DOKUZ EYLÜL UNIVERSITY

GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

DETERMINING THE ENVIRONMENTAL IMPACTS OF CIRCULAR ECONOMY IMPLEMENTATION IN AN APPAREL SECTOR

by

İrem KILIÇ

June, 2024

İZMİR

DETERMINING THE ENVIRONMENTAL IMPACTS OF CIRCULAR ECONOMY IMPLEMENTATION IN AN APPAREL SECTOR

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by

İrem KILIÇ

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İZMİR

M.S. THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"DETERMINING THE ENVIRONMENTAL IMPACTS OF CIRCULAR ECONOMY IMPLEMENTATION IN AN APPAREL SECTOR"** completed by **İREM KILIÇ** under supervision of **PROFESSOR DOCTOR NURDAN BÜYÜKKAMACI** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

Prof. Dr. Nurdan BÜYÜKKAMACI

Supervisor

Prof. Dr. Ayşe FİLİBELİ

Jury Member

Prof. Dr. Zümrüt ÜNAL

Jury Member

Prof. Dr. Okan FISTIKOĞLU

Director

Graduate School of Natural and Applied Sciences

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DETERMINING THE ENVIRONMENTAL IMPACTS OF CIRCULAR ECONOMY IMPLEMENTATION IN AN APPAREL SECTOR

ABSTRACT

The textile and apparel industry is one of the sectors that pollutes the environment the most. The increasing population and the rapid change in fashion result in an increase in the production of waste on a daily basis. In order to reduce the negative effects of the textile and apparel industry on the environment, circular economy practices are becoming increasingly common.

In this study, the environmental impacts caused by the textile and apparel industry were examined using the Life Cycle Analysis (LCA) method. In the selected pilot plants, scrap fabrics are recycled and used again in fabric production and the environmental impacts of this production process are analyzed by LCA method. Except for the current situation, 8 different situations were created to investigate how much the circular economy approach and the use of renewable energy in production will reduce environmental impacts. GaBi software was used for the LCA study. The results of 9 cases were analyzed in 11 different CML impact categories. The results of these cases according to different material types and the type of energy used were compared.

The findings show that all materials used in fabric production are recycled materials and the use of solar energy at every stage of production has the least environmental impact. It was also concluded that using organic cotton instead of conventional cotton causes less harm to the environment.

Keywords: Circular economy, recycling, life cycle assessment, sustainability, scrap fabrics, textile and apparel industry

KONFEKSİYON SEKTÖRÜNDE DÖNGÜSEL EKONOMİ UYGULAMASININ ÇEVRESEL ETKİLERİNİN BELİRLENMESİ

ÖZ

Tekstil ve Hazır Giyim endüstrisi en kirletici endüstrilerden biridir. Artan nüfus ve modanın hızlı değişimi üretimi ve dolayısıyla da oluşan atık miktarını her geçen gün arttırmaktadır. Tekstil ve Hazır Giyim endüstrisinin çevreye verdiği negatif etkileri azaltmak için döngüsel ekonomi uygulamaları giderek yaygınlaşmaktadır.

Bu çalışmada Yaşam Döngüsü Analizi (YDA) yöntemi kullanılarak Tekstil ve hazır giyim endüstrisinin neden olduğu çevresel etkiler incelenmiştir. Seçilen pilot tesislerde kırpıntı kumaşlar geri dönüştürülerek tekrar kumaş üretiminde kullanılmaktadır ve bu üretim sürecinin çevresel etkileri YDA yöntemi ile incelenmiştir. Mevcut durum hariç 8 farklı durum daha oluşturularak döngüsel ekonomi yaklaşımı ve üretimde yenilenebilir enerji kullanımının çevresel etkileri ne kadar azaltacağını araştırılmıştır. YDA çalışması için GaBi yazılımı kullanılmıştır. 9 durumun sonuçları 11 farklı CML etki kategorisinde incelenmiştir. Bu durumların farklı materyal tipine ve kullanılan enerji türüne göre olan sonuçları karşılaştırılmıştır.

Bulgular kumaş üretimindeki tüm materyallerin geri dönüştürülmüş materyal olduğu ve üretimin her aşamasında güneş enerjisi kullanıldığı durumun en az çevresel etki oluşturulduğu göstermektedir. Ayrıca konvansiyonel pamuk yerine organik pamuk kullanımının da çevreye daha az etki verdiği sonucu elde edilmiştir.

Anahtar kelimeler: Döngüsel ekonomi, geri dönüşüm, yaşam döngüsü analizi, sürdürülebilirlik, kırpıntı kumaş, tekstil ve hazır giyim endüstrisi

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CHAPTER ONE
INTRODUCTION

The textile and apparel (T&A) industry represents one of the most significant contributors to environmental impacts globally (Stone et al., 2020). The growth of the global population and the advent of fast fashion have led to a surge in production in the T&A industry. In contrast to the sustainability approach, a different methodology is employed in the supply of raw materials, yarn spinning, weaving, knitting, wet processes such as finishing, dyeing and printing, and lastly garment processes (Ayvaz and Teker, 2023). The manufacture of various products and services requires the use of a multitude of chemical substances, raw materials, energy sources, and water. Consequently, considerable quantities of waste are discharged into different receiving environments, thereby posing a significant threat to the environment and human health. The T&A industry is considered one of the sectors that causes the most harm to the environment among all industrial sectors, not only in terms of the quantity of wastewater discharged, but also in consideration of the composition of the wastewater (Alkaya and Demirer, 2014).

Various sustainable approaches are being evaluated to decrease environmental damage caused by the T&A industry. One of the most effective strategies for decreasing the environmental impact of the T&A industry is the circular economy model. The circular economy (CE) is a system designed to prolong the lifespan of products, materials, and resources within the economy, thereby reducing the generation of waste (Ruschel-Soares et al., 2022).

Life Cycle Assessment (LCA) is a detailed analysis in which the impact of products, processes or activities on the environment is determined. It involves the systematic collection and measurement of input and output data throughout their life cycle (Gonzalez et al., 2023). The objective of this study is to assess the environmental impact of recycling practices and the use of renewable energy in the T&A industry.

The environmental effects of the manufacturing of a fabric including 50% recycled cotton (r-CO) and 50% polyester (PET) were examined with LCA using data obtained from pilot facilities. To determine whether the effects of the current case vary across cases, a number of cases have been created. These cases are divided into two groups: the raw materials are different and the type of energy consumed in production is different. Consequently, it was established which case would have a less environmental impact, and it was proposed that it could serve as an alternative to the current situation.

CHAPTER TWO
TEXTILE AND APPAREL INDUSTRY

2.1. Introduction to Textile and Apparel Industry

The T&A Industry is an essential sector for human society. The production of textiles involves numerous complex processes. The production process begins with the creation of raw materials, followed by fiber, yarn, and fabric production, and finally apparel production (Figure 2.1). Each of these processes has negative effects on the environment.

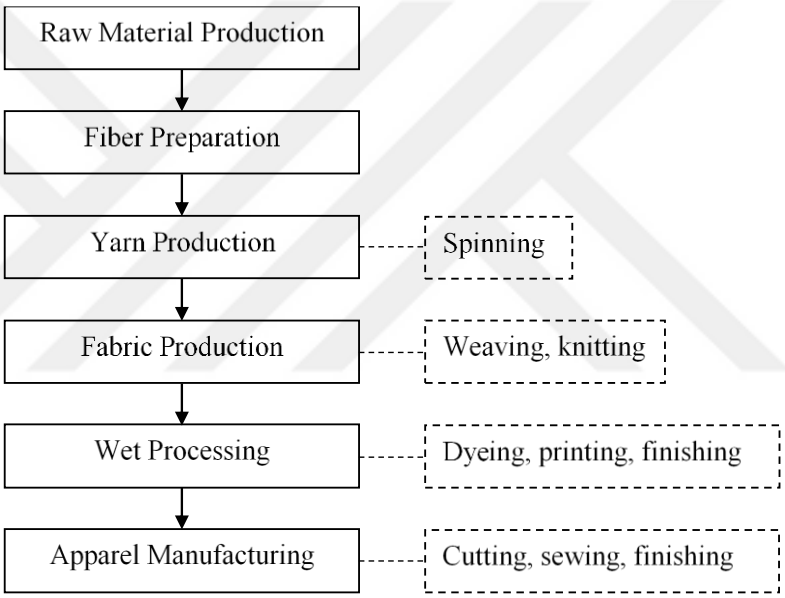


Figure 2.1 Process flow chart of the T&A Industry

The T&A Industry is a significant part of Turkey's economy. It is a major contributor to the Gross Domestic Product of the country, manufacturing, industrial production, exports, foreign exchange, employment and investment (T.C. Ticaret Bakanlığı, 2024; Uyanık ve Çelikel, 2019). Turkey is the sixth largest exporter of ready-made garment, with a 3.7% share in 2021. In terms of exports to the EU, Turkey is the third biggest exporter of garment after China and Bangladesh (T.C. Ticaret Bakanlığı, 2024). When considered collectively, the T&A Industry contributes over 10% of Turkey's Gross Domestic Product (GDP) (Uyanık and Çelikel, 2019).

The majority of textile products manufactured in Turkey are composed of cotton. Although the majority of raw materials and intermediate goods utilized in the sector, including cotton, wool, yarn, and fabric, are sourced domestically, a notable quantity of imports are also conducted. Turkey is the seventh largest cotton manufacturer around the world, according to data from the 2021/22 season. However, domestic production does not meet domestic demand, resulting in a ranking of fourth in global cotton imports (T.C. Ticaret Bakanlığı, 2024).

The T&A Industry is renowned for its numerous beneficial contributions to the economy. However, it is also associated with a number of significant environmental and social challenges in terms of long-term sustainability. These include concerns related to the industry's high energy consumption and the emission of pollutants (Harsanto et al., 2023).

The demand for textile products is rising annually because of rapid global population growth (Türemen et al., 2019). The expansion of production and consumption in T&A Industry is also attributable to the advent of fast fashion, a business model predicated on the constant introduction of new products that are not only inexpensive for consumers but also fashionable (Niinimaki et al., 2020; Zamani et al., 2017).

2.2. Environmental Effects of Textile and Apparel Industry

The T&A Industry is among the sectors that contribute the most to environmental pollution worldwide. It has been determined that there are many significant environmental impacts related to the manufacture and disposal of textiles. These include high levels of energy and water consumption, soil degradation, toxic chemical pollution in water, greenhouse gas emissions and a high carbon footprint, as well as large amounts of waste production (Shirvanimoghaddam et al., 2020).

The production of textile products consists of various manufacturing processes. There are significant negative impacts on the environmental linked to each of these processes. The processing of textiles consumes energy and resources, which results in

a high level of waste and emissions. In addition, the transportation and distribution of manufactured products also results in significant energy consumption (Moazzem et al., 2021). There are also impacts linked to activities in the textile supply chain. These impacts can be exemplified as water use, GHG emissions, acidification, eutrophication, land use, fossil energy use, climate change, human/eco-toxicity (Moazzem et al., 2021). It has been stated that textile production emits more GHG than aluminium production (Niinimaki et al., 2020).

The fiber production, the manufacture of clothing, the utilization of textile products, and the post-use processes all consume a considerable quantity of water. Waste fibers and chemical residues are left in water resources along with the effluent from water consumption. Chen et al. (2021) reported that approximately 2.72 m^3 of water are consumed in the manufacturing of one cotton t-shirt. This quantity of water consumed is equivalent to the quantity consumed by an adult over a period of 3 years (Chen et al., 2021). Water consumption continues even during other use cycles, including cleaning. This high level of consumption is particularly noticeable in regions where water is scarce. This sector is considered to be responsible for 20% of the worldwide water pollution problem. The process of dyeing and finishing during manufacture have been identified as the primary cause of this issue (Chen et al., 2021).

Wet processing, spinning, and weaving/knitting are sources of toxic emissions and rely heavily on fossil fuels, resulting in significant CO_2 emissions. It is reported that a pair of jeans causes CO_2 emissions comparable with the driving 69 miles during producing period and washing phases (Shirvanimoghaddam et al., 2020).

It has been claimed that the T&A industry will have no future if the environmental damage of textile products is not reduced. In light of this, it is evident that sustainability represents the primary concern of the T&A Industry in the current century (Moazzem et al., 2021). Industries that involve production from raw materials to products, such as the textile industry, require momentous inputs of water, energy, and chemical agents, which can lead to environmental degradation (Aguiar et al., 2023).

It has been stated that 23% of global pollution caused by raw materials and production activities, making it one of the most damaging industries to the ecosystem. It is predicted that by extending the lifespan of solid textile wastes through sustainable management, undesirable negative environmental effects resulting from the textile industry will be reduced significantly (Nyika and Dinka, 2022). To enhance the sustainability of the textile life cycle, several practices can be implemented, including the use of recycled materials, promotion of reuse, and ensuring product longevity (Moazzem et al., 2021).

2.2.1. Environmental impacts of fiber manufacture

Fiber is a significant input for the T&A Industry. It is defined as the smallest visible unit of raw material in textile production, consisting of naturally or artificially produced strands with sufficient length, elasticity, and strength to be transformed into yarn and fabric (Kırkan and Salihoğlu, 2023).

Despite the decline in global fiber production in 2020 due to the global pandemic, total fiber production in 2022 increased by 4 million tons compared to production in 2021, reaching 116 million tons. The production volume in 2022 has increased almost twofold compared to 2000. Additionally, per capita fiber production in 2022 was 14.6 kg, about 6 points higher than 1975. If current trends continue, fiber production is estimated to approach 150 million tons in 2030. The increase in fiber production has considerable effects on both society and the environment. Although awareness of reducing these impacts is increasing, the necessary changes are not yet occurring at the desired scale and speed (Textile Exchange, 2023).

The fibers utilized in the manufacture of clothing are classified into two primary categories: natural and synthetic fibers (Chen et al. 2021). Natural fibers are produced by plants or animals such as cotton, silk, wool, and flax. Synthetic fibers are further divided into two categories: artificial regenerated fibers and artificial synthetic fibers. Fibers obtained from natural fiber sources such as paper pulp are examples of regenerated artificial fibres. Synthetic fibers of a man-made are manufactured from

petrochemical substances and created through a synthetic process that is artificially produced (Moazzem et al., 2021).

In the T&A Industry, polyester is the most prevalent synthetic fiber utilized. The reason for this is that polyester is an economical material and has suitable physical and mechanical properties. It is estimated that synthetic fibers will comprise approximately 98% of all fibers in the future, with polyester accounting for 95% of this total (Chen et al., 2021).

The manufacturing process for natural fibers commences with the cultivation, farming, or animal husbandry of the raw materials. In contrast, the manufacturing process for synthetic fibers commences with the extraction of raw oil. A study comparing the amount of energy consumed in the production of different types of fibers was carried out by Moazzem et al (2021). In this study, it was found that polyester fabric consumes much more energy in production than natural fiber types, while nylon production was found to consume the most energy of all fibers (Table 2.1).

Table 2.1 Comparison of energy consumption of fibers (Moazzem et al., 2021)

Type of fibers	Energy consumption, MJ
1 kg Flax	10
1 kg Cotton	55
1 kg Wool	63
1 kg Viscose	100
1 kg Polyester	125
1 kg Acrylic	175
1 kg Nylon	250

Natural fibers such as jute, hemp, nettle and ramie are also referred to as "bast" fibers. These fibers have less impact on energy use, water consumption, and GHG emissions than synthetic fibers. Wool fiber has the highest impact on land use, while cotton is the fiber with the highest water consumption. In contrast, synthetic fibers have the highest impact on GHG emissions and energy consumption (Moazzem et al., 2021).

It is reported that 63% of textiles and fibers are derived from petrochemicals, which leads to CO_2 emissions. The production of cotton, which accounts for 37% of the total, requires considerable quantities of water and pesticides (Sandin and Peters, 2018). It was stated that driving a car 6,000 miles is equivalent to the GHG emissions resulting from the consumption of 336 tons of textiles. Textile material production also causes other types of pollution, such as excessive packaging material, product transportation, and high energy consumption (Nyika and Dinka, 2022).

2.2.1.1. Cotton

In 2022, natural fibers, including cotton, linen, hemp, jute, and others, constituted approximately 27% of the global fiber market. The proportion of cotton to total natural fiber production is approximately 80% (Kırkan and Salihoğlu, 2023) and the fiber is the second most common, with a volume of approximately 25 million tons (Textile Exchange, 2023). According to the Textile Exchange report, cotton had a market share of approximately 22% of fiber production worldwide in 2022.

Annually, 27 million tons of cotton are produced, with an expected increase to 29 million tons by 2028. However, cotton production requires a massive amount of pesticides, consuming 16% of all pesticides and 7% of herbicides used worldwide, more than any other crop. Cotton is grown on approximately 2.5% of the total agricultural land worldwide. However, almost 1 kg of hazardous pesticides are used for every hectare of cotton cultivation area worldwide (The World Counts, 2023).

Furthermore, pesticides have been found to exert toxic effects on individuals engaged in the cultivation, production, and consumption of cotton and cotton textiles. The application of chemicals for cotton cultivation has the potential to cause pollution in surrounding ecosystems, including rivers and lakes. Moreover, these chemicals may reach groundwater from these ecosystems. Additionally, the cultivation of cotton has been shown to result in the degradation of soil. For this reason, it also leads to erosion and even loss of forest lands and other habitats.

According to The World Counts (2023), more than 10 tons of water are required to produce cotton for a single pair of jeans. Additionally, Chapagain et al. (2006) state that EU countries indirectly contribute to 20% loss of water in the Aral Sea due to cotton usage.

Cotton production worldwide is responsible for releasing 220 million tons of CO_2 emission annually (The World Counts, 2023). According to Kazan et al. (2020), the production of a single shirt requires 1152 g of raw cotton, resulting in a GHG emission effect of 1341 kg CO_2 equivalent. The production of cotton T-shirts has the greatest impact on GWP (Kazan et al., 2020).

The negative environmental and health effect of conventional cotton have led to a growing awareness in sustainable alternatives in the textile sector (Ş. Fidan et al., 2023). Organic cotton represents a sustainable alternative that can help reduce the adverse environmental results of conventional cotton cultivation. Organic cotton is defined as a product that cannot be subjected to genetic modification.

In the cultivation of organic cotton, the use of chemicals such as pesticide and fertilizer are avoided, and it is grown in subtropical regions such as China, Turkey, and the United States (Eyüpoğlu, 2019). According to estimates provided by Textile Exchange, approximately 342 thousand tons of organic cotton fibers were produced on approximately 621 thousand hectares of certified organic land during the 2020/21 global harvest. This indicates that only 1.4% of all cotton grown was organic (Textile Exchange, 2022).

Organic farming systems enhance soil fertility, prevent the use of toxic chemicals, and thus support biodiverse agriculture (Eyüpoğlu, 2019). The cultivation of organic cotton avoids using synthetic chemicals including fertilizers, herbicides, insecticides, defoliants and growth regulators that are commonly used in conventional cotton cultivation (Soydan et al., 2019). Biopesticides are increasingly used in organic cotton farming to promote sustainable and ecological production methods (Eyüpoğlu, 2019; Soydan et al., 2019).

According to Delate et al. (2021), organic cotton farming consumes 91% less water than traditional cotton farming. In addition, organic agriculture is more energy efficient than conventional agriculture because it avoids the use and production of synthetic inputs and can reduce energy consumption per unit of land by up to 70% (Textile Exchange, 2021). Kazan et al. (2020) used LCA to evaluate impacts of woven shirts made with organic cotton and woven shirts made with conventional cotton. The study found that organic cotton cultivation resulted in a 58% reduction in GHG emissions compared to conventional cotton cultivation. It was found that the elimination of pesticides and fertilizers led to improvements in AP, GWP and EP (Kazan et al., 2020).

2.2.1.2. Polyester

Since the mid-1990s, synthetic fibers have dominated the fiber market, surpassing cotton in volume. In 2022, this fiber category accounted for approximately 65% of global fiber production, approximately 76 million tonnes in total (Textile Exchange, 2023).

Polyester is the most prevalent fiber utilized globally. In 2022, polyester had a global fiber production market share of approximately 54%, with a yearly production volume of around 63 million tons, up from 61 million tons in 2021. The global volume of recycled polyester (r-PET) fiber decreased from 9 million tons in 2021, equivalent to 15% of PET production, to 8.6 million tons in 2022, equivalent to around 14%. A number of factors have contributed to this phenomenon, including the competitive market for recycling PET bottles for use as raw materials, underinvestment in textile recycling to textiles, and the growth of virgin fossil-based materials (Textile Exchange, 2023).

The production of polyester textiles is associated with the consumption of significant quantities of water, energy, and chemicals. Following the synthesis of polyester as flakes or pellets, the material is extruded and spun by melting at a temperature exceeding 250°C, a process that necessitates the expenditure of

considerable energy. Additionally, the dyeing of one kilogram of polyester textiles requires approximately 50 liters of water (Qian et al., 2021).

While synthetic textiles are responsible for 8% of the microplastics discharged into European oceans, it is estimated that this rate is up to 35% worldwide (EEA, 2022). According to the European Environment Agency's (EEA) 2022 report, the textile industry contributes 200,000 to 500,000 tons of microplastics to the marine environment each year. Napper and Thompson (2016) stated that an average 6 kg synthetic fabric washing load can release in excess of 700,000 fibers.

2.2.2. Environmental impacts of the textile production

The T&A industry is regarded as one of the industries that causes the greatest threat to the environment. A multitude of processes employed in the textile industry result in the generation of considerable quantities of emissions, liquid, and solid waste (Ghaly et al., 2014). The production of yarn and fabric follows that of fiber. Textile fabrics are produced from yarns by way of knitting or weaving processes, and they require significant quantities of energy and water in wet processes. In addition, the production of textiles generates an excessive amount of waste in all production processes (Niinimaki et al., 2020).

The T&A industry is one of the highest chemical-using sector in the world in way of environmental impact. This makes it potentially the world's leading industrial water consumer and polluter (Gosavi and Sharma, 2014; Holkar et al., 2016; Yadav et al., 2022). It has been stated that an average textile factory consumes approximately 200 L/kg/day of water (Ghaly et al., 2014; Holkar et al., 2016). According to World Bank estimates, textile processes of dyeing and finishing applied to a fabric account for approximately 20% of industrial wastewater (Holkar et al., 2016). Textile wastewaters consist of high levels of environmental and human health hazards. The majority of BOD/COD ratios for textile wastewater are approximately 1:4, according to a review of the literature. This ratio indicates that the presence of non-biodegradable substances is high, necessitating the application of chemical processes for wastewater treatment (Ghaly et al., 2014).

The term "wet processes" is used to describe a variety of manufacturing operations that utilize a significant amount of water, including washing, dyeing, bleaching, printing, and finishing. During these processes, a considerable quantity of wastewater is generated (Holkar et al., 2016; Aguiar et al., 2023). Wastewater generated during dyeing and finishing processes in the textile manufacturing has a various toxic composition. These effluents contain a variety of toxic chemicals such as dyes, salts, pigments, surfactants, metals, and a multitude of organic and inorganic contaminants (Laizer et al., 2022; Yadav et al., 2022; Aguiar et al., 2023). Characterization of textile industry wastewater is shown in Table 2.2.

One of the principal sources of pollution in the textile manufacturing industry is the dyeing process. The reason for this is that the colour parameter in the wastewater generated after the process is high, which not only raises concerns regarding the environment but also causes an aesthetic challenge in receiving water environment and wastewater treatment plants (WWTP). The existence of dyes in water inhibits the photosynthetic activity of the environment and reduces the dissolved oxygen (DO) in the water. As a result, water quality decreases and toxic effects are also observed on aquatic life (Lazier et al., 2022; Aguiar et al., 2023). The presence of high concentrations of heavy metals, originated from dyes used in production, in wastewater can negatively impact microbial activity within the system, thereby inhibiting the biological treatment process (Laizer et al., 2022). Disposal of this wastewater without accommodate treatment can have a substantial negative impact on the receiving media.

Table 2.2 Characterization of textile industry wastewater

Parameters	Value	Location	References
COD (mg/L)	2540	Haryana, India	Yadav et al., 2024
	1415	Tanzania	Laizer et al., 2022
	970	Türkiye	Yurtsever et al., 2021
	1920	Poland	Thomas and Zdebik, 2019
	536-1356	Mumbai, India	Holkar et al., 2016
	150-12000	Canada	Ghaly at al., 2014
	1500	Gujarat, India	Gosavi and Sharma, 2014
	1120	Chittagong, Bangladesh	Sultana et al., 2013
	1275	Pabna, Bangladesh	
DO (mg/L)	2.98	Tanzania	Laizer et al., 2022
pH	12	Haryana, India	Yadav et al., 2024
	10-12.2	Mumbai, India	Holkar et al., 2016
	10	Gujarat, India	Gosavi and Sharma, 2014
	6-10	Canada	Ghaly at al., 2014
	9	Chittagong, Bangladesh	Sultana et al., 2013
	8.9	Pabna, Bangladesh	
BOD (mg/L)	830	Haryana, India	Yadav et al., 2024
	500	Tanzania	Laizer et al., 2022
	430	Poland	Thomas and Zdebik, 2019
	80-6000	Canada	Ghaly at al., 2014
	500	Gujarat, India	Gosavi and Sharma, 2014
	390	Chittagong, Bangladesh	Sultana et al., 2013
	450	Pabna, Bangladesh	
TDS (mg/L)	5276	Tanzania	Laizer et al., 2022
	5590	Poland	Thomas and Zdebik, 2019
	2900-3100	Canada	Ghaly at al., 2014
	1313	Chittagong, Bangladesh	Sultana et al., 2013
	1011	Pabna, Bangladesh	
TSS (mg/L)	450	Tanzania	Laizer et al., 2022
	865	Poland	Thomas and Zdebik, 2019
	120-220	Mumbai, India	Holkar et al., 2016
	15-8000	Canada	Ghaly at al., 2014
Color (mg/L)	1915	Haryana, India	Yadav et al., 2024
	98	Türkiye	Yurtsever et al., 2021
	400-500	Italy	Collivignarelli et al., 2019
Temperature	28	Haryana, India	Yadav et al., 2024
	25-33	Mumbai, India	Holkar et al., 2016
	35-45	Canada	Ghaly at al., 2014

The manufacture of textiles generates a variety of waste materials, including fibers, yarns, fabrics, and apparel products. For example, cotton fiber, damaged yarn, and incomplete cone waste are produced in the spinning process. In apparel, wastes such as fabric cutting pieces (cutting waste), excess development samples, excess clothing etc. are generated. The waste generated during yarn manufacturing can range from approximately 12% to 15%, and in some cases as high as 25-30%. Short fibers, known as 'cotton lint', accumulate around the machines and on the floor during the subsequent spinning process used to make yarn from cotton (Akter et al., 2022). These type of fibers can be recycled for remanufacturing, reducing the environmental impact of raw material and textiles.

