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The impact of circular strategies for clothing on greenhouse gas emissions related to Swedish consumption

The case of reuse in outerwear

Erasmus Mundus master's program Circular Economy
(CIRCLE)

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Abstract

Over the past two decades, Europe has witnessed a 40% increase in clothing consumption. Globally, the textile industry has emerged as a significant contributor, accounting for 4% of total greenhouse gas (GHG) emissions, primarily attributed to the production phase. In addition to the Swedish commitment to attain net-zero emissions in all sectors by 2045, the development of consumption-based targets is under consideration. However, the system's complexity in making textiles a carbon-neutral industry relies on the globally dispersed supply chain and the need for significant shifts in consumption patterns. Hence, this research seeks to explore the potential of circular strategies for decarbonizing Swedish clothing consumption, with a specific emphasis on outerwear.

The methodology is based on the prospective LCA framework, and four scenarios were developed to analyze the system's dynamic behavior. The reference scenario reflects the business-as-usual scenario where the rate of reuse continues to be the same (20%) while the energy changes at the global and national levels are considered as per the Stated Policies Scenario (SPS). The second scenario reflects a slow increase in reuse rate (30%), assuming ambitious energy change only at the national level. The third scenario reflects a high increase in the reuse rate (70%) with the same assumption of ambitious energy change similar to the second scenario. In the last scenario, a 70% rate of reuse is considered with an ambitious energy transition at the global and national levels. The energy transition scenarios are adopted from International Energy Agency's scenarios.

The result shows that the scenarios with a high rate of reuse have the potential to diminish the production of new outerwear by 15% by 2050 as compared to the levels of 2019. In terms of emissions, the last scenario shows that the consumption emission of outerwear for an average Swede can be reduced from 162 kg CO₂-eq. in 2019 to 18 kg CO₂-eq. in 2050. However, the study also highlighted the hotspots, such as the challenges of receiving low-quality used clothing/outerwear. Furthermore, durability and longevity are also discussed as essential factors to consider in designing and manufacturing of clothes for successful implementation of reuse, as circular strategy in future.

Keywords: Circular Economy, Reuse, Second-hand clothing, Textiles, Systems Dynamics, Net-zero Emissions.

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Lastly, this thesis is dedicated to the recently departed soul of my mother, who highly encouraged me to pursue this master's degree.

Nasira Ahsan, Gothenburg, June 2023

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

BAT	Best Available Technology
BAT-AELS	Best Available Technology- Associated Emissions Levels
BAU	Business as usual
CO ₂ eq.	Carbon dioxide Equivalent
CN	Combined Nomenclature
CSF	Centre for Sustainable Fashion
EOL	End of Life
EPA	Environmental Protection Agency
EPR	Extended Producer Responsibility
GHG	Greenhouse gas
GOTS	Global Organic Textiles Standards
GRS	Global Recycled Standards
ICE	Internal Combustion Engines
IEA	International Energy Agency
IVL	Swedish Environmental Research Institute
kWh	Kilowatt-hour
LCA	Lifecycle Assessment
MJ	Mega Joules
NIR	Near InfraRed
SATIN	Towards a sustainable circular system of textiles in the Nordics
SDS	Sustainable Development Policies Scenario
SPS	Stated Policies Scenario
STICA	The Swedish Textile Initiative for Climate Action
WFD	Waste Framework Directive
WMCs	Waste Management Companies

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1

Introduction

1.1 Background

The first industry to emerge during the Industrial Revolution was the textile industry (De Gree, 2022). Throughout 350 years of history, the technological innovation of the clothing sector and value chain have had a positive impact on the global welfare and trade economy (Broadberry et al., 2014). According to Lee & Östberg (2013), the production of clothing items typically thrives in economies in the early stages of development due to labor-intensive activities. Nevertheless, the country loses its cost advantage in this sector as the economy advances and becomes highly industrialized with rising wages. A similar pattern was observed in Sweden, where many textile industries were established in the eighteenth century and held a predominant percentage of Swedish exports up to the mid-20th century. However, as the economic growth progressed in Sweden, the production of clothes started to shrink. Gereffi & Memedovic (2003) state that in the post-1980s, a global shift in the value chain of production of clothes was observed when manufacturers relocated their production facilities to labor abundant emerging economies, for example, in Asia and Africa. Nowadays, Sweden has transitioned from a clothing export country to a clothing import country. In 2020, Sweden imported clothes worth 4.82 billion USD, making it a prominent import sector (Statista, 2020).

The textile industry is considered one of the most ecologically damaging industries globally (Bailey et al., 2022). With the rise of environmental consciousness and global urgency toward climate change, this sector faces new challenges in balancing the economic, social, and environmental aspects of sustainable growth (Shishoo, 2012). McKinsey & Co. (2022) reported that the current life cycle of clothes – from resource extraction to production of fiber (natural, synthetic, or man-made) fabric manufacturing, and use till the end of life – is responsible for approximately 2.1 billion tonnes of greenhouse gas (GHG) emissions, accounting for 4% of global emissions. The challenge lies in energy intensive processes such as raw material extraction, manufacturing, processing, and transport, that accounts for more than 70% of the emissions followed by approximately 30% of emissions during retail, use and end-of-life (EOL). This report further estimated that, globally, this sector will continue to grow as a result of population increase and shifts in the increased consumption of clothes. If this would be the case with no additional emissions reductions efforts, then by 2030 emissions would reach up to 2.7 billion tonnes (McKinsey & Co., 2022).

1.2 Problem Statement

Overall, Europe has experienced a 40% increase in the consumption of clothes in recent decades and it has been ranked as the fourth highest polluting sector among all categories of EU household consumption after food, housing, transport and mobility (Nikolina, 2022). With the geographically stretched supply chain, the sturdily increasing demand for clothes has resulted in the complexity of associated environmental burdens globally (Leal Filho et al., 2022). Moreover, the complexity of environmental burdens entails interrelatedness; for example, in the case of clothing sector, the discharge of various contaminants (e.g., nitrogen, carbon) in air, water or soil originating from diverse

sources (e.g., transport, agriculture, industry, interact with each other and produce diverse impacts (e.g., smog) across multiple spatial scales from national to global levels and influence earth's climate (Tuinstra & Bert de Wit, 2015).

A recent study by Sandin et al. (2019) showed that the carbon footprint related to clothes is 330 kg carbon dioxide equivalent (CO₂-eq.) per capita in Sweden, which represents 3% of the total GHG emissions of an average Swede. In Asian countries, the use of conventional technologies for fiber production and fabric manufacturing are energy-intensive, where electricity on average, is generated using 40% of coal, 20% of oil, 10% of natural gas, and the rest is on renewable sources such as which hydro, solar and wind (IEA, 2022), (Leal Filho et al., 2022). About 80% of the total greenhouse gas emissions from clothes are generated at production and transportation phases, followed by the use phase, which includes ironing and laundry and lastly at the end of life (EOL) where used clothes in Sweden are designated to be incinerated (SOU, 2020).

The Swedish Government has considered adopting consumption-based targets and the climate target of reaching net-zero GHG emissions by 2045 within the Swedish territory (Darby, 2022). The consumption-based targets aim to address the emissions that are generated from the production (both domestically and abroad) of products like food, clothing and electronics that are consumed by the inhabitants of a country (C40 Cities, 2022). This method accounts for not only the direct emissions involved in the lifecycle of the product/service. Still, it will also measure the emissions associated with the consumption behavior of the consumers (Barrett et al., 2013). Therefore, due to the climate urgency, Sweden aims to reduce its consumption-based carbon emissions by 9 tonnes CO₂-eq. per person net-zero by 2045 (Nohrén et al., 2022). Tukker et al. (2020) explain that these targets will aim to account for the emissions during production and transportation of import items, beyond the Swedish territory. It implies that consumption-based targets attribute GHG emissions from the end user perspective instead of to the producers. In Sweden, the clothing sector falls under consumption-based environmental emissions level that reflects the emissions resulting from trade in carbon-intensive goods or services (Evans, 2021). A report by McKinsey & Co. (2022) highlighted the priority for the clothing sector to incorporate technological innovations in the production phase that promises a decarbonized future. In addition, this report stated that companies need to transition from the traditional linear economy model, which involves resource extraction, manufacture products and selling them, to circular economy strategies which involves reduce, reuse and recycling.

Acknowledging these needs and the many initiatives from the public and private sectors, there is still a need for understanding of when and how these combined efforts will achieve decarbonization of the clothing sector throughout its supply chain and life cycle. Therefore, revolving around Swedish climate targets, this research will intervene in the complexity of the problem, by analyzing when and how the effects of the energy transition, technological changes, and introduction of reuse as a circular strategy could collectively lead Sweden to net-zero emissions of CO₂ in the clothing sector.

1.3 Aim

To effectively intervene in the complexity of the problem, this research analyzes reuse as one of the circular strategies on future GHG emissions related to Swedish consumption focusing on outerwear and answers the following research questions. It also aims to identify the potential hotspots that may be encountered in the application of circular strategies for achieving a decarbonized future of the

clothing sector.

RQ1: How will the implementation of reuse, as a circular strategy, change the production and consumption of outerwear in the future?

RQ2: How could implementing reuse, as circular strategy, impact the per capita CO₂-eq. emissions related to outerwear under the influence of global shifts in technology and energy?

1.4 Research Relevance

A study by Larsson et al. (2022) at Chalmers University within the Mistra sustainable consumption and Mistra carbon exit research programs, has covered the areas such as air travel, passenger car travel, public transport, food, heating and investments in building and transport infrastructure that constitutes 63% of Swedish consumption-based emissions. The study developed five scenarios based on different climate policy perspectives. The methodology utilized in the study was founded on the prospective life cycle assessment (LCA) framework, which aims to evaluate the environmental impact of a novel technology that is currently in its early stages of market introduction. The foreground system of analysis is designed to capture the market diffusion and production scale of the technology being investigated, while the background systems take into account the exogenous factors such as different climate policies focusing on changes in national and global energy systems.

Building on the same foundation, this research will focus on consumption-based emissions of outerwear that are imported, consumed, and discarded by analyzing the impacts of reuse as a circular strategy in reducing the carbon footprint of Swedish clothing consumption. Hence, this research is academically relevant to provide the baseline for further studies on the development of consumption-based emission targets for clothing items in Sweden.

2

Overview of the clothing sector and circular strategies

2.1 Clothing supply chain in Sweden

Berg & Pasand (2021) quoted the data from the Swedish Environmental Protection Agency (EPA, 2019) net inflow of textiles and observed a rapid increase between the 2000 and 2019 leading to a volume of 13.7 kgs of clothes purchased by each person in Sweden in 2019. According to WITS (2020) the countries that contribute to the supply of the Swedish clothing sector are China, with a share of 21% of imports, followed by Germany 12%, Bangladesh 9%, Denmark 8%, Netherlands 6%, Poland 5%, Turkey 4%, Italy 3%, India 3%, and 25% from other countries. The dominance of these countries in producing clothes is attributed to their attractive trade policies, lower wages, and labor-intensive industrial system (Hussain et al., 2020).

A report on project SATIN, conducted by researchers at Nordics Innovation (2022) used the extensive study by Elander et al. (2019) and provided the flow of clothes volume for the year 2019, once they enter Sweden (see figure 1). The authors highlighted the challenges in obtaining accurate statistics on flows and volumes of clothes firstly- **a**) due to the lack of standardized guidelines to register volumes of clothes and **b**) coordination among different actors such as industries, retailers, and waste management authorities. Secondly the traceability of volumes of clothes, after use becomes much more fragmented as it largely differs on the basis of user habits and preferred way of disposing off their used garments (Berg et al., 2021).

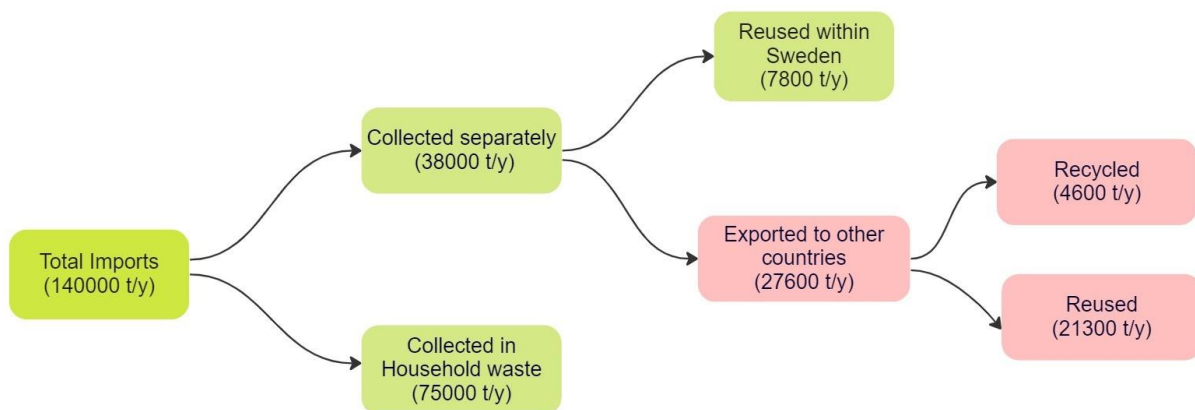


Figure 1 flow of volumes of clothes imported in Sweden adopted from Nordics Innovation (2022).

According to the report by Nordics Innovation (2022), in Sweden 66% of used clothes are collected in combination with the household wastes and eventually incinerated. The remaining 34% of used clothes are collected by kerbside separate collection bins for clothes (by charity organizations) or in-store collection bins (by companies). These separately collected used clothes are sorted on the basis of quality and sent to global or national markets. Watson & Palm (2020), mentioned that the quality grades

of these sorted clothes range from cream¹, good, average and low and destined to be sold in Europe, Africa, the Middle East and Asia respectively.

In another study by Carlsson et al. (2019), the authors state that in Sweden, the per-capita annual consumption of clothing and textiles amounts to approximately 15 kg. They further estimated that 8 kg of clothing and textiles (53%) are discarded as waste by each individual, subsequently channeled towards energy recovery. Despite the relatively high consumption rate, the volume of repurposed or recycled textiles remains low. In contrast, approximately 3 kg of textiles (20%) are reused, being collected by charities for charitable purposes, while the remaining 4 kg (27%) are either stored (e.g., within closets or wardrobes) or handled via other waste management means, such as recycling centers.

2.2 Circular Economy

According to Ellen MacArthur Foundation (2019), the concept of circular economy is founded on the principle of decoupling economic growth with use of finite resources. Instead of relying on the traditional linear model of production, consumption and disposal through exploiting natural resources, the circular economy promotes a closed-loop system that minimizes waste, maximizes the value of resources, and fosters sustainable development. The circular economy model is characterized by an industrial system that is intentionally designed to be restorative or regenerative, aiming to use and reuse natural resources in the most efficient manner possible throughout a product's lifecycle.

With a focus on the clothing sector, Ellen MacArthur Foundation (2020) has defined the circular fashion economy as restorative and regenerative, yielding positive outcomes for businesses, society, and the environment. This entails designing the fashion system in a manner that ensures clothes, textiles, and fibers retain their utmost value while in use and are reintegrated into the economy at the end of their lifecycle, avoiding waste accumulation. The circular fashion economy represents a transformative vision for a revamped global textile system that advocates prolonged clothing utilization, using renewable resources as inputs and development of effective solutions to facilitate the conversion of used garments into new products.

For the clothing sector, as one of the polluting sectors, it is vital to shift towards a logical approach of keeping the clothes and its fibers longer in the supply chain through applying circular economy strategies i.e., reduce, reuse and recycle (Sandberg, 2023). Figure 2 comprehensively explains circular economy strategies from smarter use of products (R0 to R2) to life extension of products (R3 to R7) and efficient utilization of materials (R8 & R9). It entails the implementation of sustainable design strategies, zero-waste design, product-life extension, resource recovery, and repair and remanufacture services. The following section will focus on three strategies: reduce, reuse and recycle which are relevant in the context of this research.

¹ Cream refers to the very good quality of clothes.

