LIFECYCLE PERFORMANCE OF PRODUCT SYSTEMS

SUPERVISOR: FRIOT DAMIEN

ME-516

Environmental Evaluation of Cotton vs. Synthetic t-shirt

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" Buy less. Choose well. Make it last "

—Vivienne Westwood, fashion designer

ACRONYMS

LCA	Life Cycle Analysis
FU	Functional Unit
GDP	Gross Domestic Product
ICAC	International Cotton Advisory Committee
MMF	Man-Made Fibers
GWP	Global Warming Potential
UBP	*"Umweltbelastungspunkte"* German for Environmental Impact Points
LCIA	Life Cycle Impact Assessment
COD	Chemical Oxygen Demand
LCT	Life Cycle Thinking

SUMMARY

This comparative life cycle assessment (LCA) evaluates the impact on the environment from two different brands of t-shirts; cotton and polyester. This assessment is based on the data collected from the database provided by the course: **Ecoinvent 3.71**.

Goal and Scope
The goal is to determine which brand of shirt has the largest environmental impacts and during which phases of its life. As a basis of comparison the functional unit was defined as *100 days of protection*. To scope of this study was clearly outlined in the project specifications detailed in section 2.4.

Impact Categories
Two environmental metrics were used to quantify the impact from each type of t-shirt. These were the GWP (global warming potential) and UBP (environmental impact points). GWP compares the heat absorbed by the emitting greenhouse gas in terms of mass of CO_2 equivalent. The UBP metric uses eco-points per unit of pollutant emission or resource extraction. These were used to asses the different impact on the environment each t-shirt had.

Sensitivity Analyses
The robustness of our results and our assumptions are tested in five different case scenarios.The results from these analyses identify the key parameters that contribute most to the environmental impact of our project.

- *Scenario 1: Impact of washing machine settings.*
  - Using the lower temperature washing setting (40°C) reduced the total life cycle impact by -6% $CO_2\ eq$.
- *Scenario 2: Impact of location for energy production.*
  - Using t-shirts in Germany leads to 65% increasing of CO_2 emission for both brands of t-shirts.
- *Scenario 3: Impact of alternative end of life.*
  - Sending to African country at the EOL could decrease CO_2 emission by 26.6% and 24.7% for cotton t-shirt and polyester t-shirt respectively.
- *Scenario 4: Impact of machine drying.*
  - Using machine to dry the t-shirts has larger environmental impacts, increasing both GWP and UBP.
- *Scenario 5: Impact of washing machine energy label.*
  - A+++ washing machines cut the energy consumption per shirt by doubling their load capacity. We calculated a 64% reduction in GWP emissions and 60% in UBP.

Final Results and Recommendations
Our results privilege the use of polyester t-shirts with regards to our functional unit. Clearly washing machines with **A+++** efficiency label will save more energy than traditional washing machines yet considering the indirect impacts our recommendation is to privilege shared washing machines at low temperature settings with full capacity loads and minimal detergent. Additionally, machine drying should be utilized prudently due to its large energy consumption. Lastly we recommend to donate and buy from second hand shops.

Contents

Forward

Acronyms **i**

Summary **ii**

1 Introduction **1**

2 Study scope **2**
2.1 Background 2
2.2 Objectives 2
2.3 Functional Unit 2
2.4 Reference Flows and Key Parameters 3
2.5 Boundaries & Assumptions 4
2.5.1 System 4
2.5.2 Data collection 6
2.6 Selected Environmental Impacts 7
2.6.1 Environmental Impacts in terms of climate change CO_2 7
2.6.2 Environmental Impacts in terms of ecological scarcity 8
2.7 Scenarios and Sensitivity Analysis 8

3 Results and Discussion **8**
3.1 Comparison Among Systems 8
3.2 Sensitivity Analysis Scenario 1 10
3.3 Sensitivity Analysis Scenario 2 11
3.4 Sensitivity Analysis Scenario 3 11
3.5 Sensitivity Analysis Scenario 4 12
3.6 Sensitivity Analysis Scenario 5 13
3.7 Comparison to Prior Studies 16
3.8 Study Limitations 17

4 Conclusions and Recommendations **18**

1 Introduction

Over the past 20 years the price of garments have steadily dropped, and at the same time prices dropped, consumer habits to purchase more clothes increased. On average we have 5 times more clothes than our grandparents [1]. The fashion industry is the second largest polluter in the world after the oil industry. Just as this industry grows so does its environmental damage. The fashion industry impacts the environment in a variety of different forms. Water pollution from production centers often goes untreated and dumped directly into rivers. This waste water contains toxic substances that poison aquatic and human life. Besides polluting water, the fashion industry consumes high quantity of fresh water. Nearly 20,000 liters of water are needed to produce 1kg of cotton[1]. This adds strain to an already scarce resource. Alternatively man-made fiber (MMF) such as polyester, acrylic, nylon, etc. have rapidly grown in production. As per the ICAC cotton production has remained largely stable over the past years, whilst synthetic fibers have skyrocketed in growth with polyester leading the production [2]. These MMF are made primary of fossil fuel, making its production very energy intensive. The current production of both synthetic and natural materials have a negative impact on the earth.

This opens the question of our comparative life cycle assessment (LCA).
First, what type of t-shirt is a better option for the environment and under which assumptions.
Secondly, what phase of its life has the most significant impact on CO_2 emissions and on the ecological scarcity?

2 Study scope

Before we begin, a brief background and context of the fashion industry and its tactics to build the fast fashion industry are described.

2.1 Background

Fast fashion is an extreme version of planned obsolescence to clothing. Planned obsolescence is the predefined policy of design whereby the useful life of a product is purposefully limited. Planned obsolescence is a tool used to perpetuate purchase cycles. Purchase cycles are key to the survival of the retail market. At the saturation of the automobile market in 1924, the American car manufacturer General Motors proposed to make annual model changes to encourage car owners to buy new units each year. By 1931 General Motors surpassed the long time giant Ford Motor Company in number of sales.

By the end of the 20th century the fashion industry adopted a similar transformation. New changes in the production of cloth enabled textile companies to significantly reduce their costs. Cloth became incredibly cheap thanks to new efficient supply chains, cheap sweatshop labor, new easy to produce man-made fibers (MMF) (i.e. polyester, and nylon) and improved manufacturing methods. This gave birth to the new *fast fashion* market. As in the case with General Motors, the fast fashion industry heavily marketed short fashion cycles to promote new cyclical purchases and encourage consumers to get up to current fashion trends. New fashion-conscious consumers were quickly lured by the designer cuts offered at accessible prices. This inevitably launched a new global market for cloth retail. However, this new global phenomenon came at the expense of environmental and human resources. Sweatshops have since been heavily criticized for profiting of illegal labor conditions and exploiting workers.

Many fast-fashion brands are adept at responding quickly to shifting customer preferences. However, this requires not only controlling inventory, but also minimizing the risk of unsold items, and opening more stores to ensure that factories have enough production to run. In order to push record sales, fast fashion companies leverage on cheaper prices, at the expense of lower quality and cheap human labor. The result of these efforts is that people in developing countries are forced to work under harsh labor conditions, including low wages and long hours. Clothes are purposefully made at low quality standards in order to incentivize customers to return. Shorter fashion cycles increases customer visits, brand awareness, and purchases. The quick fashion cycles creates massive amounts of waste material. This waste is specially difficult to recycle due to its low-quality fabrication. Conducting a LCA of a t-shirt is a great opportunity to learn about where, and how each piece of clothing is made. This has broaden our perspectives to the sustainability of garments and which advise to take to reduce their impact at purchase, during, use and at its end of life.

2.2 Objectives

The objective of this project is to determine the environmental impact synthetic t-shirts have over its cotton counterpart. This assessment examines all life cycle stages. The primary goal is to determine where the largest environmental impacts of these product are. The secondary goal is to target new design alternatives that could better meet environmental standards.

2.3 Functional Unit

In order to do a comparative study between the cotton and polyester a common function must be decided for the two. Since there exists preferences between cotton and polyester with regards to clothing function (i.e. Sports attire use more synthetic than cotton and daily attire use more cotton than synthetic), the functional unit must provide the same function regardless of chosen material. The primary function of a t-shirts is to provide a rudimentary level of clothing. For this reason the functional unit (**FU**) decided for this analysis is **100 days of protection**. The lifetime of a t-shirt can vary largely between the quality of build, and wash cycles. In Switzerland the average t-shirt is washed once every two weeks. Most t-shirts have a lifespan of 50 wash cycles. This results in a typical use phase of 2 years [3].