CHAPTER THREE
CIRCULAR ECONOMY AND TEXTILE INDUSTRY

3.1. Circular Economy

The linear economy (Figure 3.1) is based on a take-use-dispose model, while the circular economy (CE) is based on the use of all resources (water, raw materials, energy, etc.) for their conservation over a long period of time. In today's world, the linear economy does not work well for a number of reasons. This is because of the diversity of resources and living things such as water and food, which are indispensable for life all over the world, is decreasing, biodiversity is decreasing and the economic system is tending to collapse (Balbay et al., 2021).

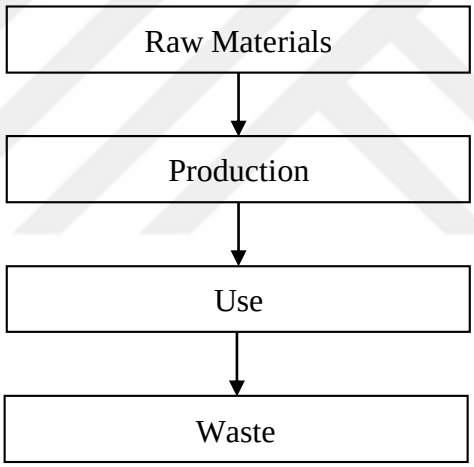


Figure 3.1 Linear economy

The European Union (EU) must adopt a growth model that reduces environmental impacts if it is to achieve climate neutrality by 2050 and decouple resource use from economic growth. In addition, by 2030, the EU should endeavor to maintain resource consumption within planetary limits, reduce its consumption footprint, and double the utilization of the CE model (EC, 2022). In order to transition towards a more circular economy rather than a linear economy, the European Commission (EC) proposed the first Circular Economy Package in December 2015. This included a comprehensive Circular Economy Action Plan (Robaina et al., 2020).

This action plan defines CE as a system that aims to preserve products, resources, and materials in the economic system for as soon as possible, while minimizing waste generation. The objective of this action plan is to facilitate the transformation required by the European Green Deal and enhance the CE initiatives that have been implemented since 2015 (EC, 2022).

In recent times, the CE model has attracted attention as an alternative to the linear economy model (Ghisellini et al., 2016). The CE model is defined as a model with a holistic process that can enable reuse of raw materials and products, recovery of waste, efficient use of energy and all resources, clean production that produces almost no waste, and an important tool for sustainability (Figure 3.2). Starting from the cradle to cradle principle based on the concept of a waste-free and environmentally sound industry, biomimetics practices, in which industrial processes emulate the natural systems, and industrial ecology, the CE aims to maximize the added value of products and services in the economic value chain, minimize residual waste, and keep resources in the economy longer (Veral, 2021).

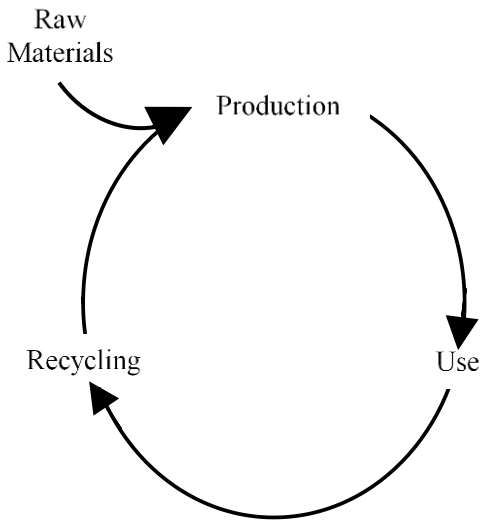


Figure 3.2 Circular economy

3.2. Circular Economy (CE) in Textile and Apparel Industry

The T&A industry is the fourth most pressurized category in terms of primary resource and water consumption, after foodstuff, housing, and transportation. In terms of GHG emissions, it is the fifth highest-pressure category. It is estimated that less than 1% of all textiles produced globally are remanufactured through recycling (EC, 2022). The global textile industry is experiencing a continual increase in consumption, due to population growth, improvements in quality of life, and the influence of fast and inexpensive fashion. For this reason, various textile wastes are generated and a large part of the textile waste is disposed of. It is considered that over 68% of the fibers used to make clothing are derived from non-renewable resources such as fossil fuels, with the resulting clothing being used for a very short time and then disposed of in landfills or incinerated (Chen et al., 2021). In Europe, the recycling rate for clothing waste is only 10% and the reuse rate is 8%. Of the remainder, approximately 57% is landfilled and approximately 25% is incinerated (Beton et al., 2014; Ütebay et al., 2019). It has been stated that the recovery rate for textile products in the USA is around 15-16% (Wang, 2010; Ütebay et al., 2019). Furthermore, the environmental problems caused by textile waste, the textile industry is one of the dirtiest and most wasteful industries globally due to the negative impacts to environment caused by all processes from fiber to textile production (Ütebay et al., 2019).

The EU Textile Strategy has been developed with the aim of strengthening the EU market for sustainable textiles, addressing fast fashion, promoting the emergence of new business models, strengthening industrial competition and innovation in the sector. The objective of this strategy is to facilitate the dissemination of new sustainable eco-designs with the aim of promoting the circularity of textiles. This will be achieved by ensuring the procurement of secondary raw materials, addressing the presence of dangerous chemicals, encouraging everyone to prefer eco-friendly textiles, and facilitating reuse and repair services. It also provides guidance on the ambitious goal of achieving a high level of separate collection of textile waste by 2025 (EC, 2022).

Effective waste management approaches are an important step in achieving a sustainable system in the textile industry (Binotto and Payne, 2017). The circular economy encourages the collection and recovery of products in the same product chain. The 3R approach to sustainable waste management, which encompasses firstly reducing, then reusing and lastly recycling materials, is regarded as one of the fundamental principles of the CE for sustainability (Yalçın-Enis et al., 2019).

According to Haq and Alam (2023), introducing circular fashion by reusing the waste of pre-consumption in the cutting department offers a sustainable approach in the T&A industry. The study revealed that approximately 219 kg of recoverable excess fabric remained after production. Of the approximately 1018 kg of scrap resulting from the order of approximately 21000 pieces, approximately 212 kg had a direct reuse value. As a consequence, Haq and Alam (2023) demonstrated that the production of 2238 circular products was feasible with the use of these fabrics and wastes. If factories implement a circular approach to production on a regular basis, it will be possible to avoid the incineration of waste (Haq and Alam, 2023).

As stated by Rathinamoorthy (2018), the scrap fabric waste generated during the production process is recycled and contributes to the sustainability of the production process. Waste from the cutting units as namely scrap was recycled into yarn and utilized to make new products. The findings suggest that garments crafted from recycled fibers are more cost-effective than those produced from conventional raw materials (Rathinamoorthy, 2018).

In a study conducted by Telli (2016), the inclusion of recycled materials in the production of denim fabric using conventional cotton was examined. This study evaluated the use of recycled cotton (r-CO) fibers from scrap fabrics and recycled polyester (r-PET) fibers from PET bottles in the production of denim fabrics (Telli, 2016).

The importance of recycling has increased significantly in recent years. The global textile production and consumption have been increasing over time. Given the ecological and economic implications of this phenomenon, recycling has become a mandatory process at every stage of production and consumption (Çorlu Ticaret ve Sanayi Odası, 2020). A number of prominent fashion companies are engaged in the progress of a CE.

“Mavi” is one of the brands that prioritizes sustainable production. In this context, it has created a collection called All Blue, which includes sustainable products. The collection utilizes recycled cotton, obtained from old clothing and textile waste, in the production of new garments. “Mavi” has set a goal of obtaining 100% of the cotton utilized in denim products from sustainable sources by 2030. In 2023, the company achieved 56% of this target, sourcing cotton from sustainable sources for the production of 56% of the denim it sold that year. Furthermore, “Mavi” recycles petroleum-based waste in the same collection process and utilizes it as recycled polyester in its products (Mavi, 2023).

CHAPTER FOUR
LIFE CYCLE ASSESSMENT

4.1. Life Cycle Assessment Analysis Tool

The Life Cycle Assessment (LCA) is a tool of examining the environmental aspects and potential environmental impacts of a manufactured goods through its life span. This encompasses the stages of raw material obtaining, manufacture, use, end-of-life applications, recycling and disposal (Vinodh et al., 2012; Wendin, 2016).

The application of this methodology, as defined in ISO 14040 and ISO 14044, can assist in the identification and analysis of opportunities for the enhancement of the environmental aspects associated with products at different points in their life span (ISO, 2006). LCA consists of 4 steps and Figure 4.1 illustrates the interaction between these steps.

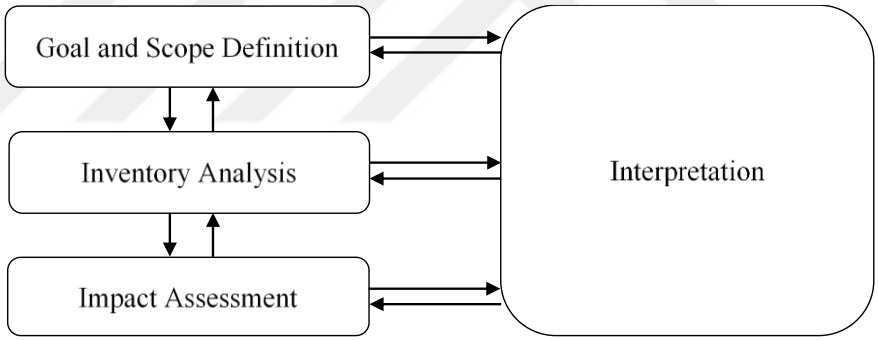


Figure 4.1 Framework of LCA (ISO 2006)

As a first step, the goal and scope definition phase defines the LCA work plan (Guinée et al., 2002). It is of paramount importance that the purpose of the study is defined in detail within the goal definition, as decisions made in the following stages of the LCA must be coherent with the goal definition. The production systems to be evaluated and the methods used to assess these systems are determined during the scope definition phase. In this phase, the methodology ensures consistency of critical steps and documents the data so that the study can be repeated. These two definition phases are considered together and are used to guide the performance of the other stages of the LCA (Bjørn et al., 2018).

Life cycle inventory (LCI) is the process of identifying and measuring the data related with the influent and effluent of a product or process (Muthu, 2014; Demirer, 2017). In this context, LCI analysis includes phases such as defining system boundaries, the generation of flow diagrams, the collection of data, and the completion of final calculations. The result of the LCI is the quantification of input and outputs related to the functional unit expressed in units such as kg CO2, m3 of natural gas, mg phenol, etc., which is used as an input for the following impact assessment (LCIA) phase (Guinée et al., 2002; Bjørn et al., 2018).

The conversion of emissions and consumptions for all the life cycle stages into environmental impacts is achieved through the third step of LCA, namely LCIA, as defined by the ISO 14040 standard (Buxel et al., 2015; Hauschild and Huijbregts, 2015). LCIA is designed to translate primary flows in LCI into potential environmental impacts considered in LCA, facilitating the interpretation phase (Hauschild and Huijbregts, 2015). The objective of the LCIA phase is to turn into the results of the LCI into potential impacts on Areas of Protection (AoPs) or damage categories (Figure 4.2). At the midpoint level, characterization models and expresses impacts through indicators situated somewhere through the environmental system. The characterization at the endpoint level models the impacts on human health, the natural environment, and natural resources, namely the AoPs (Beton et al., 2014).

In LCA, a variety of category indicators are compounded into default sets or methodologies on the in terms of specific characterization models. These are often called as LCIA methods and are used in LCA software (Hauschild and Huijbregts, 2015). As the type of LCIA methods and indicators increases, practitioners need to understand these methods and be informed about LCIA developments (Rosenbaum et al., 2018).

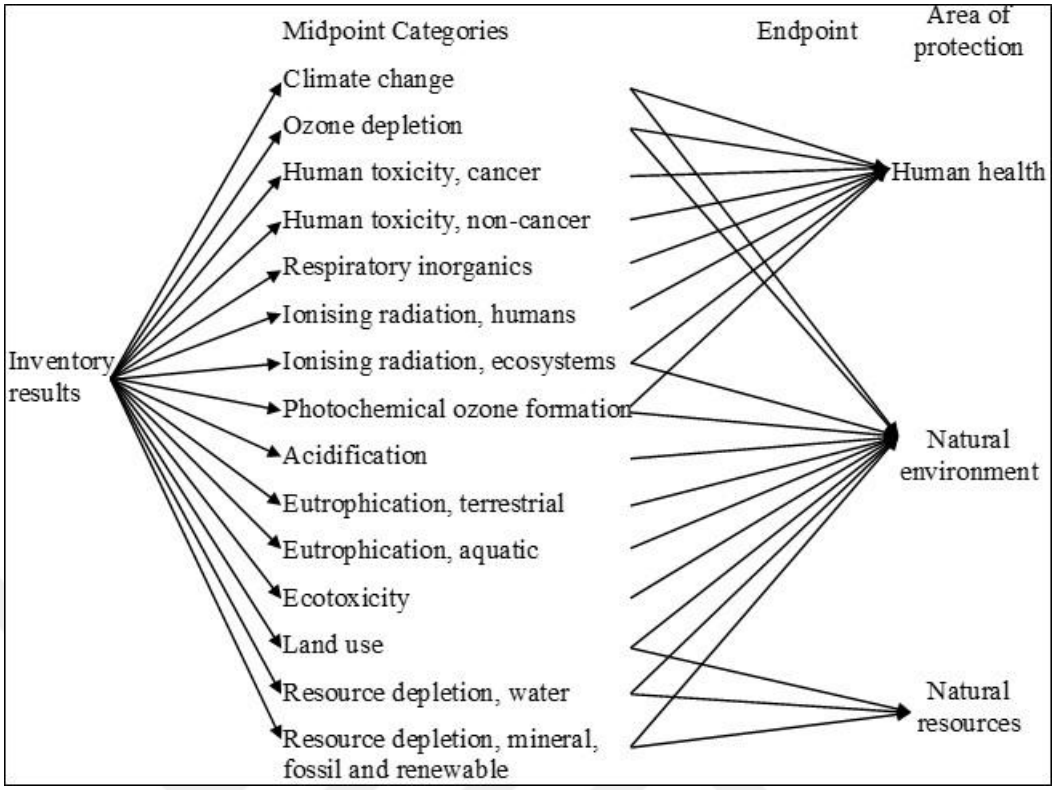


Figure 4.2 Midpoint and endpoint categories (Hauschild et al., 2013)

There are different ways to perform LCIA. One of these, the Leiden University Center for Environmental Studies (CML) methodology, was created by Leiden University in the Netherlands in 2001. CML is a method used to categorize environmental impacts into a problem focused approach (midpoint) and a harm focused approach (endpoint) (Ojoawo and Gbadamosi, 2013). The CML methodology is predicated on the notion that environmental impact categories can be expressed as emissions or resource use. This approach enables the creation of a synthetic economic value for each environmental impact unit, thereby facilitating a comparison of the results across different environmental impact categories (Vinodh et al., 2012).

The LCA methodology has intensive data, and collecting all these data is costly (Wernet et al., 2016). Therefore, LCI databases are used for data collection. These databases are used to focus on chosen activities that represent the field of action (foreground system) and to model the other events (background system) (Steubing et al., 2016).

The ecoinvent database is a comprehensive set of data on industrial and agricultural processes that all have a specific product output. The ecoinvent database offers users access to a range of impact assessment methodologies and corresponding impact categories, including IPCC 2021, EF v3.1, and ReCiPe (Ecoinvent).

4.2. LCA Studies on Textile and Apparel Industry

There are many studies about LCA application in the T&A sector and these studies mainly address the environmental effects of sustainable methods, including recycling and reuse. Islam et al. (2024) conducted a cradle-to-gate approach to manufacture 1000 shirts made from cotton. LCA was performed using openLCA 2.0 software by classifying environmental effects into categories using CML 2001 methodology. While it is reported that approximately 0.33 ha of land is required to produce 1000 kg of cotton fiber, the amounts of water, electricity, diesel and natural gas consumed to produce 1000 shirts are approximately 23 m^3, 1551 kWh, 16 L, and 73 m^3. The findings of the study indicate that fabric dyeing has the most significantly undesirable impact on the environment in the AP, GWP, and EP categories. Similarly, cotton fiber production has the highest environmental impact in the FAETP, HTP, and TAETP categories. The utilization of water, energy, fuel, pesticides, fertilizers, insecticides, fungicides in the cotton fiber cultivation results in the emissions which increased the impact on the AP and GWP categories. It has been found that these effects are less in knitting, finishing and garment production. The use of natural dyes instead of synthetic dyes, heat recovery, and water reuse have been proposed to reduce the environmental footprint of this production (Islam et al., 2024).

Roy et al. compared recycled cotton (r-CO) with virgin cotton using the LCA method and examined GHG emissions, air pollution, water footprint, and land use for 1 kg of fabric production. They found that the use of r-CO can decrease GHG emissions by 2.2-8.6%, air pollution by 1.4-11.6%, water footprint by 0.6-24.5%, and land use by 3.1-25.2%. This means that r-CO can be used to replace 100% virgin cotton in fabric production (Roy et al., 2023).

In a LCA conducted by Liu et al. (2020), the impact of cotton fiber was assessed, with a comparison made between the impact of r-CO fiber and that of virgin cotton fiber. The findings show that the impacts of r-CO are significantly less than that of virgin cotton. Compared to the environmental impacts of virgin cotton yarns, r-CO yarns were found to reduce CO_2 equivalent emitted by approximately 60%, oil equivalent consumed by approximately 11% and water consumed by approximately 79%. For human toxicity, there was a slight increase of 0.58% in r-CO results. It can be concluded that land use and water consumption for irrigation have a substantial impact in cotton cultivation. The results showed that the use of 1 ton of r-CO yarn can result in the saving of approximately 0.5 ha of agricultural land, the reduction of 6.6 tons of CO_2 equivalent, and the saving of 2783 m^3 of irrigation water. It can be said that r-CO is a suitable alternative to reduce the pressure on resources and the environment (Liu et al., 2020).

Fidan et al. (2023), as a result of the LCA study in which they examined the effects of jeans production, found that the use of organic cotton provided an improvement of approximately 48%, 85% and 8% in the FAEP, TEP and AP categories, respectively, comparing to conventional cotton. It was seen that GWP decreased from 20.1 kg CO_2 equivalent to approximately 19.5 kg CO_2 equivalent with organic cotton. When GWP results were analyzed according to life cycle stages, it was seen that the highest impacts on jeans produced with conventional cotton occurred in the usage phase with 73% and in the fabric production phase, which includes the cotton growing stages, with 21%, respectively. As a result, this study shows that organic cotton is a better choice than conventional cotton in terms of the environment (Fidan et al., 2023).

In the study by Moezzem et al. (2018), LCA of a polyester t-shirt was conducted to examine the processes that cause greenhouse gas emissions throughout its life cycle. LCA results showed that the carbon footprint (CFP) of a polyester t-shirt is approximately 21 kg CO_2-eq over its life cycle. During the consumer use phase, CFP is dominated by the washing process, and this study assumes 50 washings over the life of the product. It showed that the second highest contribution was the polyester fiber production process with approximately 29%. Spinning is the largest contributor to CFP

in the t-shirt production phase due to its high electrical energy demand. Dyeing, finishing and pretreatment stages are affected by various chemicals and energy sources. Changing how consumers care for clothes they buy can reduces the CFP from the use phase onwards. Other ways to reduce the environmental burden are recycling and reuse, which can reduce the demand for new products (Moazzem et al., 2018).

The LCA study by L'Abbate et al. examined the environmental impact of producing 1 kg of polyester fabric. The results of the study show that the dyeing process of PET yarn causes the highest water consumption, about 70%, due to the excess water used in the washing process. It has also been determined that most of the CO_2 emissions come from 60.5% PET yarn production. It is stated that formaldehyde dyeing and finishing processes have a typical emission, and the results of this study showed that 58.8% emission occurred in the PET yarn dyeing process and 40% emission occurred in the PET fiber finishing process. VOCs are most commonly seen in the PET yarn production process compared to other stages (L'Abbate et al., 2018).

CHAPTER FIVE
MATERIAL AND METHODS

5.1. Outline of the Methodology

In the scope this thesis, determination of the changes occurred in case of using recycled fiber in the existing environmental impacts of the product with the life cycle assessment (LCA) approach in an apparel sector was aimed. The stages of the study can be briefly listed as follows:

1) Identification of cases for LCA
2) Determining the facilities to receive data and visiting these facilities
3) Determination and supply of required data
4) LCA studies

5.2. Identification of Cases for LCA

Within the scope of this study, nine cases were evaluated (Table 5.1). The main objective was to determine the environmental impacts of the existing situation (Case-1). In the existing situation electricity is used for the recovery of recycled fiber from cotton fabric residues, namely scrap. Yarn and fabric production is carried out by using solar energy. In order to determine the impact of the type of energy used during this process, the use of solar energy in the recovery of recycled fiber from cotton fabric scraps was considered as the second case (Case-2). For the next case, changes have also been made for the yarn and fabric production parts. The effects of using electricity as a type of energy in both recycling and fabric production processes are evaluated in the third case (Case-3).

In the cases so far, cotton has been recycled and the process up to fabric production has been evaluated. The subsequent cases examine circumstances in which cotton is conventionally produced. The aim is to evaluate the environmental impact of manufacturing a fabric comprising 50% cotton and 50% polyester in the fourth case

(Case-4). The fifth case evaluated the environmental impact of using solar energy compared to the energy type used in the previous production process (Case-5).

So far, in these cases, the material composition of the fabric has been 50% cotton or recycled cotton (r-CO) and 50% polyester. The sixth case (Case-6) was analysed to determine the environmental impacts resulting from the production of a 100% cotton fabric without the addition of polyester. The Case-6 was used to assess whether a favorable environmental impact could be achieved without the addition of polyester. The seventh case (Case-7) was analyzed to determine the environmental impact of producing a 100% cotton fabric. Case-7 was used to assess whether a positive environmental impact could be achieved by using organic cotton substituting for conventional cotton.

Unlike the current case (Case 1), the eighth case (Case-8) evaluated the use of recycled polyester in the production of yarn and fabric. In Case-8, it was examined whether there were environmental benefits of using recycled cotton (r-CO) and recycled polyester (r-PET) in yarn and fabric production. The types of energy used in production are the same as in Case-1. Additionally, to use of r-CO and r-PET in production as in Case-8, the effects of using solar energy at all stages of production were examined in the ninth case (Case-9).

Table 5.1 Cases evaluated in this study

	Application	Energy type
Case-1	the scrap cotton fabrics were turned into recycled fibers yarn production fabric production	Electricity Solar energy Solar energy
Case-2	the scrap cotton fabrics were turned into recycled fibers yarn production fabric production	Solar energy Solar energy Solar energy
Case-3	the scrap cotton fabrics were turned into recycled fibers yarn production fabric production	Electricity Electricity Electricity
Case-4	production of a fabric with 50/50 cotton/polyester	Electricity
Case-5	production of a fabric with 50/50 cotton/polyester	Solar energy
Case-6	fabric production with 100% cotton	Electricity
Case-7	fabric production with 100% organic cotton	Electricity
Case-8	the scrap cotton fabrics were turned into recycled fibers yarn production (using r-PET) fabric production (using r-PET)	Electricity Solar energy Solar energy
Case-9	the scrap cotton fabrics were turned into recycled fibers yarn production (using r-PET) fabric production (using r-PET)	Solar energy Solar energy Solar energy

5.3. Data Collection

Required data was mainly collected from two plants placed in Uşak: BEYTEKS and HAKSA. The process in which scrap fabrics are turned into recycled fibers is carried out by a company called BEYTEKS. The production flow chart was created in line with the information provided by the company. The recycled cotton (r-CO) fiber is processed by a company called HAKSA, which produces yarn and then fabric. Yarn and fabric production flow charts were created with the information provided by the company and field investigation. Production process details of these plants are given below. In addition to these field data, database of the software was also used.

5.3.1. BEYTEKS Production Processes

Scrapped cotton fabrics have to go through some stages in order to be recycled and reused in production (Figure 5.1). Within the scope of this thesis, the method chosen for recycling is mechanical recycling. First of all, scrap fabrics are taken from different manufacturers and stored in the recycling facility. Before recycling processes, waste fabrics are separated according to color and fabric type.



Figure 5.1 Recycling facility

The waste fabrics, which are separated according to their colors, are cut into smaller pieces by the cutting machine. Fabrics that are reduced in size are turned into fiber by the rag pulling machine, which is a fiber opening machine. With these processes, cotton fibers are obtained from scrap fabrics by recycling method.

After the fabrics are made into fibers, the last step in this facility is to press and bale the fibers. The baled recycled cotton fibers are sent to the spinning facilities for processing. Figure 5.2 shows the BEYTEKS process flow chart.

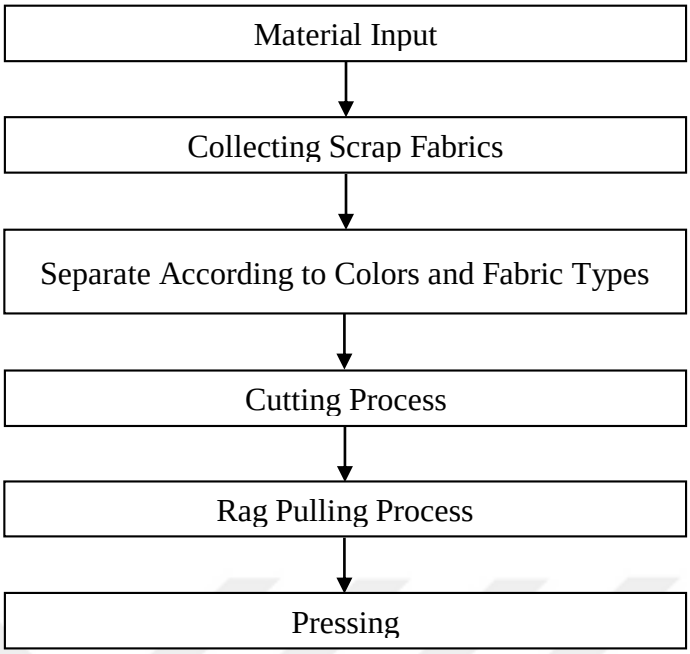


Figure 5.2 Production work flow chart of BEYTEKS

5.3.2. HAKSA Production Processes

The baled fibers coming to the facility for yarn formation are first passed through the threshing process to be mixed with the fibers according to the desired yarn properties. The yarn type examined for this thesis consists of a mixture of 70% recycled cotton (r-CO) and 30% polyester. At the threshing process, r-CO fiber and polyester fiber are mixed. Afterwards, carding and drawing processes follow respectively. Yarn is created with the open-end machine, which is the last stage of yarn formation (Figure 5.4).