Order of priority for circularity strategies in the product chain

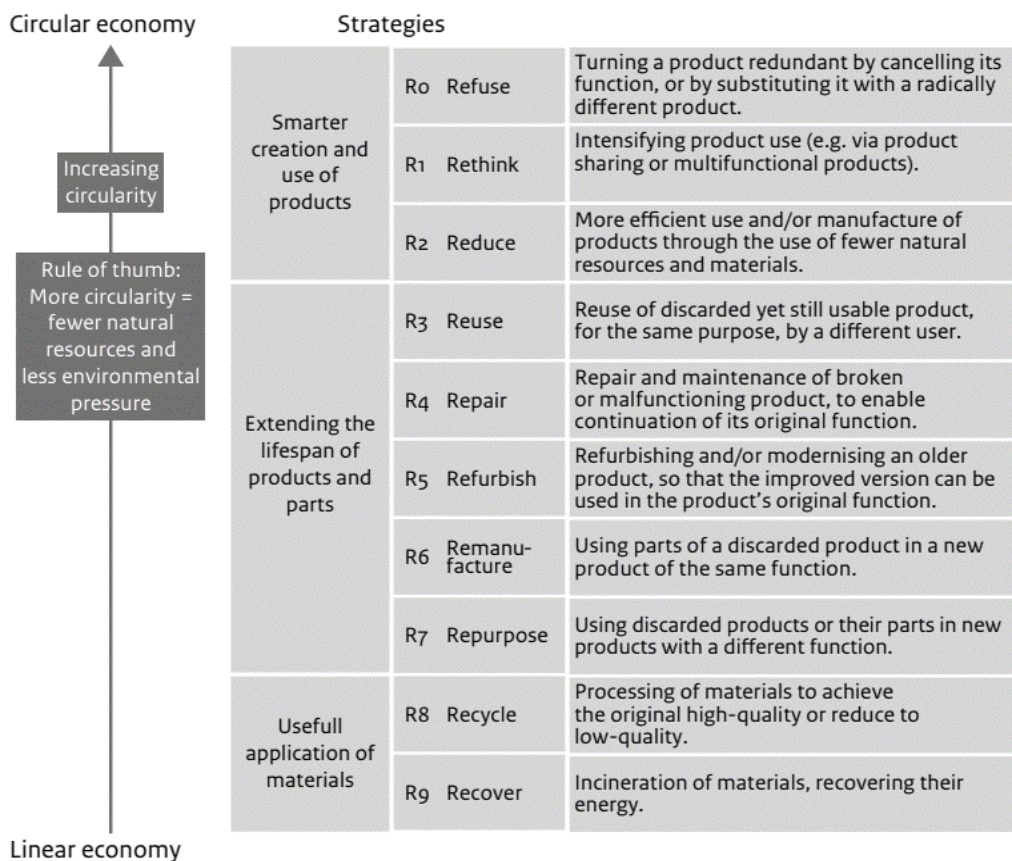


Figure 2. Circular Strategies (adopted from Potting et al., 2019)

2.2.1 Reduce

From the circular economy perspective, Potting et al. (2019), referred to this strategy as the efficient use of products with fewer natural resources used in the manufacturing of the product. According to the waste management hierarchy by EU Waste Framework Directive (2018), the concept of "reduce" involves primarily limiting unnecessary consumption, and if production is necessary, then reducing the quantity of materials used in the manufacturing process, while enhancing the product's efficiency and durability. The high-end fashion brands invest in the quality of fibers and fabrics and designs that can last longer; therefore, their products are expensive and can cater to the limited number of consumers who can afford the prices (Cassandra Elrod, 2017). In this regard fast fashion aspired to fill the gap and meet the demand of population to a larger extent. The focus of this research is the latter as the consumption of clothes has been increasing due to fast fashion and perceived obsolescence (Philip et al., 2020).

According to Bick et al. (2018), 'fast fashion' is a term referring to the massive sales of trendy and low-cost clothes. It is further explained that the business model on fast fashion aims to provide clothes at lower costs due to cheap labor and economies of scale at production. The economy of scale is a phenomenon where an increase in production of goods or services reduces the production cost per-unit (Celli, 2013). Therefore, the lower price factors result in clothing consumption surge and has transformed the consumers' behavior on purchase and disposal of clothes. Research by Philip et al. (2020), mentioned that the reason behind changed patterns in clothes consumption is the 'perceived

obsolescence'. According to them, it is a phenomenon in which customers feel pressured to keep up with the latest fashion trends and buy new clothes even if their existing clothing items are still in excellent condition. Furthermore, a study by Kotahwala (2020), emphasized the impact of the marketing strategies by fast fashion retailers that tricks the psychology of consumers and provides a 'sense of happiness' to the customers when they purchase clothes which are trendy and cheap. Another study by Linden (2016), mentioned that fast fashion consumption has increased as individuals use clothing to reflect their personality and express their social status, cultural values, and personal preferences. Given the rise in living standards, Peng et al. (2022) state that the demand for clothes is expected to grow, making it challenging to reduce consumption. This issue is multifaceted and involves cultural, psychological, and social factors that influence behavior.

According to Ozdamar Ertekin & Atik (2015), the term 'slow fashion' was coined in opposition to 'fast fashion' by the Centre for Sustainable Fashion - CSF (2009), which promotes the sustainable vision of fashion linking fashion with environmental consciousness and responsibility. This report explains the different approaches by which designers, buyers, retailers, and consumers can become more aware of the impacts of clothing on workers, communities, and ecosystems. Research by Gwozdz et al. (2017) on consumer segments and their behavior on clothing consumption has surveyed almost 4000 customers around two strategies: consuming slow and consuming differently. The results of this research showed that consumers from the segment of low budget-consumption are not suitable for 'consuming slow strategy'. However, the customers in the medium consumption-budget were the optimal target of 'consuming slow strategy' mainly because this category represents the fast fashion consumer. Previous research by Rockström et al. (2009) and Sandin et al. (2015) suggest that effective strategies to limit the desire for consumption include improving the durability of products and creating emotional connections between consumers and products. These strategies have proven successful in reducing the carbon footprint of textile products. For example, by promoting an emotional attachment to clothing, consumers may be more likely to keep and take care of their clothes, reducing the need for new purchases. According to Siderius & Poldner (2021), reducing consumption alone is not an effective solution because it may result in a rebound effect where consumers can engage in consuming another product or service that can potentially provide a sense of pleasure.

2.2.2 Reuse

This strategy refers to the utilization of the products that have been discarded by the first user but can still be used for the same purpose and by a different individual (Potting et al., 2019). Therefore, the second-hand market for clothes is considered as one of the pioneering sectors that operates on the circular economy principles (Colasante & D'Adamo, 2021).

Brooks (2015), in his book, mentioned that passing on used clothes in families and friends has been in practice traditionally or many people donate clothes to charities with intention to be reused again by deserving people. A study done by Wu (2020) states that since fast-fashion consumers purchase more than the amount of clothes they need, therefore the frequency to discard their surplus clothes needs convenience. Therefore, according to Kim-Vick & Yu (2023), the noticeable shift in the sale of the second-hand clothing industry has been caused by the progress of e-commerce. It has further led to the emergence of different business models. For example, clothes sharing, renting, and clothing libraries operate on the product service system (PSS), in which the ownership of the product remains with the business. In contrast, service around the product is being provided (Adrodegari et al., 2016). Another

approach is also observed in which ownership of clothes remains with the owner. But they receive the service around their product such as repairing, altering, and fixing minor damage to clothes, falls under this category (Moro, 2021). Another model explained by Pereira (2020), is when an e-commerce service is provided by a platform that works as an intermediary between seller and buyer. For example, Sellpy, (2021) is a platform that works on the model where clothes sent by sellers are examined, photographed, and uploaded on the website. Upon purchasing these used clothes, the seller receives monetary benefits.

Xu et al. (2014) explain the limitations on purchase of the second-hand clothes market due to perception on poor quality, hygiene, or socio-cultural reasons. A study also explains that social risks can negatively influence the intention to purchase second-hand clothing. It further explains that the motivations behind purchasing second-hand clothing are usually economically driven. This holds particularly true for the countries with limited financial means and poor purchasing power of its citizens. Baden & Barber (2005) explained that second-hand clothing businesses in developing nations play a vital role in sustaining the livelihoods of numerous individuals engaged in trading, distributing and repairing these used clothes. However, it is believed to contribute to the decline of local textile and clothing production where this phenomenon is influenced by a combination of factors, however they are not covered in this research. Another study by Turunen & Leipämaa-Leskinen (2015) examines the reasons behind purchasing second-hand products by Swedish buyers and results are characterized by themes of sustainable consumption, thrill to purchase unique and vintage items as expression of their personality. Finally, Yeap et al. (2022) sought the necessary motivations affecting the intentions to buy second-hand clothing and the results revealed that primarily economic motivations and sustainable consumption are the main drivers among the buyers of second-hand clothing.

Colasante & D'Adamo (2021) have mentioned about positive environmental impacts of reusing clothes as firstly, it enables to extend the lifetime of the clothes and secondly it can possibly avoid the production of new clothes. Research on the dynamics between the used and new clothing sectors explored in research by Persson & Hinton (2023) underscores the challenges associated with achieving a significant reduction in the consumption of new clothes through the growth of many business models around the second-hand clothing market. The results show that more proliferation of organizations incentivizing the sale of used textiles may lead to individuals selling higher quality clothes to these entities and donating lower quality textiles to non-profit organizations/charities. Furthermore, some of these businesses may rely on the revenue generated from selling new clothes to financially sustain their second-hand business models. This may inhibit the potential for a growing second-hand clothing market to replace the consumption of new clothes and associated environmental impacts. It is also argued by Gwozdz et al. (2017) that environmental benefits of second-hand clothes can be diminished if it involves increased transportation while they agree with the environmental benefits that are linked only with increased service life of the clothes. Although markets for second-hand clothes are not exempted from adverse environmental impacts, they are still widely advocated as one of the main strategies to achieve reductions in environmental impacts of the clothing sector (Valor et al., 2022), (Dahlbo et al., 2017).

2.2.3 Recycle

Recycling is processing second-hand material to achieve the original quality or sometimes processed to lower rate relative to the original (Potting et al., 2019). Textiles are attributed to mainly two types of recycling, as explained by IVA (2020), i.e., mechanical and chemical recycling.

As explained by Zethraeus et al. (2017), in the mechanical approach to recycling, defibrillation (i.e., a thread opening process) is carried out by mechanical breakdown of fabric through cutting, shredding, and carding. It is applicable preferably to fabrics made up of 100% of single fibers. The authors also explained that globally, the end products of mechanically recycled textiles (also known as down-cycled products) are used as industrial rags, fillings for insulation in automobiles, blankets, mattresses, and carpet manufacturing. On the other hand, pre-consumer textiles, i.e., leftover cuttings or dead stock from manufacturing units are the preferred input supply to mechanical recycling centers due to known quality and percentages of fiber types.

The second approach, chemical recycling, as explained in a report by IVA (2020), aims to transform the textile fibers at the molecular level. This method uses chemicals and enzymes in a controlled environment and produces fibers of virgin quality to manufacture new textiles again. The chemical processes like depolymerizing and dissolution are adopted for synthetic and natural fabrics respectively. The process becomes complex and energy-intensive when fabrics have blended fibers. Like mechanical recycling, pre-consumer textiles are also preferred as the best choice for raw materials in chemical recycling. There is very little control over the quality and information about fibers if post-consumer textiles are obtained for recycling (Saha, 2020).

The above-mentioned literature reveals the existence of a market for recycling pre-consumer textile waste. However, Celep et al. (2022) entail technical and practical difficulties when it comes to recycling post-consumer textile waste. They explained that the non-traceability of fibers and chemicals used in manufacturing makes it difficult to develop a standardized recycling procedure for clothes. Moreover, the quality of used clothes can vary significantly due to user preferences for laundry and the level of care given to clothes. Another project, the Swedish Innovation Platform for Textile Sorting (SIPTex) funded by Swedish Government, developed the customized sorting solution to cater to the unique needs of textile recyclers and the garment industry. Their report stated that the process of sorting textiles based on their distinct fiber types demands an exceptional level of accuracy. This task is performed manually; however, the outcome fails to meet the standards set by recycling companies and the fashion sector. Consequently, only a tiny portion of discarded textiles undergoes recycling, despite the immense potential for expansion (STICA, 2021).

In research by Cura et al. (2021), the authors mention that recycling of post-consumer textiles is an expensive process due to the need for an automatic or manual sorting facility to segregate the clothes on the basis of fibers, buttons, zippers, metallic clips, paint, and hang tags, etc. Additionally, in automatic sorting, Near InfraRed (NIR) spectroscopy technology has partially been successful. However, despite its capabilities of distinguishing only a specific range of fiber blends and failing to identify damage such as holes, odor, and signs of wear and tear, the technology's effectiveness is still limited. This limitation consequently necessitates the involvement of human resources to sort the clothes while accepting the probability of human error. Schumacher & Forster (2022) mentioned another concern related to post-consumer textiles that clothes present in the market are still not designed for recycling. If their recycling is implemented, then there is a high chance for hazardous chemical substances to persist in recycled fibers. The recycling of clothes can be an effective circular strategy when standardized materials are used in fabric production with the traceable origin of fibers and other attachments such as buttons, zippers, etc. (Palm, 2011).

2.3 Policies

To assess the conducive environment for implementing circular strategies in the clothing sector, this section provides the standpoint of relevant policies in European and Swedish context as summarized in Table 1. According to EU Waste Framework Directive (2018), it is obligatory for the EU member states to collect textiles waste by 2025 separately. Up until this, there was no policy proposed for textile waste collection. This directive aims to encourage waste prevention and the utilization of the waste management hierarchy to promote reuse, recycling, and recovery at the end of life. Now, it has expanded its focus on textiles waste (EU Waste Framework Directive, 2018).

The EU strategy for sustainable and circular textiles is another proposed strategy that sets out the vision and concrete actions to ensure that by 2030 textile products placed on the EU market are long-lived and recyclable, made as much as possible of recycled fibers, free of hazardous substances (microplastics, e.g.,) and produced in respect of social rights and the environment (EU Commission, Directorate-General for Environment, 2022). To achieve this objective, the textile producers (retailers and brands) will be held accountable for their products throughout the lifecycle, including disposal. The measures to be implemented comprise eco-design requirements for textiles through a compulsory Extended Producer Responsibility (EPR) program (Interreg Europe, 2022). Currently, in Sweden, a draft ordinance for EPR is under review by authorities. It is proposed that the producers register with the Swedish Environmental Protection Agency (EPA) and bear the cost of managing the clothes once discarded by users within Sweden (SOU, 2020). This draft ordinance comprehensively addresses many critical aspects of the upstream and downstream value chain. Furthermore, it covers the solution to practical and legal obstacles associated with manufacturers, importers, wholesalers, and retailers with Swedish and foreign origin. Moreover, this ordinance complements the EU strategy for sustainable and circular textiles, which discourages overproduction, overconsumption, and exports while focusing on design requirements for durability, repairability, and recyclability of clothes (EU Commission, Directorate-General for Environment, 2022).

Table 1. Policies relevant to the Textiles sector

Relevant Policies	Description	Status
1- European Waste Framework Directive (WFD)	Promoting waste management hierarchy and separate textile waste collection in all EU countries by 2025 is obligatory.	Approved and ready to be implemented, e.g., Finland has passed the law in accordance with this, and separate collection of textile waste lies with municipalities.
2- EU strategy for sustainable and circular textiles	Ensures that textiles are designed for more prolonged use, recyclable, with a maximum % of recycled fibers, free of hazardous substances, and sustainably sourced.	Proposed draft strategy. It is under review and open for discussion at EU level.
3- Extended Producer Responsibility (EPR) in Sweden	To ensure that producers, importers, retailers are responsible for bearing the cost of discarding clothes	Proposed draft ordinance by Swedish Government.

2.4 Textiles manufacturing processes

In section 1.2, it is mentioned that for Sweden, 70 % of the GHG emissions from clothing originate during the manufacturing and transportation of clothes (Schragge, 2022). Similarly, results in a report by McKinsey & Co. (2022) concludes that predominantly GHG emissions in the clothing sector originate in processes of fiber production, bleaching, dyeing, sewing, finishing, and ultimately transportation during all steps. The remaining emissions occur during retail, mode of transportation opted by customers, and use phase (Schragge, 2022). The study by Sandin et al. (2019) illustrates the same results where wet treatment in the manufacturing phase is responsible for the highest CO₂-eq. emissions, among other phases. For better understanding, Table 2 below has been compiled to provide a summarized overview of the technical processes typically involved in conventional manufacturing of clothes.