Shirts wash cycles are typically dictated by the shirts, sweat, stain, and wear.

Clothes have varied life span and intensity of use. There exists functional clothing today that is decades old and there are some clothes that are only used once or not at all.(Laitala Boks, 2012). Pieces of clothing can pass from different users as is often the case with siblings, or second-hand purchases. Two important factors to consider are the length of life span and the number of use times. A large wardrobe decreases the likelihood a garment is used often and thus is preserved much longer. For this reason measuring life alone does not provide sufficient information about the resource efficiency unless the number of uses per item is taken into account. This metric can be tied to the number of times the item is washed as in 1 use cycle = 1 wash cycle.

It is important to understand the assumptions stipulated in this analysis. The LCA assessment can make some sensitive analysis to how many wash-cycles a garment receives. Different studies shows that the total life spans of clothing depend on a wide array of factors. Clothes for teenager and children have a shorter life span than adults. Another important distinction to make is relationship between the life span and the use of the garment. In this report it is assumed that in Switzerland the majority of clothes will be disposed once it reaches it's limit wash cycle after which the garment shows fabric tear. While it is true that popular trend has fashion items used during a certain season, this clothes items are often given up to second hand shops or donated to organization such as *CARITAS* instead of thrown away.

Figure 1: Reference Flow & Key Parameter with respect to our functional unit

Product	Functional Unit	Reference Flow	Key Parameters
Cotton T-shirt	100 days of protection	1 Cotton T-shirt	Weight of T-shirt Washing Frequency Mode of Transport
Polyester T-Shirt		2 Polyester T-shirts	

2.4 Reference Flows and Key Parameters

The functional unit defined above can be related to the reference flow by identifying the key parameters that impact the environment directly. The functional unit measure environmental performances in an additive manner while key parameters measure them as the ratio of material needed for each function [4]. For the t-shirt, the impact on the environment significantly depends on the lifetime. We consider for this study that the cotton t-shirt can be worn two days before wash, whereas a polyester t-shirt can only be worn once before wash. With respects to the average lifetime of both T-shirts being at 50 was cycles [5][6], we have that **1 cotton** or **2 polyester** t-shirts are needed in order to provide 100 days of protection. The longer the lifetime, the impact on the environment decreases because the amount of material used to make the t-shirt reduces. Not just the t-shirt but the washing machine plays an important role in the life cycle. The washing machine's main parameter is the amount of electricity used during its operation, and this is expressed in a more concise unit which is the duration of washing and the power of the washing machine. The frequency of washing, the amount of water used, or the amount of detergent used are all parameters that can be controlled by the users; hence, it plays a key role and needs to be defined initially. These key parameters allow us to determine the differences in environmental impacts between cotton and polyester-made t-shirts.

2.5 Boundaries & Assumptions

The reference flows and subsequent impacts with respects to the FU are calculated based on a system. In this study, two systems are identified and analyzed: t-shirt and washing machine.

2.5.1 System

System is a collection of processes which are required to perform the functions of product and are within the system boundary. It is representative of all the processes in the life cycle of a product and the links between elements. System boundary separates the system from the environmental and economic surroundings for all scenarios.

The system for t-shirt includes 8 sections shown in Figure 2. The cotton t-shirts are produced in India while the synthetic t-shirts are produced in China. Both brands of t-shirts are transported to Switzerland, are used by a single individual and are incinerated at the end of life (EOL). The disposal at the EOL of both t-shirts and washing machine is considered to be in Switzerland as well.