After the yarn production, the yarns come to the fabric facility to be processed for the production of the fabric for which LCA work is done within the scope of this thesis. Fabrics are knitted with knitting machines. At this stage, r-CO and polyester yarn are knitted together by adding 30% polyester yarn to increase the durability of the fabric. As a result, the fabric has 50% r-CO and 50% polyester content. After the knitting process, the fabric becomes packageable after finishing and raising processes (Figure 5.5). Figure 5.3 shows the HAKSA process flow chart.

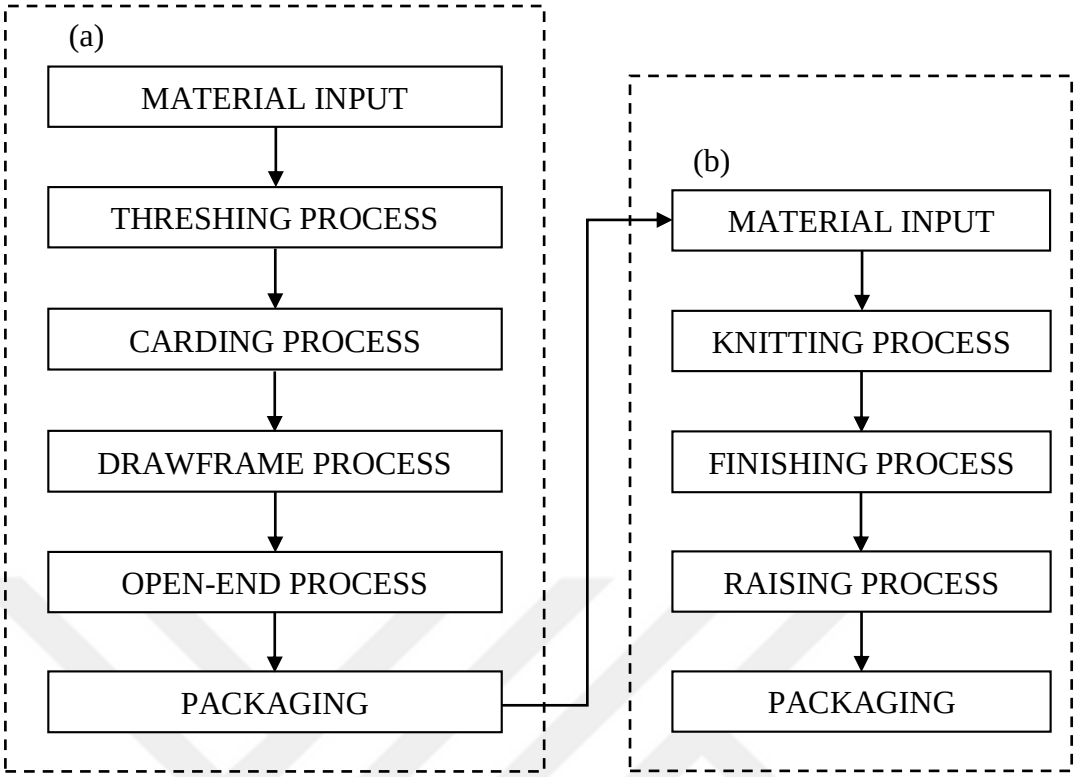


Figure 5.3 Production work flow chart of HAKSA (a) flow chart of yarn production (b) flow chart of fabric production



Figure 5.4 Yarn facility



Figure 5.5 Fabric facility

5.3.3. Data Taken from the Facilities

Data on the equipment used in production and their installed capacity, as well as water and natural gas usage information used in production was obtained from BEYTEKS and HAKSA facilities. The equipment used in production and their installed powers in these facilities are given in Table 5.2.

Water and natural gas are also used in some yarn and fabric manufacturing processes. The HAKSA yarn production facility consumes an average of 1070 m^3 of water monthly. This is equivalent to a monthly water consumption of 0.002 m^3 per 1 kg of product. The average water consumption of the HAKSA fabric production facility is 5250 m^3 of water per month. This is equivalent to a monthly water consumption of 0.03 m^3 per 1 kg of product. Additionally, the fabric production facility consumptions approximately 80,000 Sm^3 of natural gas per month. Monthly natural gas consumption per 1 kg of product is 0.6 Sm^3.

Table 5.2 Data on equipment and installed powers

Equipment	Installed Power (kW)	Data Source
Cutting machine	11	BEYTEKS
Rag pulling machine	443.76	
Press machine	11	
Threshing machine	8.55	HAKSA (Yarn)
Carding machine	17.48	
Drawframe	11.15	
Open-End machine	111.26	
Packaging unit	31	
Knitting machine	8.5	HAKSA (Fabric)
Finishing unit	55	
Raising unit	64.5	
Packaging unit	11.5	

5.4. Life cycle assessment (LCA) studies

This study conducted LCA following the ISO 14044 standard in four primary phases (ISO, 2006). The details of each phase are given below.

5.4.1. Aim and Scope

The main aim of this study is the determination of the environmental impacts of the recycling of waste fabrics (pre-consumer) to fiber and fabric production process by means of a LCA. The scope of the study was determined considering this aim and the scopes of the study are given below:

- to assess the environmental benefits of recycling cotton fiber compared to conventional cotton fiber production
- to evaluate benefits of the use of renewable energy
- to evaluate the environmental effects of using recycled polyester
- to evaluate the environmental effects of fabric production with 100% organic cotton

5.4.2. Functional Unit and Software

The functional unit was chosen as 1 kg fabric produced from recycled cotton scrap fabrics. LCA studied were carried out with GaBi software (Sphera Company). The method selected for impact assessment is CML (Centre of Environmental Science), which is part of the Ecoinvent database.

5.4.3. System Boundaries

One of the most fundamental steps in a LCA study is the definition of system boundaries. System boundaries have been determined for nine cases determined within the scope of this thesis. Accordingly, the system boundaries for Cases of 1 – 2 – 3 – 8 – 9 are the same as they have the same flow charts (Figure 5.6). The system boundary for these five cases is gate-to-gate. This system boundary includes the life process in which scrap fabrics are recycled and the final product fabric is obtained.

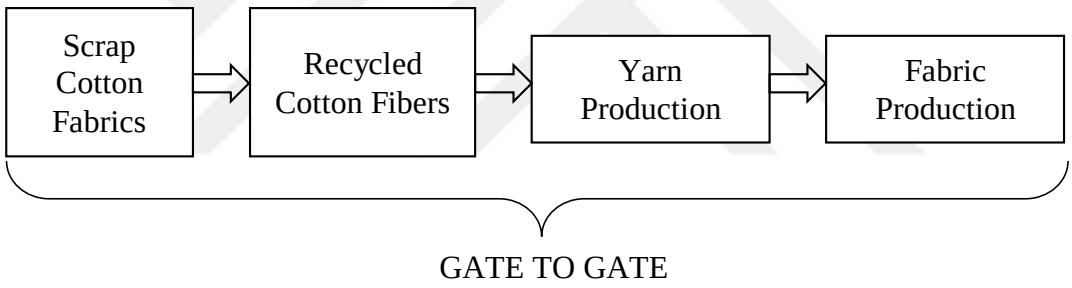


Figure 5.6 System boundary diagram for Case-1, Case-2 and Case-3

Since the process flow charts for Case-4 and Case-5 are the same, the system boundaries are also the same. System boundary for these cases are cradle-to-gate. System boundary for Case-6 and Case-7 are also cradle-to-gate. This system boundary includes the life cycle of cotton starting from the field and processing until it becomes fabric. The system boundary for Cases of 4 – 5 – 6 – 7 is shown in Figure 5.7.

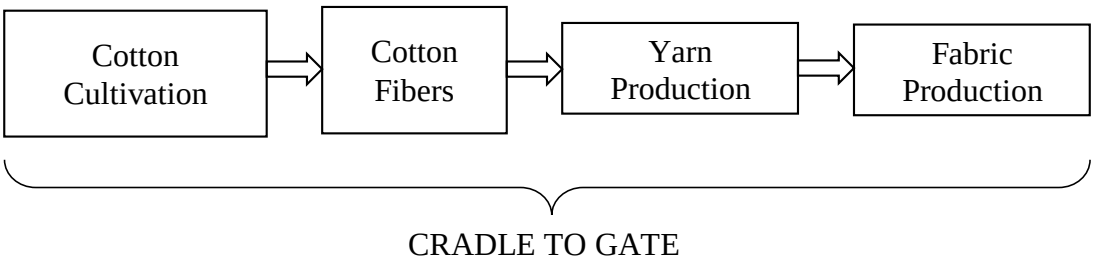


Figure 5.7 System boundary diagram for Case-4, Case-5 and Case-6

5.4.3.1. Case-1

For existing situation (Case-1), three system plans were created. Firstly, a plan was created where the scrap cotton fabrics were turned into recycled fibers. Electricity was used as a type of energy for production in this plan. The flow chart of this plan is shown in Figure 5.8.



Figure 5.8 The recycling process of scrap cotton fabrics (Case-1)

The second plan was created for producing yarn with recycled cotton fiber. The flow chart of this plan is shown in Figure 5.9. In this case, polyester fiber is added to increase durability with recycled cotton (r-CO) fiber in yarn production. As a result of the process, the material content of the yarn produced is 70% r-CO and 30% polyester.

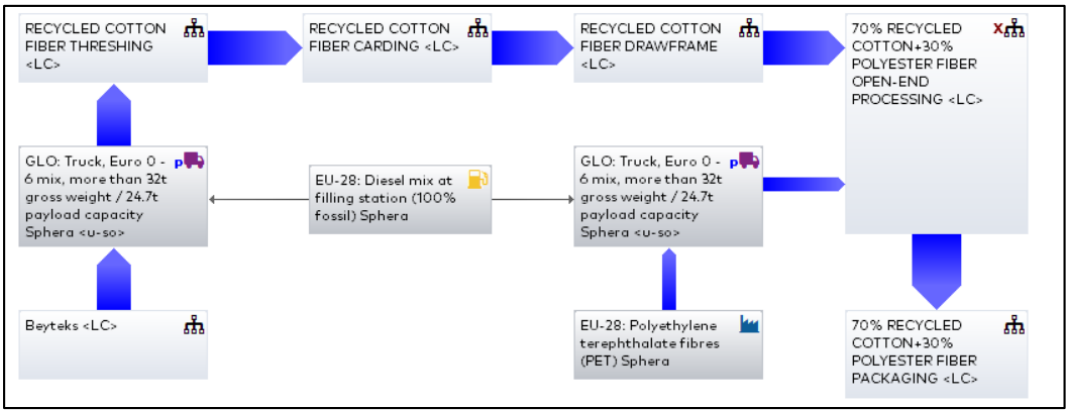


Figure 5.9 The yarn production from recycled cotton fiber (Case-1)

As a final stage, a plan was created in which fabric production from the yarn produced (Figure 5.10). As seen in the flow chart, the fabric is knitted by adding 30% polyester yarn in the knitting process to the 70% r-CO - 30% polyester blended yarn in order to increase the durability during fabric production. As a result, fabric with approximately 50% r-CO and 50% polyester content was obtained.

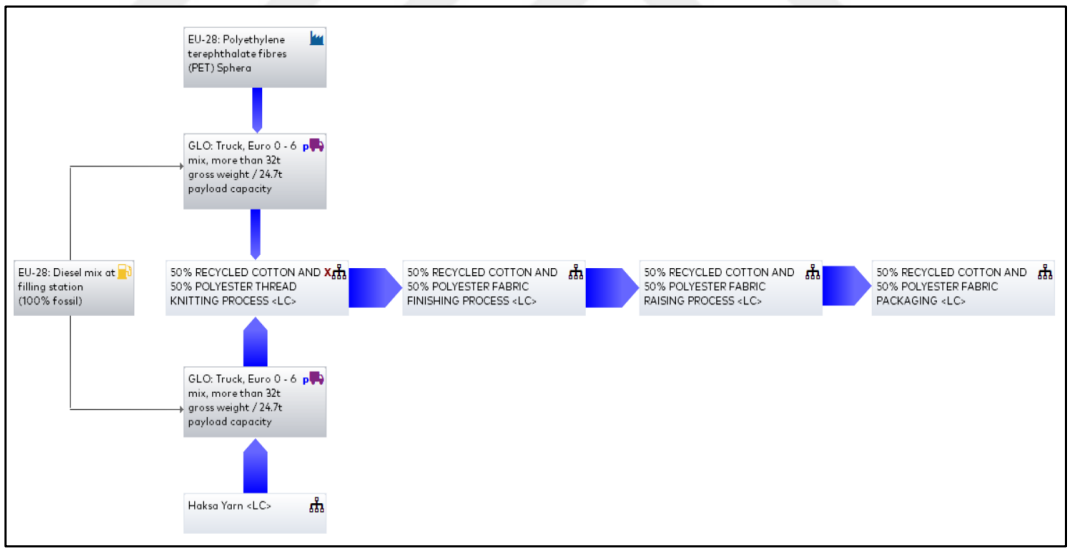


Figure 5.10 The fabric production from yarn produced from recycled cotton fibers (Case-1)

5.4.3.2. Case-2

In the second case, the same plans were created as in Case-1 except the energy types used in production. The purpose of creating this case is to determine the benefits to be obtained if solar energy is used in the recycling of scrap fabrics. In the plan which

recycled cotton (r-CO) fiber was produced, solar energy was used as the energy type (Figure 5.11).

In the Case-2, yarn and fabric production is the same as in Case-1. At the same time, these yarn and fabric production plans are linked with the production of recycled fiber. In this reason, a new yarn production plan was created in which the recycled fiber production used in the Case-2 was included in the yarn plan (Figure 5.12).

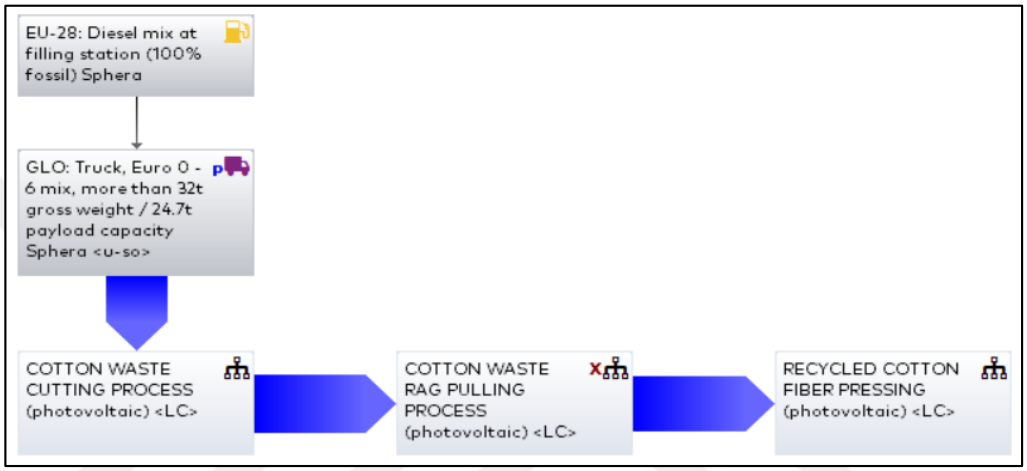


Figure 5.11 The recycling process of scrap cotton fabrics (Case-2)

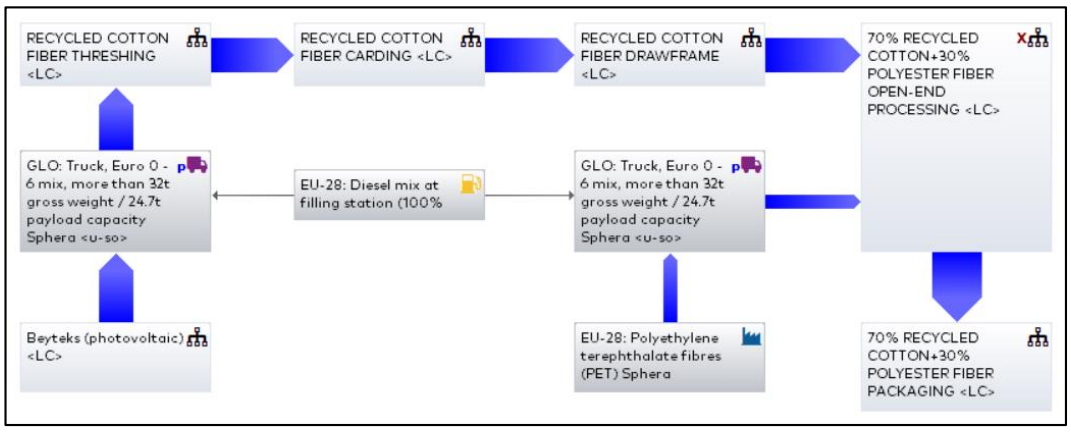


Figure 5.12 The yarn production from recycled cotton fiber (Case-2)

A new fabric production plan was created by including the newly created yarn production plan in the fabric production plan (Figure 5.13).

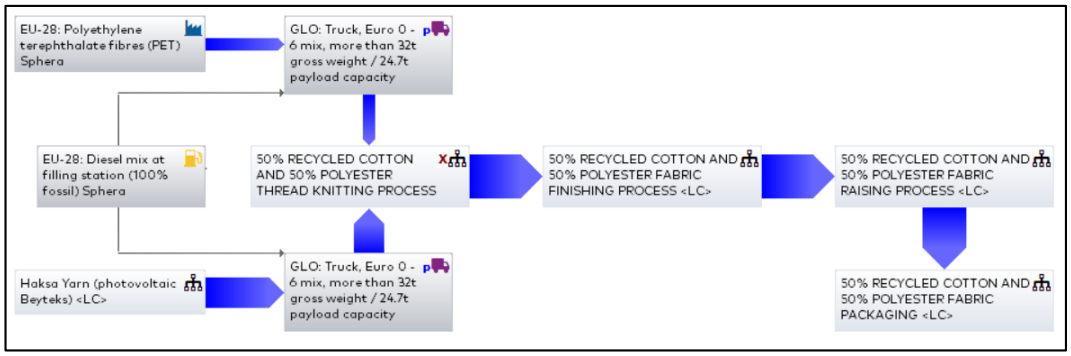


Figure 5.13 The fabric production from yarn produced from recycled cotton fibers (Case-2)

5.4.3.3. Case-3

In the next case, the environmental effects of using electricity as a type of energy in all processes were examined. The process flowcharts are the same as in the previous two cases. The only factor that changes in these three cases is the type of energy used. Flow charts for the Case-3 are as shown in Figure 5.14 - 5.16.

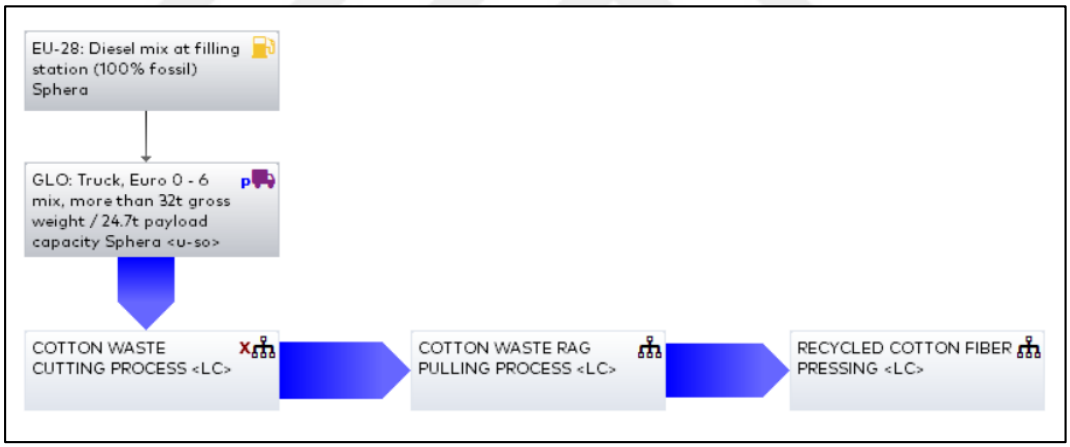


Figure 5.14 The recycling process of scrap cotton fabrics (Case-3)

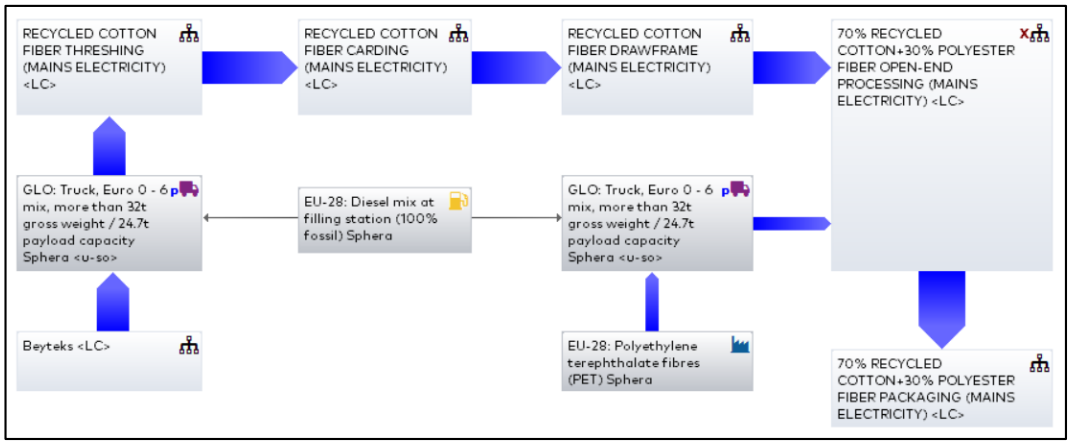


Figure 5.15 The yarn production from recycled cotton fibers (Case-3)

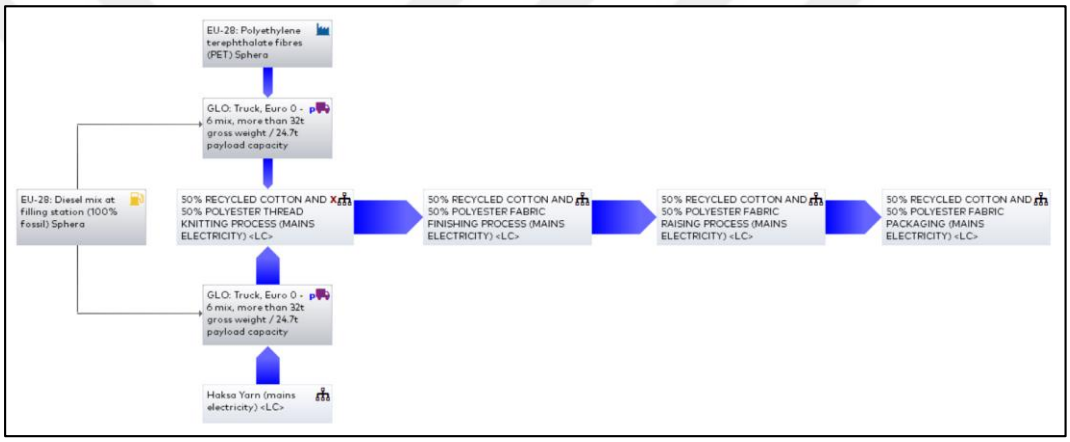


Figure 5.16 The fabric production from yarn produced from recycled cotton fibers (Case-3)

5.4.3.4. Case-4

Case-4 was created to investigate the environmental impact of producing a fabric with 50% cotton and 50% polyester content. In this case, it is assumed that electricity is used as an energy type in production (Figure 5.17). The purpose of creating Case-4 is to compare with recycled fiber and conventional fiber.

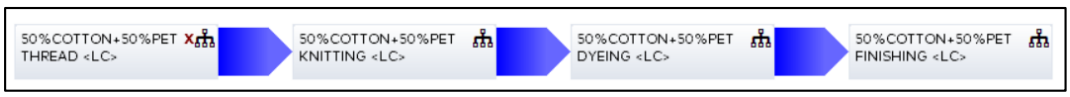


Figure 5.17 50% cotton and 50% polyester fabric production (Case-4)

5.4.3.5. Case-5

In the Case-5, the environmental effects of the same processes in Case-4 were examined. However, in the Case-5, it is assumed that solar energy is used as the energy type instead of electricity (Figure 5.18). The purpose of creating this case is to examine how much reduction will be made on environmental impacts by using solar energy.

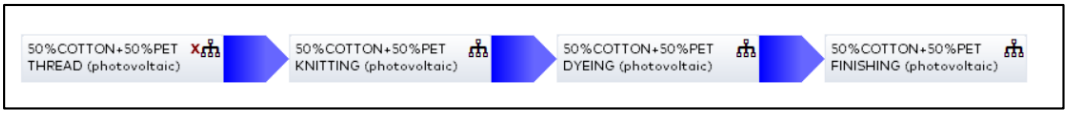


Figure 5.18 50% cotton and 50% polyester fabric production (Case-5)

5.4.3.6. Case-6

In this case, the environmental effects of fabric production with 100% cotton content were investigated by the LCA method (Figure 5.19). The data used in the plan created for this case were taken from GaBi software's database. Since scrap recycling was not implemented in this case, it will help determine the environmental impacts of recycling.