Table 2. Textiles processes from cradle to gate- summarized information from (The International Chemical Secretariat, 2023), (Whewell, 2022).

Steps in clothes production	Technical Processes	Required energy resources
<p>1- Fiber production</p> <p>Crop and animal harvesting, land use, water consumption, use of pesticides, fertilizers, sourcing fossil fuel-based feedstock.</p>	<p>Tractors, mechanical pickers/strippers for picking plants, and manual shaving of animals to extract cotton/bamboo/hemp and wool respectively. Melting PET pallets is done to achieve polyester fiber</p>	Electricity, Diesel
<p>2- Yarn Production</p> <p>Mechanical step for texturizing, drawing, twisting and winding the fiber.</p>	<p>Mechanical steps such as carding and ring spinning are done to smooth the yarn and winding is done as a final step.</p>	Electricity
<p>3- Fabric production</p> <p>Weaving, knitting or production of non-woven fabrics</p>	<p>Knitting machines: Convert the yarn into fabric by inter-looping them. Looming machines: Weaves the yarn into woven structures. The fibers are arranged in web structure for non-woven fabrics, and a thermal, pressurized, or chemical bonding is applied.</p>	Electricity and heat
<p>4- Wet treatment I- (Pre-treatment)</p> <p>Pre-treating the fabric to facilitate the following processes.</p>	<p>Burling: to remove burrs, loose threads, knots, and undesired slob. Mending: eliminating defects, holes or tears, broken yarns, and missed yarns. Washing and bleaching: to clean the fabric using detergents and chemical bleaching.</p>	Electricity, water, chemicals, and heat
<p>5- Wet treatment II- (Dyeing and printing)</p> <p>Dyeing and printing of fabrics/fibers <i>This process is energy intensive with use of hazardous chemical substances.</i></p>	<p>Dyers: Fabric/fibers are held inside an industrial sized conical vessel while the hot dye liquor is poured. Enough heat and energy are provided to have good circulation and absorption of dye. Printers: Block, roller, screen, and heat transfer printers are commonly used.</p>	Electricity, water, chemicals, and heat
<p>6- Finishing treatments: Adding different technical needs to the fabric.</p>	<p>Chemical Dipping Technique is used to dip the fabric into desired chemical (flame retardant, water resistant, or any other protective layer)</p>	Electricity, chemicals, and water
<p>7- Manufacturing, transport, sales, and retail: Cutting, sewing, adding zippers, buttons, logos, and hang tags.</p>	<p>Computerized cutting of fabric into the desired pattern, sewing, and attaching zippers and buttons. Fusing and ironing, packaging, and factory dispatch.</p>	Electricity, diesel, and heat

By looking at literature on Best Available Technologies (BATs) for textile production that promotes improved technical systems, a study by Kim et al. (2022), has identified potential solutions to manage environmental pressure from clothing manufacturing processes by analyzing the reference documents for BAT and their associated emissions levels (BAT-AELs). The results showed that the reducing wastewater and energy-saving techniques are most effective when used during the manufacturing and finishing processes rather than after treatment. For example, in dyeing processes, the common BATs are the use of automated dye injections and supply of recycled water. In the printing process, the use of digital printing methods, organic natural dyes and environmentally friendly printing thickeners are considered BATs for minimizing dye wastes and pollutant discharges. Furthermore, Zhang et al. (2023), explains another technology named Pad dyeing technique that involves submerging the fabric in the dye solution for a brief period, which typically lasts for a few seconds and is also known as short wet steaming dyeing technique. The results showed a reduction in electricity consumption and up to 24 % reduction in CO₂ emissions. Furthermore, the summarized information (table 3) by Hasanbeigi (2010) on the energy efficient measures and relevant energy savings in different technical processes compared to conventional textiles manufacturing processes is mentioned in table 2.

Table 3 Energy efficient measures and energy saving potential adopted from (Hasanbeigi, 2010).

Steps in clothes production	Energy Efficient Measures	Saving potential
1- Yarn Production Spinning Processes	Replacement of lighter spindle in place of conventional spindle can save electricity.	23MWh/year/ring frame
	Installation of energy-efficient motor in Ring frame	6.3 -18.83 MWh/year/motor
	Replacing the Electrical heating system with steam heating system for the yarn polishing machine	19.5 MWh/year/machine
	Replacement of nozzles with energy-efficient mist nozzles in yarn conditioning room	31MWh/year/humidification plant
2- Fabric production - Weaving or knitting	Energy efficiency of compressed air systems	reducing air leakage from 12% to 6%
3- Wet treatment I- Pre-treating the fabric to facilitate the next processes.	Cold-Pad-Batch pretreatment	up to 50% of electricity use
4- Wet treatment II- (Dyeing and printing)	Energy saving in the shearing machine's blower motor by interlocking it with the main motor	2.43 MWh/year/machine
	Installation of VFD on circulation pumps and color tank stirrers	138 MWh/year/plant
	Equipment optimization in jet dyeing machines	increased 0.07 - 0.12 kWh/kg fabric
5- Finishing Process	High-frequency reduced-pressure dryer for bobbin drying after dyeing process	200 kWh/ton product
	Conversion of Thermic Fluid heating system to Direct Gas Firing system in Stenters and dryers	120 MWh/year/plant
6- General cross-cutting energy measures in the factory	Utilization of heat exchanger for heat recovery from wet processes wastewater	Fuel saving of 1.1 – 1.4 GJ/ton finished fabric
	Reduction of leaks (in pipes and equipment)	up to 20% of compressed air system energy use
	Maintenance of pumping systems	2% - 7% of pumping electricity
	Boiler insulation	6% - 26% of boiler energy use
	Use of solar energy for water heating & natural lightening	

3

Methodology

3.1 Conceptual Framework

On the basis of explanation in chapter 2 about circular strategies, figure 3 visually conceptualizes the application of these circular strategies on the life cycle of clothes. Furthermore, within figure 3, the boundary in the dotted line shows the conceptual framework focusing on this study and research questions. The first research question (yellow dotted box) analyzes the lifecycle flows of the clothes that are produced and imported to meet the Swedish clothing demand. This question aims to explore the dynamic behavior of the system upon introducing circular strategy - reuse (yellow arrow) followed by accounting for the total stocks of clothes (i.e., total amount of clothes in wardrobes) and the clothes that are sent for incineration and exported (in second-hand market) at the end of life (EOL). The second question focuses on calculating the life cycle CO₂-eq. emissions of outerwear associated with global shifts in technology and energy and relevant changes in stock and flow.

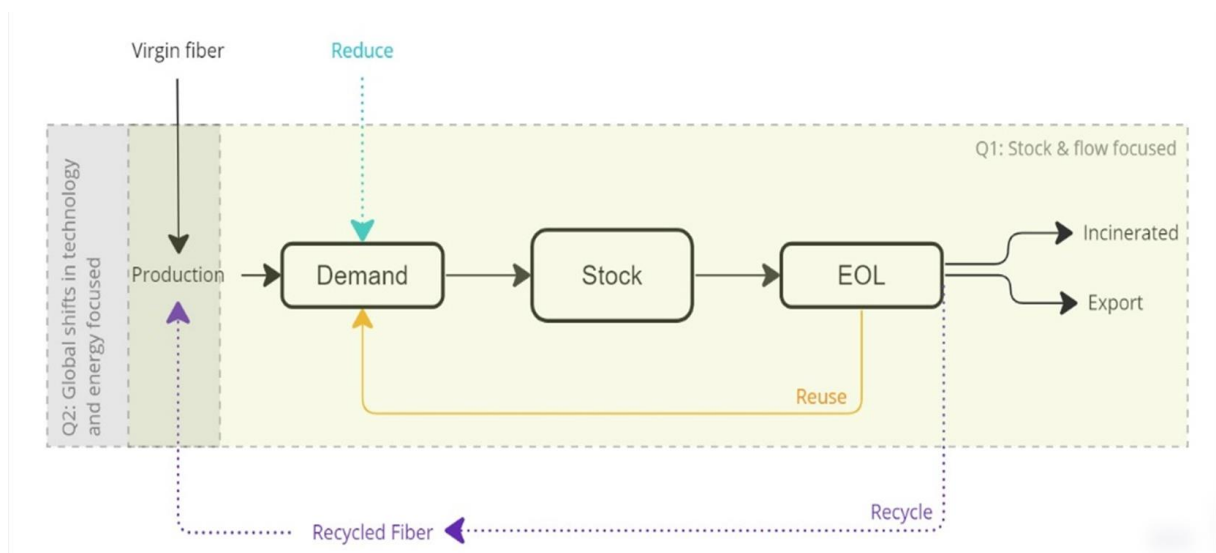


Figure 3. Conceptual Framework

3.2 System Dynamics

The analysis of this study is based on System Dynamics theory, which is used to understand the nonlinear behavior of complex systems and assists in forecasting all changes (or interruptions) that occur over time and aims to maintain the stabilization of the system (Leon et al., 2018).

Hirsch et al. (2007) explain that the cause-and-effect within system components determines the system's dynamic behavior when certain parameters - e.g., circular strategies in this study - are applied. The dynamic behavior of a system is usually represented as causal loop diagrams and stock-and-flow diagrams. The causal loop diagrams include variables connected through arrows showing the causal influences, and positive or negative feedback on each other. While stock-and-flow diagrams show more detailed information, such as the accumulations in the stocks and the flows (rates) that influence the

increase or decrease of these stocks. It conceptualizes the system’s structure and makes it easier to visualize the impacts of changes in the design on the overall system over time.

As prospective LCA explained by Thonemann et al. (2020), it is an approach to evaluate new technology and is modeled for the future. In this thesis, the reuse as an innovative circular economy strategy is modelled instead of modeling a new technology. Therefore, this study uses systems dynamics as part of the foreground systems analysis of the prospective LCA framework, to quantify the changes occurring in the future production and consumption of clothes when reuse is adopted as a circular strategy. Furthermore, the background systems focus on the future GHG emissions influenced by global and national shifts in energy and related technologies. According to Kucharavy & De Guio (2011), the diffusion of new technology will follow the S-curve growth path. This curve represents technological development, characterized by slow initial progress on performance and market adaptability, rapid growth, and eventually stabilization as technology matures (figure 4). Therefore, this study also adopted the S-curve path logic in modelling the background systems analysis.

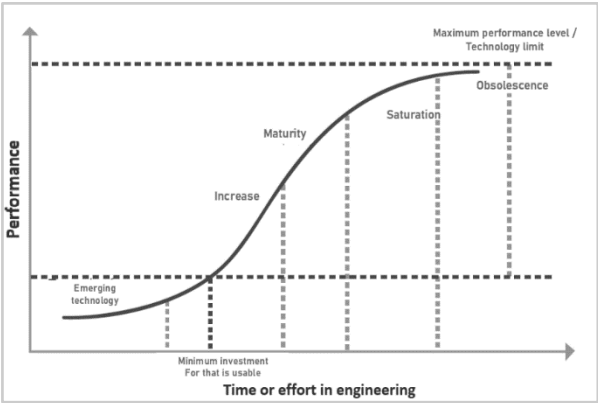


Figure 4. Phases of S-curve for technology adopted from (Dueñas Ramírez & Villegas López, 2020)

To summarize, based on the prospective LCA framework, the foreground system of the current research calculates the changes in the stocks and flow of clothes resulting from reuse as circular strategy over the period of time. While the background system calculates the decarbonization throughout the lifecycle of clothes resulting from the shifts in global and national energy systems (figure 5).

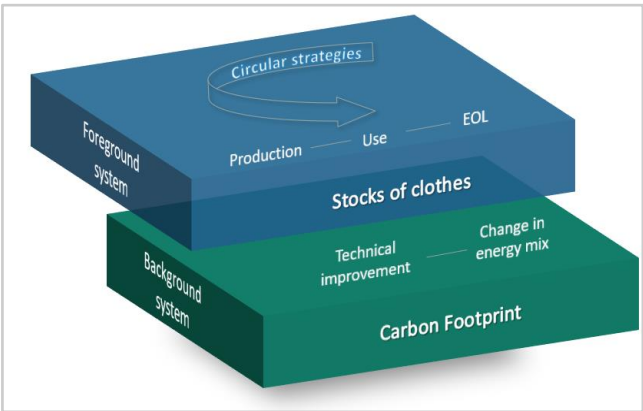


Figure 5. Conceptualization of foreground and background system

3.3 Scenario Design

To determine the dynamic stock turnover of clothes under the influence of policies for adopting circular strategies with environmental impacts of improved technology combined with shifts towards decarbonized energy systems, the following scenarios are developed between changes in foreground and background systems. The proposed scenarios are developed to understand the potential of each intervention, either individually or collectively, to reduce GHG emissions in the future.

- **Reference Scenario** - represents the business-as-usual (BAU) situation where the rate of reusing clothes (20%) is assumed to remain the same throughout modeling time frame, i.e., till 2050. While the energy changes at global and national level are considered as per the Stated Policies Scenario (SPS) by International Energy Agency (IEA) (further explained in section 3.5).
- **Slow reuse with National climate target scenario** - reflects a slow increase in the rate of reusing clothes, from 20% in 2025 to 30% till 2045 in foreground system. While at the background system IEA’s Sustainable Development Scenario (SDS) (explained in section 3.5) is adopted at the national level and global level continues to be the same as per reference scenario.
- **High reuse with National climate target scenario** - reflects a high increase in the rate of reusing clothes, from 20% in 2025 to 70% till 2045 in the foreground system. The background system of this scenario remains the same as per above mentioned second scenario.
- **Comprehensive scenario** – in this scenario foreground system remains the same as per the third scenario mentioned above, i.e., high rate of reuse. While in the background system, energy change under the IEA’s SDS is considered at global and national levels.

Table 4. Scenarios for analysis

	Reference Scenario	Slow reuse with national climate target scenario	High reuse with national climate target scenario	Comprehensive scenario
Foreground system	Reuse at BAU rate	Reuse at a slow rate	Reuse at a high rate	Reuse at a high rate
Background system	National level: Stated Policies	National level: Sustainable Development policies	National level: Sustainable Development policies	National level: Sustainable Development policies
	Global level: Stated Policies	Global level: Stated Policies	Global level: Stated Policies	Global level: Sustainable Development policies

3.4 Simulation Modeling for foreground system

For this study, Vensim PLE plus (explained in section 3.7) has been used to develop stock-and-flow models for the foreground systems analysis per scenario as explained in table 4. The model in Vensim is developed for the foreground system, as shown in figure 6, that shows the lifecycle pathway of clothes in the Swedish context. To simplify, this section will explain the model (shown in figure 6) using one piece of clothing (e.g., a jacket) produced abroad and imported to Sweden to meet their demand.

In the model, it is represented by the flow named ‘total imports’ and variables named as ‘production’. Next, this new jacket is supplied to the retailer referred to as flow named ‘supply of new

clothes.’ From here, it is purchased by a user and is used during its first life, named ‘stocks of clothes in use.’ After staying in stocks for certain years – denoted by ‘lifetime at firsthand use’- the user throws it in the waste collection bins represented as ‘collection in household waste’ - which ends up in incineration. Or in another case, the user donates this jacket to be collected by charity organizations, flow named as a ‘separate collection of used clothes’ and sent for sorting. From the sorting facility, it is chosen for a second life represented by a variable named ‘flow back of second-hand clothes’ into ‘available clothes to be reused’ in the second-hand market. Finally, a second user purchases this second-hand jacket, represented by ‘supply of old clothes’, and it for a certain time represented by ‘second-hand lifetime’. From here, it is collected to be sent for incineration. To avoid complications, this model has considered that retail of these old outerwear is the same as new ones, meaning that users either visit physical stores or shop online. The mathematical equations behind this user interface are attached for each scenario in annexures A to D.

