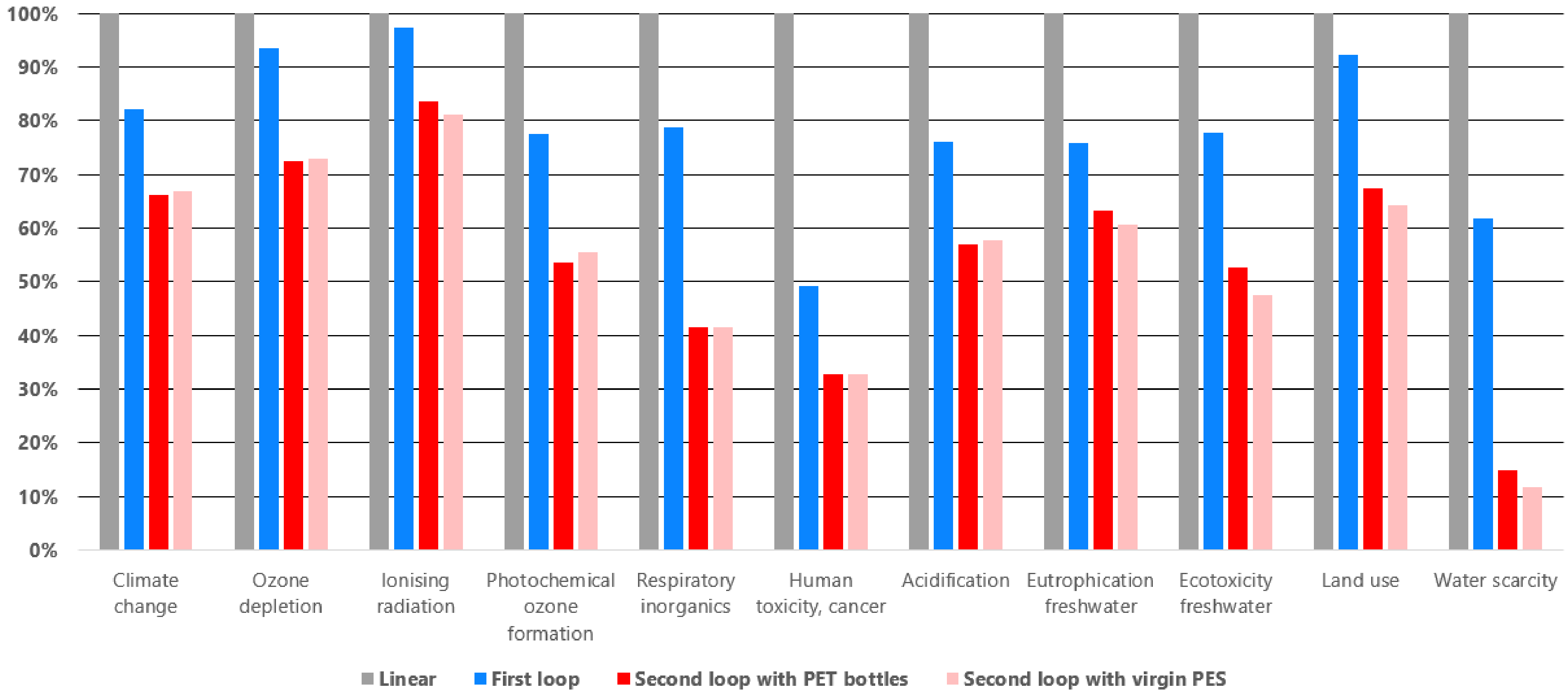

Figure 13. Impact comparison among the linear (grey), first loop (blue) and second loop. The second loop is given in two variations: Fibers are made of either recycled PET bottles (dark red) or virgin PES (light red).

The results of this modelling approach are illustrated in figure 13. We compare the linear production to the first and second production loop respectively. The second loop is provided in the two versions modelled. The first version utilizes PET bottles as the main input material for fiber production (see section 4.1). The second version presents the version where fibers are solely made from virgin PES. The results show, that both versions score always lower than the linear production as well as the first loop. The garment with PET bottle-based fibers does not have lower impacts in every category when compared to the virgin PES-based version. While the PET bottle garment (dark red) has lower scores in GHG emissions, ozone depletion, photochemical ozone formation and acidification, it has higher scores in ionizing radiation, eutrophication, land-use and water scarcity compared to the virgin PES garment (light red). Overall however, those differences are marginal.