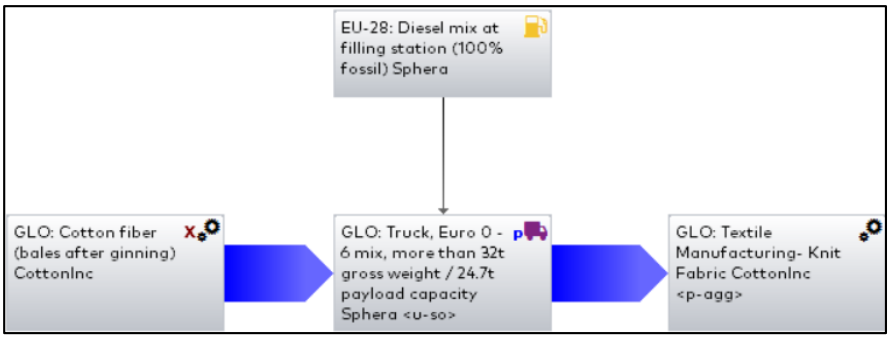


Figure 5.19 Production of 100% cotton fabric (Case-6)

5.4.3.7. Case-7

Case-7 examines the environmental impacts of producing 100% organic cotton fabric using the LCA method (Figure 5.20). The cradle of organic cotton was identified as the beginning of this case. The data used in the plan created for this case was taken from GaBi software's database. The objective of this case is to investigate whether the environmental impact of organic cotton differs from that of conventional cotton.

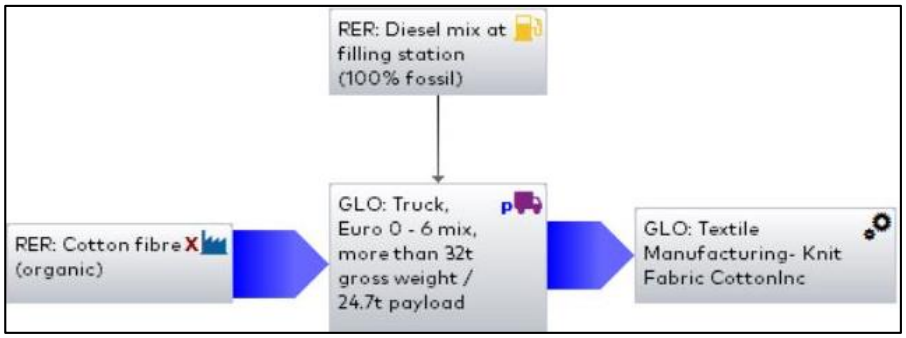


Figure 5.20 Production of 100% organic cotton fabric (Case-7)

5.4.3.8. Case-8

In this case, the environmental impacts of using both recycled cotton (r-CO) and recycled polyester (r-PET) were investigated. The issues related to the recycling of cotton have been examined in some previous cases (Case 1-2-3). In this section, in addition to cotton recycling, a case has been created on the use of polyester in the fabric content through recycling. The polyester used in this case is made from recycled plastic bottles. The plan for recycling cotton is the same as in Case-1 (Figure 5.8). A plan to produce yarn using recycled fibers was generated (Figure 5.21). The r-PET fibers are added to increase durability in yarn production, along with r-CO fibers, as shown in the flow chart. The yarn produced from the process contains 70% r-CO and 30% r-PET. This indicates that the yarn is made completely from recycled materials.

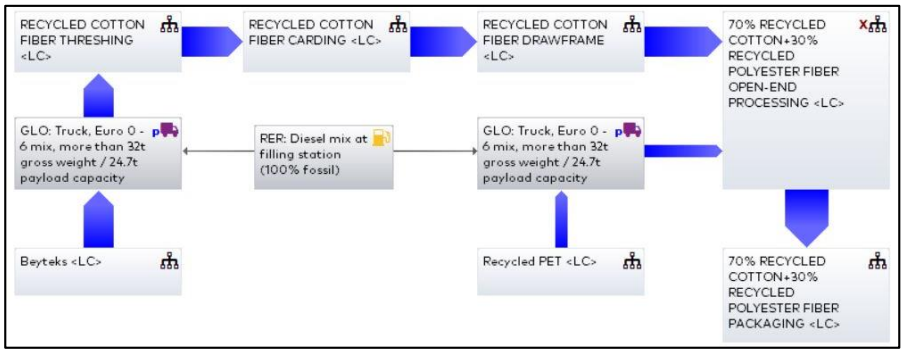


Figure 5.21 The yarn production from recycled cotton fiber and recycled polyester (Case-8)

As a final step, a plan was created for the production of fabric from the yarn. Figure 5.22 presents a flow chart outlining this process. The flow chart depicts the process of knitting the fabric with the addition of 30% r-PET yarn to the 70% cotton and 30% r-

PET blended yarn. This method is implemented to enhance the durability of the fabric during its production. Fabric containing approximately 50% r-CO and 50% r-PET was produced as a result.

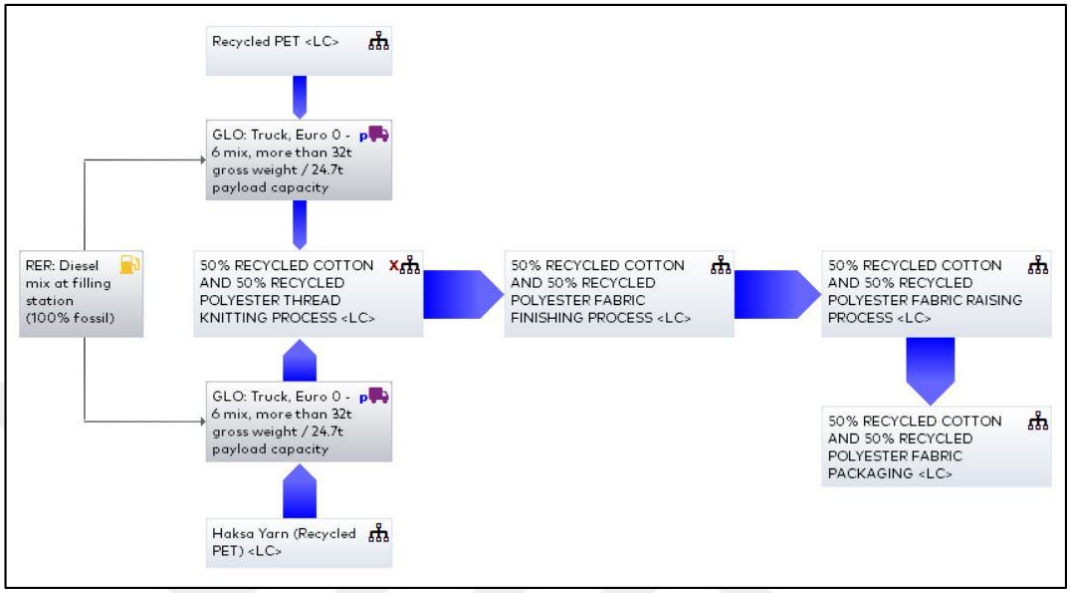


Figure 5.22 The fabric production from yarn produced from recycled cotton fibers and recycled polyester (Case-8)

5.4.3.9. Case-9

In this case, similar fibres were used with Case-8. The difference from Case 8 is the use of solar energy instead of electrical energy. The plan for recycling cotton is the same as in Case-2 (Figure 5.11). The flow charts for the production of yarn and fabric are shown in Figure 5.23 and Figure 5.24, respectively.

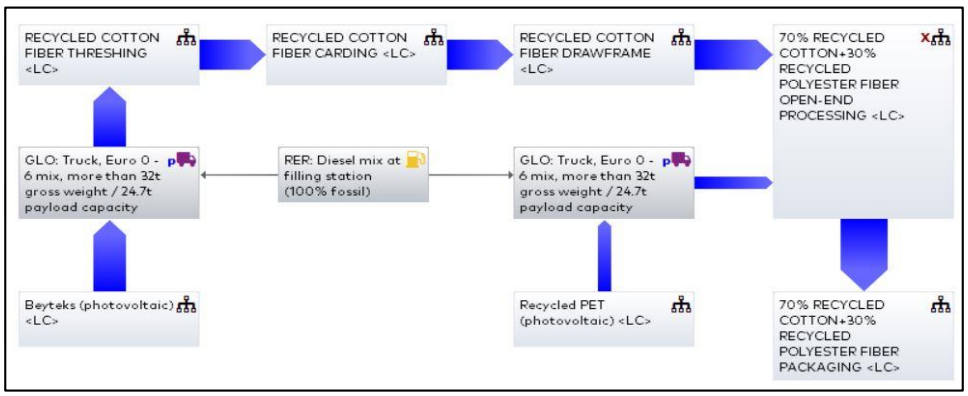


Figure 5.23 The yarn production from recycled cotton fiber and recycled polyester (Case-9)

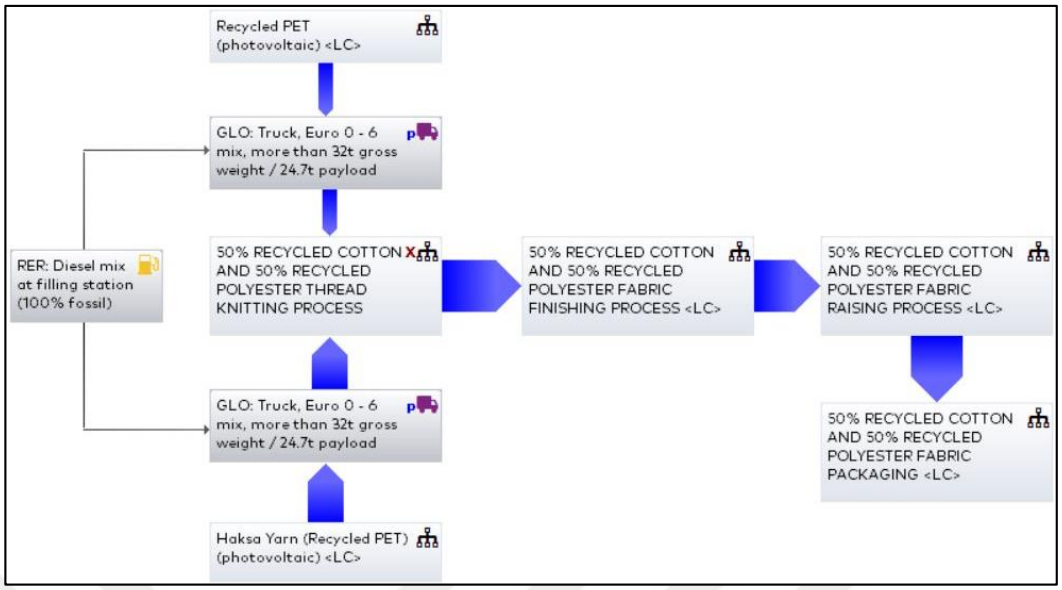


Figure 5.24 The production from yarn produced from recycled cotton fibers and recycled polyester (Case-9)

5.4.4. Impact Assessment Categories

LCA environmental impact categories, units and abbreviations evaluated by considering the CML method in this study are given in Table 5.3. These abbreviations will be used in the thesis from now on.

Table 5.3 Abbreviations of the environmental effect categories

Environmental Effect Categories	**Abbreviations**
Abiotic depletion - elements [kg Sb eq.]	ADP-E
Abiotic depletion - fossil [MJ]	ADP-F
Acidification potential [kg SO_2 eq.]	AP
Eutrophication potential [kg Phosphate eq.]	EP
Freshwater aquatic ecotoxicity potential [kg DCB eq.]	FAETP
Global warming potential – 100 years [kg CO_2 eq.]	GWP
Human toxicity potential [kg DCB eq.]	HTP
Marine aquatic ecotoxicity potential [kg DCB eq.]	MAETP
Ozone layer depletion potential [kg R11 eq.]	ODP
Photochemical ozone creation potential [kg Ethene eq.]	POCP
Terrestric ecotoxicity potential [kg DCB eq.]	TETP

CHAPTER SIX
RESULT AND DISCUSSION

6.1. LCA Results of Cases

6.1.1. Results of Case-1

In this case (Case-1) shows the existing situation of the examined plants, namely BEYTEKS and HAKSA. The environmental impacts were determined considering that scrap cotton fabrics were converted into recycled fibers using grid electricity and that yarn and fabric production was carried out with solar energy. The effects according to CML categories for the recycling process of scrap fabrics, which is the first step of Case-1, are given in Table 6.1 and Figure 6.1. It is seen that the most effective process in most effect categories is caused by the rag pulling unit. The reason for this is that the machines used in this process consume a lot of energy.

Table 6.1 LCA results of recycling process of scrap cotton fabrics (using electricity)

Impact Categories	Total	Cotton Waste Cutting Process	Cotton Waste Rag Pulling Process	r-Co Fiber Pressing	Transport
ADP-E	1.3E-07	1.6E-08	9.5E-08	2.0E-08	1.2E-09
ADP-F	27.40	3.40	19.60	4.04	0.3080
AP	0.0283	0.0036	0.0205	0.0042	2.8E-05
EP	8.2E-04	1.0E-04	5.9E-04	1.2E-04	5.9E-06
FAETP	0.0022	2.7E-04	0.0015	3.2E-04	1.1E-04
GWP	2.38	0.2960	1.71	0.3520	0.0226
HTP	0.2930	0.0367	0.2120	0.0437	4.2E-04
MAETP	1550	195	1120	231	0.3970
ODP	1.4E-11	1.7E-12	1.0E-11	2.1E-12	2.7E-15
POCP	0.0012	1.5E-04	8.7E-04	1.8E-04	-5.9E-06
TETP	0.0039	4.8E-04	0.0028	5.8E-04	2.1E-05

The second analysis for this Case was for yarn production from recycled cotton (r-CO) fiber. The results of the yarn production processes according to the CML effect categories are given in Table 6.2 and Figure 6.2. It can be seen that the highest impact in most categories is caused by the recycling process of scrap fabrics. Secondly, the

most impact is due to the use of polyester. In the abiotic depletion and ozone layer depletion categories, it is seen that the most impact is caused by the open-end process.

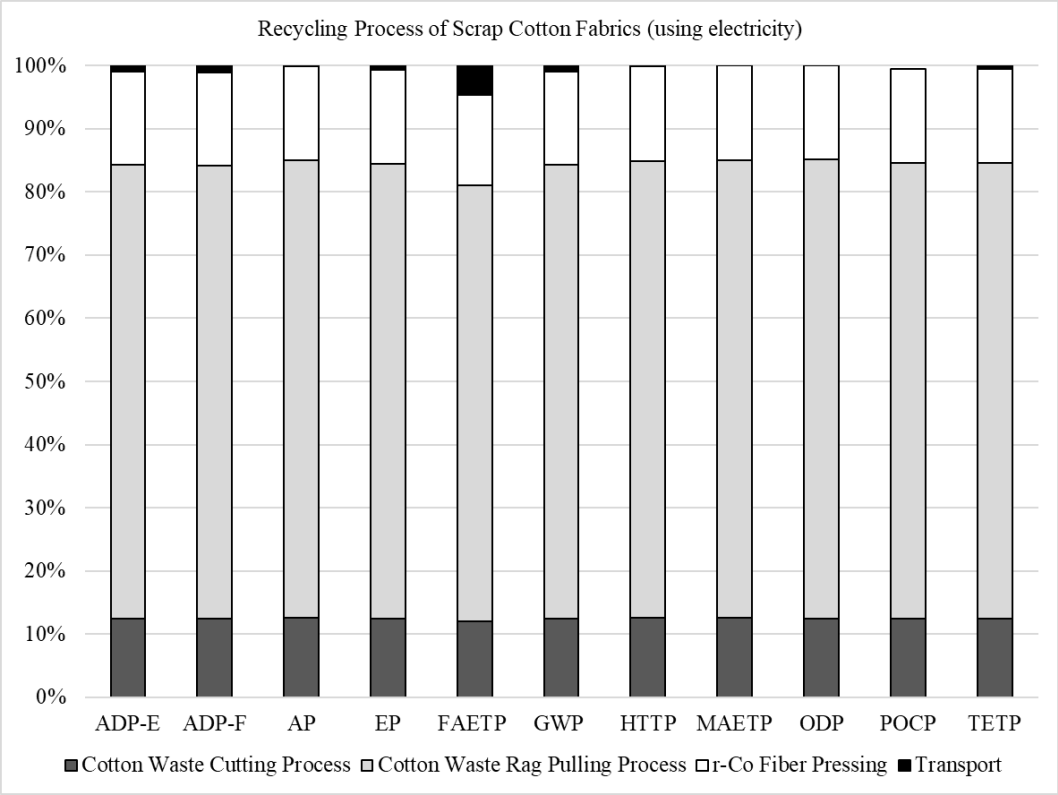


Figure 6.1 LCA results of recycling process of scrap cotton fabrics (using electricity)

Table 6.2 LCA results of yarn production (using solar energy)

Impact Categories	Total	Beyteks	r-Co Threshing	r-Co Fiber Carding	r-Co Fiber Drawframe	70% r-Co + 30% PET Fiber Open-End Processing	70% r-Co + 30% PET Fiber Packaging	PET	Transport
ADP-E	3.3E-06	1.3E-07	4.6E-07	4.9E-07	2.1E-07	1.7E-06	1.2E-07	1.8E-07	8.3E-10
ADP-F	49.40	27.40	0.0778	0.0835	0.0349	0.2940	0.0211	21.30	0.2150
AP	0.0295	0.0283	2.6E-05	2.8E-05	1.2E-05	9.8E-05	7.0E-06	0.0011	1.9E-05
EP	9.9E-04	8.2E-04	2.6E-06	2.8E-06	1.2E-06	9.8E-06	7.0E-07	1.5E-04	4.2E-06
FAETP	0.0082	0.0022	3.2E-05	3.4E-05	1.4E-05	1.2E-04	8.6E-06	0.0057	7.3E-05
GWP	3.25	2.38	0.0071	0.0076	0.0032	0.0268	0.0019	0.8020	0.0158
HTP	0.3410	0.2930	0.0013	0.0014	5.7E-04	0.0048	3.5E-04	0.0391	2.9E-04
MAETP	1610	1550	3.09	3.32	1.39	11.7	0.8380	37.40	0.2780
ODP	2.2E-10	1.4E-11	3.1E-11	3.3E-11	1.4E-11	1.2E-10	8.4E-12	2.5E-12	1.9E-15
POCP	0.0015	0.0012	2.6E-06	2.8E-06	1.2E-06	9.9E-06	7.1E-07	3.0E-04	-4.1E-06
TETP	0.0347	0.0039	8.2E-05	8.8E-05	3.7E-05	3.1E-04	2.2E-05	0.0303	1.5E-05

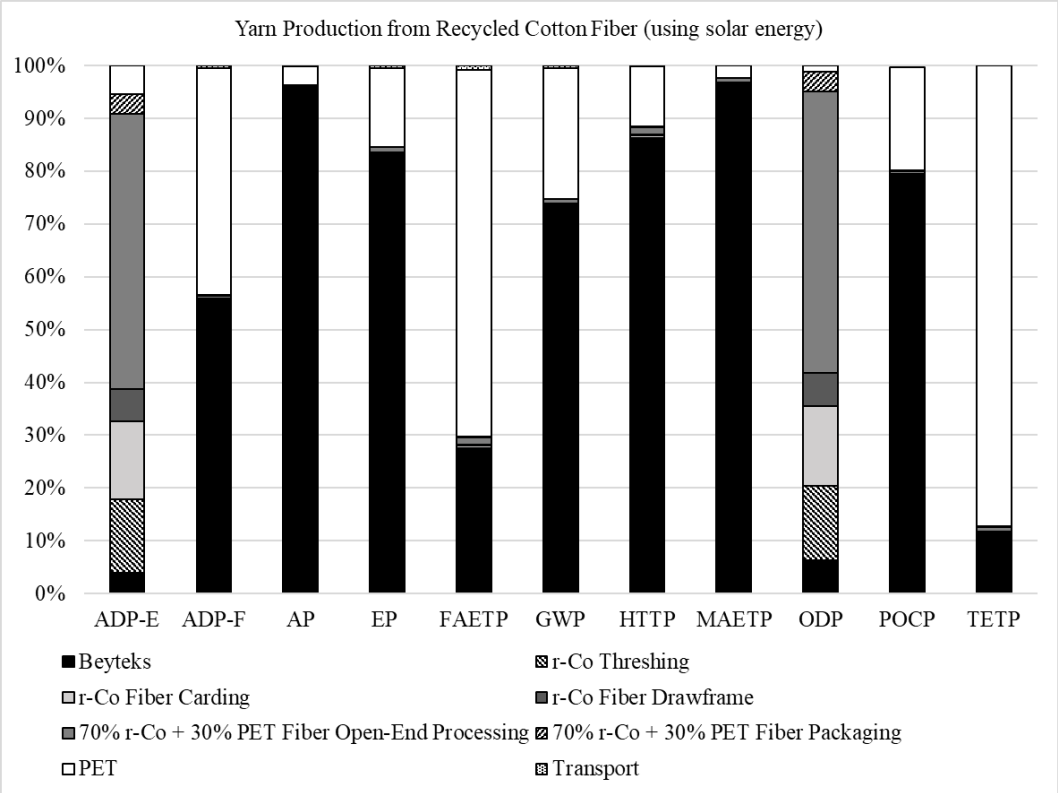


Figure 6.2 LCA results of yarn production (using solar energy)

As the final stage, analysis was made for fabric production, which is the next stage after yarn production. This analysis shows the total impact of all processes from start to finish. However, the processes affecting the fabric production are also seen (Table 6.3, Figure 6.3).

Table 6.3 LCA results of fabric production (using solar energy)

Impact Categories	Total	Haksa Yarn (+Beyteks electricity)	50% r-CO and 50% PET Thread Knitting Process	50% r-CO and 50% PET Fabric Finishing Process	50% r-CO and 50% PET Fabric Raising Process	50% r-CO and 50% PET Fabric Packaging	PET	Transport
ADP-E	3.9E-06	2.3E-06	2.9E-07	1.0E-06	9.1E-08	6.2E-08	1.8E-07	3.5E-10
ADP-F	76.2	34.4	0.049	20.3	0.015	0.011	21.3	0.091
AP	0.023	0.021	1.6E-05	0.001	5.1E-06	3.5E-06	0.001	8.2E-06
EP	0.001	6.9E-04	1.6E-06	3.0E-04	5.2E-07	3.5E-07	1.5E-04	1.8E-06
FAETP	0.012	0.006	2.0E-05	6.5E-04	6.3E-06	4.3E-06	0.006	3.1E-05
GWP	4.35	2.26	0.004	1.27	0.001	9.6E-04	0.802	6.7E-03
HTP	0.303	0.237	8.0E-04	0.025	2.5E-04	1.7E-04	0.039	1.2E-04
MAETP	1170	1120	1.93	8.21	0.612	0.419	37.4	0.1180
ODP	2.3E-10	1.5E-10	2.0E-11	3.9E-11	6.2E-12	4.2E-12	2.5E-12	7.9E-16
POCP	0.002	0.001	1.6E-06	1.6E-04	5.2E-07	3.6E-07	3.0E-04	-1.8E-06
TETP	0.057	0.024	5.1E-05	0.002	1.6E-05	1.1E-05	0.030	6.1E-06

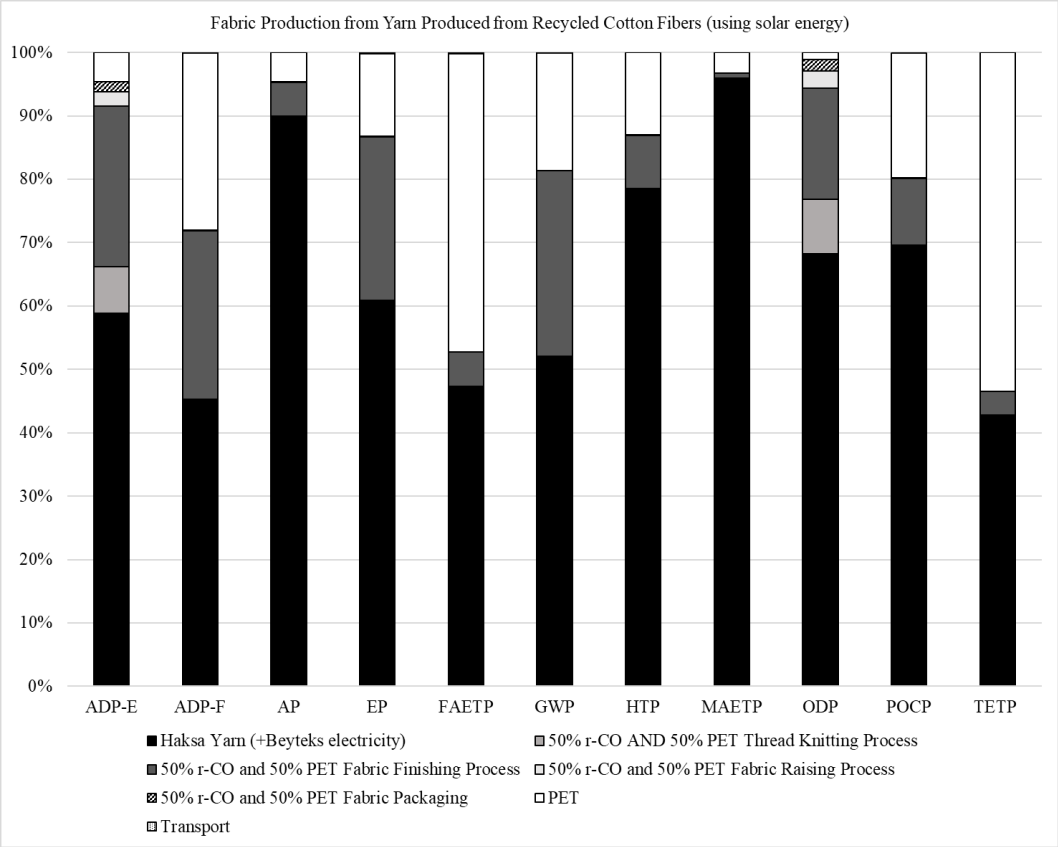


Figure 6.3 LCA results of fabric production (using solar energy)

As seen from the Table 6.3 and Figure 6.3, yarn production has the highest effects on the most impact categories and a large part of the impact on yarn production comes from the recycling process. Since the most important factor causing environmental impact in recycling processes is energy consumption, the use of solar energy, which is thought to be more environmentally friendly, has been considered as a way to reduce this impact.

It was determined that the highest impact after electricity consumption was caused by the use of polyester. From this result, it can be concluded that the production of polyester has a high environmental impact.

6.1.2. Results of Case-2

The use of renewable energy resources in production is an effective way to reduce the environmental impact of textile products (Büyükkamacı et al., 2023). Therefore, Case-2 was generated where solar energy was used instead of electricity for the recycling of scrap fabrics. The results of this Case by CML impact categories are given in Table 6.4 and Figure 6.4.

