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Environmental Consequences of Closing the Textile Loop—Life Cycle Assessment of a Circular Polyester Jacket

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Abstract: The textile industry is recognized as being one of the most polluting industries. Thus, the European Union aims to transform the textile industry with its "European Green Deal" and "Circular Economy Action Plan". Awareness regarding the environmental impact of textiles is increasing and initiatives are appearing to make more sustainable products with a strong wish to move towards a circular economy. One of these initiatives is wear2wear^{TM}, a collaboration consisting of multiple companies aiming to close the loop for polyester textiles. However, designing a circular product system does not lead automatically to lower environmental impacts. Therefore, a Life Cycle Assessment study has been conducted in order to compare the environmental impacts of a circular with a linear workwear jacket. The results show that a thoughtful "circular economy system" design approach can result in significantly lower environmental impacts than linear product systems. The study illustrates at the same time the necessity for Life Cycle Assessment practitioners to go beyond a simple comparison of one product to another when it comes to circular economy. Such products require a wider system analysis approach that takes into account multiple loops, having interconnected energy and material flows through reuse, remanufacture, and various recycling practices.

Keywords: circular economy; life cycle assessment; textiles; circular design; sustainability; climate change; polyester; PET

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1. Introduction

The textile industry is recognized as being one of the most polluting industries in the world [1]. Textile production causes various environmental impacts covering issues such as global warming, water scarcity, and land-use changes [2,3]. Those impacts are expected to become more severe due to the increasing demands for textiles driven by a higher global income levels per-capita and shorter clothing utilization phases known as "fast fashion" [4]. Additionally, 73% or more of all textiles produced worldwide are either incinerated or landfilled at the end of their life [1,5,6]. In fact, today's textile industry is mostly of a linear nature (take–make–waste). However, the movement of Circular Economy (CE) is becoming increasingly popular. CE promises to create economic value while lowering the environmental impacts of production through reducing resource consumption, reusing products, and recycling materials [7,8]. A recent report has shown that CE strategies have the potential—if correctly implemented—to reduce global greenhouse gas (GHG) emissions by more than a third while lowering the demand for resources by more than a quarter [9]. The textile industry—as a mostly linear sector—could therefore benefit extraordinarily from CE strategies. Awareness regarding its environmental impact is increasing and initiatives are appearing to make the textile industry more sustainable with a strong wish to move towards a CE. For example, the European Union addresses with its "European Green Deal" [10] and its "Circular Economy Action Plan" [11] the textile industry along with four other resource-intensive industrial sectors.

While the CE approach sounds promising, it is far from obvious if it can make a significant contribution to the design of an environmentally sustainable economy. Several limitations and uncertainties exist that can prevent the environmental superiority of a CE approach over the linear way of today's production [12,13]. For example, a high percentage of recycled materials in a product could reduce the lifetime of that product. Thus, increasing the share of recycled materials does not necessarily lead to a better environmental performance [14]. Recycling practices could also result in more GHG emissions of production due to additional transport needed for collecting products from the costumer and bringing them back to the producer for recycling/reusing [15].

In order to cope with the uncertainty that comes along with applied and new CE strategies, a robust and science-based method is required in order to assess the environmental impacts of circular product systems compared to a linear product system. The Life Cycle Assessment (LCA) method can fulfil those needs by: (1) quantifying various environmental impacts; (2) taking into account the entire life cycle; (3) relying on high scientific standards; while (4) being transparent and accepted by the scientific community [16,17]. Some LCA studies on textile recycling have already been published [18–21]. However, most of the studies focus only on one or two indicators, foremost on "climate change" and "energy use". Only a few of these studies address a broader set of environmental impacts. Thus, there is currently the risk that relevant impacts so far have been missed and problems have simply been shifted. In addition, most studies consider that textile waste sent to recycling is free of environmental burdens; however, textiles can still retain strong toxic substances that need further treatment [22–24]. In addition, these studies are focusing on end-of-life (EoL) strategies, i.e., recycling/reuse versus incineration or landfilling. To the best of the authors' knowledge, no study has compared the complete life cycle of a linear and circular textile product system so far.

Hence, in order to fill this gap, this study compares the environmental consequences of the change from a linear to a circular product system using the example of the wear2wear^{TM} functional workwear jacket made of polyester (PES). Eleven different impact categories are considered and the allocation of waste is not environmental burden free. Section 2 of the manuscript describes the methodology applied here, the wear2wear^{TM} product system, its stakeholders and production steps, the circular design and the cornerstones of the investigated PES jacket and its translation into LCA. Subsequently in Sections 3 and 4, the results are shown and discussed, before we outline in the final section the conclusions of this case study for the wear2wear^{TM} product system, as well as general conclusions for CE for the textile industry as a whole.

2. Materials and Methods

LCA is a well-established and situated methodology to assess the environmental performance of circular product systems. Thus, LCA is the method of choice in this study following the guidelines of the International Standards Organization [25]. The objective of the study is a comparison of the environmental performance of a circular jacket based on CE principles in comparison to a similar, but linear jacket. The jacket is in both cases water repelling and permeable to heat and moisture. The circular jacket is manufactured by the wear2wear^{TM} consortium (https://www.wear2wear.org/) (accessed on 15 January 2021) (for more details, see Section 2.1). There are three main differences between the circular and linear jacket. The circular version has (1) a fabric that is partly made from polyethylene-terephthalate (PET) bottles while the linear jacket's fabric is made from virgin PES only, (2) a reusable zipper that is removed at the EoL, and (3) a recycling process that regranulates the entire fabric in order to be used for another jacket (so called closed loop recycling), instead of being incinerated. Note that the production of PET bottles for the circular jacket have caused environmental impacts themselves when produced. As PET bottles cannot be considered a waste stream in general—they are well recycled in many countries—an allocation approach must be chosen [26]. The 50/50 allocation rule for open-loop recycling from the Product Environmental Footprint (PEF) guide [27] is utilized for this study, meaning that 50%