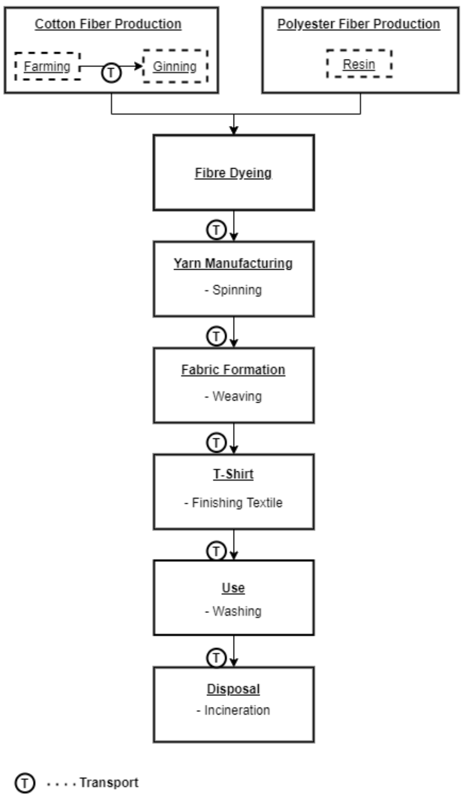


Figure 2: System for t-shirt

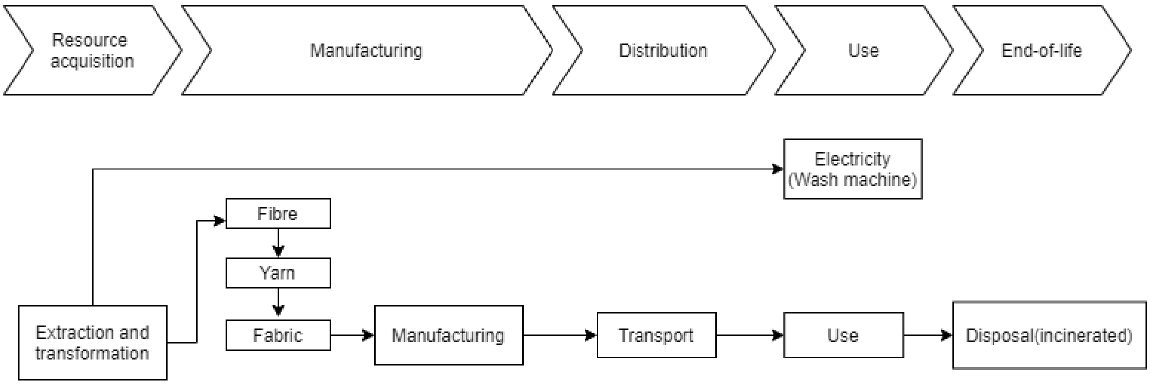


Figure 3: System boundary for t-shirt

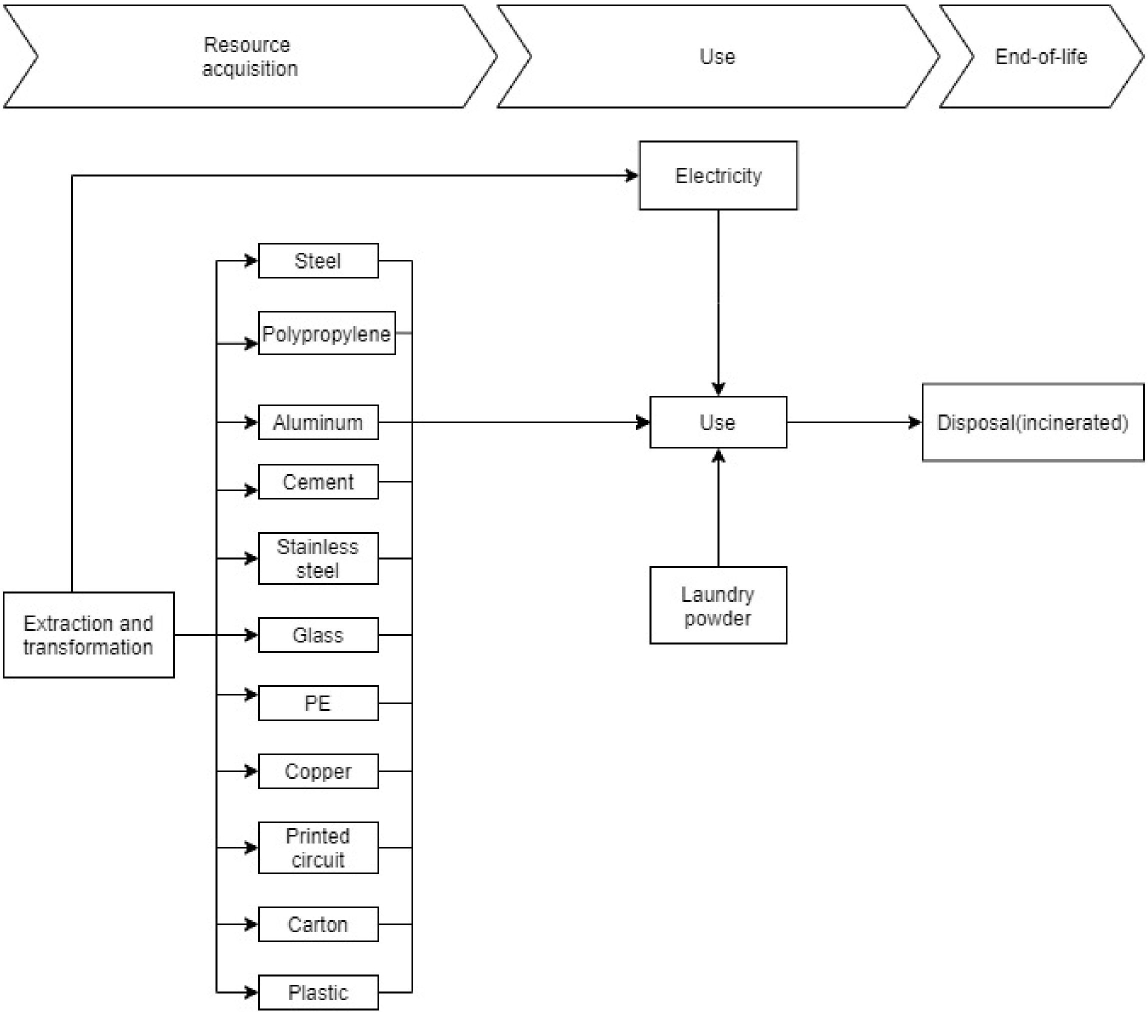


Figure 4: System boundary for washing machine

The system boundaries are in accordance to the evaluation of impacts in terms of climate change and in terms of ecological scarcity. The diagrams of system boundaries for t-shirt and washing machine are illustrated in Figures 3 and 4 respectively. The processes which emit CO_2 or use electricity, as well as laundry powder will be considered in our LCA.

Concerning the system boundary for the washing machine, we only consider the environmental impact generated from the extraction and production of the materials used, the energy, water and detergent consumption throughout the use phase as well as the incineration at the EOL. The manufacturing processes and transportation of the washing machine are not considered in this report.

2.5.2 Data collection

The data for climate change and ecological scarcity used in this study are acquired from the provided database: Ecoinvent database 3.71.

The impact values provided to us within this data base were normalized and reported with respects to the functional unit.

Cotton and Polyester t-shirt data:

As specified in the project outline and by the reference flows, we have that the weight of a cotton t-shirt is 220 g whereas the weight of a polyester t-shirt is only 80 g. Furthermore, we have that a cotton t-shirt can be worn two days before wash, whereas a polyester t-shirt can only be worn once before wash.

Considering that the process steps for dyeing, weaving and incinerating all take place at the same production stages (Fiber, Yarn, Fabric stages respectively) for both t-shirts, we assume that they results in the same amount of environmental impact per kg of material.

Additionally, since the manufacturing is mechanical, we assume material losses in between each production stage for both t-shirts. For cotton t-shirt, it is assumed that 120 kg of raw cotton is needed to produce 100 kg of cotton yarn and 118,5 kg of yarn results in 100 kg of fabric considering the losses during the ginning, spinning and weaving steps [7]. For the polyester t-shirt production, we considered 120 kg of resin is used to produce 100 kg of yarn [6] then results in 84,4 kg of fabric. For the finishing of textiles (turning fabric into t-shirts), 14.38% losses are assumed for both materials. The weight of material fabric and the weight of t-shirts are shown in Table 1.

Two different distribution methods will be considered in this report. For cotton t-shirts, 70% of the t-shirts are delivered from Port Mumbai to Switzerland by boat until the Port Le Havre (distance is 12'812,136 km[8]) and then to Geneva by truck (distance is 729,7 km[8]). 30% of the t-shirts are however directly sent by plane to Geneva (distance is 6716 km[9]), in order to increase flexibility in stocks management. For synthetic t-shirts, all deliveries from Port Shanghai to Switzerland are by boat until the Port Le Havre (distance is 21749,888 km[8]) and the rest of the trip is by truck. Transportation distance by truck to the incineration facility for the t-shirts is considered to be 10km .

Brand of t-shirt	Weight of fabric (g)	Weight of t-shirt (g)
Brand A (cotton t-shirt)	256,96	220
Brand B (synthetic t-shirt)	93,44	80

Table 1: Weight of fabric needed in order to produce both brands of t-shirts.

Washing Machine data

The following specifications were provided in the project outline:

- The lifespan of the washing machine is set to be at 2000 cycles.
- The textile quantity per wash is set at 4 kg.
- The washing machine (70kg) with its packaging (3,3kg) is made of the following materials:

List of Materials

- Stainless steel: 5,5 kg
- Steel: 24,5 kg
- Copper: 1,4 kg
- Aluminum: 1,3 kg
- Glass: 2,5 kg
- Cement: 18 kg
- Polypropylene: 16 kg
- Polyethylene HD: 0,5 kg
- Polyethylene LD: 1,3 kg
- Printed circuits: 0,3 kg
- Carton: 2 kg

Similarly to the t-shirts, we have assumed a transportation distance to the incineration facility of 10 km for the washing machine.

To determine the impact of the t-shirt's use phase (washing), with respect to our functional unit, we first had to calculate the impact values per wash cycle of our washing machine. To do this, we first calculated the different environmental impacts per unit washing machine, then we divided those values by the lifespan of the machine. Secondly, we consider how many cycles are needed to wash the quantity of t-shirts indicated by our functional unit. We established that for 100 days of use, a person would need to wash 50 times a single cotton t-shirt (220 g) or wash 50 times the equivalent of two polyester t-shirts (160 g) over their lifetime (see Reference Flows and Key Parameters).
Finally, we needed to determine the proportional environmental impacts of our t-shirts with respects to the number of wash cycles indicated by our functional unit. We assumed that for each wash cycle, a full load (4kg) of the respective t-shirt brand was used. In other words that a wash cycle contained 18 cotton t-shirts ($rounded\, down\, (4/0.220) = 18$) of brand A or 50 polyester t-shirts ($4/0.08 = 50$) of brand B.

The following equations demonstrates the conversion of the environmental impact values per unit washing machine to our functional unit for the cotton and polyester t-shirts respectively:

$$\frac{Impact\,[Unit\, washing\, machine]}{2000\, Cycles} \times 50\, Cycles \times \frac{1}{18\, Cotton\, shirts} = Impact\,[100\, Days] \tag{1}$$

$$\frac{Impact\,[Unit\, washing\, machine]}{2000\, Cycles} \times 50\, Cycles \times \frac{2}{50\, Polyester\, shirts} = Impact\,[100\, Days] \tag{2}$$

2.6 Selected Environmental Impacts

Two environmental metrics were used to quantify the impact from each type of t-shirt. These were the GWP used to measure climate change and UBP used to measure the ecological scarcity.

2.6.1 Environmental Impacts in terms of climate change CO_2

The main driver of climate change is the greenhouse effect. This effect is caused by several gases trapping heat in the atmosphere leading to the Earth's warming. Many of these greenhouse gases occur naturally, but human activity is increasing the concentrations of some of them. For this reason, the Global Warming Potential (GWP) was developed to allow comparisons of the global warming impacts of different gases. Specifically, it is a measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time, relative to the emissions of 1 ton of carbon dioxide (CO_2). The larger the GWP, the more that a given gas warms the Earth compared to CO_2 over that time period. The time period usually used for GWPs is 100 years [10].

2.6.2 Environmental Impacts in terms of ecological scarcity

UBP measures the ecological scarcity. This metric weights the impact by using two different approaches: damage modeling and distance to target. The Ecoinvent database provided both of these metrics for the environmental impact of our products [11]. The ecological scarcity method discussed in this publication follows the second approach. It totals all of the environmental impacts using the metric of eco-points (UBP). For this reason it is also called the eco-points method.

2.7 Scenarios and Sensitivity Analysis

The purpose of sensitivity analysis is to test the robustness of our results by testing their sensitivity to the data, assumptions and models used [4]. Therefore, we have identified the key parameters that have the greatest impact on the results. The following case scenarios serve to highlight the impact of each one of them.

- Scenario 1: Impact of washing machine settings.
  The washing machine has three washing temperatures: 40°C, 60°C and 95°C. Different washing temperature modes consume different amount of water and electricity.