Table 6.4 LCA results of recycling process of scrap cotton fabrics (using solar energy)

Impact Categories	Total	Cotton Waste Cutting Process	Cotton Waste Rag Pulling Process	r-Co Fiber Pressing	Transport
ADP-E	6.8E-06	8.6E-07	5.0E-06	1.0E-06	1.2E-09
ADP-F	1.47	0.1460	0.8430	0.1740	0.3080
AP	4.1E-04	4.9E-05	2.8E-04	5.8E-05	2.8E-05
EP	4.5E-05	4.9E-06	2.8E-05	5.8E-06	5.9E-06
FAETP	5.8E-04	6.0E-05	3.5E-04	7.1E-05	1.1E-04
GWP	0.1290	0.0133	0.0770	0.0158	0.0226
HTP	0.0195	0.0024	0.0138	0.0029	4.2E-04
MAETP	46.60	5.80	33.50	6.89	0.3970
ODP	4.7E-10	5.8E-11	3.4E-10	7.0E-11	2.7E-15
POCP	3.3E-05	4.9E-06	2.8E-05	5.8E-06	-5.9E-06
TETP	0.0012	1.5E-04	8.9E-04	1.8E-04	2.1E-05

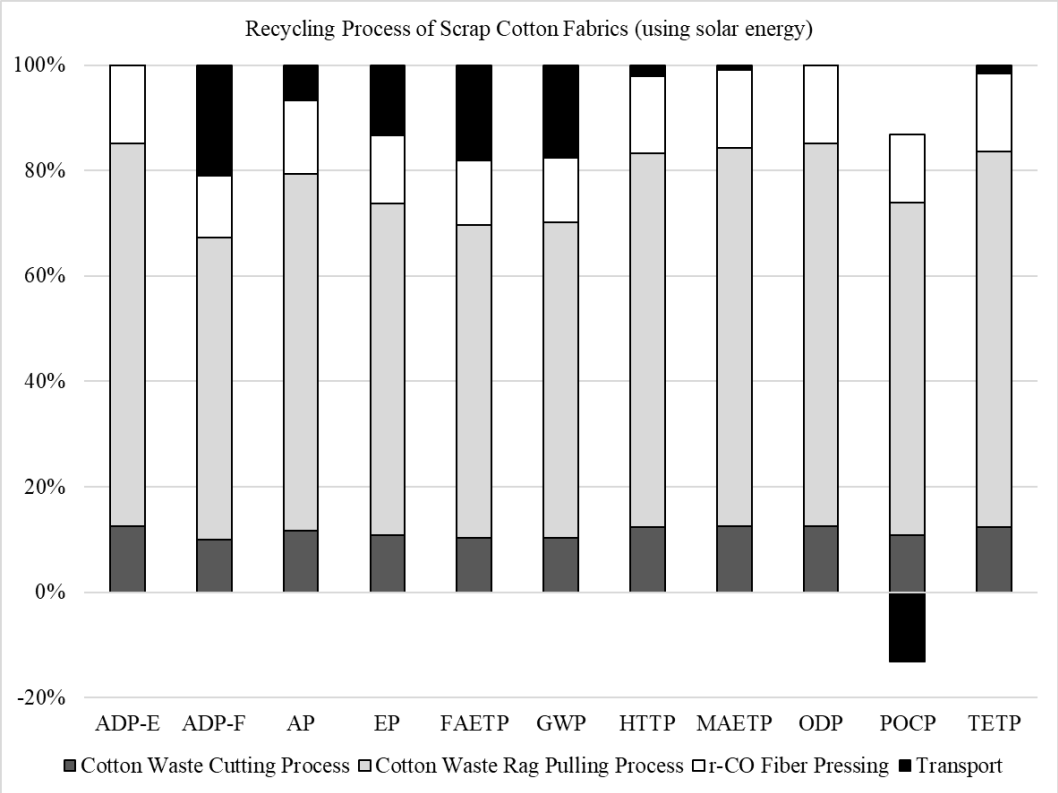


Figure 6.4 LCA results of recycling process of scrap cotton fabrics (using solar energy)

As can be seen from the results, the most impact in this process is caused by the rag pulling unit, as in Case-1. Compared to Case-1, although we use solar energy in this Case, the greatest effect is still seen in the same unit. The comparison of the Cases will be made in the next section.

The yarn and fabric production processes of this Case are as in Case-1. However, since changes were made in the first process, the results of the next processes also changed. Therefore, new processes have been created for yarn and fabric production. The effects of yarn production can be seen in the Table 6.5 and Figure 6.5.

Table 6.5 LCA result of yarn production (using solar energy)

Impact Categories	Total	Beyteks (solar energy)	r-Co Threshing	r-Co Fiber Carding	r-Co Fiber Drawframe	70% r-Co + 30% PET Fiber Open-End Processing	70% r-Co + 30% PET Fiber Packaging	PET	Transport
ADP-E	1.0E-05	6.8E-06	4.6E-07	4.9E-07	2.1E-07	1.7E-06	1.2E-07	1.8E-07	8.3E-10
ADP-F	23.50	1.47	0.0778	0.0835	0.0349	0.2940	0.0211	21.30	0.2150
AP	0.0017	4.1E-04	2.6E-05	2.8E-05	1.2E-05	9.8E-05	7.0E-06	0.0011	1.9E-05
EP	2.2E-04	4.5E-05	2.6E-06	2.8E-06	1.2E-06	9.8E-06	7.0E-07	1.5E-04	4.2E-06
FAETP	0.0066	5.8E-04	3.2E-05	3.4E-05	1.4E-05	1.2E-04	8.6E-06	0.0057	7.3E-05
GWP	0.9930	0.1290	0.0071	0.0076	0.0032	0.0268	0.0019	0.8020	0.0158
HTP	0.0673	0.0195	0.0013	0.0014	5.7E-04	0.0048	3.5E-04	0.0391	2.9E-04
MAETP	105	46.60	3.09	3.32	1.39	11.70	0.8380	37.40	0.2780
ODP	6.7E-10	4.7E-10	3.1E-11	3.3E-11	1.4E-11	1.2E-10	8.4E-12	2.5E-12	1.9E-15
POCP	3.4E-04	3.3E-05	2.6E-06	2.8E-06	1.2E-06	9.9E-06	7.1E-07	3.0E-04	-4.1E-06
TETP	0.0321	0.0012	8.2E-05	8.8E-05	3.7E-05	3.1E-04	2.2E-05	0.0303	1.5E-05

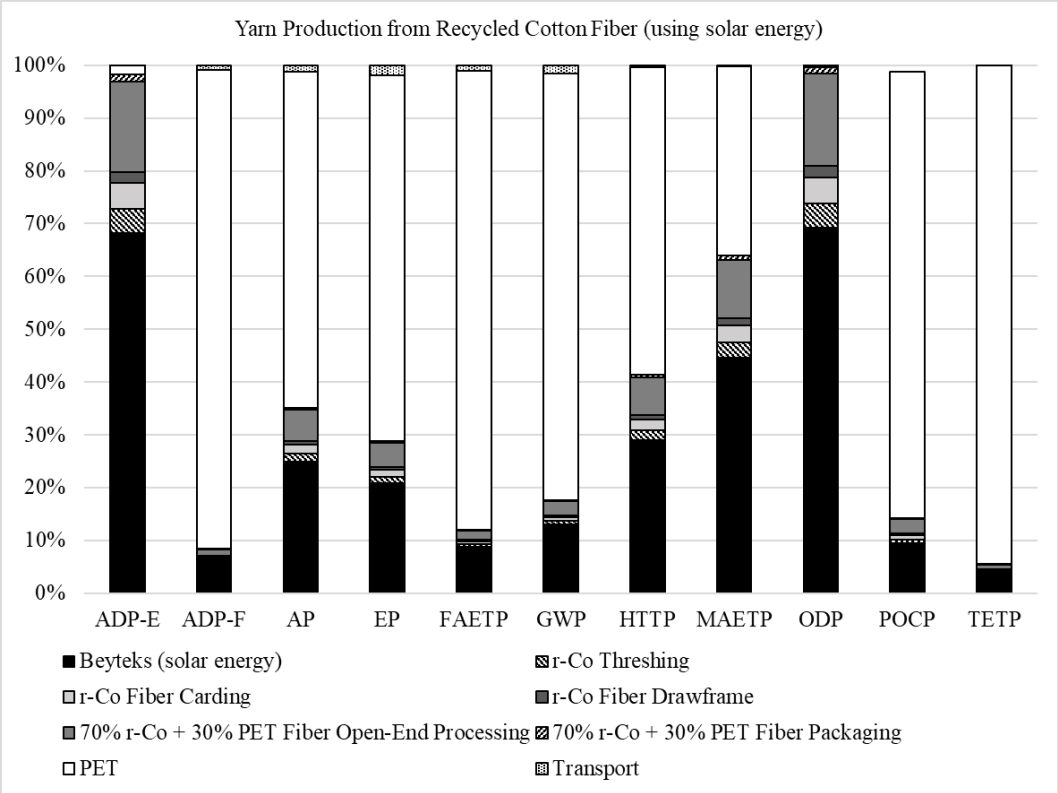


Figure 6.5 LCA result of yarn production (using solar energy)

As can be seen in the Table 6.5 and Figure 6.5, it is seen that the most impact in almost all categories is caused by polyester. In this Case, since solar energy is used, it is seen that the effects from electricity consumption are reduced. In this way, it is clearly seen in this Case that the environmental impacts caused by polyester production are high.

As can be seen from the Table 6.6 and Figure 6.6, 3 processes affect the CML impact categories the most. These processes are yarn production, finishing process and polyester. It is clearly seen that the most impact in abiotic depletion, marine aquatic ecotoxicity potential and ozone layer depletion categories is caused by yarn production. In the Freshwater aquatic ecotoxicity potential and terrestrial ecotoxicity potential categories, it is clearly seen that polyester gives most effect. It can be said that there is a balanced distribution in some other categories.

Table 6.6 LCA results of fabric production (using solar energy)

Impact Categories	Total	Haksa Yarn (+Beyteks electricity)	50% r-CO and 50% PET Thread Knitting Process	50% r-CO and 50% PET Fabric Finishing Process	50% r-CO and 50% PET Fabric Raising Process	50% r-CO and 50% PET Fabric Packaging	PET	Transport
ADP-E	8.6E-06	7.0E-06	2.9E-07	1.0E-06	9.1E-08	6.2E-08	1.8E-07	3.5E-10
ADP-F	58.1	16.3	0.049	20.3	0.015	0.011	21.3	0.091
AP	0.003	0.001	1.6E-05	0.001	5.1E-06	3.5E-06	0.001	8.2E-06
EP	6.0E-04	1.5E-04	1.6E-06	3.0E-04	5.2E-07	3.5E-07	1.5E-04	1.8E-06
FAETP	0.011	0.005	2.0E-05	6.5E-04	6.3E-06	4.3E-06	0.006	3.1E-05
GWP	2.78	0.692	0.004	1.27	0.001	9.6E-04	0.802	6.7E-03
HTP	0.113	0.047	8.0E-04	0.025	2.5E-04	1.7E-04	0.039	1.2E-04
MAETP	122	72.9	1.93	8.21	0.612	0.419	37.4	0.1180
ODP	5.4E-10	4.7E-10	2.0E-11	3.9E-11	6.2E-12	4.2E-12	2.5E-12	7.9E-16
POCP	7.0E-04	2.4E-04	1.6E-06	1.6E-04	5.2E-07	3.6E-07	3.0E-04	-1.8E-06
TETP	0.055	0.022	5.1E-05	0.002	1.6E-05	1.1E-05	0.030	6.1E-06

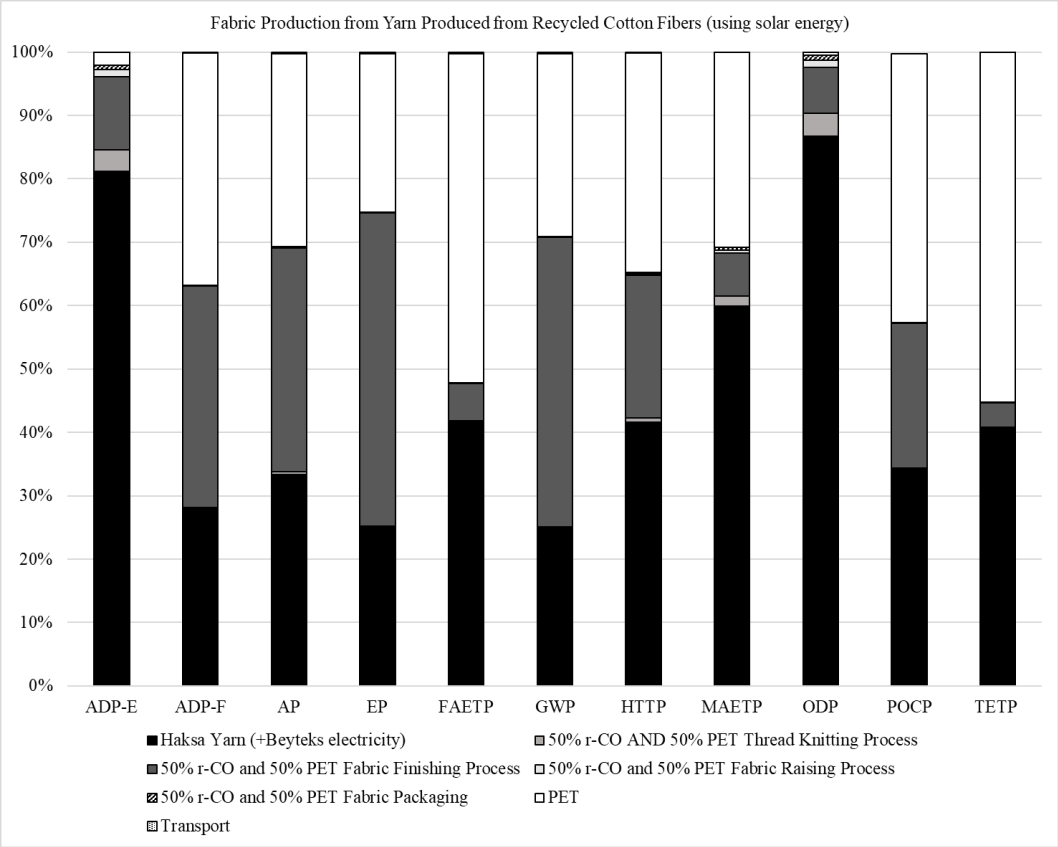


Figure 6.6 LCA results of fabric production (using solar energy)

6.1.3. Results of Case-3

In this Case, unlike the other two Cases, electricity was used as a type of energy in all processes. The purpose of Case-3 is to investigate how much the environmental impacts will be as a result of all production being made with electricity.

For the first process of this Case, the recycling of scrap fabrics, the results are the same as in Case-1. The same process was used for recycling in both Cases. The LCA results of this process have been previously examined in Case-1.

As a second step, the environmental impacts of the yarn production process were investigated in case of using electricity as a type of energy. The results of the yarn production processes according to the CML categories are shown in the Table 6.7 and Figure 6.7.

Table 6.7 LCA results of yarn production (using electricity)

Impact Categories	Total	Beyteks	r-Co Threshing	r-Co Fiber Carding	r-Co Fiber Drawframe	70% r-Co + 30% PET Fiber Open-End Processing	70% r-Co + 30% PET Fiber Packaging	PET	Transport
ADP-E	3.7E-07	1.3E-07	8.8E-09	9.4E-09	3.9E-09	3.3E-08	2.4E-09	1.8E-07	8.3E-10
ADP-F	60.70	27.40	1.81	1.94	0.8110	6.84	0.4900	21.30	0.2150
AP	0.0418	0.0283	0.0019	0.0020	8.5E-04	0.0072	5.1E-04	0.0011	1.9E-05
EP	0.0013	8.2E-04	5.5E-05	5.9E-05	2.5E-05	2.1E-04	1.5E-05	1.5E-04	4.2E-06
FAETP	0.0089	0.0022	1.4E-04	1.5E-04	6.4E-05	5.4E-04	3.9E-05	0.0057	7.3E-05
GWP	4.24	2.38	0.1580	0.170	0.0708	0.5970	0.0428	0.8020	0.0158
HTP	0.4610	0.2930	0.0196	0.0210	0.0088	0.0740	0.0053	0.0391	2.9E-04
MAETP	2270	1550	104	111	46.50	392	28.10	37.40	0.2780
ODP	2.2E-11	1.4E-11	9.3E-13	1.0E-12	4.2E-13	3.5E-12	2.5E-13	2.5E-12	1.9E-15
POCP	0.0020	0.0012	8.1E-05	8.7E-05	3.6E-05	3.1E-04	2.2E-05	3.0E-04	-4.1E-06
TETP	0.0359	0.0039	2.6E-04	2.8E-04	1.2E-04	9.7E-04	7.0E-05	0.0303	1.5E-05

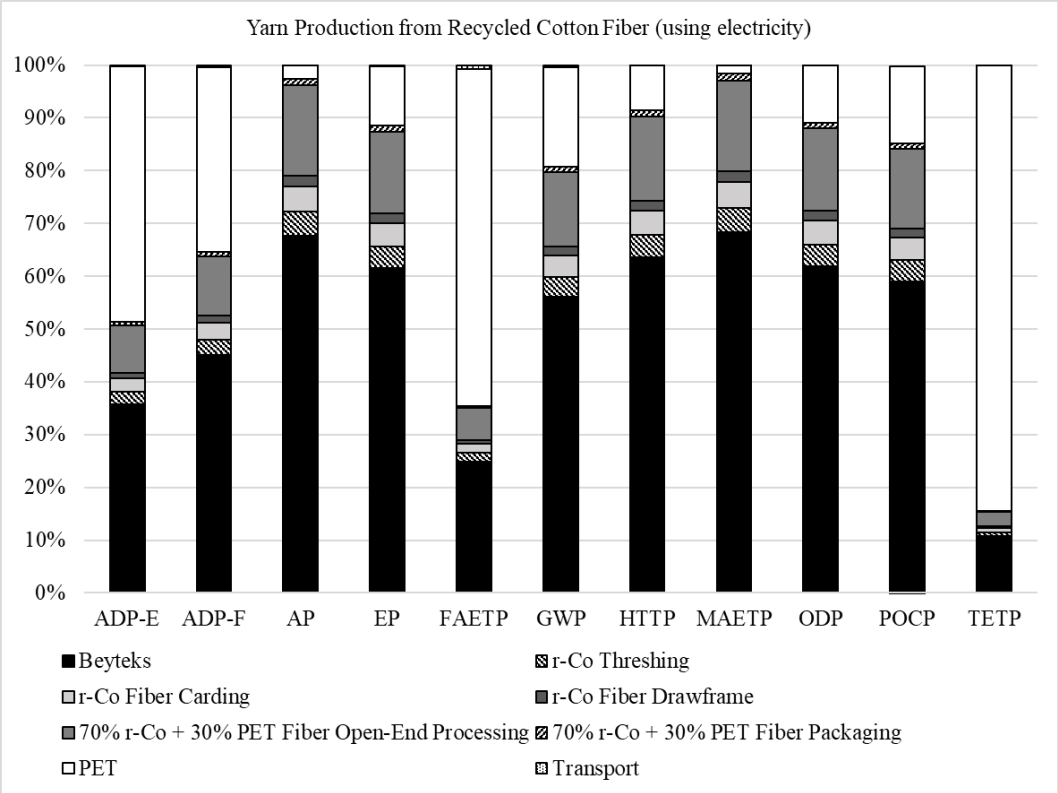


Figure 6.7 LCA results of yarn production (using electricity)

As seen in the Table 6.7 and Figure 6.7, the processes that have the most impact on CML categories are the recycling process of scrap fabrics and polyester. It is clearly seen that the open-end process, which is a stage of yarn production, has an effect on almost all CML categories.

As the last stage of this Case, LCA study was carried out for fabric production. At this stage, the environmental effects of using electrical energy for fabric production were investigated. The results of fabric production in CML categories are shown in the Table 6.8. According to the results in the Table 6.8 and Figure 6.8.

Table 6.8 LCA results of fabric production (using electricity)

Impact Categories	Total	Haksa Yarn (+Beyteks electricity)	50% r-CO and 50% PET Thread Knitting Process	50% r-CO and 50% PET Fabric Finishing Process	50% r-CO and 50% PET Fabric Raising Process	50% r-CO and 50% PET Fabric Packaging	PET	Transport
ADP-E	8.8E-07	2.6E-07	5.5E-09	4.3E-07	1.7E-09	1.2E-09	1.8E-07	3.5E-10
ADP-F	87.9	42.3	1.13	22.5	0.358	0.245	21.3	0.091
AP	0.036	0.029	0.001	0.004	3.8E-04	2.6E-04	0.001	8.2E-06
EP	0.001	9.3E-04	3.4E-05	3.6E-04	1.1E-05	7.4E-06	1.5E-04	1.8E-06
FAETP	0.013	0.006	8.9E-05	7.9E-04	2.8E-05	1.9E-05	0.006	3.1E-05
GWP	5.38	2.95	0.099	1.46	0.031	0.021	0.802	6.7E-03
HTP	0.427	0.321	0.012	0.048	0.004	0.003	0.039	1.2E-04
MAETP	1850	1580	64.9	134	20.5	14.1	37.4	0.118
ODP	2.1E-11	1.6E-11	5.8E-13	1.6E-12	1.8E-13	1.3E-13	2.5E-12	7.9E-16
POCP	0.002	0.001	5.0E-05	2.6E-04	1.6E-05	1.1E-05	3.0E-04	-1.8E-06
TETP	0.058	0.025	1.6E-04	0.002	5.1E-05	3.5E-05	0.030	6.1E-06

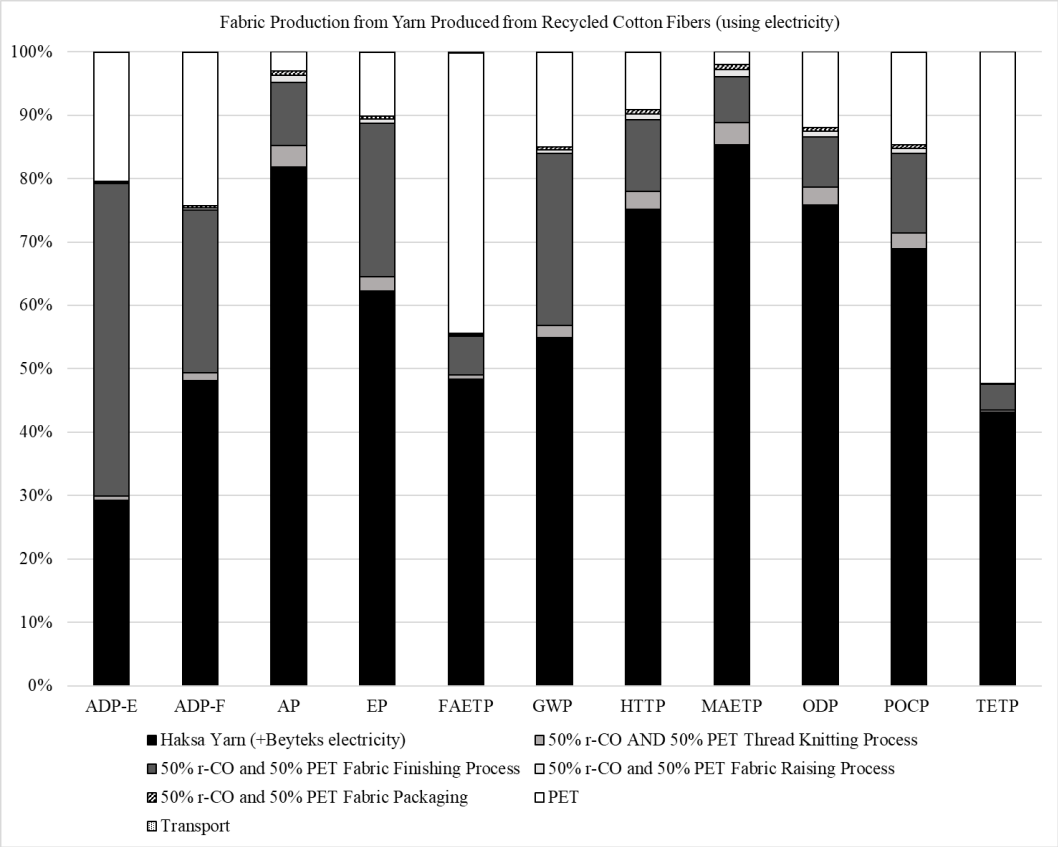


Figure 6.8 LCA results of fabric production (using electricity)

Based on the results in the Table 6.8 and Figure 6.8, it is observed that the most impact in almost all categories is caused by yarn production. It is seen that the effect of polyester is high in categories such as freshwater aquatic ecotoxicity potential and terrestric ecotoxicity potential. The finishing process also has a significant impact in most categories.

6.1.4. Results of Case-4

The results of this Case, which was created to evaluate the LCA of the production of fabric included 50% cotton and 50% polyester content, are shown in the Table 6.9 and Figure 6.9. In this Case, it is assumed that electricity is used as a type of energy in the production process.