of the environmental impacts from the production of PET bottles are allocated to the wear2wear^{TM} jacket (for more information, please see the Supplementary Materials (SM)). The functional unit of this LCA is defined as "use of a three-layer-laminate jacket, repellent to water and permeable to heat and moisture, for a period of four years". Four years is the typical lifetime of a workwear jacket. The investigated jacket has the size large (L). The scope of the study includes all life cycle stages of the jackets. Figure 1 illustrates the system boundaries of the analysis. The necessary in- and output data of the defined system are collected from two general data sources. Mostly, case-specific unit process data collected from the partner companies are used in the life cycle inventory (LCI). Where no data were available (e.g., electricity mix used from the subsupplier of the zipper), generic data from a background database were used.

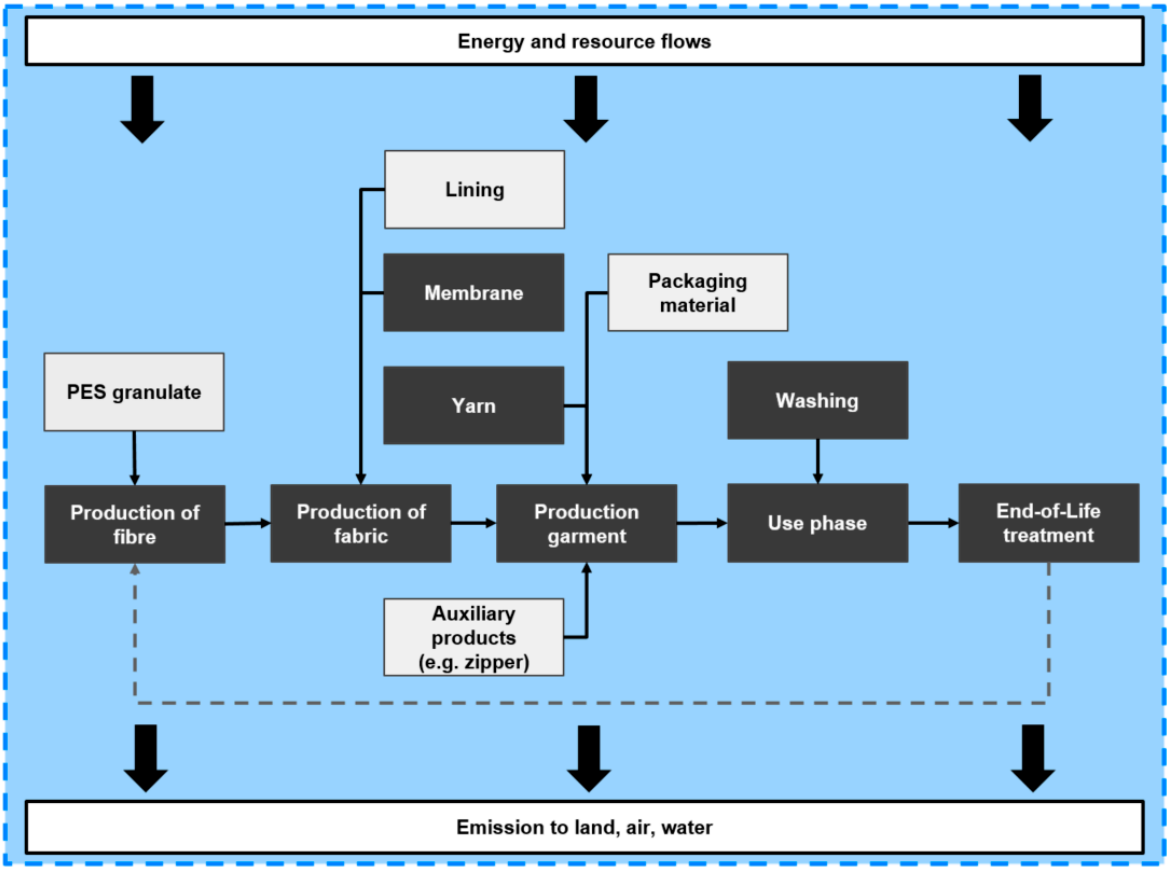


Figure 1. The system boundaries as set for this study. All the life cycle stages are included for the production of a three-layer laminate jacket. For the black boxes, primary data is collected directly from the partner companies. For the four grey boxes, secondary data from the ecoinvent database is utilized together with assumptions made by the partner companies (e.g., how much packaging is required) because primary data from the corresponding subcompanies are not (entirely) available.

For the modelling of the two systems, the LCA software tool SimaPro (version 9.1.1.1) together with version 3.6 (recycled-content system model) of the database ecoinvent (https://www.ecoinvent.org/) (accessed on 15 January 2021) was used in this study. The Environmental Footprint (EF) version 3.0 is used as the life cycle impact assessment (LCIA) method. With the EF method, the product systems are evaluated in several midpoint impact categories in order to identify if burden-shifting of the environmental impact is taking place [28]. The following eleven impact categories are included: (1) global warming potential (GWP) in kg CO_2-equivalent; (2) ozone depletion in kg CFC-11-eq.; (3) ionizing radiation in kB_q ^{235}U-eq.; (4) photochemical ozone formation in kg Non-Methane Volatile Organic Compounds-eq. (NMVOC eq).; (5) respiratory inorganics in kg $PM_{2,5}$; (6) human toxicity (cancer) in Comparative Toxic Unit for humans (CTUh); (7) acidification of soil

and water in mol H+ eq., (8), eutrophication of freshwater in kg P eq.; (9) ecotoxicity of freshwater in CTUe; (10) land use in P_t; and (11) water scarcity in m^3. Not all impact categories of the EF are included in this study for illustrative purposes in the result section. For example, the impact category human toxicity (noncancer) is excluded in this study, because the category human toxicity (cancer) is included and both lead to very similar results. More information is provided in the SM.