In this model, the yearly turnover of quantities of clothes in use, second-hand market, incineration, and exports are calculated on the information provided by the current rate of flows and historical data of imports of (new and used) outerwear by Nordics Innovation (2022), and Statistics of Sweden (2023) respectively. The models assume the average annual per capita demand of 5 kg of outerwear in Sweden as demand that influences the production and imports of clothes in outerwear category each year. The Swedish clothing demand is predominantly fulfilled by the clothes that are manufactured abroad and are imported to Sweden; therefore, for the current analysis, it is assumed that each year the total quantities of imported outerwear, all are entirely purchased (i.e., 100%) by the consumers in Sweden. Depending on the usage, the lifetime of clothes is when clothes are kept in the wardrobe. The data from Sandin et al. (2019) has been used to obtain the average lifetime of clothes. This lifetime is represented by the delay symbol used in the flows leaving from the use phase (see Figure 6). Each of the following flows is determined by current rates of separate collection, i.e., 33% mainly through charity organizations within the country, such as Human Bridge, Myrorna, Stadsmissionen, and Swedish Red Cross, which have designated locations throughout Sweden (Ekström & Salomonson, 2014). While the remaining 67% of clothes are collected through the household waste collection system and designated for incineration (Sandin et al., 2019). The model is further extended for clothes, which have been collected separately and end up in the sorting phase. This is where used clothes are divided into three flows. These flows are **a)** the rate of redistribution, i.e., 20% for reusing clothes within Sweden, **b)** 40% is the rate of exporting used clothes to other countries, and **c)** the rest of 40% is discarded after sorting and sent for incineration (Nordics Innovation, 2022).

To analyze the influence of policies, a set of variables are assumed to change over time as those policies are implemented, which are listed in table 4. The time period selected for the introduction of these set of variables under each scenario is from 2025 (representing the starting year for separate collection of textile wastes) to 2045 (representing the final year of net-zero climate policy of Sweden). Furthermore, in the modeling, it is assumed that from the year 2025, the amount of used clothes entering the system will fulfill the Swedish clothing demand and provide negative feedback to production. Therefore, the future models for all scenarios are designed so that any increase in the number of reused clothes will replace the production of new clothes in the same quantity and vice versa. While the values for demand per capita, i.e., 0.005 tons/capita/Y, lifetime of clothes during firsthand use, i.e., four years till 2024 and 8 years onwards, and second-hand use two years till 2024 and 4 years ahead were derived from a study by Sandin et al., (2019) and are kept fixed in all scenarios.

Table 5. Scenario wise assumptions of auxiliary variables

Auxiliary Variables	Reference Scenario	Foreground System		
		Slow reuse with national climate target scenario	High reuse with national climate target scenario	Comprehensive scenario
Separate collection rate	33% each year	from 33% to 40%	from 33% to 95%	from 33% to 95%
Collection rate by WMC	67% each year	from 67% to 60%	from 67% to 5%	from 67% to 5%
Reuse rate (referred to as redistribution rate in the model)	20% each year	from 20% to 30%	from 20% to 70%	from 20% to 70%
Discarding rate	40% each year	from 40% to 35%	from 40% to 15%	from 40% to 15%
Export rate	40% each year	from 40% to 35%	from 40% to 15%	from 33% to 15%
<i>Reference:</i>	<i>(Nordics Innovation, 2022)</i>	<i>Adopted from (Ellen MacArthur Foundation, 2021)</i>	<i>Derived from (Naoko, 2019)</i>	

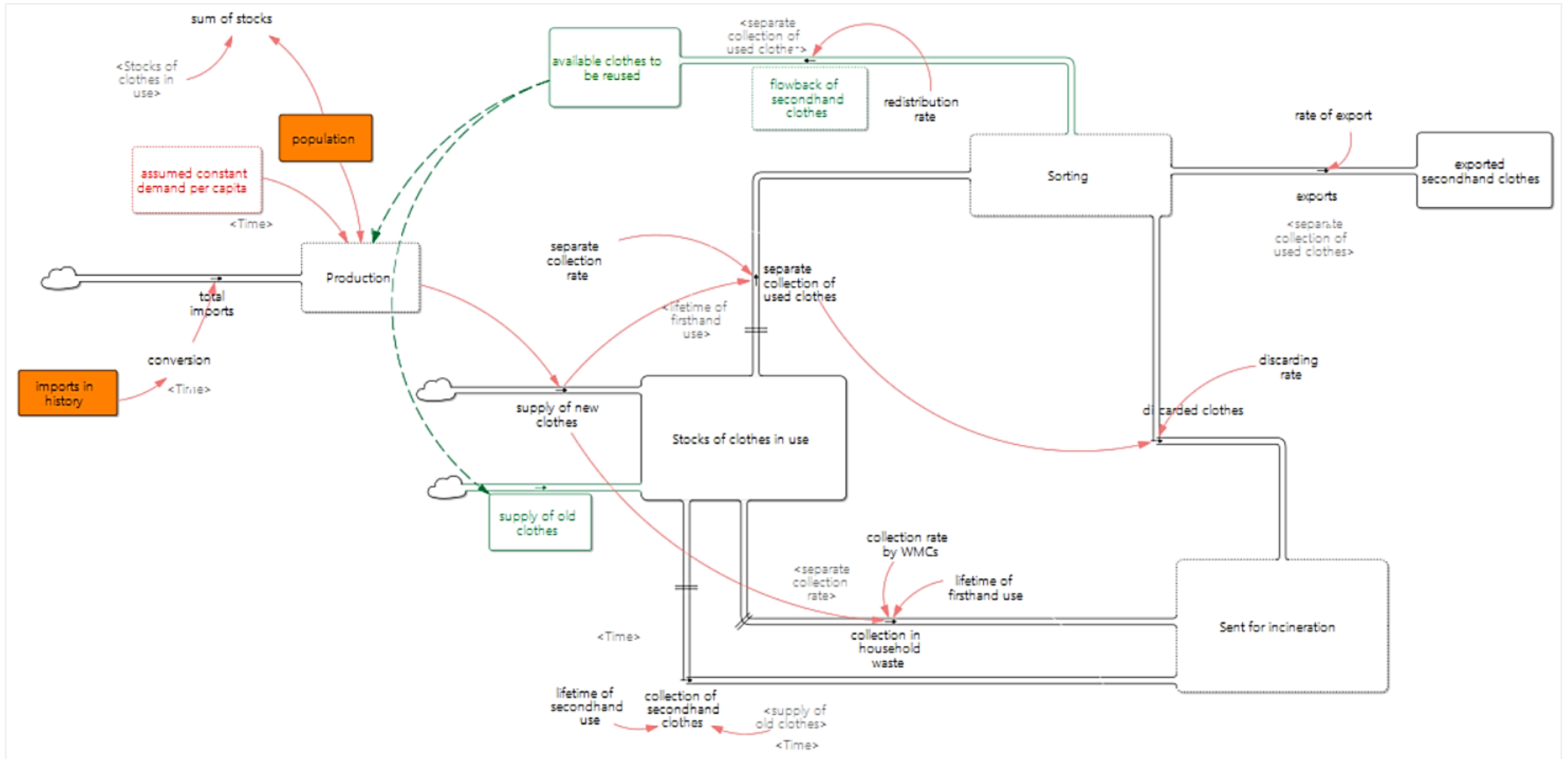


Figure 6. Model developed in Vensim – Reference Scenario

3.5 Assumptions for background system

In the next step, the model calculates the future emissions associated with the energy consumed to produce and transport the quantities of outerwear as calculated in the foreground system. The emissions calculations in this section are done by keeping in mind the future systems of energy as proposed by the International Energy Agency (IEA). Essentially, in the concept of prospective LCA, different base years for foreground and background systems are assumed. Still, due to the lack of historical emissions data for 2022, data from 2019 (representing pandemic year) has been considered as the base year for this analysis. While the final year 2050 reflects the climate policy 2045 of net-zero emissions targets but additional five years well represents by the delay i.e., use time of clothes.

IEA has developed the scenarios for the energy sector and named them as stated policies and sustainable development policies. **The stated Policies Scenario (SPS)** attempts to illustrate the path that the global energy system will follow if governments adhere to their current policy commitments and announced measures. It serves as a reference point to understand the potential energy landscape if no additional policy actions are taken beyond those already in place or planned. This scenario aims to hold up a mirror to today's plans and illustrate their consequences IEA (2019), where share of renewables in electricity generation is expected to rise by 44% in 2040 and will achieve close-to-full decarbonization of the electric grids if countries follow pathways in line with the Paris Agreement's goals. While in contrast, to achieve close-to-full decarbonization of the electric grids, the **Sustainable Development Scenario (SDS)** is developed that considers more ambitious measures to achieve a path fully aligned with the Paris Agreement². This path requires rapid and widespread changes across all parts of the energy system through sharp emission cuts (IEA, 2019).

IEA has developed these scenarios from a global and country-wise perspective. Therefore, in this study to represent the energy used during production of outerwear- it is calculated by the global energy scenario while the energy used during retail, use and EOL - is calculated by Sweden's national energy scenario as proposed by IEA. The background system of the reference scenario covers the SPS both at global and national levels to reflect the business-as-usual situation. As in table 4, the second and third scenarios have the same background systems that consider SD policies for Sweden, while at the global level, the energy system continues to be the same as in the reference scenario. The first motivation behind developing these scenarios is that according to the current emission abatement policy - i.e., net-zero emissions by 2045, Sweden has largely decarbonized its electricity production. The second motivation is that it is very unlikely for all the countries (at the global level) where production of Swedish clothing happens, to adopt SDS especially in the time horizon of this study, i.e., 2050. In short, the difference is only in the foreground systems of these two scenarios, i.e., the rate of reuse. Lastly, the comprehensive scenario reflects the adoption of SD policies at global and national levels.

Furthermore, all background scenarios have considered the changes in production and transportation technologies. In production processes, this study considers the upcoming technology of short wet-steaming pad dyeing as a technological improvement in clothing manufacturing compared to the conventional dyeing method. This short-wet steaming pad dyeing technology is listed in the European BAT reference document for the textile industry by EU Joint Research Centre (2023) and ensures the reduction in; dyeing time by 17.4 %, CO₂-eq emissions by 24.6 %, power consumption by 27.1 % as

² Keeping the rise in global temperatures to well below 2°C and limit it to 1.5°C.

compared with traditional dyeing (Zhang et al., 2023). While in transportation, as Sandin et al. (2019) mentioned, the textile manufacturing processes are energy-intensive, and transportation mode changes throughout the textile supply chain. During production, there is the use of fossil fuel-based trucks with internal combustion engines (ICE), while in retail, three modes of transportation take place: a) diesel-based transoceanic transport (from, e.g., China to Sweden) b) big trucks for distribution within Sweden, and c) during purchase users either use public transport or their own car to access the shops with a share of 50% each. At the EOL, the discarded outerwear is again transported by trucks for incineration. Furthermore, to represent a shift from current emissions due to baseline technology (from conventional dyeing to short pad dyeing technology) and change in the fuel types for future emissions, the logic of the S-curve path (as explained in Chapter 2) has been applied to background system of all scenarios.

To assess the lifecycle CO₂-eq. emissions resulting from energy, the baseline data obtained from research by Sandin et al. (2019) was in primary energy demand (MJ) for clothes. Hence to convert this primary energy demand into final energy consumption (kWh), the data from IEA's World Energy Outlook (2019) has been obtained, and the primary energy demand for the power sector is divided by the total amount of produced electricity and the primary oil demand divided with the final oil used. It is important to note that the factors for electricity vary between regions. Therefore, as a fair assumption, the global average has been obtained. As a result, the factor 8.65 MJ per produced kWh of electricity and 4.0 MJ per used kWh of oil has been applied on the results from a study by Sandin et al. (2019) on energy demand (MJ) to achieve the final consumption of energy in kWh calculating the future emissions. For calculating the type of energy use in transportation at the global level this study has considered the average global share of fossil fuels derived from the research by Morfeldt et al. (2023). For Sweden, it is assumed that all modes of transport within the country are expected to be electrified in the future, implying one-third (1/3rd) use of energy compared to conventional Internal Combustion Engines (ICE). For transoceanic transportation, it is assumed to have a current share of fossil fuels due to many hindrances faced by the maritime sector to achieve decarbonization in the near future (Lind & Lehmacher, 2022).

3.6 Data sources

Desk research opts as a research instrument for this study. The main sources of data collection are secondary such as literature reviews, annual reports, policy documents, newsletters, and websites of ministries or executive agencies. The prime source of data that provided the common ground for further analysis is the imports and exports of clothes from Statistics Sweden under the category of commodity goods. The database is published on the country's website for foreign trade of goods through the combined nomenclature (CN) system that provides the most detailed level information about goods (in monetary terms and weight) and is available from CN 2 to CN 8 level (Statistics of Sweden, 2023). Under CN 2 classification, the most relevant categories to continue with; CN 61- Import of new articles of apparel and clothing accessories, knitted or crocheted and, CN 62- Imports of new articles of apparel and clothing accessories, non-knitted or crocheted. Furthermore, 34 sub-categories at the CN4 level represent the comprehensive clothing types imported each year for Swedish consumption. Therefore, data at the CN4 level provided sufficient information that helped in categorizing the outerwear.

Table 6. Categorization of outerwear imported in Sweden (Statistics of Sweden, 2023).

Outerwear		
6101	6201	Men's or boy's overcoats, car coats, capes, cloaks, anoraks (incl. ski jackets), and similar articles
6102	6202	Women's or girl's overcoats, car coats, capes, cloaks, anoraks (incl. ski jackets) and similar articles
6110	-	Sweaters, pullovers, sweatshirts, waistcoats (vests)
6113	6210	Garments made up of fabrics that are rubberized or impregnated, coated, etc. with plastics.
6112	6211	Tracksuits, ski suits, and similar articles

3.7 Vensim software

Vensim is a simulation software that imitates actual world system operations over time to promote understanding of the interactions between many system elements, primarily supporting continuous simulation models (Vensim, 2023). Continuous Simulation refers to simulation approaches where a system is modeled with the help of continuously changing variables according to a set of differential equations. The user interface presents the visuals of the model, as shown in figure 6, while built-in mathematical functions are operated in the background. For example, a box showing the accumulated total outerwear used represents the 'Stock' variable. 'Flow' variables are defined by rates represented by double lines connected to boxes causing an increase or decrease in the stocks with each time step. Lastly, 'auxiliary' variables are related by orange arrows that are used to control the changes in flows. Development of the model in Vensim starts with the modeling time horizon from 2000-2050. Then input of historical data on imports of clothes from 2000-2022 is uploaded into the basic model, and mathematical functions (as listed below) are used throughout the model.

- FIXED DELAYS is a function that represents the delays in the flows: This function returns the value of the input delayed by the delay time.
- IF THEN ELSE is used to execute both the actual part and the false part of a given condition.
- TIME STEP is used to see the impact of any change proposed to the system at a particular year.

The detailed equation formula sheets are in annexures A, B, C & D.

3.8 Limitations

The scenarios are developed with references from the literature. However, in modeling, sorting for example is considered to occur in Sweden (in reality it is shifted to countries in western Europe). Therefore, this assumption is considered as limitations of the vensim models developed in this study. Furthermore, due to time limitations, there is focus on only one type of category of clothes i.e., Outerwear. It is acknowledged that it does not reflect the complete clothing consumption of Swede and hence, allows the prospects of future research on this.

4

Results

4.1 Changes in the future flows and stocks of outerwear

The following section provides the results for answering the first research question and reflects the changes in per capita stocks of outerwear in Sweden. Figure 7 shows the impact on production when reuse as a circular strategy has been applied to the system, i.e., from 2025 to 2045. The reference scenario indicates that if the current percentage of reusing clothes (20%) stays constant in coming years, then 2050 there would be production of 55,000 tonnes of outerwear. It is because that assumption in the reference scenario is optimistic due to the constant demand for clothing per capita. Therefore, the increase is only related to population increase. It does not consider the increase in per capita demand in response to economic growth. The scenario with slow reuse in the foreground shows a marginally slow production of new outerwear as compared to the reference scenario, i.e., about 52,000 tons per year. While rest of two scenarios with high reuse show the same results since both scenarios' foreground systems have a high rate of separate collection (95%) of used clothes, from which 70% of clothes are redistributed/reused within Sweden. These scenarios show that the production of new outerwear can be significantly lowered to about 35,000 tons per year (T/y) by 2050.