- Scenario 2: Impact of location.
  It is assumed that the t-shirts are shipped to Germany and used in Germany rather than Switzerland. 70% of the cotton t-shirts are imported by boat from Mumbai to the port of Hamburg (7,451 nm [8]) and then trucked to Hamburg (11 km); 30% of the t-shirts are shipped directly to Hamburg by airplane (6,536 km [12]). Polyester t-shirts are all delivered by boat from Shanghai to Hamburg (12,277 nm [13]) and then by truck to Hamburg. Electricity is different in Germany and Switzerland, but all other assumptions are the same.

- Scenario 3: Impact of alternative end of life.
  Assume at the EOL, the t-shirts are sent to Kenya by airplane and have a second life in Kenya instead of incinerated in Switzerland. The delivery distance is 5939 km [14]. People in Kenya wash t-shirts with their hands instead of machines, so the impact of washing machines is not considered in Kenya.

- Scenario 4: Impact of machine drying.
  In winter, assuming the user decides to dry the t-shirt with the same washing machine. Electricity for drying is estimated at twice the electricity for washing (at 40°C).

- Scenario 5: Impact of washing machine energy label.
  To decrease the global warming impact, the user decides to change the washing machine for an A+++ machine. We decided to use the washing machine model *V-ZUG ADORA SLQ* because the manual data provided information on the water consumption and energy consumption for different temperature settings (Appendix).

3 Results and Discussion

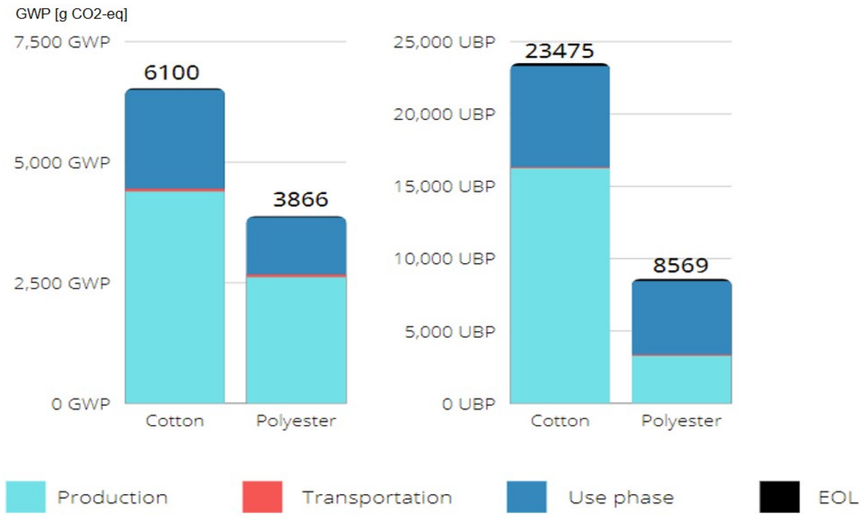
3.1 Comparison Among Systems

Assuming the 40°C temperature setting and a full load for both t-shirts, the overall results in terms of GWP and UBP are shown in Figure 5. The GWP caused by cotton t-shirt is 6100 g $CO_2 - eq$ and 3866 g $CO_2 - eq$ by polyester t-shirt. In terms of UBP, cotton t-shirt has an impact of 23475 UBP and 8569 UBP for the polyester t-shirt. Therefore, polyester t-shirt is the best t-shirt from an environmental point of view, and using polyester t-shirt reduces GWP by 37% and UBP by 63%.

From the life cycle phases comparison in Figure 6, it is worth noting that the transportation and EOL only produced a small amount of the overall impact, while the production and use phase accounted for more than 97% for the two impact values.

Figure 5 compares GWP and UBP for both cotton and polyester. The results fair significantly better for polyester t-shirts on both metrics. It is important to note that for the GWP metric both

Figure 5: GWP and UBP metric comparison



cotton and polyester produce the greatest impact during the *production phase*. This is the same for cotton in the UBP metric but not for polyester. Polyester t-shirts have a larger UBP impact during the *use phase*. This is because for polyester the transformation from non-woven polyester to yarn yields significantly less impact than its cotton counterpart.

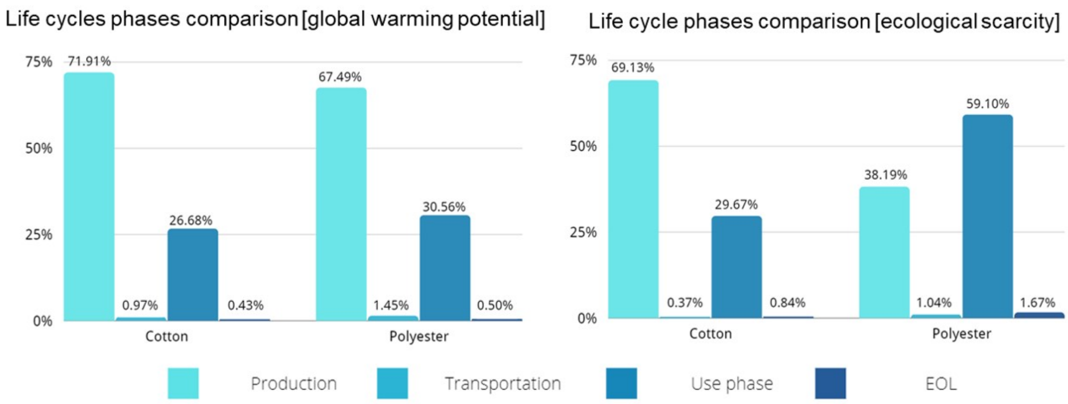


Figure 6: Phases comparison of climate change and ecological scarcity for two t-shirts

Figure 6 normalizes these value in terms of percentages. Cotton t-shirts experience their about 70% of their environmental impact for both metrics during the *production phase*. This result changes for polyester where 59% of UBP impact is during the use phase and 67% of its GWP impact is during the *production phase*. This is the case because the UBP for cotton is very high due to the high UBP costs to transform cotton into fiber then yarn and then fabric.

We equally compared the impact of both t-shirts during their EOL. Both t-shirts are assumed to go through an incineration process. The incineration process creates some environmental gain through the electricity produced. The energy regained from the washing machine incineration can be assumed to be *null* since the majority of its components are metals. A kilogram of textile waste produces 1.36 mega-Joules of electric energy, and 2.86 mega-Joules of waste thermal energy (according to the database). The cotton t-shirts waste for our FU is :

$$\frac{0.22\ kg}{Cotton\ t-shirt\ weight} \times \frac{1.36\ MJ}{1\ kg\ textile\ waste} \times \frac{0.277778\ kWh}{1\ MJ} = 0.083\ kWh \tag{3}$$

$$2 \times \frac{0.08\,kg}{Polyester\ t-shirt\ weight} \times \frac{1.36\,MJ}{1\,kg\ textile\ waste} \times \frac{0.277778\,kWh}{1\,MJ} = 0.060\,kWh \tag{4}$$

The washing machine's incinerable components are: *Carton, Printed Circuits, PE, Plastics, Prolyproplene, and Cement*. These components give back 78.46 MJ at incineration.

$$78.46\,MJ \times \frac{0.277778\,kWh}{1\,MJ} = 21.794\,kWh \tag{5}$$

A 100-watt, classic light bulb running for one full day would use up 2.4 kWh of energy. As calculate here the amount of electricity produced back during the incineration is enough to fully power one light bulb for nine full days. This is very small and negligible return on electricity.

Lastly we made a comparison of material during the *production stage*. In the production phase, five steps were considered: fiber production, yarn production, textile woven, dyeing and finishing textile. From the production phase comparison for both t-shirts in Figure 7, the fiber production is the step causing the highest amount of environmental impacts. For GWP, the fiber production takes 32.8% for cotton t-shirt and 36.0% for polyester t-shirt. In terms of UBP, fiber production accounted for 70.8% in production phase for cotton t-shirt, which mainly due to the vast amount of resources needed to grow cotton. The dyeing step also has considerable impact in terms of GWP due to the water contamination and toxic waste it produces.