Additionally, we have developed three scenarios based on the modelling approach illustrated in figure 12. We compare the impacts of 5, 25, and 50 wear2wear loops to an equal amount of linear products. The results are provided in figure 14. They show, that the more loops we simulate, the smaller the impacts are in comparison to the linear product. For an infinite number of loops, the impact differences between the wear2wear and the linear production system would be equal to the differences between one linear product and one wear2wear product from the second loop (see figure 13). The reason is simple: Simulating an infinite amount of loops means that the first loop (blue) has higher impacts than the all following loops (the red loops in figure 12). Therefore, the more (red) loops simulated, the closer the results get to the impact differences of one single second loop (red) to one linear product (grey). That means, the maximum impact reduction that the wear2wear system can provide in comparison to our assumed linear system are illustrated in figure 13 above (the difference between *linear* and *second loop with virgin PES*). For example, the wear2wear system can lower GHG emissions by 33% compared to a traditional linear product.

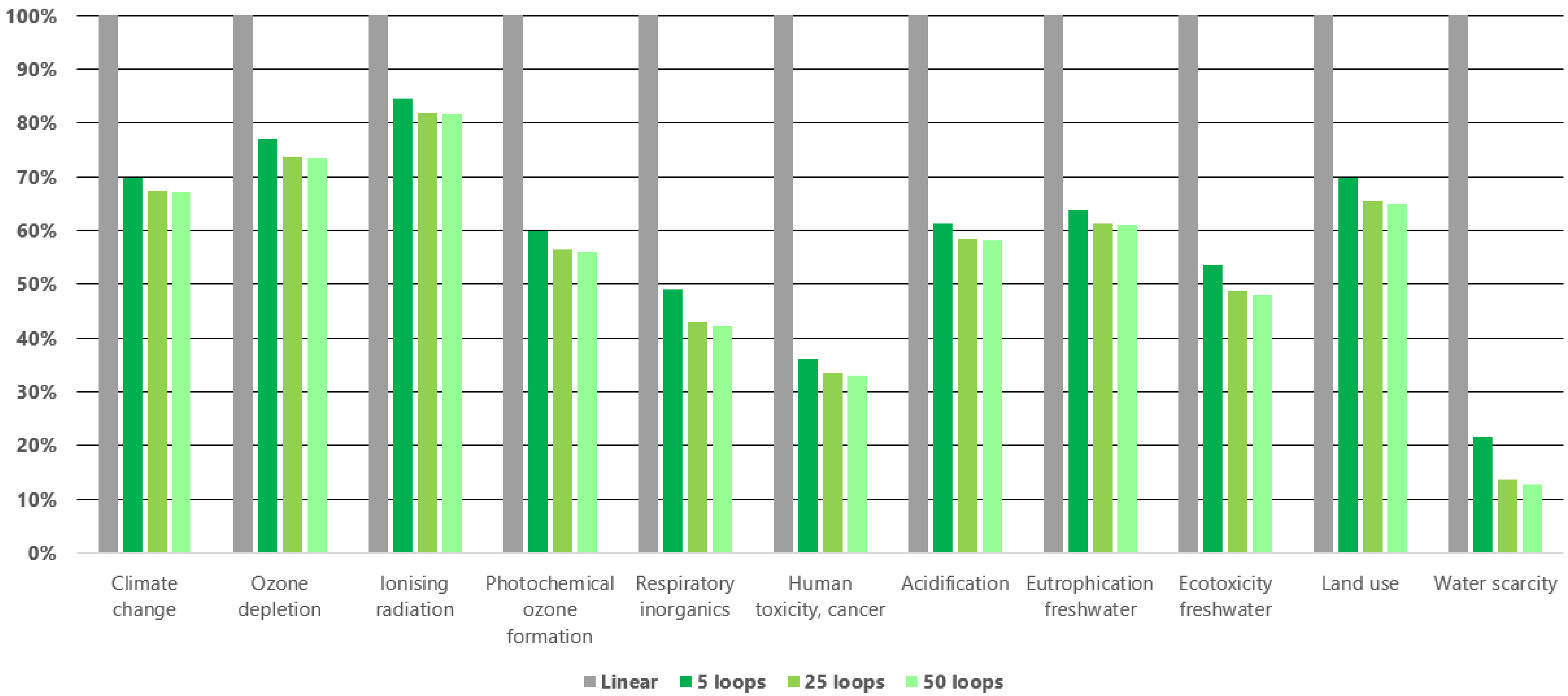

Figure 14. Impact comparison of the linear (grey) version to three different production scenarios of the wear2wear system. Due to the input of virgin PES (starting from the second loop) the quality of the PES granulate can be kept at a high level enabling an infinite (assumed) amount of production loops. We have chosen three scenarios illustrated with different green color shades.

5. Discussion and Conclusion

This chapter represents the interpretation phase of our LCA according to the ISO standards 14040 and 14044. We do this in relation to the goal of the study, i.e. *assess the environmental consequences of closing the loop of the wear2wear^{TM} textile production system*. The results of this study have shown that the wear2wear garment does perform better among a wide range of environmental and health categories compared to a traditional, linear produced garment. The two production systems differ in three terms: The input material for the fibers, the reuse/ non-reuse of the zipper, and the EoL phase of the fabric. Due to the interconnectedness of the wear2wear system, no simple comparison can be made between the two production systems. Thus, the average from the total impacts generated by the three wear2wear production loops is compared to the total impacts from one linear produced garment. This method of comparison is necessary, as each of the three interconnected production loops of the wear2wear system is structured differently and thus generate divergent results (see figure 7 above).