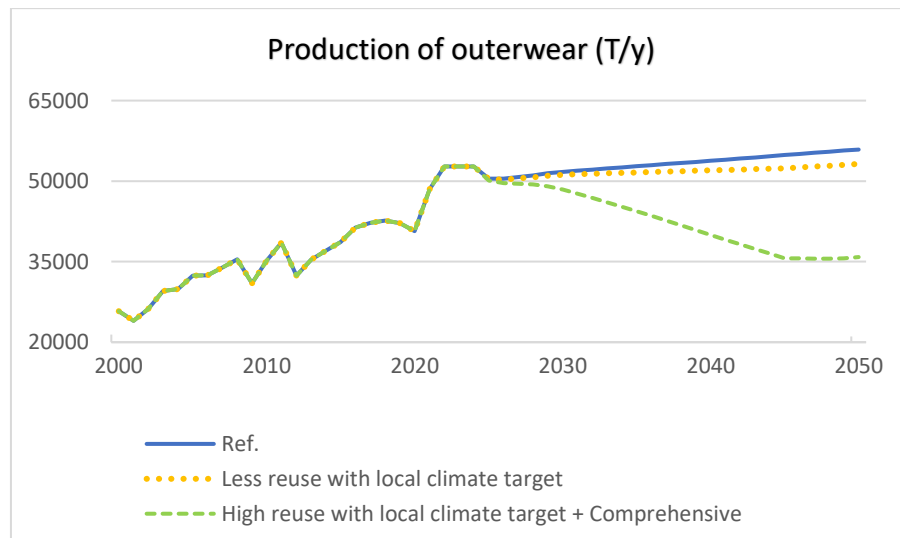


Figure 7. Scenario wise projections for outerwear production (T/y)

Figure 8 shows the quantities of newly produced outerwear and second-hand clothes entering in the stocks of clothes for each scenario. In the reference scenario, the inflow of second-hand clothes remains well under 5,000 tons and production of new outerwear will increase by 55,000 tons in 2050. An improved yet similar pattern can be observed in the second scenario with slow reuse, where the amount of second-hand outerwear by 2050 reaches up to 8,000 tons while production of 52,000 tons of new outerwear is predicted. The third and fourth scenario, with a high reuse rate, shows similar results in growing quantities of second-hand outerwear and reduced production of new outerwear. The high reuse rate resulted in approximately 24,000 tons and 35,000 tons of new outerwear by 2050. This shows that

increased use of second-hand clothes can cover up to 40% of the amount of clothes needed to be consumed by the Swedish population in 2050.

These results imply the availability of suitable platforms to be available for resale of second-hand clothes as report by Nordics Innovation (2022), also stated that implementation of a separate collection of used clothes in 2025 will require upscaling of existing infrastructure or even new infrastructure that can manage the increasing flows of used clothes in coming future.

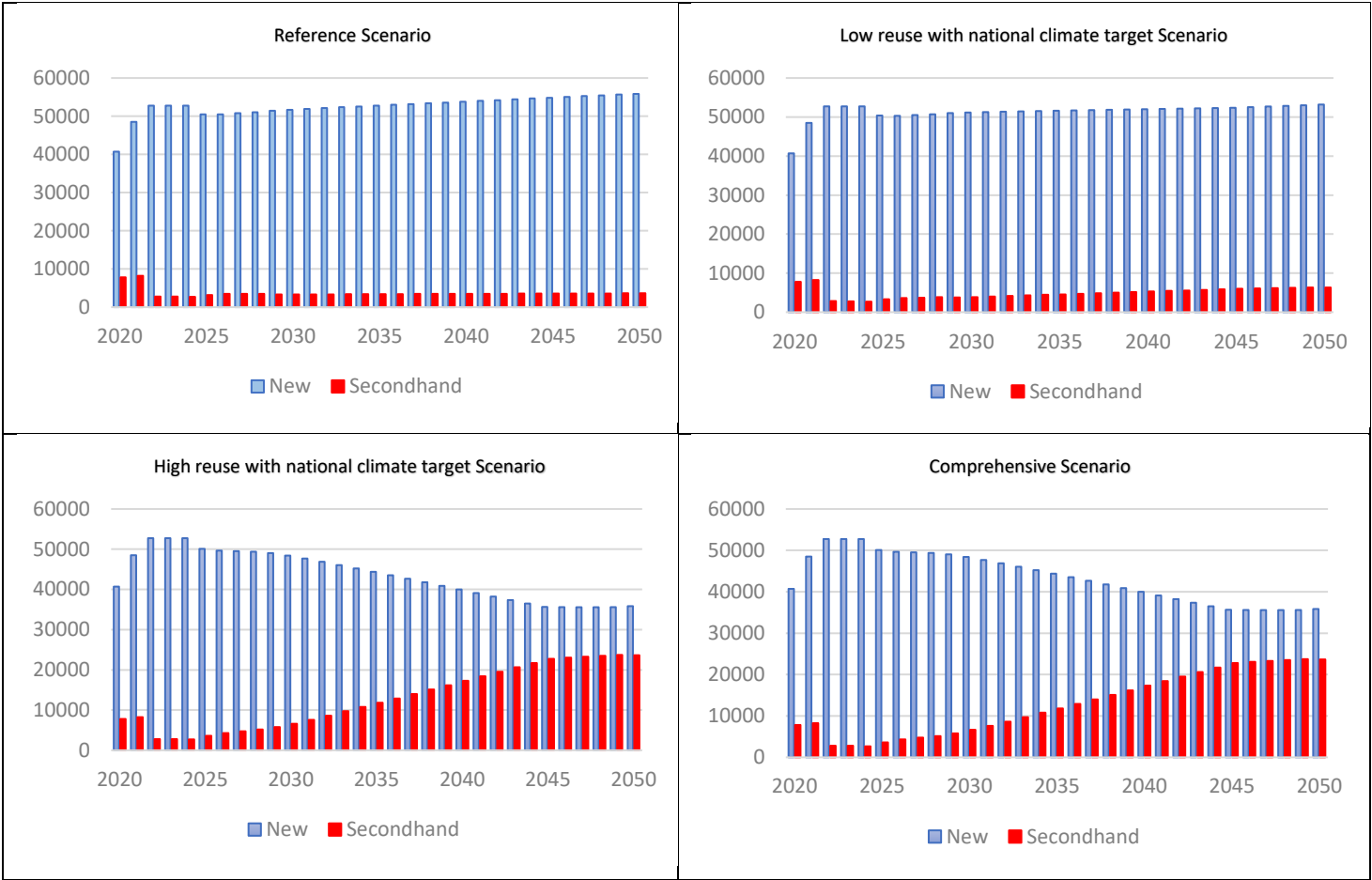


Figure 8 Inflow of outerwear in the stocks (T/y)

Furthermore, the change in average per capita stocks of outerwear for each scenario can be seen in figure 9. By stocks, this study refers to the quantity of outerwear (kg/capita) that is already under use or stored in the wardrobes. In 2019, all scenarios had the same stock per capita, i.e., 17 kgs. But under the assumptions of slow reuse rate, the change from 17 kgs to approximately 19 kgs is observed in the first two, i.e., reference and slow reuse scenarios. While in the scenarios with high rate of reuse the change in per capita ownership of the average stock of outerwear from 17 kgs to 16 kgs has been observed. This effect in stocks is associated with the different lifetimes of first and second-hand clothes. Thus, when the flow of second-hand clothes is high as in a scenario with a high reuse rate, it eventually affects the stocks.

These results show the system's dynamic behavior and confirm the study by Fletcher (2009), where it is stated that the textile system tries to maintain its stability by reducing its outputs when it encounters a negative feedback loop such as implementing separate collection of textiles policy.

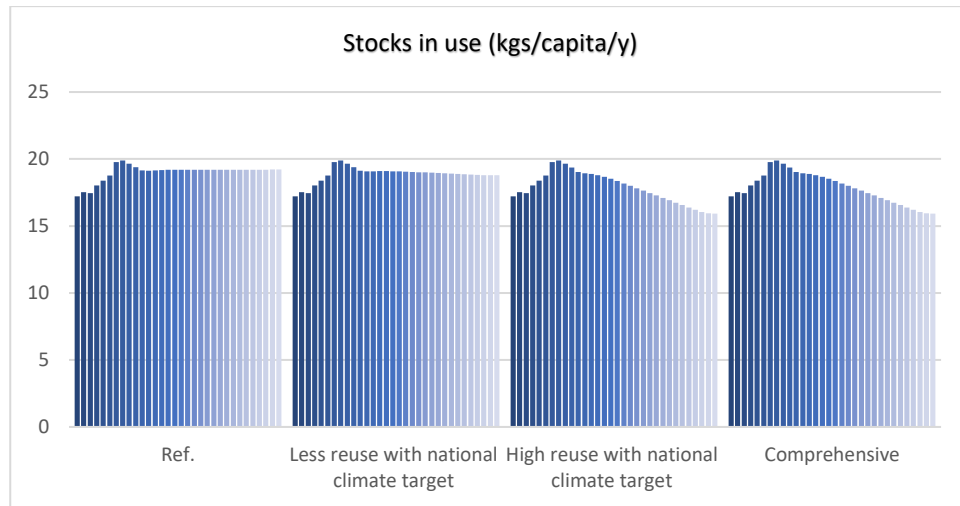


Figure 9 Stocks of outerwear in use (kg/capita/y)

4.2 Impact on GHG emissions under the Influence of global shifts in technology and energy

This section provides a holistic analysis of the system’s dynamic behavior when foreground and background systems interact collectively. A scenario-wise comparative overview of the lifecycle emissions for Swedish outerwear is shown in the Figure 10. The trend in the *reference scenario* implies that if the business-as-usual scenario of reusing clothes (i.e., 20%) is kept intact with no change or improvement in technology and energy worldwide, then lifecycle emissions of outerwear in the Swedish context will reduce from 162 kg CO₂-eq. per person in the year 2019 to 128 kg CO₂-eq. per capita in 2050. While in the scenario with *slow reuse with national climate target*, these emissions reduce from 162 kg CO₂-eq. per person to 112 kg CO₂-eq. per person. In the third scenario, *high reuse with national climate target*, where the global energy system continues to follow stated policies, the impact on emissions goes from 162 kg CO₂-eq. per person to 76 kg CO₂-eq. per person. In the last comprehensive scenario, where the global and national energy systems follow the SDS path with a high reuse rate, the results show a reduction from 162 kg CO₂-eq. per person to 18 kg CO₂-eq. per person by the year 2050.

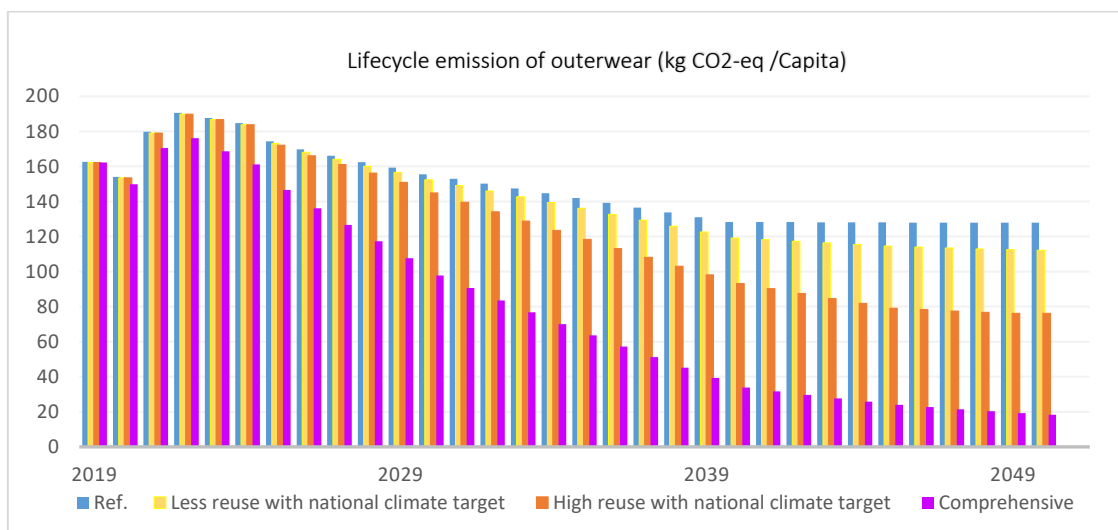


Figure 10. Lifecycle CO₂-eq emissions of outerwear (kg/capita)

It is pertinent to mention here that if the global shift in energy policies that follow the Paris Agreement pathway for climate change accelerates, combined with the adoption of technological changes, and changing the consumption patterns with high amount of second-hand outerwear (or in other words prolonged use of outerwear), still it is challenging to achieve the net-zero target by 2045. However, by looking at the comprehensive scenario, the results imply an increased share of second-hand clothing in Sweden, the influence of improved technologies and global & national shifts in energy under SDS can result in approximately 90% reductions of CO₂-eq. per capita till 2050.

The Ellen MacArthur Foundation (2021) shared the results of their study with 2030 as its final year of analysis. It stated that global business models in the textile sector, such as resale and repair, if continue to capture 23% of the market by 2030, then it could result in a 16% reduction in emissions, implying that it is the only one-third of the abatement needed for the 1.5-degree pathway. And, by looking at the results of the reference scenario of the current study- where the rate of reuse is kept constant (i.e., 20%) during the whole analysis period with the background systems of stated policies both at the national and global level- the emissions during 2030-2035 shows the similar pattern of results as stated by Ellen MacArthur report. Further, it is also concluded that the remaining cut in emissions is achievable through the use of a decarbonized upstream value chain of clothes. The result of the comprehensive scenario confirms the conclusion of Ellen MacArthur's report that the combined effect of the high rate of reuse and global decarbonization of energy systems with national climate targets is able to achieve the emissions reductions needed for the 1.5-degree pathway.

4.2.1 Breakdown of GHG emissions per lifecycle phase

The breaking down of each scenario in different lifecycle phases of outerwear, figure 11. 90% of the emissions are from production, followed by 8-9% from the transportation sector. The negligible emissions from retail, use, and EOL are attributed to the fact that the low carbon intensity of electricity in Sweden is considered for all scenarios in this study. Therefore, the next section will mainly explain the emissions associated with production & transportation during the lifecycle of outerwear.

In the reference scenario, the reduction in emissions from production and transportation is attributed to the assumption where it is considered that an increased amount of clothes for reuse will reduce the production of new clothes. Therefore, if the system continues the 20% reuse of clothes within the system to meet the demand, emissions to produce new clothes in the same quantities can be avoided. While in the scenario with slow reuse with national climate target, the minor reduction in emissions (as compared to reference scenario) can be observed due to the effect of adopting decarbonized electrical system at the national level and the avoided production of new clothes under slow reuse. The projection of future emissions in the rest of two scenarios shows different results although their foreground system remained the same, i.e., high reuse. It is due to the difference in adopting other energy policies at global and national levels in the background system. In the scenario with high reuse and adoption of SDS at the national level, it can significantly reduce transportation and production phase emissions. However, still, it is challenging to achieve net-zero emissions targets even with changes in consumption patterns. Only the comprehensive scenario provides promising abatements in GHG emissions, reaching up to 90% reduction in 2050 only if the clothes production countries start to decarbonize energy systems from 2025. If this ambitious scenario continues, it will still need 10-15 years post-2050 to reach net-zero emissions. Nevertheless, emissions beyond 2050 have not been covered in the current study.

According to Sandin et al. (2019), when they studied six pieces of garments representing the whole wardrobe of an average Swedish person they concluded that 330 kg CO₂-eq. per capita is the carbon footprint of Swedish clothing consumption. The results from the current study, which is 162 kg CO₂-eq. per capita in 2022 for outerwear is slightly lower compared to study of 6 garments because this study has only focused on one type of clothing.