2.1. The Wear2wear^{tm} System

The logic of the wear2wear^{TM} product system consists of eight steps—each executed by different companies—which include circular elements to reduce the resource input or emission output of the system by closing or slowing energy and material cycles. In other words, the goal of this partnership is to incorporate CE principles (such as reduce, reuse, recycle) to design sustainable products.

The design of the jacket represents thereby an important leverage point in order to substantially lower the environmental performance. The jacket is designed on a recycling-based concept known as Design-2-Recycle. No mixed materials are used in the loop—e.g., no cotton/PES blend, which is known to be difficult to recycle [29]. The fibers of the outer layer are made from PET bottles. The membrane and lining are made from virgin PES. The fabric is produced fluorocarbon-free and uses C-0 chemistry where possible to ensure water and dirt repellent properties. All materials are free from polytetrafluoroethylene (PTFE) and perfluorochemicals (PFC). Hydrophilic building blocks in the otherwise hydrophobic membrane allow the permeability of heat and moisture. The lamination of the membranes with the outer and lining material leads to single-origin PES composites. The jacket has also a simplified design with a minimum amount of seams and trims. An innovative sewing yarn is used for the seams that dissolves in boiling water to separate the zipper from the fabric at the EoL. Furthermore, the jacket is manufactured in a production facility within Europe to minimize transportation within the loop. After manufacturing, the jacket is rented out by the clothing supplier to the customer for a certain period. The clothing supplier takes care of the laundry service during the use phase and offers repair services. At the EoL the garments are collected, examined and cleaned. 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 jackets are optimally prepared for the subsequent recycling process. Lastly, the recycler (the same company that makes the fibers in the first step) removes the zipper by dissolving the sewing yarn in boiling water. The zipper is used again for a new jacket. The remaining fabric is shredded into small fragments or fiber structures, which are turned into granulate through supplemental polymer melting processes. This granulate is then used in order to produce new PES fibers and the loop starts again. The PES that has been lost along the supply chain is replaced by granulate made from virgin PES in order to keep the quality of the entire PES sufficiently high for manufacturing. For more details regarding the LCI, please consult the SM.

2.2. LCA Modelling Approach for a Closed-Loop System

Based on this information and the respective LCI data provided by all partner companies (for details, see SM), an interlinked product system according to Figure 2 is modeled within the LCA software system. The first jacket produced is the result of the blue highlighted product system. This first product system is unique compared to all following product systems (in orange) because (1) the main ingredients for the fabric are about 650 g of PET bottles entering the system and (2) the auxiliary products include the zipper that has to be produced for this very first loop. All following product systems (in orange) do not include the production process of the zipper, as it is reused from the first jacket (outflow of the previous dismantling process—shown inside the circle in Figure 2). The PES material

that is lost along each supply chain is replaced by the following supply chain with virgin PES (orange box on the very left). The reason why virgin PES is used instead of PET bottles is the high-quality requirements of the fabric. If PET bottles or other PES waste streams were used to replace the missing raw material part, the PES granulate would degrade after each recycling loop. Material losses along the supply chains result because of efficiency losses at every process step. The process efficiencies are given in the right upper corner of each box in Figure 2. Where no percentage is given, data were not available or no sound estimate was possible. Note that the membrane, lining and all auxiliary products (except the zipper) must be re-produced again for every product system. During the four years use phase, the jacket is washed three times in an industrial setting. The blue and orange product systems ("loops") are closely interconnected. The orange version reuses the zipper and PES material from the blue one. Therefore, in this model, the blue loop is the first product system and the orange one comes second.