Table 6.9 LCA results of 50% cotton and 50% polyester fabric production (using electricity)

Impact Categories	Total	50% CO + 50% PET Thread	50% CO + 50% PET Knitting	50% CO + 50% PET Dyeing	50% CO + 50% PET Finishing	Cotton fiber	PET
ADP-E	1.5E-05	3.5E-09	1.2E-08	8.2E-06	6.1E-06	4.1E-07	3.0E-07
ADP-F	88.9	0.728	2.47	37.1	7.07	6.08	35.5
AP	0.037	7.2E-04	0.002	0.015	0.004	0.013	0.002
EP	0.005	2.1E-05	7.0E-05	7.6E-04	1.7E-04	0.004	2.5E-04
FAETP	0.17	7.0E-05	2.4E-04	0.003	0.001	0.156	0.010
GWP	4.59	0.063	0.204	2.51	0.548	-0.074	1.34
HTP	0.412	0.007	0.025	0.182	0.074	0.059	0.065
MAETP	1320	39.0	132	740	212	134	62.3
ODP	7.6E-09	3.5E-13	1.2E-12	7.6E-09	3.0E-12	2.4E-11	4.1E-12
POCP	0.002	3.0E-05	1.0E-04	8.2E-04	2.3E-04	5.9E-05	5.0E-04
TETP	0.096	1.0E-04	3.4E-04	0.004	0.038	0.003	0.051

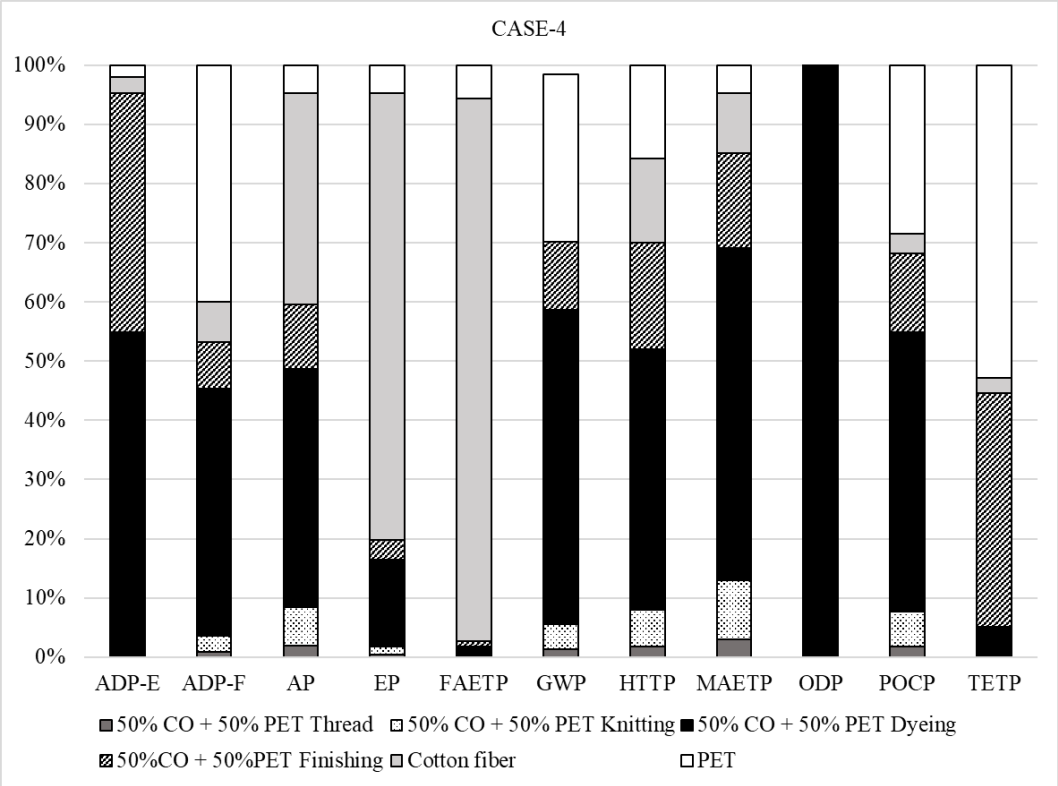


Figure 6.9 LCA results of 50% cotton and 50% polyester fabric production (using electricity)

According to the results in the Table 6.9 and Figure 6.9, it can be seen that the most impact on the CML categories in Case-4 comes from the dyeing and finishing processes, polyester and cotton. It can be concluded that the processes with the use of chemicals have a significant impact. Due to cotton production, the effects are mostly seen in the eutrophication potential and freshwater aquatic ecotoxicity potential categories.

6.1.5. Results of Case-5

In the Case-5, the LCA of 50% cotton and 50% polyester fabric production was made. The difference of this Case from Case-4 is that the type of energy used in production is solar energy in this Case. Accordingly, the LCA results of this Case are shown in Table 6.10 and Figure 6.10.

Table 6.10 LCA results of 50% cotton and 50% polyester fabric production (using solar energy)

Impact Categories	Total	50% CO + 50% PET Thread	50% CO + 50% PET Knitting	50% CO + 50% PET Dyeing	50% CO + 50% PET Finishing	Cotton fiber	PET
ADP-E	2.0E-05	1.7E-07	5.8E-07	1.1E-05	6.9E-06	4.1E-07	3.0E-07
ADP-F	71	0.078	0.267	25	4.05	6.08	35.5
AP	0.018	1.5E-05	4.3E-05	0.002	8.0E-04	0.013	0.002
EP	0.005	2.0E-06	4.1E-06	4.0E-04	8.3E-05	0.004	2.5E-04
FAETP	0.169	2.9E-05	1.0E-04	0.002	0.001	0.156	0.010
GWP	3.03	0.006	0.013	1.46	0.285	-0.074	1.34
HTP	0.222	5.5E-04	0.002	0.054	0.042	0.059	0.065
MAETP	276	1.22	4.17	37.7	36.9	134	62.3
ODP	7.9E-09	1.2E-11	4.0E-11	7.8E-09	5.6E-11	2.4E-11	4.1E-12
POCP	9.3E-04	1.1E-06	4.9E-06	2.8E-04	9.6E-05	5.9E-05	5.0E-04
TETP	0.094	3.4E-05	1.2E-04	0.003	0.037	0.003	0.051

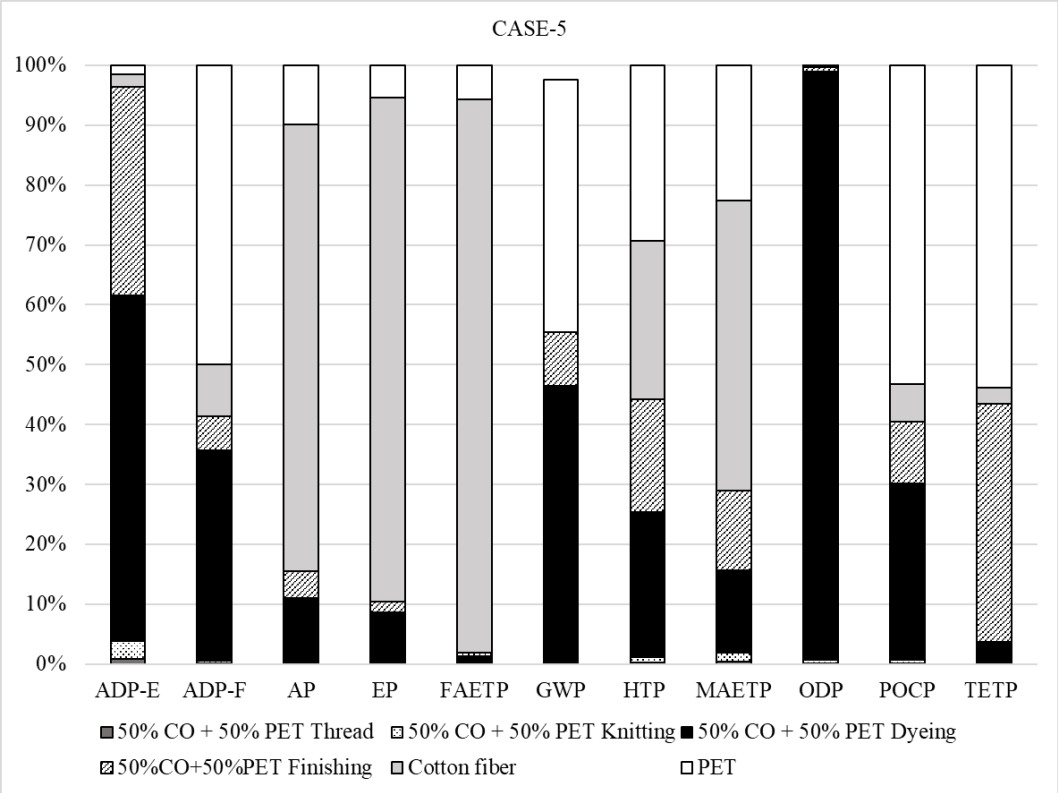


Figure 6.10 LCA results of 50% cotton and 50% polyester fabric production (using solar energy)

Looking at the Table 6.10 and Figure 6.10, it is seen that the effects of cotton and polyester are high in the Case-5. In addition, due to the high use of chemicals, it is seen that finishing and dyeing processes have a significant effect.

6.1.6. Results of Case-6

The LCA results of the production of 100% cotton fabric are shown in Table 6.11. According to the results in the table, the contribution of each process to the effect categories is clearly seen in the chart below.

Table 6.11 LCA results of 100% cotton production

Impact Categories	Total	Cotton fiber	Textile Manufacturing - Knit Fabric	Transport
ADP-E	4.3E-05	8.3E-07	4.3E-05	1.6E-09
ADP-F	101	12.2	88.3	0.419
AP	0.066	0.026	0.040	3.8E-05
EP	0.013	0.008	0.005	8.1E-06
FAETP	0.728	0.311	0.416	1.4E-04
GWP	5.92	-0.149	6.04	0.031
HTP	1.06	0.118	0.94	5.7E-04
MAETP	3100	268	2840	0.540
ODP	9.7E-09	4.7E-11	9.7E-09	3.6E-15
POCP	0.002	1.2E-04	0.002	-8.1E-06
TETP	0.086	0.005	0.081	2.8E-05

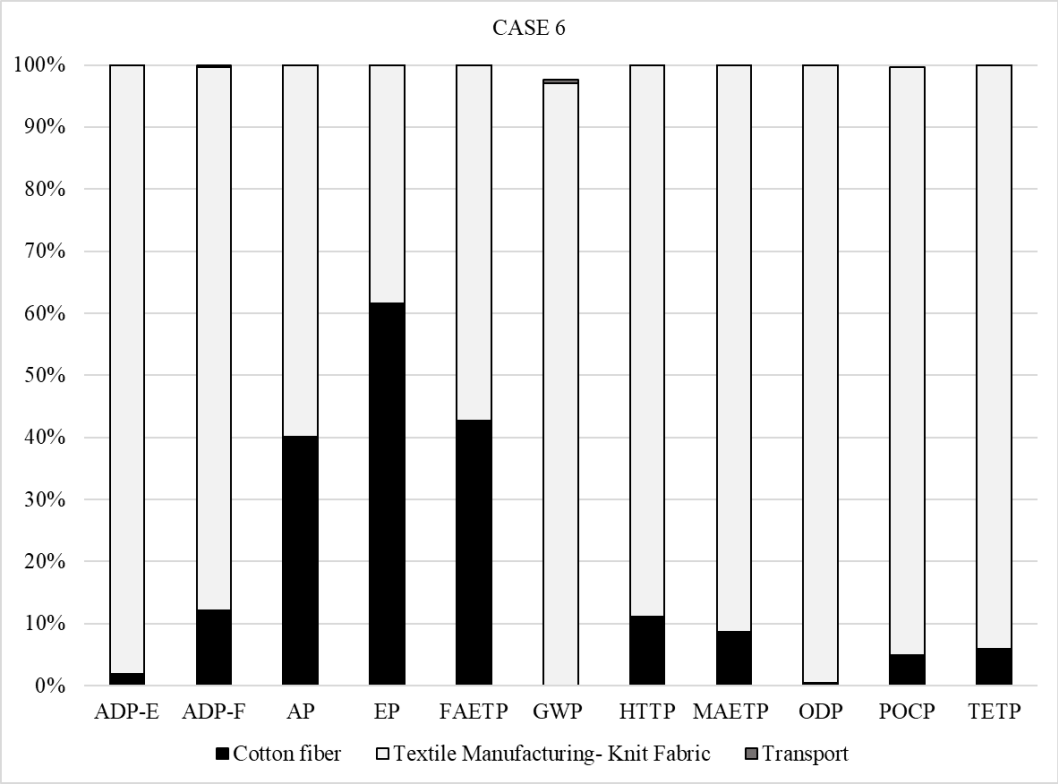


Figure 6.11 LCA results of 100% cotton production

Considering these results, it is seen that cotton production and textile manufacturing processes have a significant effect on CML categories. Based on the results of this Case, reuse or recycling ways can be preferred to reduce the impacts from cotton production. In addition, when recycling is preferred in processes that use chemicals during the fabric production phase, the use of chemicals will be reduced. As seen in the previous sections, an LCA study has been carried out for recycling within the scope of this thesis. The results of this Case and the results of Case-1 will be compared in the next section. In this way, it was investigated whether recycling is beneficial or not.

6.1.7. Results of Case-7

The LCA outcomes for manufacturing 100% organic cotton fabric are presented in Table 6.12. According to the table results, the chart below clearly displays the impact of each process on the effect categories.

Table 6.12 LCA results of 100% organic cotton production

Impact Categories	Total	Organic Cotton Fiber	Textile Manufacturing - Knit Fabric	Transport
ADP-E	4.3E-05	8.5E-08	4.3E-05	5.3E-10
ADP-F	94.90	6.06	88.31	0.5362
AP	0.0457	0.0062	0.0395	4.1E-05
EP	0.0077	0.0029	0.0049	8.5E-06
FAETP	0.4275	0.0111	0.4162	1.8E-04
GWP	5.26	-0.8254	6.04	0.0385
HTP	1.04	0.0964	0.9399	7.2E-04
MAETP	3158.61	321.53	2836.43	0.6489
ODP	9.7E-09	2.5E-15	9.7E-09	5.2E-15
POCP	0.0023	9.3E-05	0.0022	-7.3E-06
TETP	0.0821	0.0008	0.0812	3.5E-05

Considering these results, it is seen that a significant part of the effects on CML categories is in the textile production process. The production of organic cotton also appears to have an impact in a number of categories. Considering these findings, the importance of fabric recycling is clear.

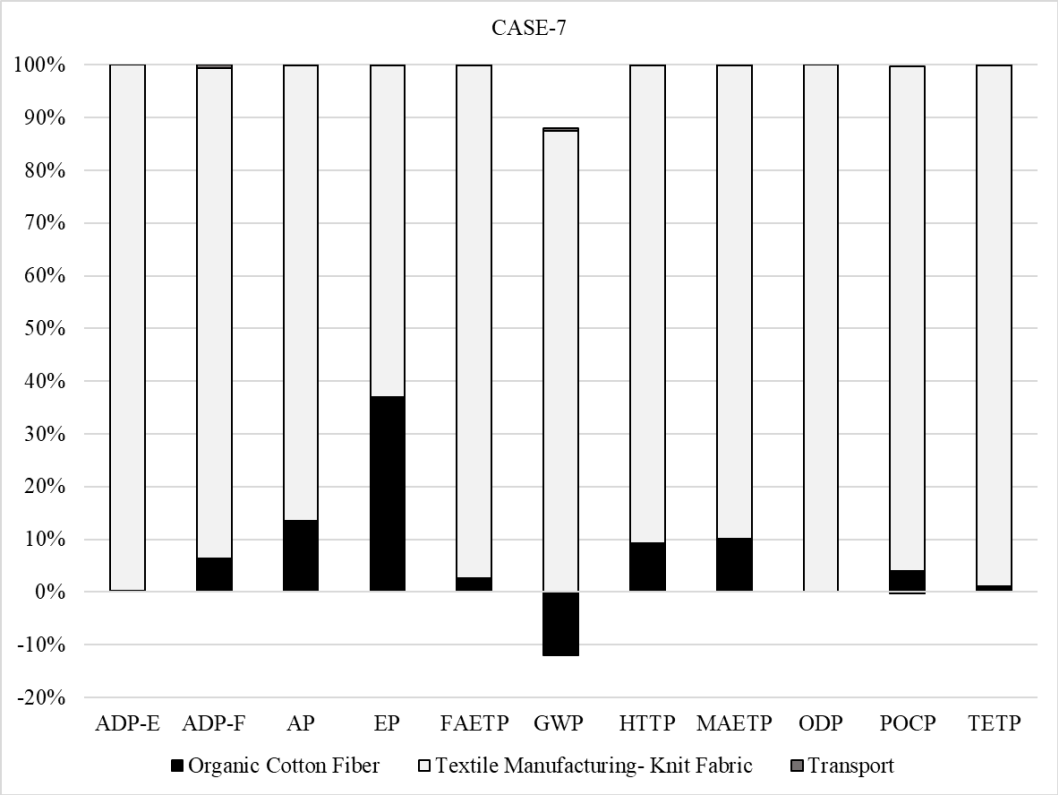


Figure 6.12 LCA results of 100% organic cotton production

6.1.8. Results of Case-8

The section provides an analysis of LCA results of yarn and fabric production using 50% recycled cotton (r-CO) and 50% recycled polyester (r-PET). The purpose of this case is to examine the environmental benefits of polyester recycling in addition to the current cotton recycling. The types of energy used in production are the same as in the current case, Case-1.

For the first process of this Case, the recycling of scrap fabrics, the results are the same as in Case-1. The LCA results of this process have been previously examined in Case-1. The LCA results of recycling process are shown in the Table 6.1 and Figure 6.1.

In a second step, the environmental impact of the yarn production process using r-CO and r-PET was investigated. The results of the yarn production processes according to the CML effect categories are shown in the Table 6.13 and Figure 6.13.

Table 6.13 LCA results of yarn production with recycled cotton and recycled pet

Impact Categories	Total	Beyteks	r-PET	r-CO Fiber Threshing	r-CO Fiber Carding	r-CO Fiber Drawframe	70% r-CO + 30% r-PET Fiber Open-End Processing	70% r-CO + 30% r-PET Fiber Packaging	Transport
ADP-E	1.2E-06	1.8E-07	2.8E-08	1.5E-07	1.6E-07	6.7E-08	5.7E-07	4.1E-08	2.7E-10
ADP-F	27.24	24.53	1.93	0.0770	0.0826	0.0345	0.2911	0.0209	0.2699
AP	0.0321	0.0306	0.0012	2.7E-05	2.9E-05	1.2E-05	1.0E-04	7.3E-06	2.4E-05
EP	8.9E-04	8.2E-04	5.2E-05	2.7E-06	2.9E-06	1.2E-06	1.0E-05	7.3E-07	5.1E-06
FAETP	0.0027	0.0021	2.8E-04	3.3E-05	3.5E-05	1.5E-05	1.2E-04	8.9E-06	9.2E-05
GWP	2.59	2.24	0.2807	0.0072	0.0077	0.0032	0.0271	0.0019	0.0194
HTP	0.3202	0.2967	0.0145	0.0013	0.0014	5.8E-04	0.0049	3.5E-04	3.6E-04
MAETP	1649	1562.09	65.75	3.17	3.40	1.42	11.98	0.8581	0.3266
ODP	2.2E-10	1.6E-11	2.3E-12	3.1E-11	3.3E-11	1.4E-11	1.2E-10	8.4E-12	2.6E-15
POCP	0.0013	0.0012	5.6E-05	2.7E-06	2.9E-06	1.2E-06	1.0E-05	7.3E-07	-5.4E-06
TETP	0.0041	0.0033	2.1E-04	8.6E-05	9.2E-05	3.8E-05	3.2E-04	2.3E-05	1.7E-05

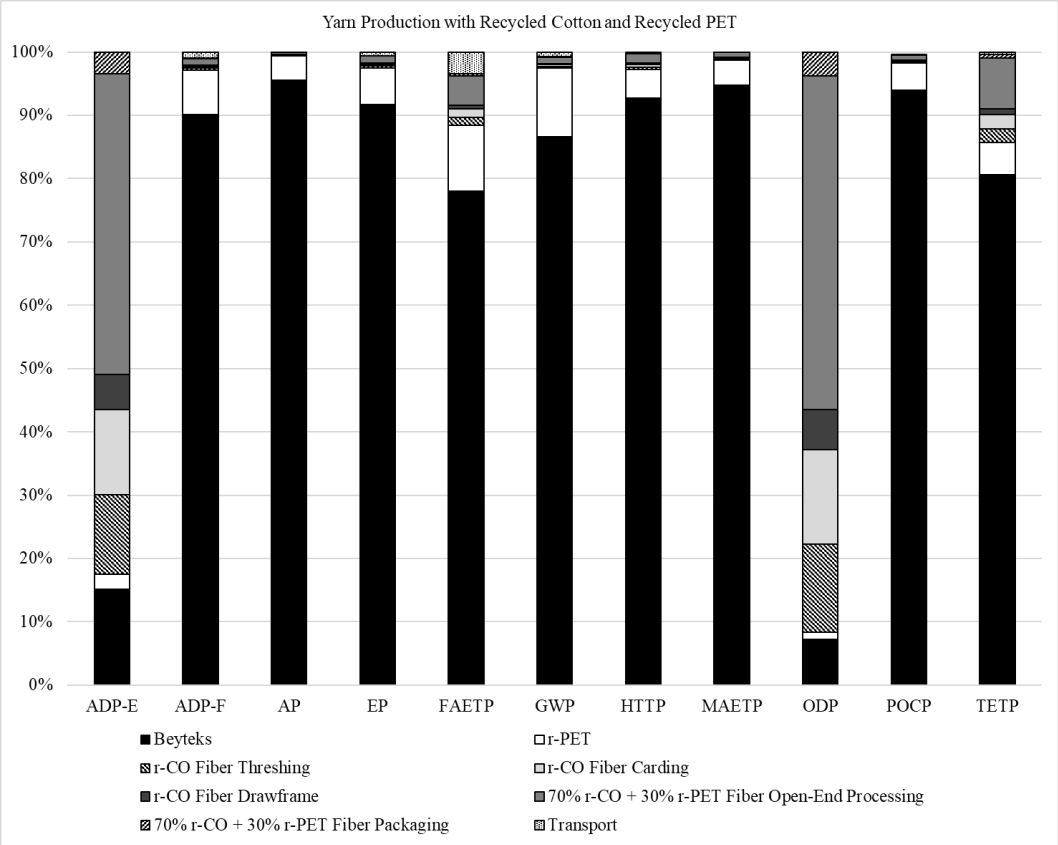


Figure 6.13 LCA results of yarn production with recycled cotton and recycled pet

Examining the results in Table 6.13 and Figure 6.13, it can be seen that the highest impact in most categories is caused by the scrap fabric recycling process. It is clear that the drawframe process, which is a yarn production process, has the highest impact in the ADP elements and ODP categories.

As the last stage of the Case-8, LCA study was carried out for fabric production. At this stage, the environmental effects of using recycled cotton and recycled PET for fabric production were investigated. The results of fabric production in CML categories are shown in the Table 6.14 and Figure 6.14.

It can be seen that yarn production has the highest impact in almost all categories based on the results in Table 6.14 and Figure 6.14. In the current case, a significant impact of polyester was observed. Examining the findings from Case-8, it is evident that recycling has greatly diminished the impact of polyester.

Table 6.14 LCA results of fabric production with recycled cotton and recycled pet

Impact Categories	Total	Haksa Yarn (r-PET)	r-PET	50% r-CO and 50% r-PET Thread Knitting Process	50% r-CO and 50% r-PET Fabric Finishing Process	50% r-CO and 50% r-PET Fabric Raising Process	50% r-CO and 50% r-PET Fabric Packaging	Transport
ADP-E	1.6E-06	8.3E-07	2.8E-08	9.4E-08	5.6E-07	3.0E-08	2.0E-08	1.1E-10
ADP-F	41.83	18.97	1.93	0.0481	20.74	0.0152	0.0104	0.1144
AP	0.0249	0.0223	0.0012	1.7E-05	0.0013	5.3E-06	3.7E-06	1.0E-05
EP	9.8E-04	6.2E-04	5.2E-05	1.7E-06	3.0E-04	5.3E-07	3.6E-07	2.2E-06
FAETP	0.0028	0.0019	2.8E-04	2.0E-05	6.1E-04	6.5E-06	4.4E-06	3.9E-05
GWP	3.39	1.81	0.2807	0.0045	1.29	0.0014	9.7E-04	0.0082
HTP	0.2644	0.2230	0.0145	8.1E-04	0.0255	2.6E-04	1.8E-04	1.5E-04
MAETP	1225.79	1148.55	65.75	1.98	8.31	0.6271	0.4291	0.1385
ODP	2.3E-10	1.6E-10	2.3E-12	1.9E-11	3.9E-11	6.2E-12	4.2E-12	1.1E-15
POCP	0.0011	9.0E-04	5.6E-05	1.7E-06	1.7E-04	5.3E-07	3.6E-07	-2.3E-06
TETP	0.0051	0.0028	2.1E-04	5.4E-05	0.0019	1.7E-05	1.2E-05	7.4E-06

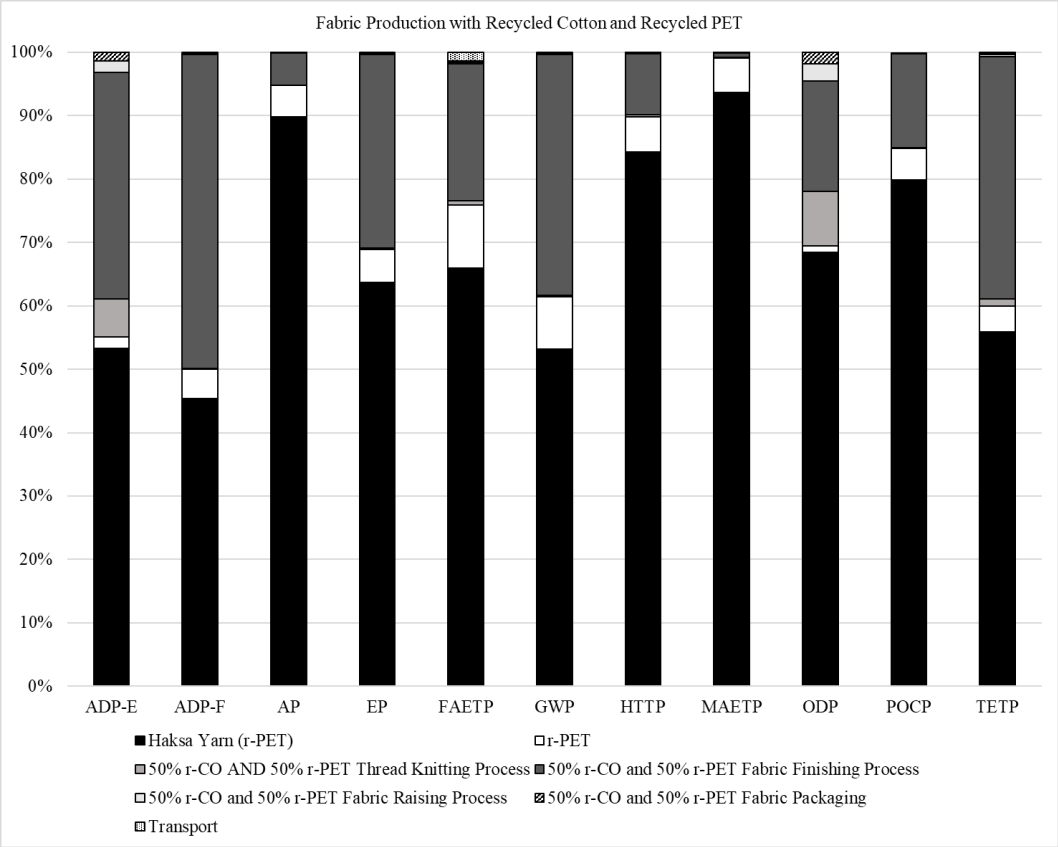


Figure 6.14 LCA results of fabric production with recycled cotton and recycled pet

6.1.9. Results of Case-9

The section provides an analysis of LCA results of yarn and fabric production using 50% r-CO and 50% r-PET. Unlike Case-8, this scenario used solar energy for production. The purpose of Case-9 is to examine the environmental impact of production process using entirely eco-friendly methods.