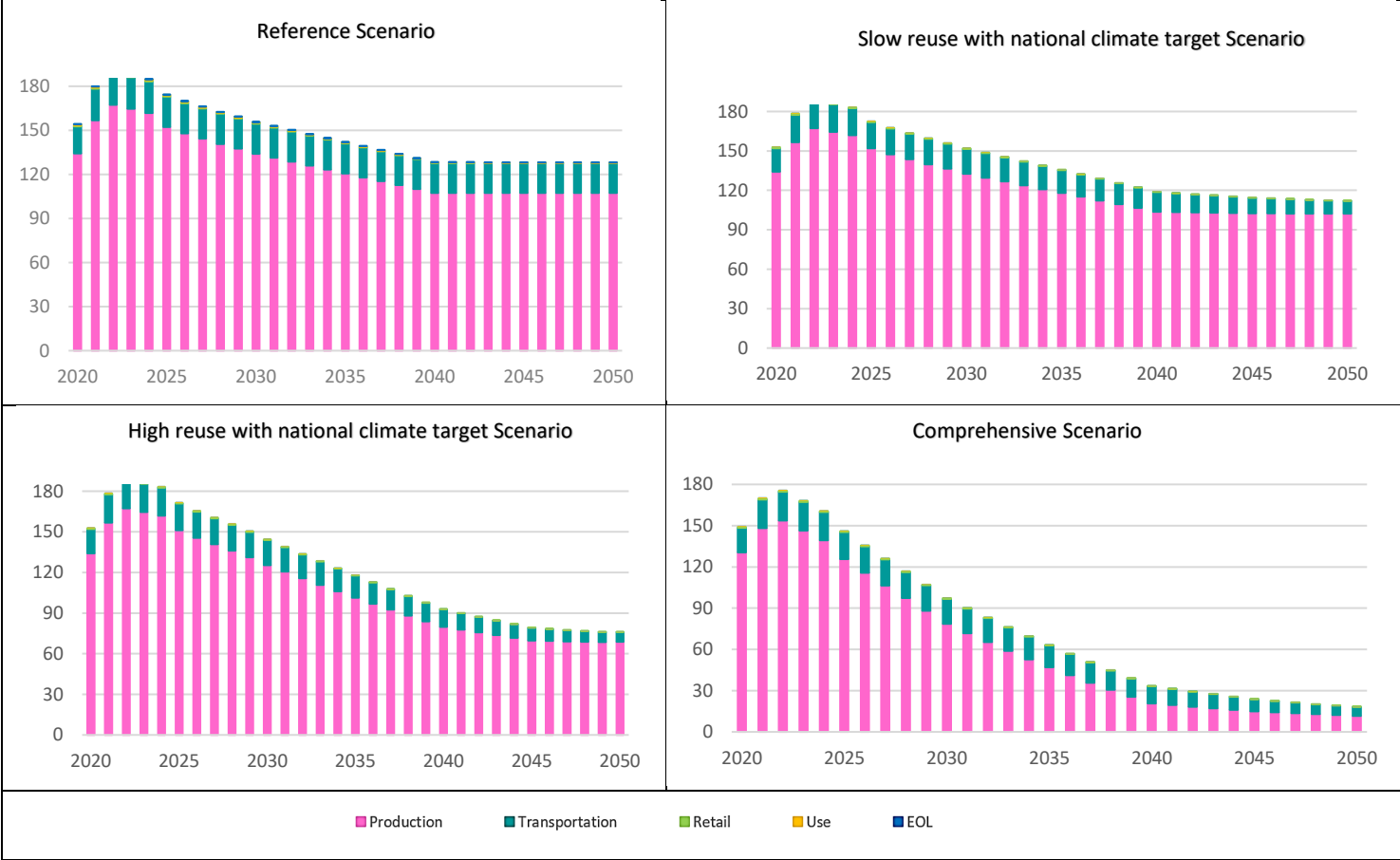


Figure 11 Lifecycle emissions of outerwear (kg CO₂-eq./capita)

4.2.2 Impact on GHG emissions during production

Figure 12 shows the trajectory of per capita emissions of CO₂-eq. resulting from production in different scenarios. At the base year for all scenarios, the results show that the average emission of outerwear is 134 kg CO₂-eq. per capita. It reduces and reaches 107 kg CO₂-eq. per capita in the case of *reference scenario*. In *slow reuse with national climate targets scenario*, it reaches 102 kg CO₂-eq. per capita in. For the third scenario, *high reuse rate and national climate targets* these emissions reach up to 70 kg CO₂-eq. per capita, while in the last *comprehensive scenario* the emissions are lowered to 12 kg CO₂-eq. per capita by 2050.

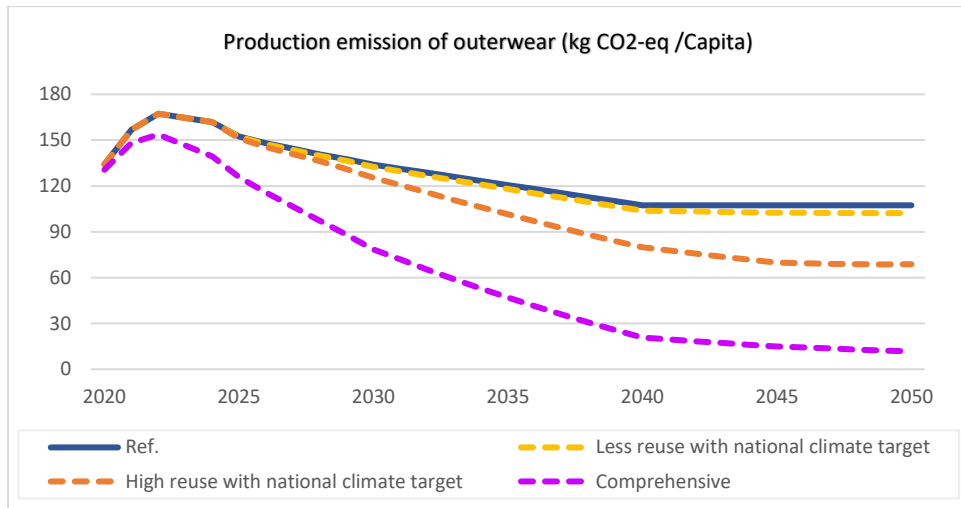


Figure 12. Scenario wise comparison of emissions at production (kg CO₂-eq. per capita)

As the results above have shown that production is ranked at the highest among the life cycle phases for GHG emissions. Figure 13 below shows the scenario-wise comparison of quantities of outerwear needed to be produced with their relevant emissions. The reference and slow reuse with national climate targets scenario have projected the production to reach approx. 55,000 tons and 52,000 tons by 2050, respectively. The impact of slight changes in the quantities of newly produced outerwear and energy shifts at the national level has slightly affected their corresponding emissions from 1.4 million tons of CO₂ to 1.2 million tons of CO₂ by 2050. To analyze the impact of improved reuse rate while background systems stay the same, the third scenario shows emissions have been reduced to 0.81 million tons of CO₂-eq. to produce approximately 35,000 tons of outerwear in 2050. The comprehensive scenario shows a further decline in emissions, reaching 0.13 million tons by 2050 to produce the same quantities of outerwear. This drastic difference is due to background systems where the third scenario considers slow decarbonization in the energy systems globally. At the same time, it accelerates at the national level and the result of this scenario shows to achieve a 56% reduction by 2050 as compared to its base year. In contrast, in the comprehensive scenario 90% reduction in GHG emissions for the production of new outerwear of the same quantity as the last scenario has been observed. This accelerated abatement is primarily due to the reason if globally the countries (such as China, India, and Bangladesh) will also shift towards decarbonizing their electric systems combined with the already decarbonized electric system of Sweden then it can be said that trajectory of emissions at production can reach to zero or neutralize in years after 2050.

These results are similar to the study by Peng et al. (2022), which highlighted the necessity to explore long-term decarbonization pathways to determine GHG emission for textile products and concluded that power decarbonization has the most significant reduction effect on carbon emissions.

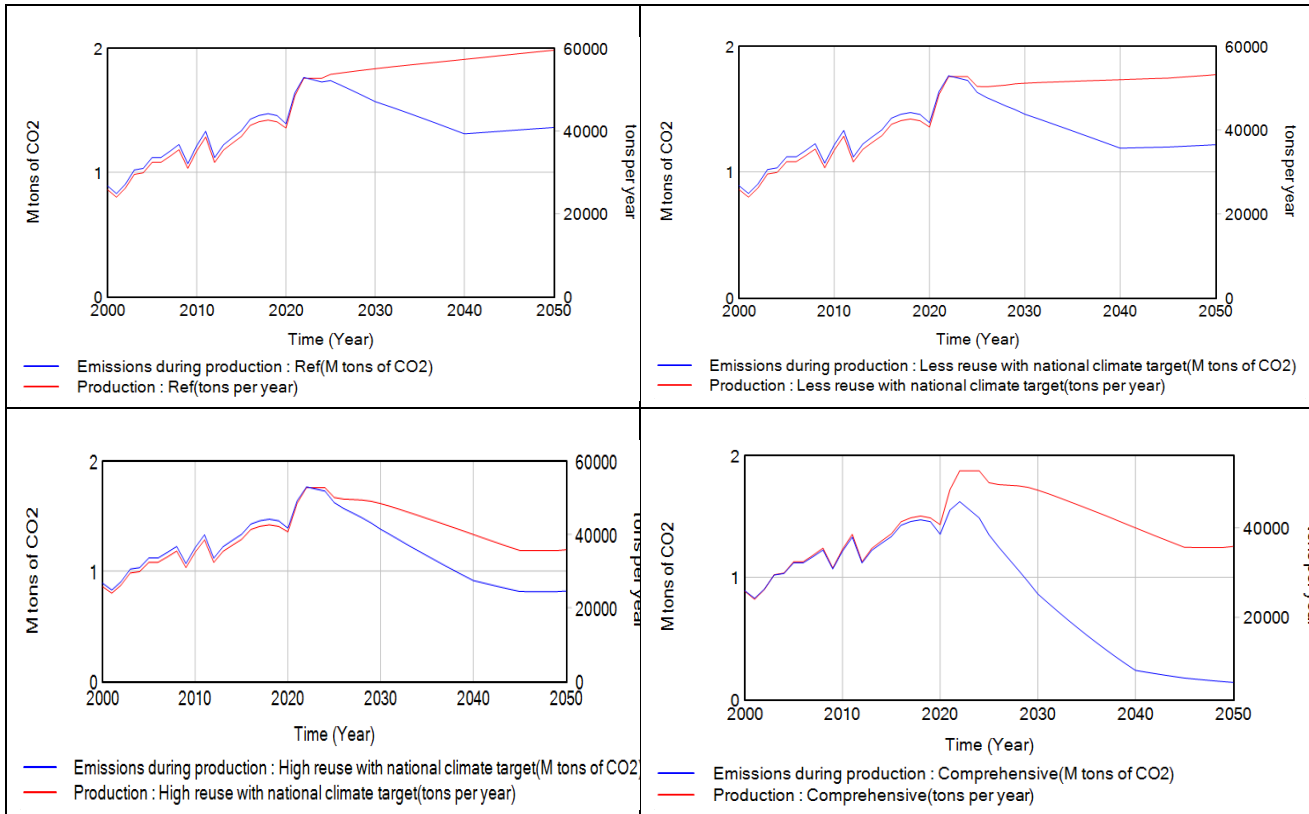


Figure 13. Scenario wise comparison of amount of production of new outerwear and associated emissions

4.2.3 Emissions during transport

To analyze the transport emissions, figure 14 shows the sum of transportation emissions that occur during the lifecycle of outerwear. The reference scenario shows that from 18 kg CO₂-eq. per capita transportation emissions from the base year it reaches 20 kg CO₂-eq. per capita till 2050. In the second scenario, where slow reuse is implemented considering the shift in transportation technology along with the electric system within Sweden, the per capita emissions are halved, i.e., 10 kg CO₂-eq. as compared to the reference scenario in 2050.

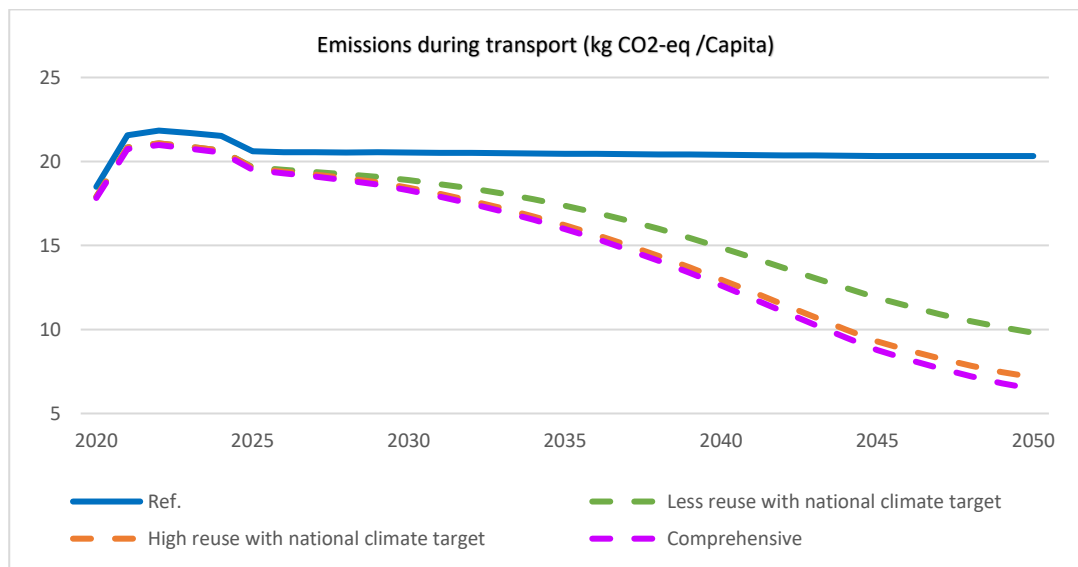


Figure 14. Scenario wise transport emissions of outerwear (kg CO₂-eq. per capita)

In the rest of the scenarios where foreground systems remained the same a high rate of reuse, and the background system differs based on energy shifts at national and global levels along with the adoption of relevant technologies in transportation. The results of both scenarios show that emissions from transport can reach up to 7 and 6 kg CO₂-eq. per capita for the scenario with only national climate policy and comprehensive scenario respectively. These results show that Sweden succeeds in achieving vehicular electrification for all types of vehicles by 2045 then, the concern raised by Gwozdz et al. (2017) can be solved due to decarbonized transportation in Sweden.

The impact of a circular strategy, i.e., reuse at a high rate will result in slow production and eventually slow transportation beyond Sweden. Still, it will increase the transportation within Sweden to supply the same amount of clothes. These results can be seen in figure 15 that to supply outerwear (approx. 60000 tons), each scenario reflects the difference in the transportation emissions. These emissions are divided into global and local transport. Global transport represents transport beyond Swedish boundaries (through trucks and ships), while local transport represents transport within Sweden (through electrified trucks, private vehicles, and public transport). The comparison of all scenarios shows that a change in consumption patterns through implementing a circular strategy, i.e., reuse, can indeed result into more transportation within Sweden. Still, it is highly mitigated with the transition towards vehicular electrification. Another study by Peng et al. (2022) stated that the textile supply chain could narrow the emission upon the use of efficient renewable energy technologies, highlighting the potential of implementing clean power sources for the electrification of transportation in mitigating carbon emissions.