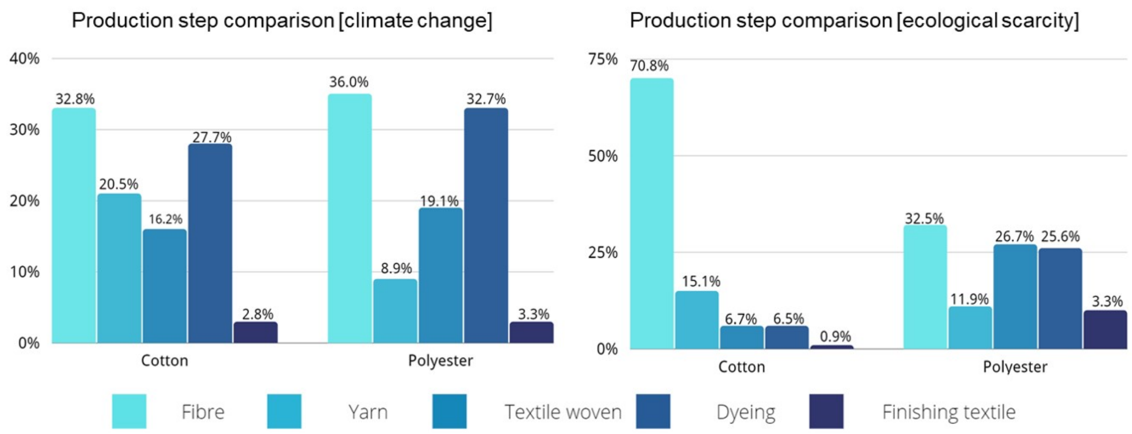


Figure 7: Production phase comparison of climate change and ecological scarcity for two t-shirts

3.2 Sensitivity Analysis Scenario 1

In this study, we also consider three different washing machine modes, as seen in Table 2, with 70ml of detergent per wash cycle.

Washing temperature, water and electricity consumption (per wash)			
	Temperature (℃)	Water (L)	Electricity (kWh)
Scenario 1	40	70	0.8
Scenario 2	60	65	1.3
Scenario 3	95	75	2.2

Table 2: Washing temperature, water and electricity consumption (per wash) for three different case scenarios.

The aim of this is to understand the influence of the increasing the washing temperature towards the environmental quality. The Table 2 demonstrates the water and electricity consumption for different temperatures of 40°C, 60°C and 95°C. The contribution of the use-phase to the electricity consumption is increasing as the washing temperature increases. Washing t-shirts in the temperature of 95°C consumes more electricity from what is actually needed.

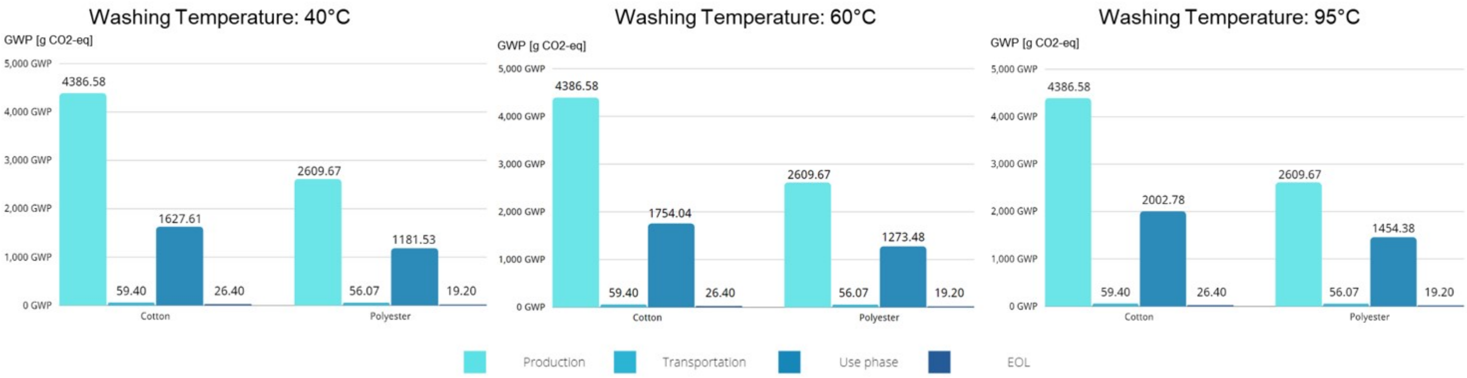


Figure 8: Comparison of climate change between different washing modes

According to the scenario analysis results shown in Figure 8, increasing the washing temperature increases the contribution of the use-phase. For a washing temperature of 40°C, the proportion of use-phase is 32%, while that of 60°C is 33% and that of 95°C is 38%. As a consequence, the proportion of the production phase decreases by the increase of temperature but maintains the status of constituting the highest out of all. Comparing 40°C and 95°C washing modes, the GWP of use phase increases 19% for both t-shirts.

For the washing machine users, it would be ideal for them to alter the washing temperature according to the reason of washing, in order to optimize the balance between the environmental impact and the degree of cleaning necessary. Normally laundry with temperature of 40°C is enough for regular uses while a higher washing temperature would be more suitable for cases where the t-shirt has contaminated a lot of food or dirt, used during an action of sport or other intense sweating activity, or any other professional clothing that may be contaminated. The higher the water temperature, the easier it is to remove stains. However, when dealing with delicate fabrics, such as wool and fashionable clothes, it is better to wash them at a water temperature below 30°C to prevent color fading and shrinkage, thus there is a need to educate people so that they can choose the best temperature when washing.

3.3 Sensitivity Analysis Scenario 2

In this scenario, the user is living in Germany. The transportation and the electricity in use phase changed. The change of transportation values is relatively small compared to the production and use phase. Assuming both brands of t-shirt are delivered to Hamburg and other delivery steps not changes. The CO_2 emission and UBP values decrease 0.03% and 0.027% respectively when delivered by plane because Germany is slightly close to the production location. The electricity in Switzerland has 0.096 climate change and 178.678 UBP value per kWh but in Germany has 0.577 climate change and 434.804 UBP value per kWh, which leads to the difference for use phase, shown in Figure 9. For both t-shirts, the climate change in use phase increase 65%. In overall, the production still has the largest impact, followed by the use phase, shown in Figure 10. Comparing to the scenario in Switzerland in Figure 6, the GWP of use phase increases from 26.68% to 37.69% for cotton t-shirt and from 30.56% to 31.35% for polyester t-shirt. Therefore, the environmental impact also depends on the country's energy production, the greener energy will have less environmental impact.

3.4 Sensitivity Analysis Scenario 3

In this scenario, the t-shirts are sent to Kenya by plane at the EOL instead of incineration in Switzerland. Since the t-shirt will get a second life in Kenya, the impact of production can be regarded as half that of Switzerland. Due to the delivery distance between Switzerland and Kenya, the impact of EOL has increased.

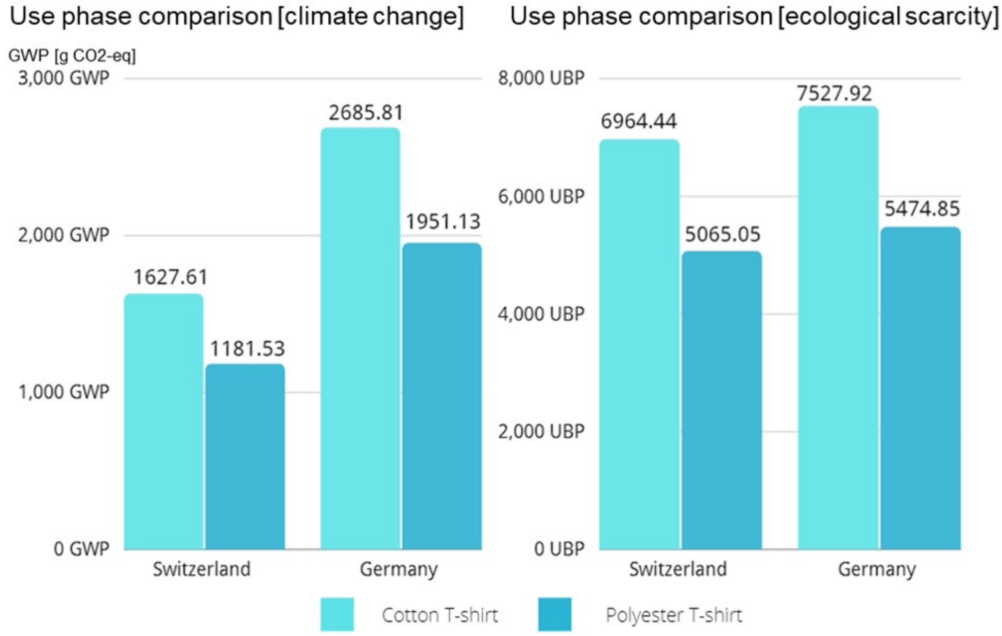


Figure 9: Use phase comparison of climate change and ecological scarcity in Switzerland and in Germany

Whether washing is conducted by hand or machine is a key to the amount of water consumption, electricity consumption and the emission of wastewater. In Africa, the washing behavior will be ones focusing on hand washing, drying with sunshine, and no ironing. There could be an idea to introduce washing machines to local residents in Africa, however, it is not realistic because it is very difficult to alter the behavior of residents who are used to washing by hand because speeding up their pace of life or improving their living standards may not be their highest interest. For this reason, the use-phase contribution can be assumed to be much lower than developed countries'.