For the first process of this Case, the recycling of scrap fabrics, the results are the same as in Case-2. The LCA results of this process have been previously examined in Case-1. The LCA results of recycling process are shown in the Table 6.2 and Figure 6.2. In a second step, the environmental impact of producing yarn from recycled cotton and recycled PET using solar energy was investigated. The results of the yarn production processes according to the CML effect categories are shown in the Table 6.15 and 6.15.

Table 6.15 LCA results of yarn production with recycled cotton and recycled pet (using solar energy)

Impact Categories	Total	Beyteks	r-PET	r-CO Fiber Threshing	r-CO Fiber Carding	r-CO Fiber Drawframe	70% r-CO + 30% r-PET Fiber Open-End Processing	70% r-CO + 30% r-PET Fiber Packaging	Transport
ADP-E	3.3E-06	2.2E-06	9.9E-08	1.5E-07	1.6E-07	6.7E-08	5.7E-07	4.1E-08	2.7E-10
ADP-F	3.44	1.54	1.13	0.0770	0.0826	0.0345	0.2911	0.0209	0.2699
AP	8.3E-04	4.4E-04	2.0E-04	2.7E-05	2.9E-05	1.2E-05	1.0E-04	7.3E-06	2.4E-05
EP	9.5E-05	4.7E-05	2.5E-05	2.7E-06	2.9E-06	1.2E-06	1.0E-05	7.3E-07	5.1E-06
FAETP	0.0012	6.2E-04	2.3E-04	3.3E-05	3.5E-05	1.5E-05	1.2E-04	8.9E-06	9.2E-05
GWP	0.4088	0.1348	0.2075	0.0072	0.0077	0.0032	0.0271	0.0019	0.0194
HTP	0.0338	0.0200	0.0049	0.0013	0.0014	5.8E-04	0.0049	3.5E-04	3.6E-04
MAETP	82.11	47.80	13.16	3.17	3.40	1.42	11.98	0.8581	0.3266
ODP	6.9E-10	4.7E-10	1.8E-11	3.1E-11	3.3E-11	1.4E-11	1.2E-10	8.4E-12	2.6E-15
POCP	5.9E-05	3.2E-05	1.5E-05	2.7E-06	2.9E-06	1.2E-06	1.0E-05	7.3E-07	-5.4E-06
TETP	0.0020	0.0013	1.4E-04	8.6E-05	9.2E-05	3.8E-05	3.2E-04	2.3E-05	1.7E-05

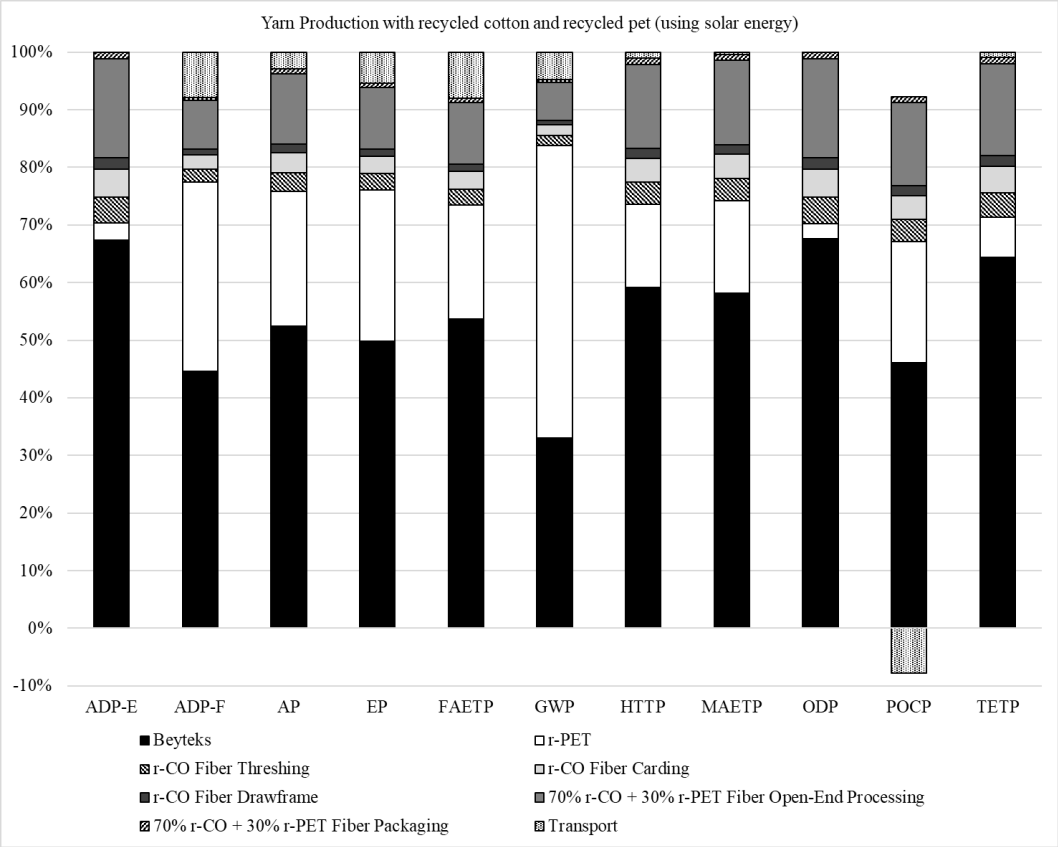


Figure 6.15 LCA results of yarn production with recycled cotton and recycled pet (using solar energy)

As shown in Table 6.15 and Figure 6.15, the most significant impact in the CML impact categories for yarn production is from the scrap fabric recycling process. In terms of GWP category, recycling polyester has the most significant impact.

As the last stage of the Case-9, LCA study was carried out for fabric production. The results of fabric production in CML categories are shown in the Table 6.16 and Figure 6.16. According to the findings presented in Table 6.16 and Figure 6.16, yarn production and the knitting process have a significant impact in nearly all categories.

Table 6.16 LCA results of fabric production with recycled cotton and recycled pet (using solar energy)

Impact Categories	Total	Haksa Yarn (r-PET)	r-PET (photovoltaic)	50% r-CO and 50% PET Thread Knitting Process	50% r-CO and 50% PET Fabric Finishing Process	50% r-CO and 50% PET Fabric Raising Process	50% r-CO and 50% PET Fabric Packaging	Transport
ADP-E	3.1E-06	2.3E-06	9.9E-08	9.4E-08	5.6E-07	3.0E-08	2.0E-08	1.1E-10
ADP-F	24.46	2.40	1.13	0.0481	20.74	0.0152	0.0104	0.1144
AP	0.0021	5.8E-04	2.0E-04	1.7E-05	0.0013	5.3E-06	3.7E-06	1.0E-05
EP	3.9E-04	6.6E-05	2.5E-05	1.7E-06	3.0E-04	5.3E-07	3.6E-07	2.2E-06
FAETP	0.0017	8.1E-04	2.3E-04	2.0E-05	6.1E-04	6.5E-06	4.4E-06	3.9E-05
GWP	1.80	0.2847	0.2075	0.0045	1.29	0.0014	9.7E-04	0.0082
HTP	0.0554	0.0236	0.0049	8.1E-04	0.0255	2.6E-04	1.8E-04	1.5E-04
MAETP	81.84	57.19	13.16	1.98	8.31	0.6271	0.4291	0.1385
ODP	5.7E-10	4.8E-10	1.8E-11	1.9E-11	3.9E-11	6.2E-12	4.2E-12	1.1E-15
POCP	2.2E-04	4.1E-05	1.5E-05	1.7E-06	1.7E-04	5.3E-07	3.6E-07	-2.3E-06
TETP	0.0036	0.0014	1.4E-04	5.4E-05	0.0019	1.7E-05	1.2E-05	7.4E-06

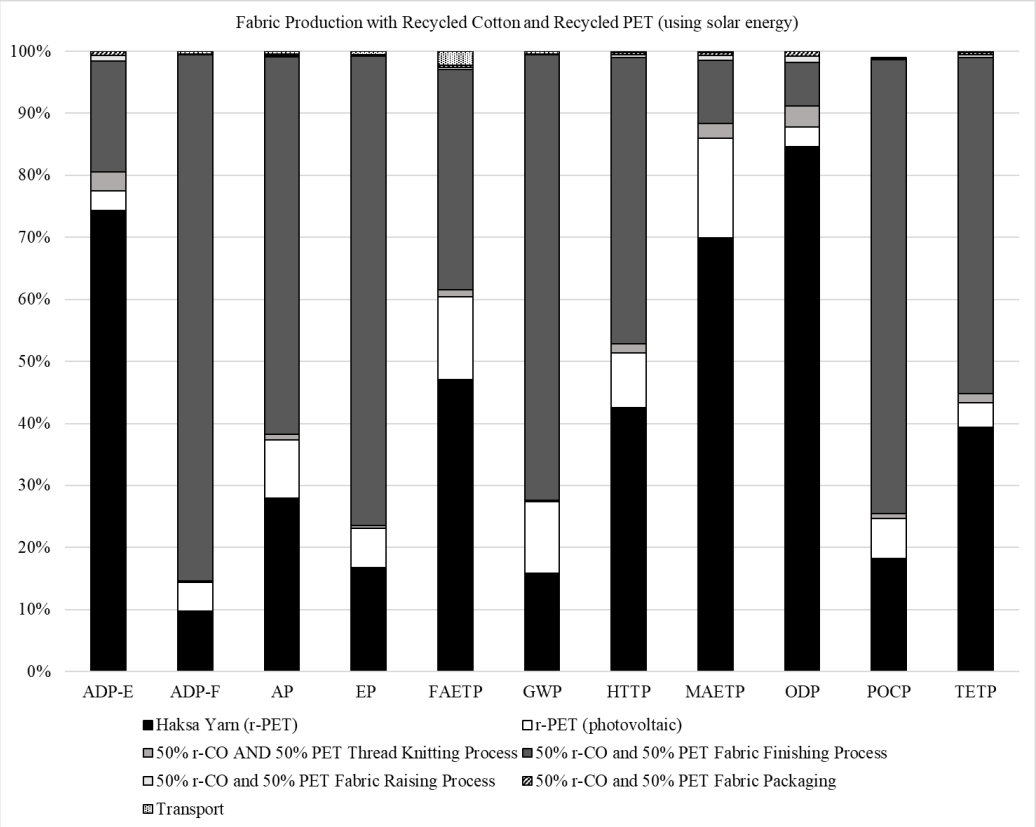


Figure 6.16 LCA results of fabric production with recycled cotton and recycled pet (using solar energy)

6.2. Comparison of the Results

The objective was to identify the most environmentally friendly application by comparing the environmental impacts of nine cases, the results of which were given in detail in the previous section. In some of the created cases, the energy type was changed and the effect of solar energy use was investigated. In some cases, the environmental effects of using recycled fiber and polyester instead of virgin materials have been investigated. Thus, the effects of using recycled materials were determined.

In this section, various comparisons of the cases examined were performed and it was examined which cases were better. As a result, it was evaluated whether cases that gave better results than Case-1, which represents the current situation, could be used to improve the current situation.

6.2.1. Comparisons by Energy Type

6.2.1.1. Comparison of Cases 1 – 2 – 3

This section compares the LCA results of Cases 1-2-3, which are cases with the same production processes but changes in the types of energy used in production. In these cases, recycled fiber is used in textile production. The aim of this comparison is to investigate the impact of different energy sources used in production on the environment. Case-1 represents the current situation, in which electricity is used for the recovery of recycled fiber from cotton fabric residues while yarn and fabric production is carried out by using solar energy. Solar energy and electrical energy is used in all production steps in Case 2 and Case 3, respectively. This comparison identified the option with the lowest environmental impact. The comparison also helped to identify areas for improvement in the current production processes. Comparisons of the three cases are shown in Figure 6.17 according to each impact category.

There is a 119% increase in Case-2 compared to Case-1 and 78% reduction in Case-3 compared to Case-1 for the ADP-elements category. Similarly, for the ODP category, Case-2 has 139% higher impact compared to Case-1, whereas Case-3 has 91% lower impact compared to Case-1. In Case-2, where solar energy is used in all processes, these effects are thought to be greater due to the materials used during the construction of solar energy panels. It can be concluded that Case-3 has the least impact of these three cases in the ADP elements category. As expected in the ADP-fossil category, the lowest impact was determined in Case-2, where solar energy was used in all phases.

For the category of AP, Case-2 has 85% less impact than Case-1. Furthermore, it is apparent that Case-3 has a 55% higher impact than Case-1. In the EP, FAETP, HTP, MAETP, and POCP categories, the order from highest impact to lowest impact is Case 3, Case1 and Case 2.

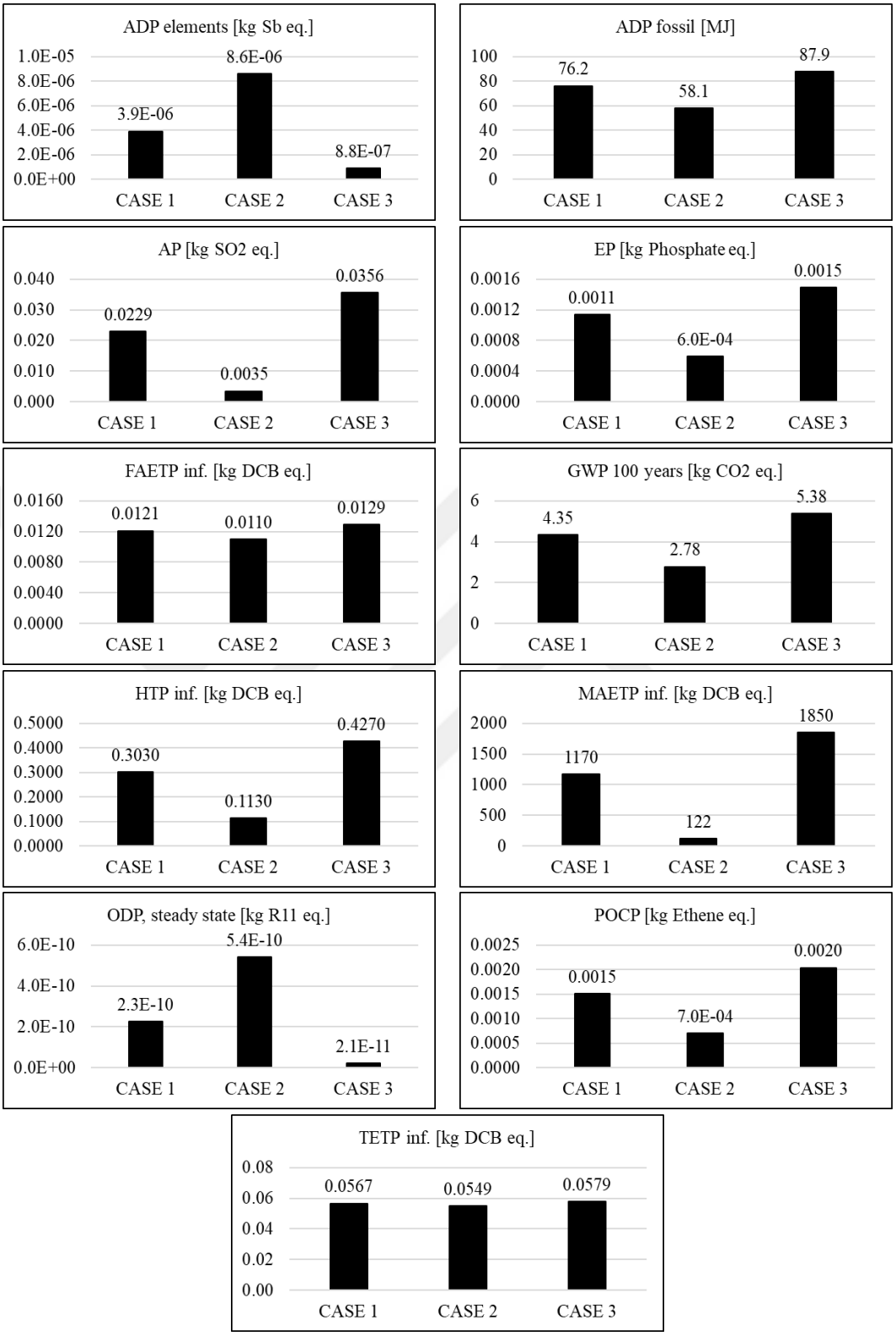


Figure 6.17 Comparison of the energy type for recycled cotton (Case 1: fiber production with electricity and fabric production with solar energy, Case 2: solar energy for all steps, Case 3: electricity energy for all steps)

Energy consumption is a factor that directly affects the greenhouse gas effect. The results obtained in the GWP category also support this. As seen from Figure 6.17, Case-2 is about 36% lower GWP effect than Case-1, while Case-3 is about 23% higher than Case-1. For TETP category, almost the same effects were determined for all cases.

The findings indicate that Case-2 has the least impact in most of the impact categories comparing to Case-1 and Case-3. As a result of this comparison, it can be concluded that utilizing solar energy for production is eco-friendlier than grid electricity.

6.2.1.2. Comparison of Cases 4 – 5

In this section, a comparison is made for Case-4 and Case-5. These two cases illustrate the environmental impact of the production of 50% cotton and 50% polyester fabrics with different energy sources. This comparison was made in order to examine the environmental impact of a change in the type of energy used in production. Case-4 represents electricity use and Case-5 represents solar energy. It is being investigated to what extent the effects that occur when grid electricity is used in the production process can be reduced through the use of solar energy. The results are given in Figure 6.18.

In the comparison of Case-4 and Case-5, results similar to those obtained in the previous section were obtained. The lowest impacts were determined in Case-5, where solar energy was used in all impact categories except the ADP-element and ODP categories. The impact of Case-5 in the GWP category has decreased by approximately 34% compared to Case-4. Based on the results, it can be seen that Case-5 has a significantly lower impact in the majority of the impact categories in comparison to Case-4. Utilizing solar energy for production is eco-friendlier option compared to grid electricity from.

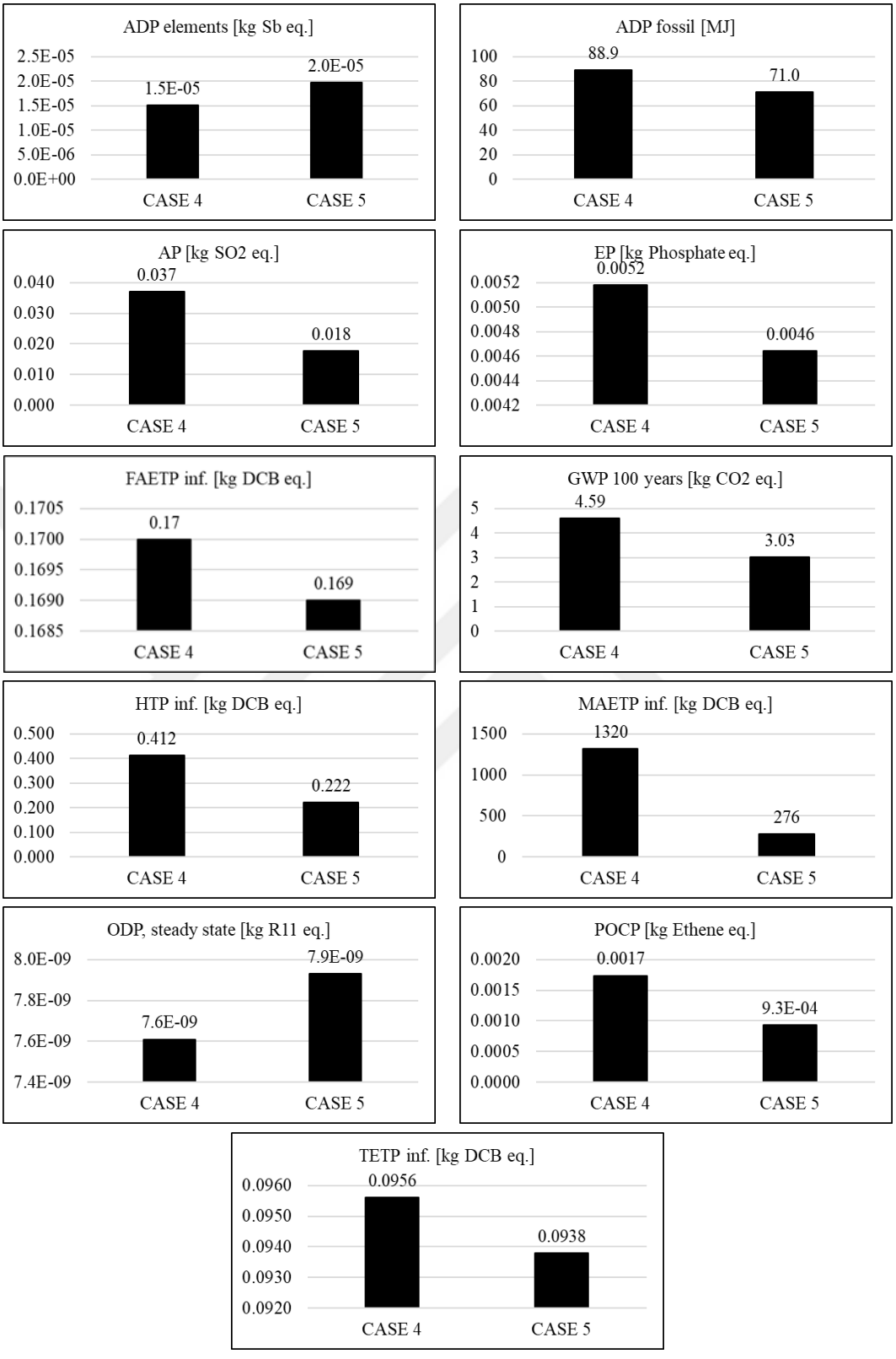


Figure 6.18 Comparison of the energy type for 50% cotton + 50% PET (Case 4: electricity energy, Case: solar energy)

6.2.2. Comparisons by Material Types

6.2.2.1. Comparison of Cases 2 – 5

This section compares the environmental impacts of using recycled cotton (r-CO) and virgin cotton as raw materials for fabric production. Case-2 represents the use of 50% r-CO + 50% PET and Case-5 represents the use of 50% cotton + 50% PET. Solar energy is used for the production in both cases. In this way, the benefits of raw material recovery through recycling have been investigated. Figure 6.19 shows the results of this comparison.

Case-2, which represents the use of recycled fiber, had lower impacts at all impact categories. For example, it has 129%, 409%, and 677% less impact than Case-5 in the ADP-Elements, AP, and EP category, respectively. Considering the GWP category, Case-2 has 9% less impact than Case-5. However, when biogenic CO_2 was excluded, it was determined that this reduction in this effect was around 37%.

Based on the results, it is concluded that using recycled cotton has a lower environmental impact compared to using virgin cotton as better results were obtained in Case-2 compared to Case-5.

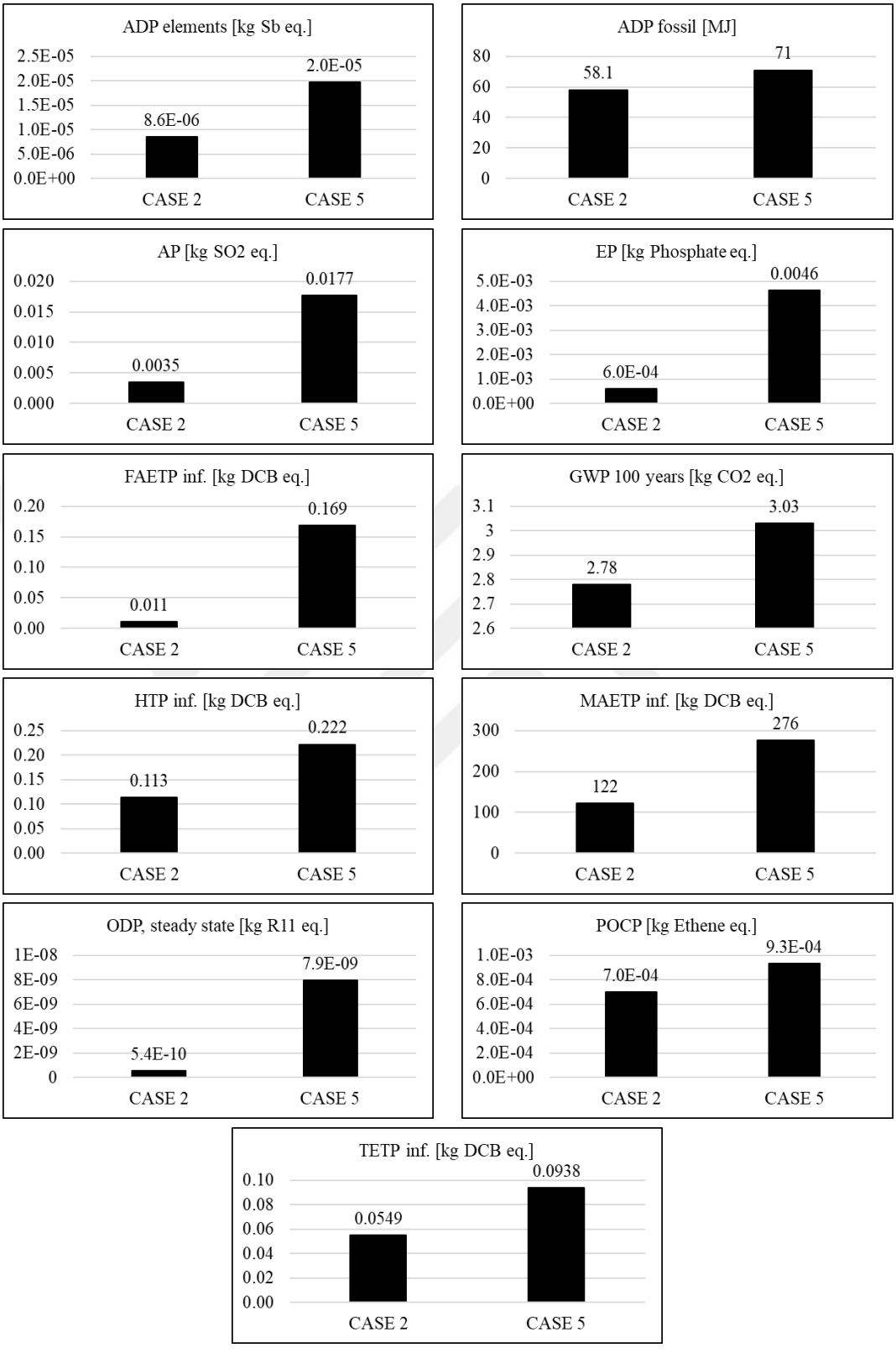


Figure 6.19 Comparison of the material type - solar energy (Case-2: 50% recycled fiber + 50% PET, Case-5: 50% cotton + 50% PET)

6.2.2.2. Comparison of Case 3 – 4

This section compares Case-3 and Case-4. Case-3 represents the use of 50% r-CO + 50% PET and Case-4 represents the use of 50% cotton + 50% PET. The difference between the previous Case-2 and Case-5 comparison is that the type of energy used is mains electricity instead of solar energy. In both cases, grid electricity is used as the energy type in production phases. The purpose of the comparison in this section is to see the environmental benefits of recycling compared to using virgin cotton. Figure 6.20 shows the results of this comparison.