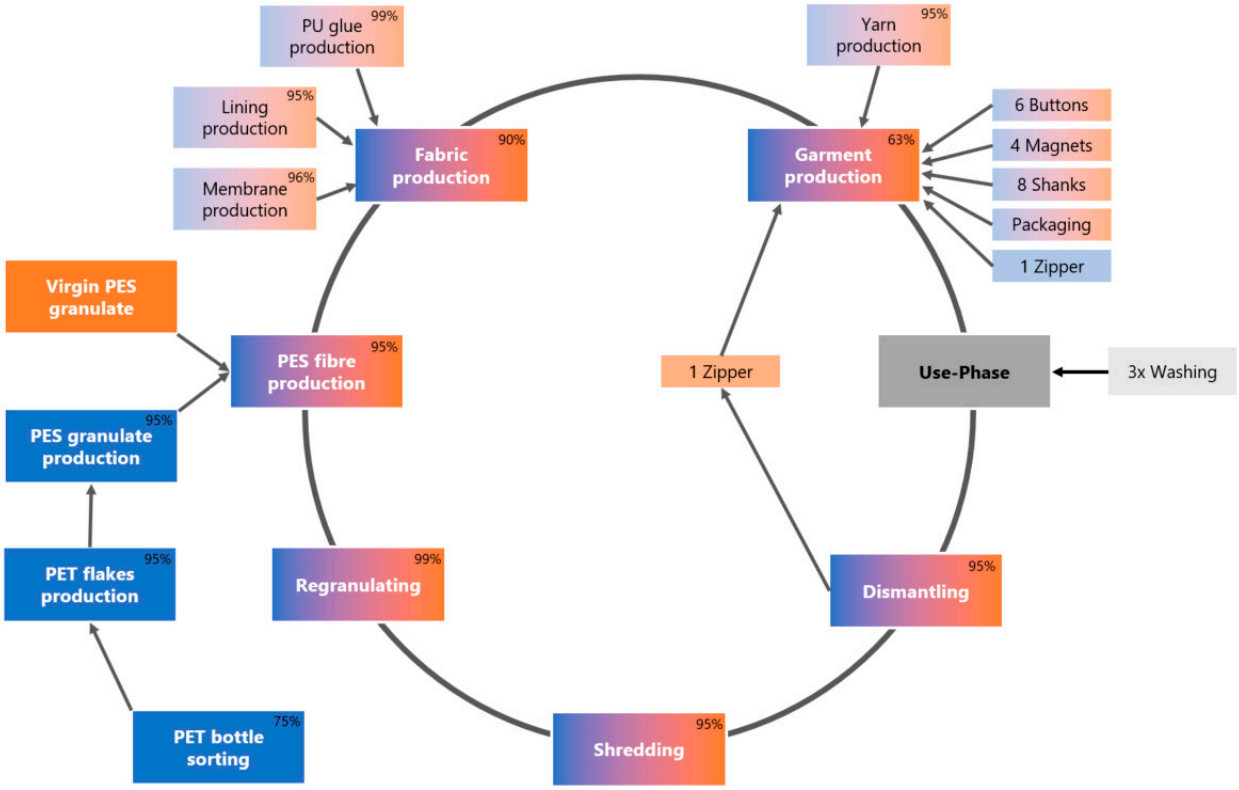


Figure 2. Multiple wear2wear^{TM} product systems interlinked by recycling and reusing activities (in blue the first loop—in orange all subsequent loops). The raw material (polyethylene-terephthalate (PET) bottles or polyester (PES) granulate) are transformed into fibers, which are manufactured into a fabric by adding the lining, membrane, and polyurethane glue. Adding the auxiliary products, the fabric is assembled into a ready-to-wear jacket (i.e., the garment). During the use phase, the retailer washes it in an industrial plant as a service. In the entire lifetime of the jacket (four years), it is washed three times. After the use phase, the zipper is dismantled for reuse. The remaining fabric is shredded and the PES is regranulated by a polymer melting process to be available for the next product loop. The material losses occurring in every manufacturing process (displayed by the process efficiencies given in percentage) are replaced by virgin PES, indicated by the orange box.

In theory, there can be an infinite number of product systems connected with each other, as long as the recycled PES material keeps the required quality for producing new fibers again. For this reason, different scenarios are modelled in the results section to test how a varying number of connected product loops alter the environmental impact compared to the linear product system. Three scenarios are modelled in this study. Each scenario assumes a different number of orange loops connected to one blue loop. In the first scenario, three loops (one blue and two orange ones) are modelled. The second scenario

includes five loops (i.e., one blue and four orange ones), the third scenario ten (i.e., one blue and nine orange ones).

As previously described, this wear2wear^{TM} jacket system is compared to a (fictive) linear jacket that has the same components and is produced with the same technologies and process efficiencies. Hence, this linear product system is very similar to the one of the wear2wear^{TM} jacket (shown in Figure 2). There are only three main differences between the two. As opposed to the circular jacket, the linear version is (1) entirely made from primary materials (e.g., only virgin PES), (2) does not reuse the zipper and (3) is completely incinerated at EoL with energy recovery.

3. Results

The environmental impacts in each impact category (as classified in Section 2) for the individual product systems (linear, first loop and second loop) are presented relative to each other in Figure 3. The linear jacket has the highest impacts in all categories (grey bars). The "second loop" product system (orange in Figure 2)—utilizing virgin PES to replace the losses from the "first loop" product system (blue in Figure 2)—always scores lowest in all categories (orange bars). This second loop product system shows even lower impacts compared to the first loop product system, because it requires fewer newly produced raw materials as it utilizes the PES material and the zipper from the previous loop. The biggest impact differences between the linear and circular product system occur in the categories of (1) respiratory inorganics (2) human toxicity and (3) water scarcity. Responsible for the lower impacts of the circular product systems are, respectively: (1) fewer transportation and electricity needs due to lower PES material requirements; (2) less incineration of materials and (3) less virgin material production and water consumption.