Another key occurrence is how the t-shirt will not be recycled as well as when it is recycled at developed nations due to the lack of energy-efficient facilities, storage systems, and know how for conducting and laying a recycling system.

3.5 Sensitivity Analysis Scenario 4

In this scenario, the user dries the t-shirt by the same washing machine. In our calculations the electricity for drying is estimated at twice the electricity for washing. The results of climate change and UBP are presented in Figure 12.

Taking our FU of 100 days of use, we consider the GWP and UBP impact if these were spent in the months of winter when a drying machine would be used instead of air-drying the t-shirts. The difference in GWP would be **422,40**g CO_2-eq higher and the UBP metric would be **786,18** higher when washing at 40°C. This represents a respective 4.75% and 5.11% increase. This behavior is not significant taking into consideration that both the washing and drying machine are the same machine so the main difference is in the electricity usage. A more drastic change would be evident if a separate drying machine would be needed to dry clothes during these winter months.

CO_2 emissions and UBP values in the use phase increase as a result of the drying process, but there is no change in other stages and the production still causes the largest impact. However, if we consider the user lives in Germany, the GWP of the use phase exceeds that of the production phase. This is because of the less clean energy sources Germany uses to produce electricity. Comparing to no drying in Switzerland scenario in Figure 6, the GWP of use phase increases from 26.68% to 54.05% for cotton t-shirt and from 30.56% to 58.79% for polyester t-shirt. This big increase indicates the importance of the energy source which can vary from country to country.

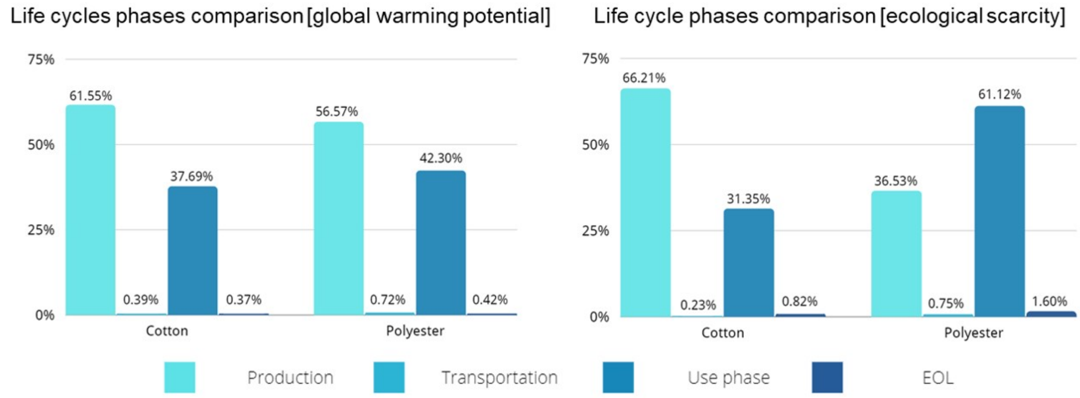


Figure 10: Phase comparison of climate change and ecological scarcity in Germany

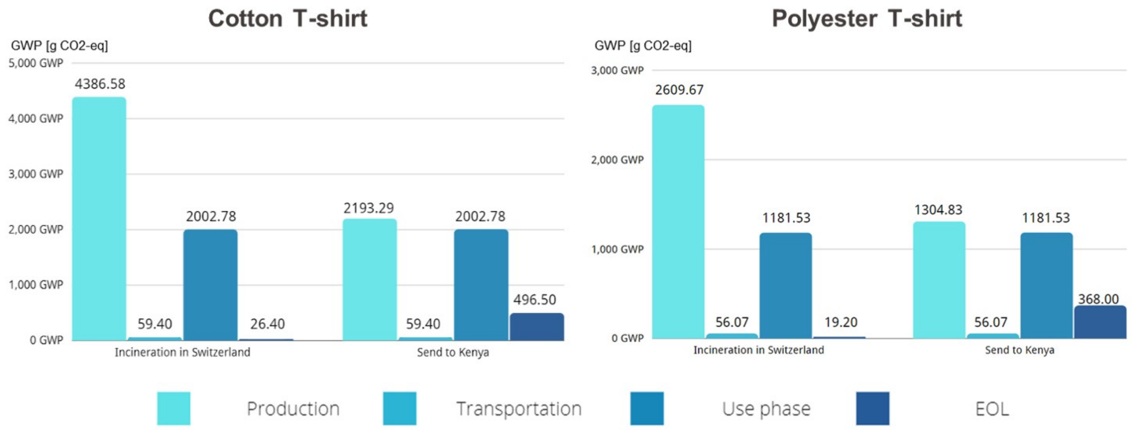
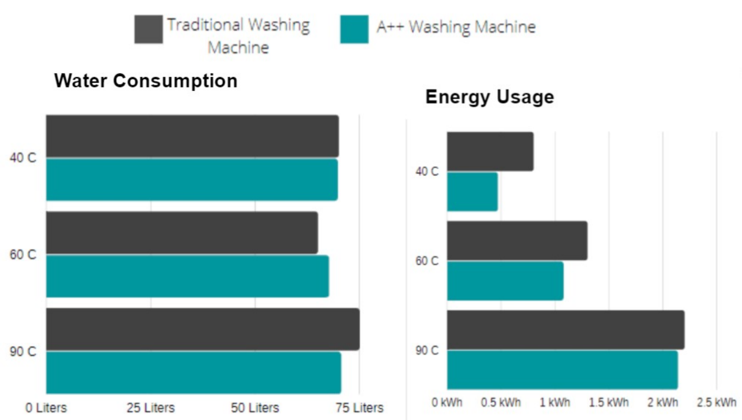


Figure 11: Comparison of alternative EOL: Send to Kenya

3.6 Sensitivity Analysis Scenario 5

This sensitivity analysis considers the impact of a more energy efficient washing machine. The Swiss washing machine V-ZUG ADORA (V-ZUG) rated A+++ was chosen and compared with the the washing machine described in the project outline. Both machines have very similar water consumption for three temperature settings, however, the energy usage is lower for the V-ZUG, specially for the 40°C temperature setting.