While it was expected to have less impact in Case-3, where recycled fiber was used, as in the previous comparison, it was determined that the recycling application had a negative impact in some impact categories. For example, the impact of Case-4 has 15% and 29% less impact compared to Case-3 in the GWP and MAETP categories. It has been concluded that the equipment used for recycling purposes consumes high energy and the use of electricity as an energy source in these cases causes these results.

The reason for there being more GWP in Case-3 is that the machine used for cotton recycling in Beyteks has high electricity consumption. Similarly, it was also reported by Abagnato et al. (2024) that recycling processes give worse results in some impact categories because they are energy-intensive processes.

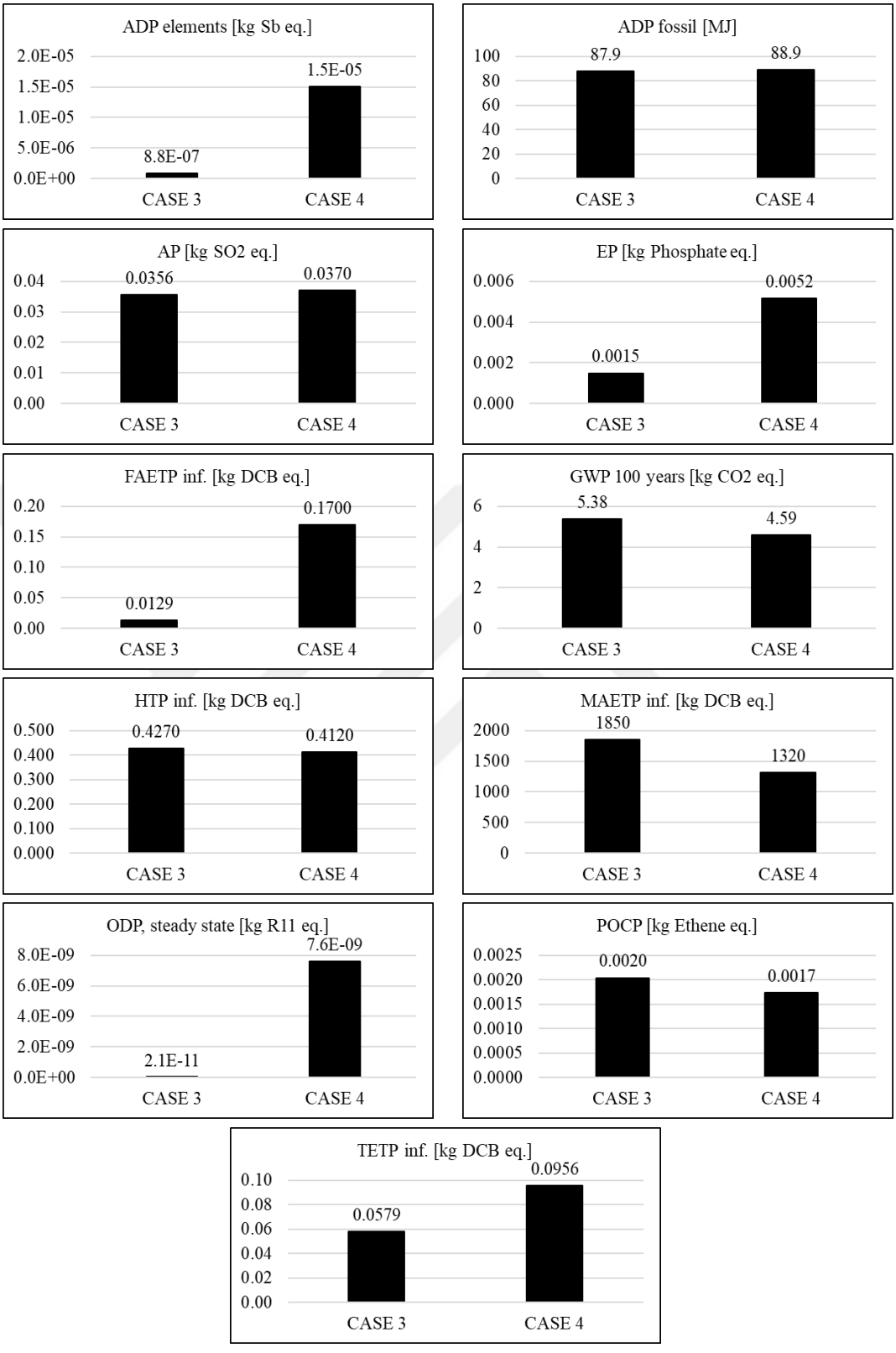


Figure 6.20 Comparison of the material type – grid electricity energy (Case-3: 50% recycled fiber + 50% PET, Case-4: 50% cotton + 50% PET)

6.2.2.3. Comparison of Cases 3 – 6 – 7

By comparing Cases 3, 6 and 7, it was aimed to study the effect of using recycled fiber, conventional cotton and organic cotton. In all cases, grid electricity is used in all production phases (Figure 6.21).

It can be seen that Case-3 has the least impact in almost all of the impact categories. Since recycled cotton was used in Case-3, the results were obtained as expected. The main reason why recycling is advantageous is that huge amount water is consumed and highly toxic chemicals are used in cotton production.

When conventional and organic cotton are compared, organic cotton (Case-7) has less impacts in most categories. For instance, in the AP, EP and FAETP categories, the effect of organic cotton (Case-7) is less than conventional cotton (Case-6), with a difference of about 31%, 39% and 41%, respectively. Considering the GWP category, organic cotton (Case-7) has 11% less impact than conventional cotton (Case-6). In the remaining cases, the difference in impact between organic cotton and conventional cotton is limited to 2-5%. These results suggest that organic cotton have a significant advantage over conventional cotton.

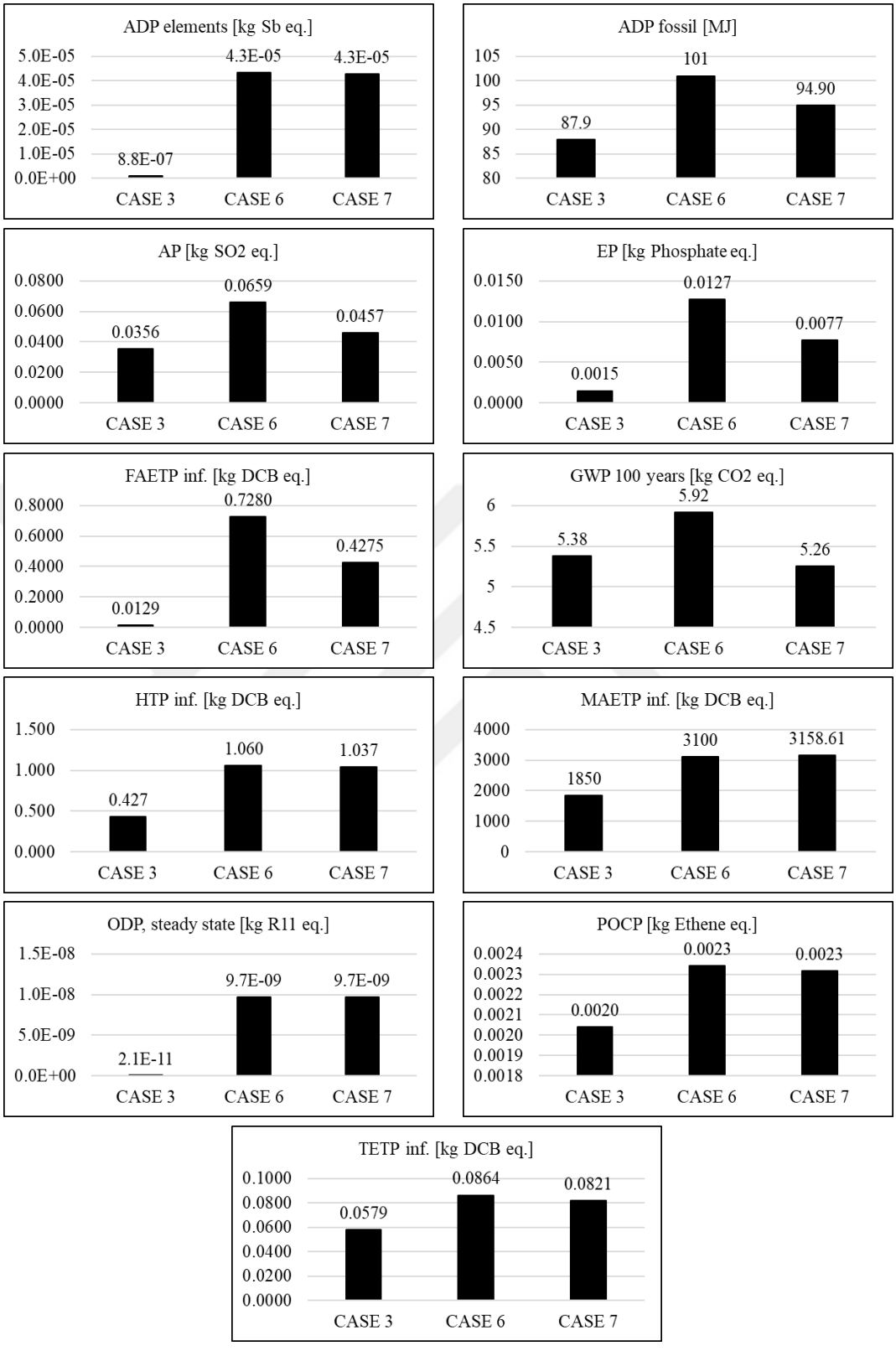


Figure 6.21 Comparison of the material type – recycled cotton, conventional cotton, organic cotton (Case-3: 50% recycled fiber + 50% PET, Case-6: 100% conventional cotton, Case-7: 100% organic cotton)

6.2.2.4. Comparison of Case 1 – 8

Case-1 represents the existing situation in which use of 50% r-CO + 50% PET and Case-8 represents the use of 50% r-CO + 50% r-PET. In Case-1, mains electricity is used in the recycling phase, while solar energy is used in the yarn and fabric manufacturing phase. The types of energy used in Case-9 are the same as in Case-1. The purpose of this comparison is to examine how the environmental impact changes when r-PET is used instead of the PET used in the existing situation. Figure 6.23 shows the results of this comparison.

It can be seen that Case-8 has less impact in most impact categories, except for AP, MAETP and ODP categories, compared to the current situation (Case-1). For example, Case-8 has 60%, 77% and 91% less impact than Case-1 in the ADP-Elements, FAETP and TETP category, respectively. Considering the GWP category, Case-8 has 22% less impact than Case-1. In the AP, MAETP, and ODP categories, Case-1 has a lower impact of 9%, 5%, and 1%, respectively.

These results show that using recycled cotton and recycled PET in fabric production is environmentally more advantageous compared to using recycled cotton and non-recycled PET.

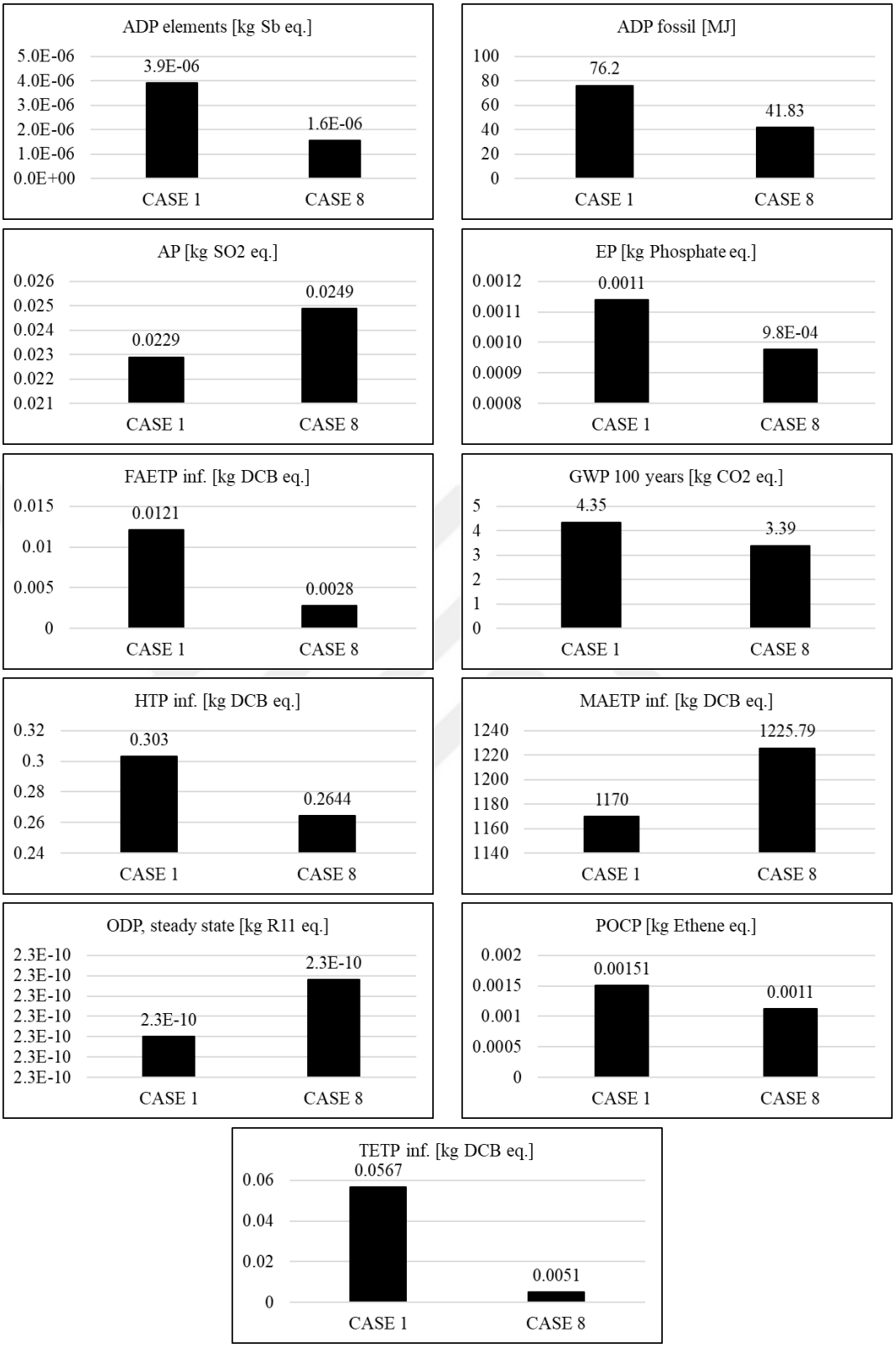


Figure 6.22 Comparison of the material type - fiber production with electricity - yarn and fabric production with solar energy (Case 1: 50% recycled fiber + 50% PET Case 8: 50% recycled fiber + 50% recycled PET)

6.2.2.5. Comparison of Case 2 – 9

This section compares Case-2 and Case-9. Case-2 represents the use of 50% r-CO + 50% PET and Case-9 represents the use of 50% r-CO + 50% r-PET. Solar energy is used for the production in both cases. Results are shown in Figure 6.22.

Case-9, which represents the use of 50% r-CO + 50% r-PET, has lower impact in all impact categories except the ODP category. For example, Case-9 has 64%, 84%, 68% and 93% less impact than Case-2 in the ADP-Elements, FAETP, POCP and TETP category, respectively. Considering the GWP category, Case-9 has 35% less impact than Case-2. In the ODP category, Case-2, which represents the use of 50% r-CO + 50% PET, has a lower impact. This is thought to be due to the materials used in the manufacture of solar panels, as mentioned in previous comparisons.

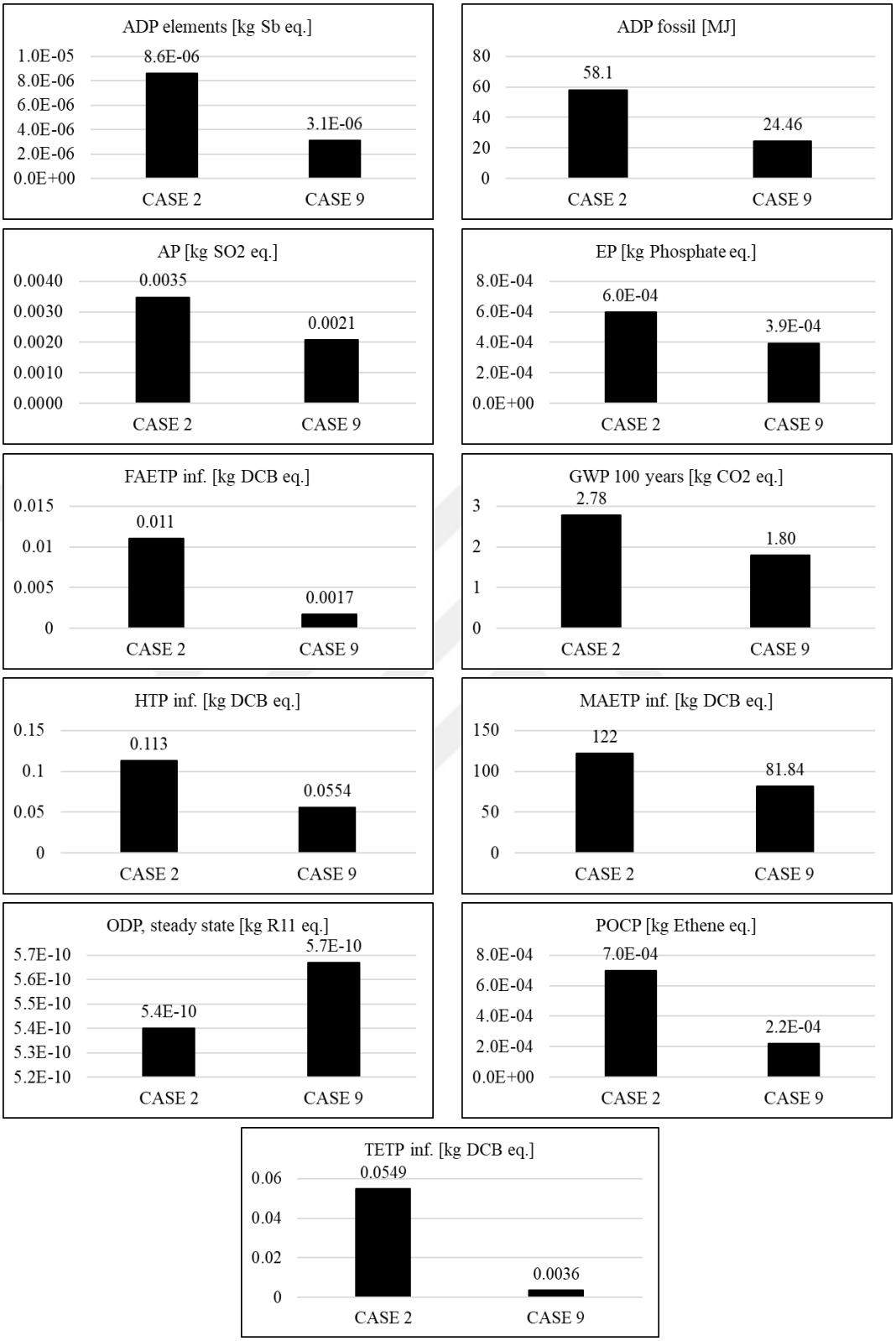


Figure 6.23 Comparison of the material type – solar energy (Case-2: 50% recycled cotton + 50% PET, Case-9: 50% recycled cotton + 50% recycled PET)

6.3. Water Consumption of Cases

Due to the decrease in clean water resources, it is vital to determine the amount of water used in production and to use production methods that consume less water. Therefore, there is an increasing interest in evaluating water use while examining the environmental impact of products throughout their life cycle. Accordingly, ISO 14046 - Life cycle assessment (LCA) - Water footprint (WF) - Requirements and guidelines standard has also been added to the LCA standards in 2014. Within the scope of this thesis, blue water use, blue water consumption, and total water consumption amounts were calculated on the basis of evaluated cases with GaBi software. The results are given in Figure 6.24. Blue water calculated for a process refers to all fresh water, excluding rainwater, drawn from groundwater or surface water bodies. “Water use” and “water consumption” are two different concepts in water footprint calculations. The amount used in a process is expressed as "water use" and there is no information about the fate of the water used in this expression. “Water consumption” refers to all water losses such as evaporation, evaporation from plants, remaining water in the product, etc.

Case-9 provided the best results in all water use and consumption values. It was determined that the use of recycled cotton and recycled PET was a good alternative to reduce the stress on water resources, as well as other environmental impacts.

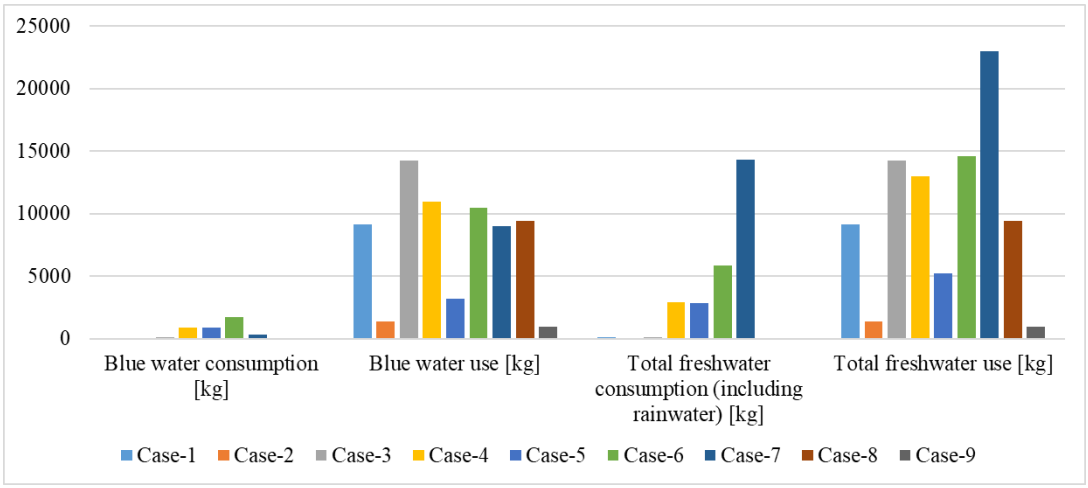


Figure 6.24 Water footprint of cases

CHAPTER SEVEN
CONCLUSION AND RECOMMENDATION

The production of textiles is on the rise due to the rapid growth of the global population and the prevalence of fast fashion trends. As a result, a significant amount of textile waste is generated. The sustainable management of textile waste is crucial for reducing the environmental impacts. As a result, there has been a growing number of studies on the circular economy.

This thesis discusses the recycling of scraps generated in a textile factory. The life cycle assessment (LCA) method was used to analyze the environmental impacts of recycling scrap fabrics, using data from pilot plants. The LCA was conducted for nine different cases, including the current case. The case with the least environmental impact was investigated. In these cases, the use of different type of material and the use of different energy sources in production are under discussion. The results obtained when comparing all cases are as follows:

1. Recycled cotton has lower environmental impacts than conventional cotton.
2. Recycled polyester is more environmentally friendly than conventional polyester.
3. The utilization of solar energy in production decreases the environmental impact compared to grid electricity.
4. Organic cotton production has less environmental impact than conventional cotton production.

Based on the LCA studies, it was concluded that the most environmentally friendly option, except for ADP elements and ODP categories, was Case 9, which involved recycling all materials and utilizing solar energy during production. Given that the typical lifespan of solar panels is approximately 30 years (Kazan et al., 2020), the production and disposal of these panels has led to an increase in the impact categories of ADP elements and ODP. Therefore, it has been observed that these categories have the least impact when recycled cotton is used and mains electricity is used in all

production processes. In Case 9, water consumption was significantly lower compared to the current situation, with a decrease of approximately 90%.

The thesis also examined the environmental impacts of production with organic cotton. Upon analyzing the results comparing organic cotton production with conventional cotton, it was found that organic cotton showed a decrease in almost all impact categories.

In conclusion, recycling is an important method for reducing environmental impacts of T&A industry. Additionally, the use of renewable energy sources, such as solar energy, is more environmentally friendly. Therefore, especially due to the energy consumption of equipment used for recycling purposes, the use of renewable energy resources at this stage will help reduce the environmental impacts of garments prepared with recycled fibers. Within the scope of this thesis, the environmental impacts for the production of one kg of fabric have been determined, and the environmental impacts of the garments to be produced using these fabrics in the apparel industry will similarly vary depending on the type of fiber and energy used. In the apparel industry, the environmental impacts of clothes produced using recycled fiber and solar energy will be much less than clothes produced with raw cotton and electricity.

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