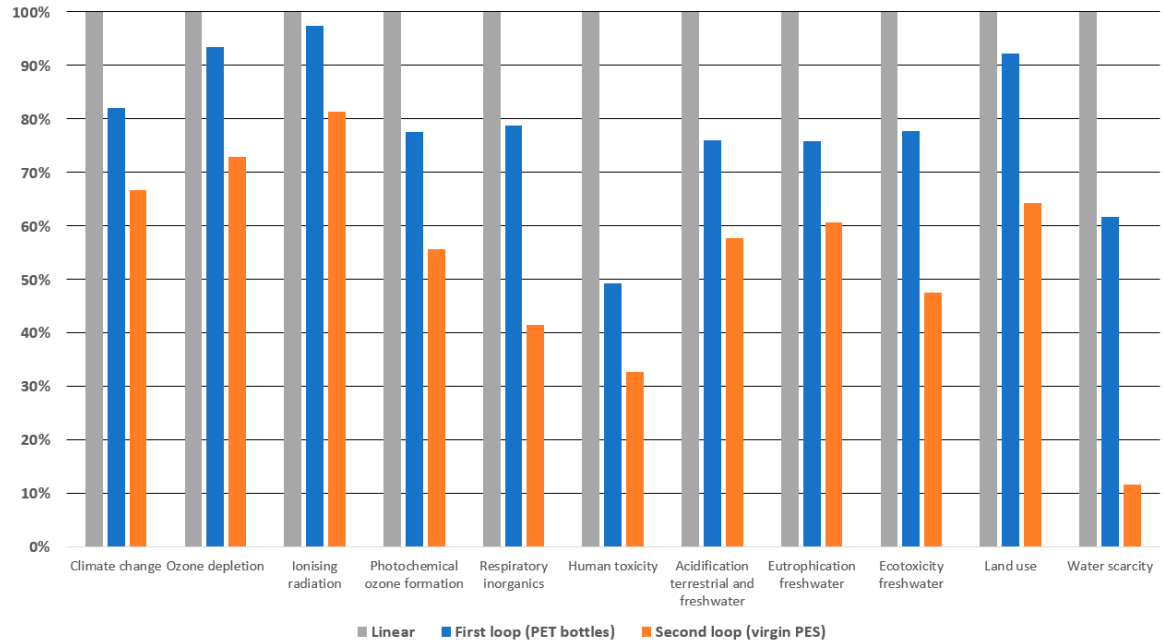


Figure 3. Environmental impact comparison between the linear product system (grey) and the first (blue) and second loop (orange) product systems.

The major impact differences between the two circular product systems (blue and orange bars) are visible in the categories respiratory inorganics, ecotoxicity freshwater and water scarcity. For respiratory inorganics, this is again due to lower emissions resulting from less transportation (due to fewer materials transported on shorter routes). The ecotoxicity for freshwater is higher for the first loop mostly due to more materials being produced (e.g., the zipper) and thus more mining required. Additionally, in the first loop product system, more materials are incinerated (especially the losses from the PET bottle

recycling). Regarding water scarcity, the impact allocation of the PET bottle production and the higher water demand in the first loop (due to more materials being produced) lead to higher impacts in this category compared to the second loop. Note that due to the input of high quality virgin PES material starting from the second loop, this second loop can now be theoretically repeated for an unlimited number of loops as long as the quality of the recycled PES material is sufficiently high enough for the fiber spin process.

As explained in the method section of this study, in a second step the average impacts across several wear2wear^{TM} loops are calculated. The impacts of these average product systems can be compared to one linear product system. Due to the unique fact that the orange product system (meaning the second loop) can be prolonged significantly as long as the quality of the PES material is sufficiently high, three scenarios are modelled in this study that vary the number of interconnected loops (one blue loop connected to x number of orange loops). In the first scenario, the average impacts of three wear2wear^{TM} loops (one blue and two orange ones) are compared to the impacts of one linear product system. The second scenario includes five loops (i.e., one blue and four orange ones), the third scenario ten (i.e., one blue and nine orange ones).

The results are illustrated in Figure 4. They show that the more subsequent orange product systems are being simulated, the smaller the impacts are of the combined wear2wear^{TM} product system (containing one blue and a number of orange loops) in comparison to one single linear product system. For an infinite number of orange loops connected to one blue version, the impact differences of the wear2wear^{TM} to the linear product system would be equal to the impact differences between one linear and one wear2wear^{TM} jacket from the second (orange) loop. The reason is simple: simulating an infinite amount of loops means that the first product system (blue) has higher impacts than the all following ones (orange). Therefore, the more orange loops are simulated, the closer the overall impacts of the entire wear2wear^{TM} product system becomes to the impacts of one single orange product system. That means that the maximum impact difference between the wear2wear^{TM} and the linear jacket is equal to the difference of one single orange loop to one linear product system shown in Figure 3 above. For example, this maximum impact difference amounts to 32% less GHG emissions for the wear2wear^{TM} product system compared the linear product system.

For the GHG emissions, this lower impact is mainly due to lower energy requirements for material production and the prevention of incineration of PES at the EoL, which results in fossil CO_2 emissions in the linear product system. Of all indicators measured, the water scarcity indicator shows the biggest differences. While most synthetic textiles have the highest water use during the use phase due to washing practices, the workwear jacket of this study is only washed three-times in its four-year lifetime. Therefore, most of the water is used in the material production. Due to the fact that the production of virgin material for the wear2wear^{TM} product system is significantly lower than for the linear product system, this variance is reflected in the water scarcity indicator. Note the water scarcity indicator takes into account where the water is used. If water is used in a rather water scarce region, the indicator reflects this fact by having a higher score. This leads to an even lower score of the water indicator for the orange product systems, because the recycling—providing most of the raw materials—is taking place in Germany, a country with no severe water scarcity today. For the linear jacket, the raw materials are sourced globally, including from water scarce regions. This combination of factors lead to a very low score of the water indicator for the three scenarios in comparison to the linear product system.

As it has been mentioned already several times, one critical element of the circularity of the wear2wear^{TM} product system is the lifetime prolongation of the materials along several loops. For example, if PET bottles or other PES waste streams were to be used as the main ingredient for the fiber production not only for the first loop but also continued in the following loops, the quality of the PES would quickly deteriorate. Nevertheless, we have additionally modeled the second loop that also contains PET bottles as the main ingredient and compared it to the second loop with virgin PES (see Figure 2 above). The

results of this comparison are given in Figure 5 below. In general, the differences in the impact levels do not vary significantly. Only for the water scarcity indicator is the difference greater than 10% in favor of the PES version. Overall, one PET bottle-based product system scores lower in six out of eleven impact categories, meaning that it cannot be concluded that it is generally better than one PES-based product system. Above all, the PES version has the advantage that the quality of the granulate after recycling (one or more times) is significantly higher compared to the granulate in the PET version. Therefore, using virgin PES for the fibers extents the number of possible loops tremendously. This in fact is a strong argument for the use of virgin PES instead of PET bottles or other waste streams.