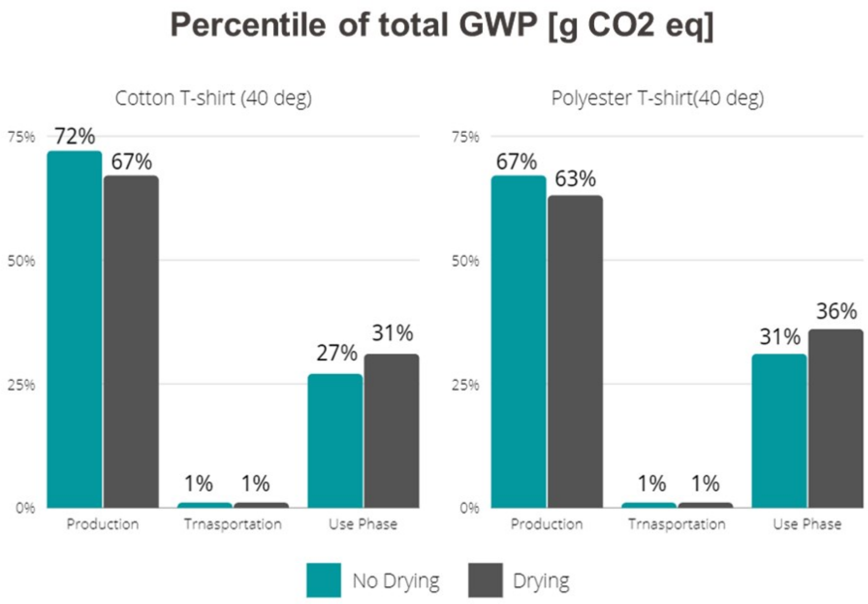


Figure 12: Comparison of climate change for no drying and machine drying

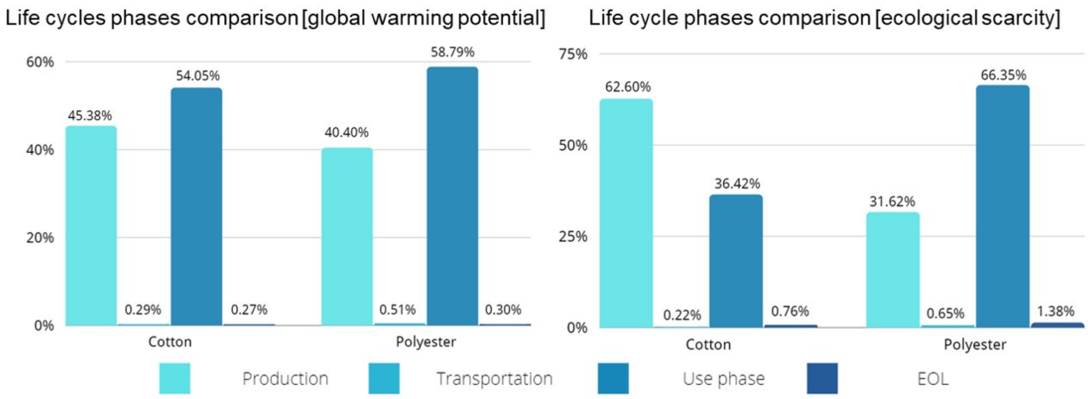
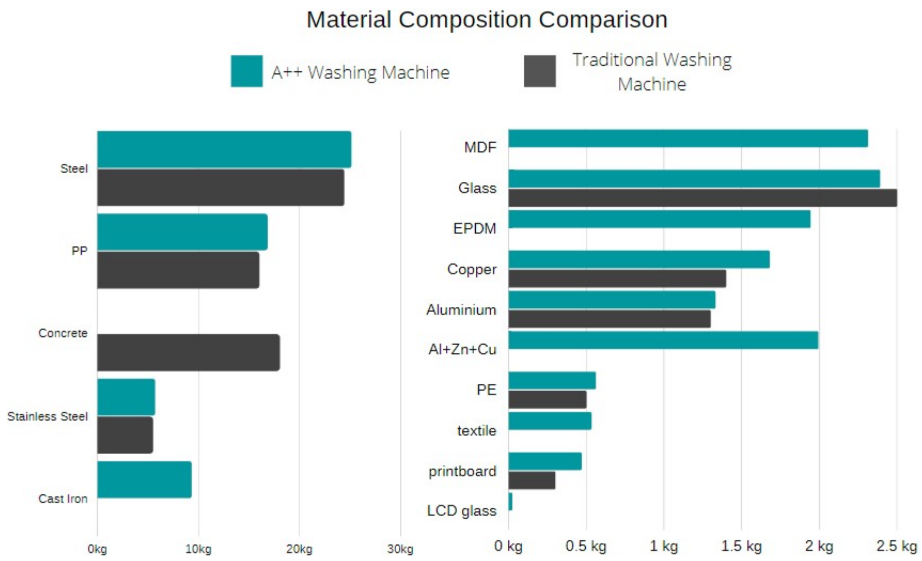
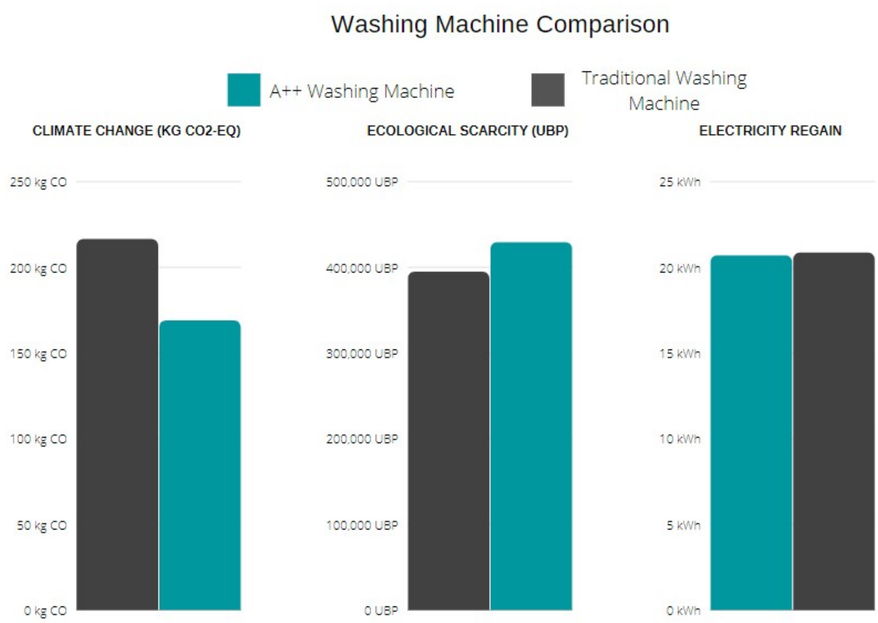


Figure 13: Comparison of climate change and UBP for machine drying in Germany

Additionally, an LCA was done for both washing machines considering exclusively their material composition. These were done on a separate sheet on the excel file.



Both machines had very similar composition and weight (70 kg traditional, 70.10 kg V-ZUG). Two notable differences became evident through this analysis. The climate change unit for V-ZUG machine was lower thanks to the use of cast iron instead of cement for the stabilization system. Secondly the new V-ZUG machine carries a larger printedboards (i.e. electronics). Newer models are expected to keep up to date with the digital transformation. These are using larger printboard to include more functions and connectivity. Out of all the materials used printboards have the largest GWP and UBP impact per weight. The V-ZUG has almost a twofold increase in printboard weight. This results in slight overall increase in UBP impact (+8.71%) for the V-ZUG machine compared to traditional machines. We assumed that both machines reached the same incineration process at the end of life. Unsurprisingly the return on electricity was negligible and there was no notable difference between the two.



We investigated the annual environmental impacts for the V-ZUG versus a traditional machine. Equations 6-7 show the environmental pact of a traditional washing machine in terms of GWP.

Equations 8-9 calculate this same metric but for the V-ZUG machine.

Traditional Machine:

$$\frac{394,635.06 \quad UBP}{2000\ wash\ cycles} \times \frac{1\ wash\ cycle}{18\ cotton\ shirts} \times \frac{183\ washes}{1\ year} = 2,006.06 \tag{6}$$

$$\frac{394,635.06 \quad UBP}{2000\ wash\ cycles} \times \frac{1\ wash\ cycle}{50\ polyester\ shirts} \times \frac{365\ washes}{1\ year} = 1,440.42 \tag{7}$$

V-ZUG Machine:

$$\frac{479,233 \quad UBP}{2000\ wash\ cycles} \times \frac{1\ wash\ cycle}{36\ cotton\ shirts} \times \frac{183\ washes}{1\ year} = 1,218.05 \tag{8}$$

$$\frac{479,233 \quad UBP}{2000\ wash\ cycles} \times \frac{1\ wash\ cycle}{100\ polyester\ shirts} \times \frac{365\ washes}{1\ year} = 874.60 \tag{9}$$

.

Traditional Machine:

$$\frac{216.350 \quad kg\ CO_2\ eq}{2000\ wash\ cycles} \times \frac{1\ wash\ cycle}{18\ cotton\ shirts} \times \frac{183\ washes}{1\ year} = 1.100 \tag{10}$$

$$\frac{216.350 \quad kg\ CO_2\ eq}{2000\ wash\ cycles} \times \frac{1\ wash\ cycle}{50\ polyester\ shirts} \times \frac{365\ washes}{1\ year} = 0.790 \tag{11}$$

V-ZUG Machine:

$$\frac{154.03 \quad kg\ CO_2\ eq}{2000\ wash\ cycles} \times \frac{1\ wash\ cycle}{36\ cotton\ shirts} \times \frac{183\ washes}{1\ year} = 0.391 \tag{12}$$

$$\frac{154.03 \quad kg\ CO_2\ eq}{2000\ wash\ cycles} \times \frac{1\ wash\ cycle}{100\ polyester\ shirts} \times \frac{365\ washes}{1\ year} = 0.281 \tag{13}$$

. The energy and water usage between both machines were very similar with V-ZUG scoring slightly better as shown in figure (show figures of water and electricity usage). However a distinguishing factor between the two is the capacity per load. The V-ZUG has a max load capacity of 8 kg compared to the project's 4 kg. As mentions before the UBP value for the V-ZUG machine was higher thanks to the larger printed board weight. Taking these factors into consideration we made the calculation to find the annual impact on the GWP and UBP values for cotton and polyester. In the case of the A+++ V-ZUG washing machine there was a reduction of about 64.45% in GWP and a reduction of about 60% for the UBP value. With the new machine one is able to reduce the environmental impact by more than half by doubling the washing capacity whilst using similar values of water and electricity.