The inventory analysis of this study consists of high quality data that have been either measured or calculated together with the involved partner companies. The only exception to this are the sub-suppliers where no direct access to data has been possible. For example, a Chinese company produces the buttons of the jacket where we were not able to get data for the manufacturing process. Therefore, the raw materials and production efforts necessary for the buttons are taken into account via data from the ecoinvent database. Additionally, in some cases the energy inputs were calculated indirectly. For example, the natural gas input for the production of the fabric cannot be measured exactly in the production facility. Only the overall natural gas input over the year of the fabric supplier was available. However, energy inputs differ by the type of fabric. Therefore, the exact amount of natural gas required of the specific PES fabric for the wear2wear garment is unknown. Instead, an average energy requirement per kg of fabric produced was calculated here using the amount of materials that the fabric supplier produces over one year.

Another point to raise here is the comparison of the wear2wear garment to the linear version. As explained in chapter two, the linear garment is simply the copy of the wear2wear garment without the circular elements (namely the PET bottle input, reuse of the zipper, and recycling at EoL). Producing a garment is a complicated endeavor consisting of various components and production steps. Overall, assuming that the product of comparison is equal to the wear2wear garment (except the circular elements), is sufficient for the goal of this study, but can be refined in the future, allowing to encounter for (future) improvements of the wear2wear system.

Regarding the assumptions made in this study, three points must be highlighted here. First, the lifetime assumption of four years has been made based on similar garments from the fabric manufacturer, because the wear2wear garment is not yet on the market for that period of time. A varying lifetime can have significant impacts on the LCA of the garment. Second, the PET bottle input for the production of fibers requires an allocation. We have allocated 50% of the impacts generated by the PET bottle production to the garment. Varying the allocation principle does not influence the results significantly (see section 4.3), as the major impacts arrive from other production steps further down the production chain. Third, the assumed number of production loops utilizing the same PES is based on expert judgement. This assumption can influence the results of the LCA (figure 11), especially when the number of loops is decreasing. A possible outlook is provided in section 4.4, how the wear2wear system can be designed in the future in order to extent the number of loops. Our respective scenario analysis (figure 14) illustrates, that the impacts of the wear2wear system further decrease for each impact category with an increasing number of loops compared to the linear product. Note that all assumptions should be checked again once the wear2wear garment has fully entered the market.