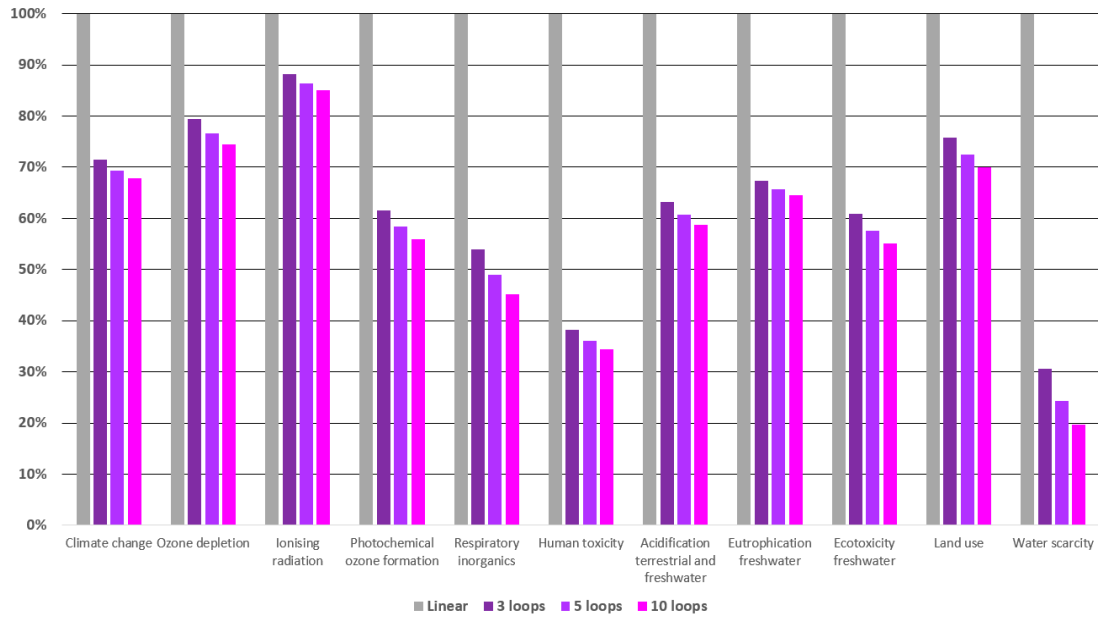


Figure 4. Environmental impact comparison between one linear product system and the average impacts of three, five and ten wear2wear^{TM} product systems. Each of the product systems contain one first (blue) loop. The remaining product systems are second (orange) loops.

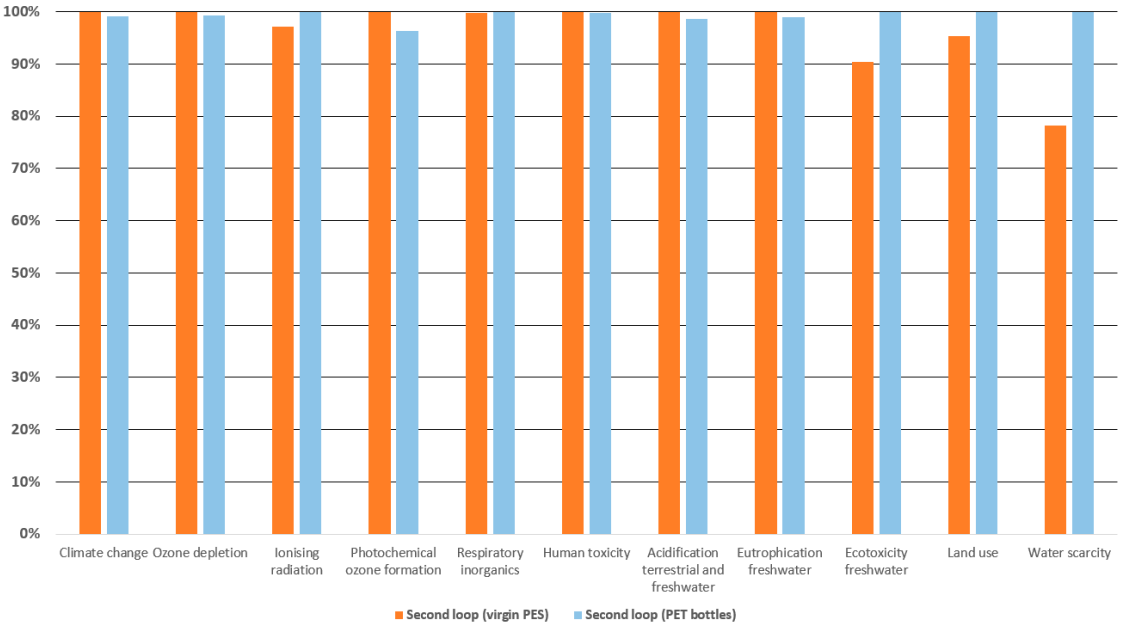


Figure 5. Impact comparison between the second loop product systems once with virgin PES and once with PET bottles as the main input for fiber production.

The reasons why the environmental impact reduction of the wear2wear^{TM} jacket compared to the linear one vary for each impact category can be explained with Figure 6. This figure illustrates, for the linear product system, the impact contribution of the five main production activities (energy use and transportation over the whole life cycle, material production, washing and incineration). Note that only the washing and incineration activities take place at one single phase along the life cycle—namely the use phase (washing) and EoL (incineration). The other three activities are taking place at every step of the life cycle. For example, energy (in the form of heat or electricity) is used at every step all along the life cycle. Looking at Figures 3 and 6 together, a pattern between those two figures can be spotted. When the impact shares of material production and the EoL are large in one category in Figure 6 (e.g., human health effects), large impact reductions can be found in Figure 3 between the wear2wear^{TM} and the linear jacket. This makes sense, because the wear2wear^{TM} jacket requires less primary material and no incineration at the EoL and thus can reduce the environmental impacts of those two particular activities.