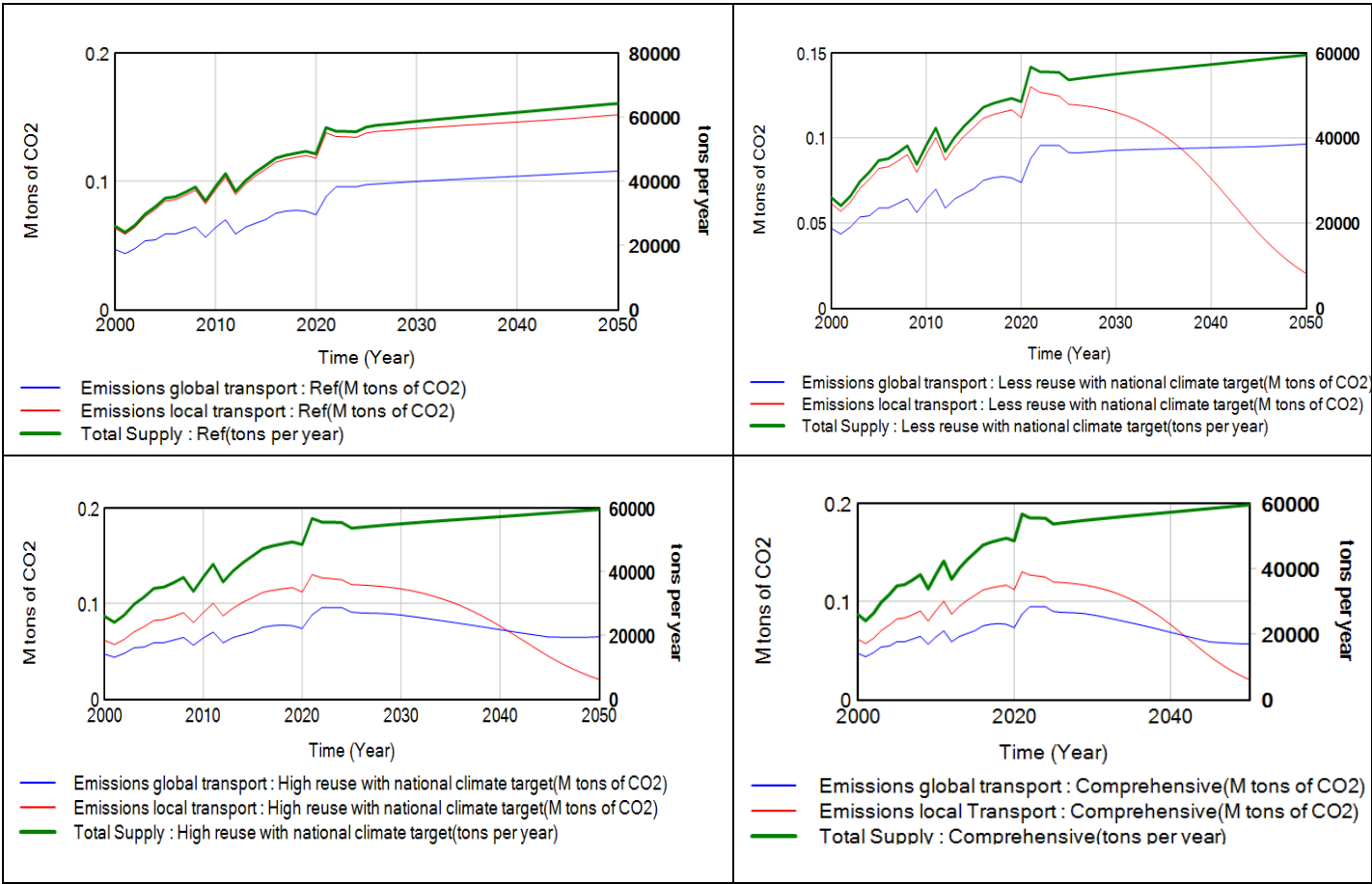


Figure 15 Transportation emissions (global and within Sweden) M tons of CO₂

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Discussion

Clothing ranks high on the list of non-food items consumers frequently purchase, indicating a substantial demand for global resources from the systems thinking perspective (Moon et al., 2013). UNEP (2017) defines systems thinking as an approach that considers all system components to understand the system's intricate and dynamic complexity. Similarly, Fletcher (2009) states that in achieving decarbonization in the clothing sector, the 'external' influences - such as production practices, international energy policy, and consumption patterns by society - play an important role. Therefore, to unwind the complexity, this study explores a holistic approach to system dynamics in identifying the hotspots upon implementing reuse as a circular strategy and understanding the significance of reuse as a circular strategy under different energy scenarios.

According to Rissman et al. (2020), there are two main options for extending the life of a product to increase circularity and reduce environmental impacts - keeping it for longer by regular maintenance or repairs or transferring it to a new user. First, the EU Waste Framework Directive (2018) mandates that separate collections of used textiles must be aimed for increasing the use of second-hand clothes within the country and is neither aimed at exporting more nor increasing recycling as for now. This implies the challenge of systemic transition of the current linear systems towards a circular system as the exports of more used clothes can pose additional environmental risks as open disposal is mainly practiced in developing countries (Sandin & Peters, 2018). Secondly, the increased amount of used clothes is also attributed to a potential ban on the import of second-hand clothes from the global North by African countries as it is impacting their domestic textile industry (BBC, 2018).

According to Dahlbo et al. (2017), a significant proportion (50% to 75%) of the gathered textile waste could be reused. The authors also mentioned that the quantity of textile waste collected is expected to increase but will not guarantee the availability of second-hand clothing. Because increased quantities of low-quality clothes are anticipated in the initial years due to separate waste collection of clothes by 2025. The short-term solution to this has been explained by Carlsson et al. (2017). Firstly, by convincing consumers to provide clothes that are of good quality – perhaps compromising the shorter life during firsthand use. While the long-term solution involves the production of clothes from innovative materials and technologies that can withstand repeated use and wash cycles without losing their quality.

Carlsson et al. (2017) explain that businesses in fast fashion needs to incorporate longevity factors during the design phase of clothing that can potentially extend the clothing's target lifetime. The production teams should consider the empathetic and aesthetic qualities that consumers desire in addition to ensuring durability and effective physical and technical attributes during the development of clothes. Utilizing poor-quality materials and inexpensive stitching processes can compromise the physical durability of a garment. Apart from ensuring design for durability and longevity, the aspect of the emotional association of consumers with the clothes is also essential. It involves supporting consumers through communication and after-sales services, considering their preferences on size, designs, colors, and styles.

Previous studies have also shown that sorting used clothes is attributed to economic challenges. Dahlbo et al. (2017) explain that manual sorting will remain widely adopted in textile waste processing, owing to the nascent stage and high cost of automated sorting technology for textile waste (as explained in section 2.2.3). But the efficiency of manual sorting is very low as only 100-150 kg of textiles per hour is humanly possible compared to the automated facility, where clothes of 900-1,500 kg per person per hour can be sorted (Dahlbo et al., 2017). The costs associated with exclusively inspecting every piece of garment and labor wages must be considered during this phase. Watson & Palm (2020) also explained a significant uncertainty for second-hand businesses as it is difficult for them to determine the quantity and quality of the used clothes they will receive now and in the future. Furthermore, Dahlbo et al. (2017) also mention that no company has the logistics infrastructure to retain an inventory of clothes that must be stored and distributed according to temperature and seasons.

In the context of stakeholders, it is common practice for municipalities across various countries to bear the responsibility of collecting household waste. However, the specific management of textile waste upon implementation of policies (as explained in section 2.3) has been described in a comprehensive report by Elander et al. (2016). They highlight the inherent conflicts of interest among stakeholders and underscore the potential uncertainties surrounding waste ownership if municipalities do the responsibility for collection. Because a possibility for municipalities to selectively sell economically advantageous portions will exist as there is no legislation mandating the municipalities to relinquish the sorted products/material to the producers. The complexity further deepens when it comes to handling textile waste because textile waste is ideal for incineration due to the energy content of different fibers. Consequently, certain municipalities may want to retain the textile waste stream because there is a decline in input of other waste streams for incineration due to diverse recycling initiatives.

In this context, Sweden has acknowledged practical challenges upon implementing textile waste management policies; therefore according to Watson et al. (2020), the Swedish Government has decided to outsource the collection of textiles to external entities, notably following the example of France. According to this report, France stands out as the only country that has implemented a producer responsibility system exclusively for household textiles by outsourcing the collection process. Furthermore, France consistently revises its textile waste collection targets aligned with evolving circumstances every year, coupled with a structured framework of incentives for producers, municipalities, collectors, and sorting facilities. The results yielded substantial advancements in collection rates, albeit starting from a comparably modest baseline. Notably, the quantity of collected materials has undergone a nearly fourfold increase from 2006 to 2018.

Sweet et al. (2021) explain that consumers' role is significant in the shift toward consumption of reused clothes. In contrast to conventional, straightforward supply chains, the supply chains of second-hand retailers are intricate due to their reliance on customers as both suppliers and consumers referred to as so-called 'prosumers'. Their business of handling and selling second-hand clothes results in resembling the model of logistics companies rather than fashion companies. Despite the potential value that can be derived from second-hand apparel, the costs associated with collecting, sorting, and presenting attractive offerings remain significant. The future development of the second-hand clothing market in the coming years is therefore difficult to predict. Moreover, the recycling of these used clothes on such a large scale will not be feasible given the technical and economic challenges of chemical and mechanical recycling, as explained in section 2.2.3. Further, to date, not all clothes are suitable for recycling. Therefore, it is essential that compliance with the relevant standards for recycling, for example,

the Global Organic Textile Standard (GOTS) and the Global Recycled Standard (GRS), is considered in the planning and design phase to facilitate efficient and credible recycling in a later phase of the life of the textiles (Carlsson et al., 2017).

Overall, there is a broad consensus that the potential of circular economy strategies can be held back if all the above-explained challenges are not managed systemically (Rissman et al., 2020). However, the result of the current research also confirms that introducing more consumption of second-hand outerwear proposed in the foreground systems of all scenarios helps but does not entirely achieve net-zero emissions. Therefore, this study also considers the influences of other systems, such as energy, known as 'external factors, from the systems thinking perspective.

The 'external factors' in this case are the background systems under different energy and climate policies, and the outcomes have shown their significant influence on greenhouse gas emissions. The environmental impact of producing clothes varies based on the types of fibers. For example, natural fibers, such as cotton and wool, have a high impact on water and land use. In contrast, synthetic fibers (namely nylon, polyester and acrylic) generally have a more significant impact on greenhouse gas emissions due to their fossil fuel-based origin and the energy required for their production (Sandin, Roos, & Johansson, 2019). The composition of fibers in the outerwear category is dominated by polyester and nylon. The findings by Sandin et al. (2019) demonstrate that utilizing clothing items twice as much in their original state can reduce the environmental impact by nearly 50% as the reduction is primarily linked to the avoided energy consumed during the production of clothes.

As mentioned earlier that the production of clothes for the Swedish population is mainly occurring in countries where non-renewable energy sources are used in manufacturing; the results in scenarios with changing background systems - especially in the scenario 'high reuse with national climate target' and 'comprehensive' - show clear benefits for the supplier countries to undergo ambitious energy transition. In order to realize global efforts in achieving net-zero emissions, countries with emerging economies - such as China and India - require a transformation in their established industrial systems by incorporating a substantial proportion of low-carbon energy sources. While for other developing countries a fair and equitable transition process will be beneficial. This entails support through sustainable financing schemes for the energy sector to mitigate the potential socio-economic disruptions that may arise from ambitious commitments to shift towards low-carbon energy sources (Babayomi et al., 2022).

Gwozdz et al. (2017) mention that if more clothes are reused - or in other words, stay within the system for a more extended period - then it poses a potential tradeoff between emissions. This is further explained that the emissions avoided by not producing the new clothes can be replaced by higher emissions due to the transportation of used clothing. However, in the case of Sweden, the country is quickly transitioning towards electrified transportation, which was reflected in all scenarios with national climate targets. Therefore, the results show that even if more transportation is required within Sweden, the emissions from transport could be reduced due to electric vehicles and a decarbonized electricity system. The exception is the use of liquid fuel for transoceanic transportation, which is considered to remain the same also in the future. However, it is essential to note that currently, manufacturing batteries for electric vehicles is a carbon-intensive process; therefore, zero emissions in transportation is difficult to achieve if battery manufacturing processes are not fully decarbonized globally (Morfeldt et al., 2021).

This research is one of its kind that combines system dynamics perspectives with circular economy

strategies. The results are expected to be helpful in analyzing how consumption-based targets for clothing items in Sweden could be met and provide future emissions projections for achieving net-zero consumption-based emissions. In addition, this research offers avenues to explore further the potential of other circular strategies on one or all categories of clothes for decarbonized clothing consumption in any given country.

6

Conclusion

This study concludes that pursuing a decarbonized textile industry must be approached from a holistic perspective to avoid fragmented solutions. The results show the intricacy of systems dynamics where changes in one part of the system demonstrate the effects on the other parts of the system and concludes the significance of reuse as a circular strategy, under different energy scenarios, as an effective approach to meet the targets of net-zero emissions.

The first research question states to assess the implementation of reuse as a circular strategy for the production and consumption of outerwear. The results of the foreground system show that scenarios with a *high reuse rate*, i.e., up to 70% by 2050, have the potential to diminish the production of new outerwear. This implies that the 'low quality-high volume model' of fast fashion can be slowed down with an increased rate of reuse and still is able to meet the Swedish demand for outerwear. The challenges associated with the supply chains of second-hand clothing were also discussed, where consumers are referred to as prosumers because of their significance as both suppliers and consumers of used clothes. Another challenge associated with the higher costs of second-hand apparel, in the collection and sorting phases, was also discussed due to reliance on manual labor. Furthermore, the study investigated the challenges of sorting the increased volumes of reused outerwear. It concluded with the example of France, where the implementation of extended producer responsibility in textiles waste has adopted a systemic change through legislation and consensus from stakeholders.

Regarding the second research question, per capita kg CO₂-eq. After implementation of reuse, emissions were calculated according to future shifts in global and national energy and climate policy scenarios as provided by the IEA and technology shifts in production and transportation. The results of the scenarios under the influence of global and local changes in technology and energy are compared with the reference scenario. The *reference scenario*, projects that per capita emissions for outerwear consumption is 162 kg CO₂-eq. in 2019 and will decline to 128 kg CO₂-eq. in 2050 due to the changes in the carbon intensity of electricity under stated policies. In the '*slow reuse with national climate target scenario*' per capita emissions decrease to 112 kg CO₂-eq. in 2050 due to adoption of 40% of reuse and shift towards energy and climate policies in line with national climate targets. While in the third scenario '*high reuse with national climate targets*', where background systems are assumed to be the same, the per capita emission are reduced to 76 kg CO₂-eq. in 2050. The reason for this difference in the per capita emissions from the second and third scenario is due to the difference in the reuse rates. Lastly, the results for the comprehensive scenario show a decrease in per capita emissions to 18 kg CO₂-eq. in 2050. These results indicate that even with the comprehensive approach, where high rates of reuse as a circular strategy are combined with sharp reductions in emissions from energy and production systems at the global and national level, it is not able to achieve zero emissions by 2045 completely. However, the results of comprehensive scenarios show that high reuse rates are promising for achieving emissions abatement. This further provides an avenue for future research, where in addition to the reuse, a combination of other circular strategies could be studied to analyze the potential of circular systems to achieve net-zero emissions in the clothing sector.

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Annexure A

Vensim Equations for Reference Scenario

- (01) assumed constant demand per capita = 0.005 - Units: tons per person
- (02) available clothes to be reused= flowback of second-hand clothes - Units: tons per year
- (03) collection in household waste= DELAY FIXED (supply of new clothes*collection rate by WMCs, lifetime of firsthand use, 0) - Units: tons per year
- (04) collection of second-hand clothes= DELAY FIXED (supply of old clothes, lifetime of second-hand use, 0) - Units: tons per year
- (05) collection rate by WMCs= 1-separate collection rate - Units: Dmnl
- (06) conversion= imports in history (Time) Units: **undefined**
- (07) conversion for second-hand= IF THEN ELSE(Time>2021, 0, imports of second-hand) Units: *undefined**
- (08) discarded clothes=discarding rate*separate collection of used clothes - Units: tons per year
- (09) discarding rate=0.4Units: Dmnl
- (10) Emissions during EOL= (Sent for incineration*I emissions S1)/1e+06 - Units: M tons of CO2
- (11) Emissions during production= (Production*P emissions S1)/1e+06 - Units: M tons of CO2
- (12) Emissions during retail= (total supply*R emissions S1)/1e+06 - Units: M tons of CO2
- (13) Emissions during Use= (Stocks of clothes in use*U emissions S1)/1e+06 - Units: M tons of CO2
- (14) Emissions global transportation= (Production*T global emissions S1)/1e+06 - Units: M tons of CO2
- (15) Emissions local transportation= (total supply*T local emissions S1)/1e+06 -Units: M tons of CO2
- (16) exported second-hand clothes= exports - Units: tons per year
- (17) exports= rate of export*separate collection of used clothes - Units: tons per year
- (18) FINAL TIME = 2050 Units: Year The final time for the simulation.
- (19) flowback of second-hand clothes=redistribution rate*separate collection of used clothes Units: tons per year
- (20) I emissions S1: INTERPOLATE: Units: **undefined**
- (21) imports in history ((0,0) - (10,10)), (2000,25812), (2001,23990), (2002,26200), (2003,29510), (2004,29885), (2005,32425), (2006,32435), (2007,33890), (2008,35466), (2009,30973), (2010,35178), (2011,3531), (2012,32388), (2013,35389), (2014,37060), (2015,38645), (2016,41349), (2017,42241), (2018,42633), (2019,42205), (2020,40700), (2021,48500), (2022,52739)) Units: **undefined**
- (22) INITIAL TIME = 2000 Units: Year The initial time for the simulation.
- (23) lifetime of firsthand use=IF THEN ELSE (Time<2025, 4, 8) Units: Year
- (24) lifetime of second-hand use=IF THEN ELSE(Time>2025, 4, 2) Units: Year
- (25) P emissions S1: INTERPOLATE: Units: **undefined**
- (26) population: INTERPOLATE: Units: **undefined**
- (27) Production=IF THEN ELSE (Time<2025, total imports, assumed constant demand per capita *population) Units: tons per year
- (28) R emissions S1: INTERPOLATE: Units: **undefined**
- (29) rate of export=0.4 Units: Dmnl
- (30) redistribution rate=0.2 Units: Dmnl
- (31) SAVEPER = TIME STEP Units: Year [0,?]The frequency with which output is stored.
- (32) Sent for incineration=collection of second-hand clothes + collection in household waste + discarded clothes Units: tons per year
- (33) separate collection of used clothes=DELAY FIXED (supply of new clothes*separate collection rate, lifetime of firsthand use, 0) Units: tons per year
- (34) separate collection rate= 0.33 Units: Dmnl
- (35) Sorting=separate collection of used clothes-discarded clothes-exports-flowback of second-hand clothes Units: tons per year