3.7 Comparison to Prior Studies

In order to fully ensure the accuracy of our studies, we've compared our methodology to to the following life cycle assessments: [5].

These studies focused on the environmental impact of cotton t-shirts and polyester t-shirts respectively. These studies were used as a reference with regards to many of our assumptions such as the average lifespan of a cotton and polyester t-shirt.

Now, comparing the results for the global warming potential impact, we can observe that there are clear differences with respects to the emissions of the production and use phases. Both prior studies indicate that the use phase contributes to the highest GWP emissions whereas we defined that the production phase is the most polluting. These divergences between studies are caused by many factors.

First of all, the production facilities are considered to be in Turkey for the cotton t-shirts and in Great Britain for the polyester t-shirt. Our values, provided by the database, are considered to be a global average with respects to the production phase of both t-shirts. In a second time, we can also observe that the functional unit is not the same as our study. For the use phase, the washing machine and electricity values are completely different from our case scenarios as well.

Therefore, comparisons between different life cycle assessments have to be carefully analyzed and brought back to the same functional unit to be accurately evaluated. Assumptions and external data such as for the washing machine also need to be indicated for a proper comparison. For these reasons, the prior studies are solely used to validate our choices of assumptions.

3.8 Study Limitations

Our LCA study focuses primarily on the environmental component of sustainability. However, in order to properly compare both brands of t-shirts, an economical and societal analysis also have to be done. Information concerning the brands capabilities on exercising due diligence and providing good working conditions and healthcare for their employees is necessary to make a proper comparison. The price of the t-shirts, which is not considered in this report, might also reflect on the use of alternative eco-friendly manufacturing or distribution methods by the brands.

With regards to the environmental component, the main limitations of our studies, comes from the data collection. Most of the impact values provided in our results, represent activities which are considered to be an average valid for all countries in the world. However in order to properly evaluate our two products, it is essential to take into consideration their origin as well as the specific processes throughout each steps of the supply chain. Every country has their own laws and regulations with respects to agriculture and chemical production. Additionally, information such as the type of material used whether or not it's recycled or from organic cultivation is not considered in this report.

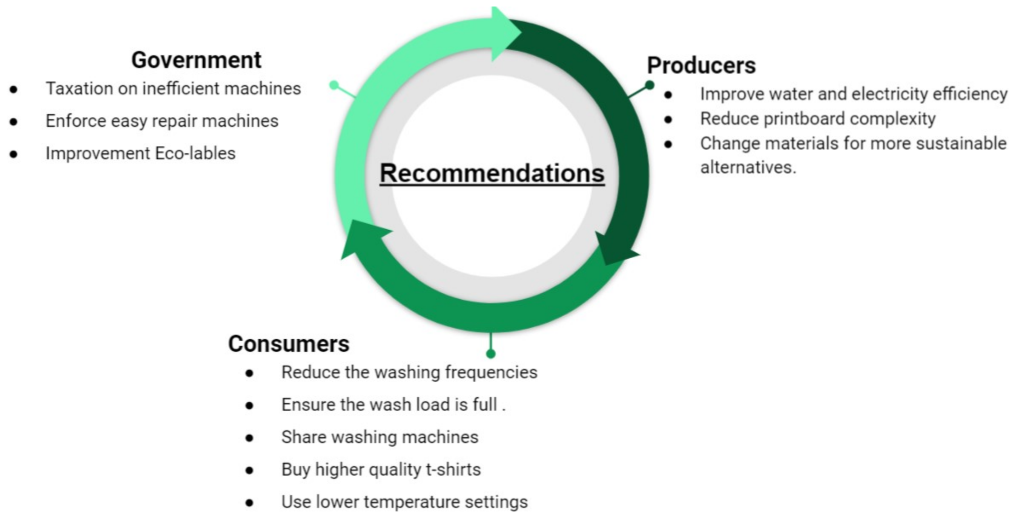
In this project, many assumptions were defined to simplify the LCA process, but real-life situations are much more complex. Therefore, more real-life situations should be analyzed in order to get more accurate results. The indicators used in this report are climate change and ecological scarcity, which are not sufficient for a full understanding of environmental impacts. Also the impact indicators considered are not sufficient to take into account all the environmental impacts of the t-shirt. In this project, only GWP and UBP are counted as impact indicators. Considering the environmental impact, systems or objects should be analyzed according to their ability to damage the environment and human health. CO_2 is not the only substance emitted by the system and other pollutants did not counted in this project, such as NO_x, CH_4, etc. These pollutants can be transferred through environmental media and enter the food chain, eventually accumulating in the human body. Multiple environmental media (air, water, soil) and multiple environmental issues should be considered in parallel. To do a more comprehensive LCA, a wider range of impact indicators should be considered. Due to the complexity of the task and the many sources of uncertainty, there is currently no reference impact assessment. The EU recommended impact assessment is the ILCD manual, which includes 17 indicators.

4 Conclusions and Recommendations

The results of the study show that polyester t-shirts have a better environmental performance than one made from cotton.Our studies have shown that in terms of ecological scarcity (UBP) and greenhouse gas emissions (GWP), polyester t-shirts represent the more sustainable alternative. Out of these two impact categories, polyester t-shirts have an impact that is 63.7% and 37.0% that of cotton t-shirt. For both t-shirts the production phase and the use phase had the highest impact.

The sensitivity analysis highlighted key parameters that can make a considerable influence on the impact polyester t-shirts can have on the environment. With regards to washing, it is clear that a washing machine marked with an **A+++** efficiency label will save more energy than traditional washing machines yet considering the indirect impacts our recommendation is to privilege shared washing machines at low temperature settings with full capacity loads and minimal detergent. Machine drying should be utilized prudently due to its large energy consumption. Lastly the location where energy is produced and teh end of life alternative given the the t-shirt can play a role in its final environmental impact.

A broader analysis would consider life cycle thinking (LCT), which includes not only the environmental impact, but also the governmental and social consequences of a product over its lifetime. A holistic approach accounts for all the entities involved, such as the governmental policies, producer's manufacturing, and consumer habits. The figure below addresses each entity with recommendations we found useful for each one of them.



There seems no reversal to the trend of textile products becoming cheaper and more accesible to the public. The continual reduction of prices will only continue to fuel more purchase and create a larger environmental impact from this industry. The biggest change required is a change of the consumer behavior. This can be achieved by creating ecological awareness and making individuals realize the impact of their daily activities on the environment. An environmentally conscious society would use washing machines prudently and only when required which would greatly reduce their overall impact. Buying less and buying from sustainable brands or from second hand shops can dramatically reduce the environmental impact of this industry.

Our recommendation can be summarized in the words fashion designer Vivienne Westwood.

buy less, choose well, and make it last

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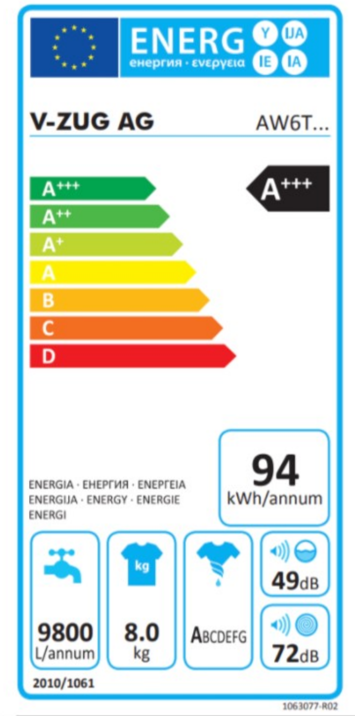
Appendices

Model	V-ZUG ADORA SLQ
Type	WA-ASLQ
Dimensions	85cm x 59.5cm x 60cm
Weight of Machine	69.91 kg
Weight of Packaging	3.23 kg



User Manual Data	40 degrees	60 degrees	95 degrees
Weight of Clothes	1-8 kg	1-8 kg	1-8 kg
Time taken for a wash	1h 05 - 1h 14	1h 15 - 1h 32	1h 38 - 2h 15
Water Consumption	70 L	65 L	75 L
Energy Consumption	0.80 kWh	1.30 kWh	2.20 kWh