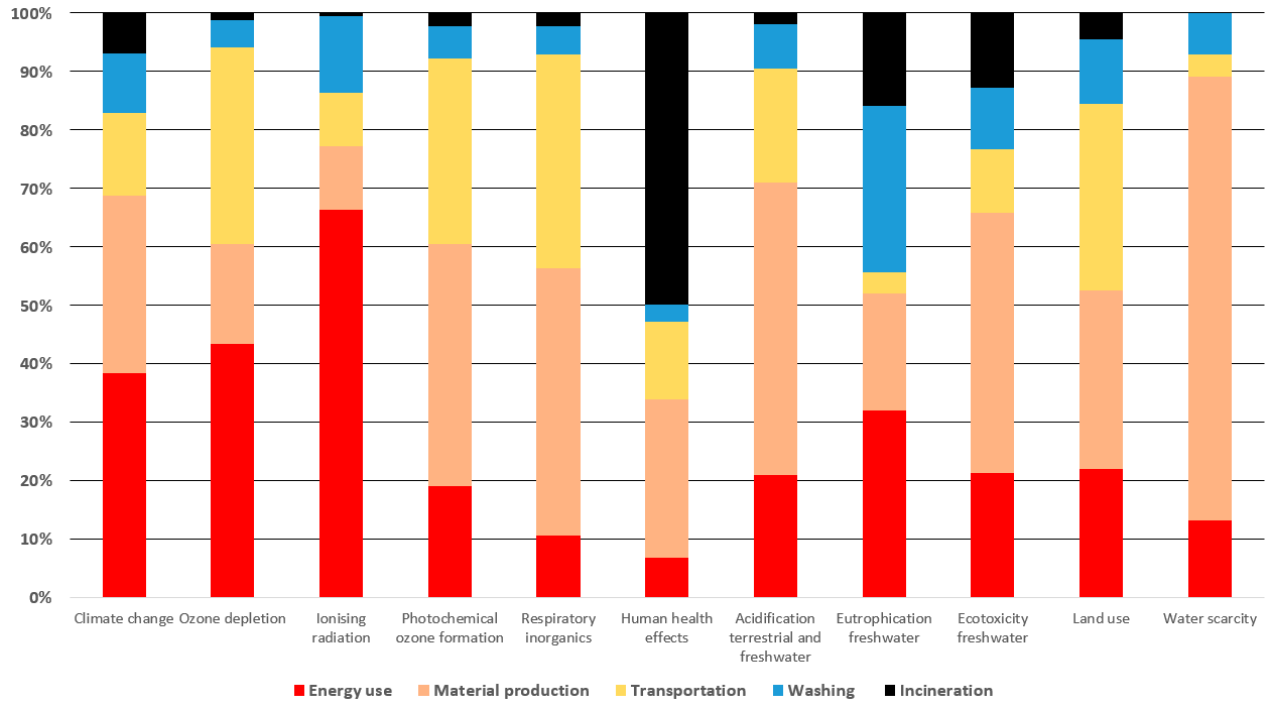


Figure 6. Relative impact shares of the five main production activities—energy use, material production, transportation, washing and incineration-along the life cycle of the linear product system.

From all the above analysis, three conclusions can be drawn. First, the wear2wear^{TM} jacket has a significantly lower environmental footprint than the linear version among a wide range of impact categories. Second, because the wear2wear^{TM} jacket is manufactured from a circular product system, multiple interlinked product systems must be considered for the comparison analysis in order to take into account the individual product systems (blue and orange loops). If the quality of the PES material stays sufficiently high for remanufacturing new fibers out of it, the number of interlinked product systems can be extended tremendously (if not infinitely). Third, the lower impacts of the wear2wear^{TM} jacket come from the fact that the primary materials are substituted by secondary materials from the former loop based on reuse and recycling principles. It is relevant to note that the lower impacts of the wear2wear^{TM} jacket do not come from the utilization of recycled PET from bottles.

4. Discussion

The results of this study show that the wear2wear^{TM} jacket does perform better among a wide range of environmental categories compared to a traditional linear produced jacket, because well implemented CE principles allow for the substitution of primary materials with secondary ones. This substitution is the very core idea of CE. CE in LCA terms means that product systems are connected with each other by reuse or recycle activities. This has been done in this study as explained in Section 2.2. As a result of CE practices, the wear2wear^{TM} product system requires fewer primary materials and incinerates fewer materials at the EoL. This reduces the impacts, especially in the categories photochemical smog formation, respiratory inorganics, human toxicity and water scarcity. Those results are reasonable. The pollutants emitted from the combustion of fossil fuels and waste in incineration plants, such as particulate matter or oxides of nitrogen, cause photochemical smog, respiratory symptoms and have in general effects on human health [30]. Thus, reducing the combustion of waste and the production of PES (which is based on fossil fuels) by means of CE principles leads to the reduction of impacts in the mentioned impact categories. The reduction of the water scarcity indicator is already sufficiently discussed in the result section and requires no further discussion here. Naturally, the direct reduction in primary PES material production (and thus of fossil fuels) reduces the impact of the circular jacket in the climate change category and subsequently the acidification of freshwater, as freshwater bodies absorb some of the anthropogenic CO_2 emissions [31]. Overall, the results are consistent when interpreted in a wider scientific perspective.

However, several limitations still exist which are identified here. While all the partner companies provided detailed data for their production processes, data from some of the subsuppliers were not available and proxies have been used instead. For example, a Chinese company producing the jacket's buttons, was not able to deliver data for their manufacturing process. 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 of the fabric supplier over the course of the year was available. However, the energy inputs differ by the type of fabric. Therefore, the exact amount of natural gas required for the specific PES fabric is unknown. Instead, an average energy requirement per kg of fabric produced was calculated, using the amount of materials that the fabric supplier produces over one year.