In conclusion, the present LCA study analyzes the wear2wear production system and compares it to a traditional, linear produced garment with the goal to assess the environmental consequences of closing a textile product system. The wear2wear garment is manufactured in a production system that incorporates different circular elements. The analysis has included eleven impact categories. The results of the LCA shows, that the wear2wear production system improves the environmental performance among all included impact categories. Improvements range up to 50% compared to the linear produced jacket. Even though, the improvements are significant, limits exists for the Design-to-Recycle approach in terms of impact reduction potential. The main reasons are that (1) material losses occur along all production steps that must be replaced, that (2) the additional energy requirement for recycling increases the overall energy demand of the system, and that (3) the number of times the PES material of the garment can be recycled/reused is limited due to quality concerns.

The three main lessons learned from this study for the Circular Economy are the following:

- First, significant improvements of environmental performance of product systems can be achieved through a new arrangement of the physical flows towards a more cyclical model.
- Second, every Circular Economy product, process or project should be carefully analyzed by established analysis methods that are able to quantify the net contribution in terms of environmental sustainability. Simply designing a cyclic production flow system does not guarantee lower environmental impacts.
- Third, assessing product systems in the field of Circular Economy requires a wider cradle-to-cradle perspective that must go beyond the simple comparison of one product to another due to the interconnectedness of product systems.

6. Outlook

There might still be some limitations within the current wear2wear system. For example, there is the risk that polyester from unknown sources enters the system, bringing along the risk that harmful substances accumulate along the loops. For example, antimony is an often-used additive for polyester textiles, which might pose risks to humans if the concentration transgresses a certain level. An optional chemical recycling process might therefore be attractive as it could separate those harmful substances from the monomers. However, a chemical recycling requires a higher energy input.

Other limitations might arise from the use of dyes. This is because when garments with different colors are recycled, the recycled polyester has a color as well. Attempts are currently being made to use chemical solvents to clean the goods during the recycling process so that as much color as possible can be removed from the recycled material. Depending on the dye and in particular the depth of the color (darker shades are more difficult), the dying process is currently still a challenge for circularity.

In general it is noted, that any change of the current wear2wear system will lead to differences in the LCA results as presented in this study.

References

Ashby, M. F. (2012). *Materials and the environment: eco-informed material choice*: Elsevier.

Desing, H., Brunner, D., Takacs, F., Nahrath, S., Frankenberger, K., & Hischier, R. (2020). A Circular Economy within the planetary boundaries: towards a resource-based, systemic approach. *Resources, Conservation and Recycling, 155*, 104673.

Geissdoerfer, M., Savaget, P., Bocken, N. M., & Hultink, E. J. (2017). The Circular Economy–A new sustainability paradigm? *Journal of cleaner production, 143*, 757-768.

Hauschild, M., Jeswiet, J., & Alting, L. (2005). From life cycle assessment to sustainable production: status and perspectives. *CIRP annals, 54*(2), 1-21.

ISO. (2006). *Environmental Management: Life Cycle Assessment; Principles and Framework*: ISO.

Korhonen, J., Honkasalo, A., & Seppälä, J. (2018). Circular economy: the concept and its limitations. *Ecological economics, 143*, 37-46.

MacArthur, E. (2013). Towards the circular economy. *Journal of Industrial Ecology, 2*, 23-44.

MacArthur, E. (2017). A new textiles economy: redesigning fashion's future. *Retrieved from: https://www.ellenmacarthurfoundation.org/assets/downloads/publications/A-New-Textiles-Economy_Full-Report.pdf.*

Shen, L., Worrell, E., & Patel, M. K. (2010). Open-loop recycling: A LCA case study of PET bottle-to-fibre recycling. *Resources, Conservation and Recycling, 55*(1), 34-52.

Stahel, W. R. (2016). The circular economy. *Nature, 531*(7595), 435-438.

Zink, T., & Geyer, R. (2017). Circular economy rebound. *Journal of Industrial Ecology, 21*(3), 593-602.