A further limitation involves the comparison of the wear2wear^{TM} with the linear jacket. As explained in the results section, the linear jacket is simply the copy of the wear2wear^{TM} version without the circular elements (namely the PET bottle input for the first loop, reuse of the zipper, and recycling at EoL). Producing a jacket is a complicated endeavor consisting of various components and production steps. Assuming that the linear jacket is equal to the wear2wear^{TM} jacket (except for the circular elements), it is sufficient for the goal of this study to analyze the environmental consequences of implementing CE elements into a textile product system. However, a comparison to a jacket that exists on today's market can lead to more findings about the environmental performance of the wear2wear^{TM} jacket—and CE textiles in general. For example, a comparison between a durable (but nonrecyclable) and a circular (but less durable) textile products that are produced with different technologies, is a very interesting question with possible findings being relevant even beyond the textile industry.

Regarding the assumptions made in this study, two points need further thoughts. First, the lifetime assumption of four years has been made based on similar garments produced by the fabric manufacturer, because the wear2wear^{TM} jacket is not on the market for such a long period of time. Varying this lifetime can have significant impacts on the LCA of a textile product. Secondly, the assumed number of product loops utilizing the same PES again is based on expert judgement and early stage experiments conducted by the partner companies. Varying this assumption can influence the results of the LCA, especially when the quality of the PES material decreases quickly due to possible risks such as the contamination of the recycling processes with impurities.

When reflecting the results of the study in a broader system perspective, other sustainability-related challenges emerge. Zink and Geyer [15] highlighted the so-called "circular economy rebound" describing the phenomena when CE activities—representing lower per-unit-production impacts—nevertheless increase the overall production of materials (e.g., of the company), and thus circumvent the impact reduction potential of CE activities from an industry perspective. Such rebound effects can be caused by several factors. For example, if the price of a product decreases compared to the average market price because it utilizes secondary materials, the result is most likely that costumers will demand more due to the primary law of economics: when prices go down, demand goes up (and vice versa). However, promising design approaches have been developed to cope with such phenomena [32,33].

Although the production system designed by the wear2wear^{TM} consortium has the concept of CE at its heart, the impacts of the current wear2wear^{TM} jacket can be further reduced. For example, all the auxiliary products could be dismantled and reused before the fabric is recycled. Furthermore, advancing other CE strategies, such as reducing the carbon intensity of the energy supply along the entire supply chain, would bring further environmental improvements along the entire wear2wear^{TM} product system. Despite this improvement potential, several challenges exist for the Design-2-Recycle approach to further reduce the impacts of textiles in general. First, there will be always material losses along the supply chain. As Desing, Brunner, Takacs, Nahrath, Frankenberger and Hischier [8] (p. 7) put it: " ... many different mechanisms, such as dispersion, dilution, contamination, degradation and process losses, inevitably transform materials into a state of high entropy, where it is essentially lost for technical use and thus material cycles cannot be fully closed". Second, the recycling process has its limitations, especially when it comes to textiles that are made of mixed fibers. No technologies are yet able to deal with such material mixes efficiently. However, during the last decade various recycling techniques have evolved for textile products, fibers and materials, such as mechanical recycling, different types of chemical and enzymatic recycling processes and combinations of it [34]. This development might bring new technologies in the future, which are able to recycle even textiles composed of different materials. Third, the accumulation of hazardous substances can hinder the recycling processes. As some types of textiles have to fulfil high requirements for functionality, hazardous chemicals might be sill necessary. Therefore, it becomes increasingly relevant to substitute such hazardous substances in future or to design "clean cycles" and safe "final sinks" that systematically remove and dispose such substances before, during and after recycling [35]. Lastly, logistics should be monitored closely with the aim of keeping the transportation impacts low. CE product systems can require more transportation due to additional activities along the supply chain compared to the linear product system, such as the collection and recycling of discarded products [15].

The findings of this study are of relevance for the growing interest of governments, companies and the scientific community in CE. The study can support policy makers with scientific insights about the environmental opportunities and risks related to CE textile products. Furthermore, the results are directly useful for textile companies in understanding that CE practices are not per se more environmentally sustainable than today's existing practices. Nevertheless, they have the potential to lower impacts significantly if the entire product system—starting from the design of the textile—is aligned to CE principles. For the scientific community, this study gives a first glimpse of the possible risks involved in CE practices for the textile industry, such as the accumulation of hazardous substances. Further research is needed to identify all major risks inherent in CE production processes for textiles and how technology can advance to overcome these challenges.

5. Conclusions

The present LCA study analyzes a circular jacket and compares it to a traditional, linear produced jacket with the goal to assess the environmental consequences of closing a textile product system. The circular jacket is manufactured in a product system that incorporates

different circular elements (e.g., reuse and recycling). The results show that the circular product system tremendously improves the environmental performance among all eleven included impact categories. Even though the improvements are significant, challenges exist for the Design-2-Recycle approach in terms of its impact reduction potential. The main reasons are that: (1) material losses occur along all production steps that must be replaced; (2) the additional energy required for recycling increases the overall energy demand of the circular system; and (3) the number of times the materials can be recycled/reused can be limited due to quality concerns. Based on this study, three main lessons learned can be derived for the circular economy: first, significant environmental improvements of product systems can be achieved through a new arrangement of the physical flows towards a more circular model. Second, every circular economy product should be carefully analyzed with established analysis methods such as LCA, which are able to quantify the net contribution in terms of environmental sustainability. Simply designing circular product systems does not guarantee low 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 the product systems through the reuse and recycling processes.

Supplementary Materials: The following are available online at https://www.mdpi.com/2076-3417/11/7/2964/s1, Table S1: general assumptions; Tables S2 and S3: LCI data; Figure S1: the wear2wear product system in detail; Figure S2: the linear product system in detail.

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