- (36) Stocks of clothes in use= INTEG (supply of new clothes + supply of old clothes-collection in household waste - collection of second-hand clothes-separate collection of used clothes, 0) Units: tons per year
- (37) sum of stocks=Stocks of clothes in use/population Units: tons per person
- (38) supply of new clothes=Production Units: tons per year
- (39) supply of old clothes=available clothes to be reused: tons per year
- (40) T global emissions S1: INTERPOLATE: Units: **undefined**
- (41) T local emissions S1: INTERPOLATE: Units: **undefined**
- (42) TIME STEP = 1 Units: Year [0,?] The time step for the simulation.
- (43) total imports= conversion Units: **undefined**
- (44) total supply= supply of new clothes + supply of old clothes Units: tons of CO₂
- (45) U emissions S1: INTERPOLATE: Units: **undefined**

Annexure B

Vensim Equations for Slow Reuse with National Climate Targets Scenario

- (01) assumed constant demand per capita=0.005 Units: tons per person
- (02) available clothes to be reused=flowback of second-hand clothes Units: tons per year
- (03) change in future rates=MIN (0.2, 0.2) Units: Dmnl
- (04) collection in household waste= DELAY FIXED (supply of new clothes*collection rate by WMCs, lifetime of firsthand use, 0) Units: tons per year
- (05) collection of second-hand clothes=DELAY FIXED (supply of old clothes, lifetime of second-hand use, 0)
Units: tons per year
- (06) collection rate by WMCs= 1-separate collection rate Units: Dmnl
- (07) conversion= imports in history (Time) Units: **undefined**
- (08) conversion for second-hand=IF THEN ELSE(Time>2021, 0, imports of second-hand)
Units: **undefined**
- (09) discarded clothes=discarding rate*separate collection of used clothes Units: tons per year
- (10) discarding rate=IF THEN ELSE(Time>2024, IF THEN ELSE (Time<=2045, (0.45- change in future rates /2- 0.4)/ (2045-2024) * (Time-2024) + 0.4, 0.45- change in future rates/2), 0.4) Units: Dmnl
- (11) Emissions during EOL= (Sent for incineration*I emissions S2)/1e+06 Units: M tons of CO2
- (12) Emissions during production= (P emissions S2*Production)/1e+06 Units: M tons of CO2
- (13) Emissions during retail= (R emissions S2*Total Supply)/1e+06 Units: M tons of CO2
- (14) Emissions during Use= (Stocks of clothes in use*U emissions S2)/1e+06 Units: M tons of CO2
- (15) Emissions global transport = (T global emissions S2*Production)/1e+06 Units: M tons of CO2
- (16) Emissions local transport= (T local emissions S2*Total Supply)/1e+06 Units: M tons of CO2
- (17) exported second-hand clothes= exports Units: tons per year
- (18) exports=rate of export*separate collection of used clothes Units: tons per year
- (19) FINAL TIME = 2050 Units: Year The final time for the simulation.
- (20) flowback of second-hand clothes=redistribution rate*separate collection of used clothes Units: tons per year
- (21) I emissions S2: INTERPOLATE: Units: tons of CO2 per ton of clothes
- (22) imports in history ((0,0) - (10,10)), (2000,25812), (2001,23990), (2002,26200), (2003,29510), (2004,29885), (2005,32425), (2006,32435), (2007,33890), (2008,35466), (2009,30973), (2010,35178), (2011,38531), (2012,32388), (2013,35389), (2014,37060), (2015,38645), (2016,41349), (2017,42241), (2018,42633), (2019,42205), (2020,40700), (2021,48500),(2022,52739) Units: **undefined**
- (23) INITIAL TIME=2000 Units: Year The initial time for the simulation.
- (24) lifetime of firsthand use=IF THEN ELSE (Time<2025, 4, 8) Units: Year
- (25) lifetime of second-hand use=IF THEN ELSE(Time>2025, 4, 2) Units: Year
- (26) P emissions S2: INTERPOLATE: Units: tons of CO2 per ton of clothes
- (27) population: INTERPOLATE: Units: **undefined**
- (28) Production=IF THEN ELSE (Time<2025, total imports, assumed constant demand per capita *population-available clothes to be reused) Units: tons per year
- (29) R emissions S2: INTERPOLATE: Units: tons of CO2 per ton of clothes
- (30) rate of export=IF THEN ELSE(Time>2024, IF THEN ELSE (Time<=2045, (0.45- change in future rates /2- 0.4)/ (2045-2024) *(Time-2024) +0.4, 0.45- change in future rates/2), 0.4) Units: Dmnl
- (31) redistribution rate=IF THEN ELSE (Time>2024, IF THEN ELSE (Time<=2045, (0.1 + change in future rates -0.2)/ (2045-2024) *(Time-2024) +0.2, 0.1 + change in future rates), 0.2) Units: Dmnl
- (32) SAVEPER =TIME STEP Units: Year [0,?] The frequency with which output is stored.
- (33) Sent for incineration= collection of second-hand clothes + collection in household waste + discarded clothes Units: tons per year
- (34) separate collection of used clothes= DELAY FIXED (supply of new clothes*separate collection rate,

lifetime of firsthand use, 0) Units: tons per year

(35) separate collection rate=IF THEN ELSE (Time>2024, IF THEN ELSE (Time<=2045, (0.4-0.33)/(2045-2024) *(Time-2024)+0.33, 0.4), 0.33) Units: Dmnl

(36) Sorting=separate collection of used clothes-discarded clothes-exports-flowback of second-hand clothes Units: tons per year

(37) Stocks of clothes in use= INTEG (supply of new clothes + supply of old clothes-collection in household waste-collection of second-hand clothes-separate collection of used clothes, 0) Units: tons per year

(38) sum of stocks=Stocks of clothes in use/population Units: tons per person

(39) supply of new clothes=Production Units: tons per year

(40) supply of old clothes=available clothes to be reused Units: tons per year

(41) T global emissions S2: INTERPOLATE: Units: **undefined**

(42) T local emissions S2: INTERPOLATE: Units: **undefined**

(43) TIME STEP = 1 Units: Year [0,?] The time step for the simulation.

(44) total imports= conversion Units: **undefined**

(45) Total Supply=supply of new clothes + supply of old clothes Units: **undefined**

(46) U emissions S2: INTERPOLATE: Units: tons of CO2 per ton of clothes

Annexure C

Vensim Equations for High Reuse with National Climate Targets Scenario

- (01) assumed constant demand per capita=0.005 Units: tons per person
- (02) available clothes to be reused=flowback of second-hand clothes Units: tons per year
- (03) change in future rates=MIN (0.2, 0.2) Units: Dmnl
- (04) collection in household waste= DELAY FIXED (supply of new clothes*collection rate by WMCs, lifetime of firsthand use, 0) Units: tons per year
- (05) collection of second-hand clothes=DELAY FIXED (supply of old clothes, lifetime of second-hand use, 0)
Units: tons per year
- (06) collection rate by WMCs= 1-separate collection rate Units: Dmnl
- (07) conversion= imports in history (Time) Units: **undefined**
- (08) conversion for second-hand=IF THEN ELSE(Time>2021, 0, imports of second-hand)
Units: **undefined**
- (09) discarded clothes=discarding rate*separate collection of used clothes Units: tons per year
- (10) discarding rate= IF THEN ELSE(Time>2024, IF THEN ELSE (Time<=2045, (0.25- change in future rates /2- 0.4)/ (2045-2024) *(Time-2024) +0.4, 0.25- change in future rates/2), 0.4) Units: Dmnl
- (11) Emissions during EOL= (Sent for incineration*I emissions S2)/1e+06 Units: M tons of CO2
- (12) Emissions during production= (P emissions S2*Production)/1e+06 Units: M tons of CO2
- (13) Emissions during retail= (R emissions S2*Total Supply)/1e+06 Units: M tons of CO2
- (14) Emissions during Use= (Stocks of clothes in use*U emissions S2)/1e+06 Units: M tons of CO2
- (15) Emissions global transport = (T global emissions S2*Production)/1e+06 Units: M tons of CO2
- (16) Emissions local transport= (T local emissions S2*Total Supply)/1e+06 Units: M tons of CO2
- (17) exported second-hand clothes= exports Units: tons per year
- (18) exports=rate of export*separate collection of used clothes Units: tons per year
- (19) FINAL TIME = 2050 Units: Year The final time for the simulation.
- (20) flowback of second-hand clothes=redistribution rate*separate collection of used clothes Units: tons per year
- (21) I emissions S3: INTERPOLATE: Units: tons of CO2 per ton of clothes
- (22) imports in history ([{(0,0) - (10,10)}, (2000,25812), (2001,23990), (2002,26200), (2003,29510), (2004,29885), (2005,32425), (2006,32435), (2007,33890), (2008,35466), (2009,30973), (2010,35178), (2011,38531), (2012,32388), (2013,35389), (2014,37060), (2015,38645), (2016,41349), (2017,42241), (2018,42633), (2019,42205), (2020,40700), (2021,48500),(2022,52739)) Units: **undefined**
- (23) INITIAL TIME=2000 Units: Year The initial time for the simulation.
- (24) lifetime of firsthand use=IF THEN ELSE (Time<2025, 4, 8) Units: Year
- (25) lifetime of second-hand use=IF THEN ELSE(Time>2025, 4, 2) Units: Year
- (26) P emissions S3: INTERPOLATE: Units: tons of CO2 per ton of clothes
- (27) population: INTERPOLATE: Units: **undefined**
- (28) Production=IF THEN ELSE (Time<2025, total imports, assumed constant demand per capita *population-available clothes to be reused) Units: tons per year
- (29) R emissions S3: INTERPOLATE: Units: tons of CO2 per ton of clothes
- (30) rate of export= IF THEN ELSE(Time>2024, IF THEN ELSE (Time<=2045, (0.25- change in future rates/2- 0.4)/ (2045-2024) *(Time-2024) +0.4, 0.25- change in future rates/2), 0.4) Units: Dmnl
- (31) redistribution rate= IF THEN ELSE(Time>2024, IF THEN ELSE (Time<=2045, (0.5 + change in future rates -0.2)/ (2045-2024) *(Time-2024) +0.2, 0.5 +change in future rates), 0.2) Units: Dmnl
- (32) SAVEPER =TIME STEP Units: Year [0,?] The frequency with which output is stored.
- (33) Sent for incineration= collection of second-hand clothes + collection in household waste + discarded clothes Units: tons per year

- (34) separate collection of used clothes= DELAY FIXED (supply of new clothes*separate collection rate, lifetime of firsthand use, 0) Units: tons per year
- (35) separate collection rate= IF THEN ELSE (Time>2024, IF THEN ELSE (Time<=2045, (0.95-0.33)/ (2045-2024) *(Time-2024) +0.33, 0.95), 0.33)
Units: Dmnl
- (36) Sorting=separate collection of used clothes-discarded clothes-exports-flowback of second-hand clothes Units: tons per year
- (37) Stocks of clothes in use= INTEG (supply of new clothes + supply of old clothes-collection in household waste-collection of second-hand clothes-separate collection of used clothes, 0) Units: tons per year
- (38) sum of stocks=Stocks of clothes in use/population Units: tons per person
- (39) supply of new clothes=Production Units: tons per year
- (40) supply of old clothes=available clothes to be reused Units: tons per year
- (41) T global emissions S3: INTERPOLATE: Units: **undefined**
- (42) T local emissions S3: INTERPOLATE: Units: **undefined**
- (43) TIME STEP = 1 Units: Year [0,?] The time step for the simulation.
- (44) total imports= conversion Units: **undefined**
- (45) Total Supply=supply of new clothes + supply of old clothes Units: **undefined**
- (46) U emissions S3: INTERPOLATE: Units: tons of CO2 per ton of clothes

Annexure D

Vensim Equations for Comprehensive Scenario

- (01) assumed constant demand per capita=0.005 Units: tons per person
- (02) available clothes to be reused=flowback of second-hand clothes Units: tons per year
- (03) change in future rates=MIN (0.2, 0.2) Units: Dmnl
- (04) collection in household waste= DELAY FIXED (supply of new clothes*collection rate by WMCs, lifetime of firsthand use, 0) Units: tons per year
- (05) collection of second-hand clothes=DELAY FIXED (supply of old clothes, lifetime of second-hand use, 0)
Units: tons per year
- (06) collection rate by WMCs= 1-separate collection rate Units: Dmnl
- (07) conversion= imports in history (Time) Units: **undefined**
- (08) conversion for second-hand=IF THEN ELSE(Time>2021, 0, imports of second-hand)
Units: **undefined**
- (09) discarded clothes=discarding rate*separate collection of used clothes Units: tons per year
- (10) discarding rate= IF THEN ELSE(Time>2024, IF THEN ELSE (Time<=2045, (0.25- change in future rates /2- 0.4)/ (2045-2024) *(Time-2024) +0.4, 0.25- change in future rates/2), 0.4) Units: Dmnl
- (11) Emissions during EOL= (Sent for incineration*I emissions S2)/1e+06 Units: M tons of CO2
- (12) Emissions during production= (P emissions S2*Production)/1e+06 Units: M tons of CO2
- (13) Emissions during retail= (R emissions S2*Total Supply)/1e+06 Units: M tons of CO2
- (14) Emissions during Use= (Stocks of clothes in use*U emissions S2)/1e+06 Units: M tons of CO2
- (15) Emissions global transport = (T global emissions S2*Production)/1e+06 Units: M tons of CO2
- (16) Emissions local transport= (T local emissions S2*Total Supply)/1e+06 Units: M tons of CO2
- (17) exported second-hand clothes= exports Units: tons per year
- (18) exports=rate of export*separate collection of used clothes Units: tons per year
- (19) FINAL TIME = 2050 Units: Year The final time for the simulation.
- (20) flowback of second-hand clothes=redistribution rate*separate collection of used clothes Units: tons per year
- (21) I emissions S4: INTERPOLATE: Units: tons of CO2 per ton of clothes
- (22) imports in history ([{(0,0) - (10,10)}, (2000,25812), (2001,23990), (2002,26200), (2003,29510), (2004,29885), (2005,32425), (2006,32435), (2007,33890), (2008,35466), (2009,30973), (2010,35178), (2011,38531), (2012,32388), (2013,35389), (2014,37060), (2015,38645), (2016,41349), (2017,42241), (2018,42633), (2019,42205), (2020,40700), (2021,48500),(2022,52739)) Units: **undefined**
- (23) INITIAL TIME=2000 Units: Year The initial time for the simulation.
- (24) lifetime of firsthand use=IF THEN ELSE (Time<2025, 4, 8) Units: Year
- (25) lifetime of second-hand use=IF THEN ELSE(Time>2025, 4, 2) Units: Year
- (26) P emissions S4: INTERPOLATE: Units: tons of CO2 per ton of clothes
- (27) population: INTERPOLATE: Units: **undefined**
- (28) Production=IF THEN ELSE (Time<2025, total imports, assumed constant demand per capita *population-available clothes to be reused) Units: tons per year
- (29) R emissions S4: INTERPOLATE: Units: tons of CO2 per ton of clothes
- (30) rate of export= IF THEN ELSE(Time>2024, IF THEN ELSE (Time<=2045, (0.25- change in future rates/2- 0.4)/ (2045-2024) *(Time-2024) +0.4, 0.25- change in future rates/2), 0.4) Units: Dmnl
- (31) redistribution rate= IF THEN ELSE(Time>2024, IF THEN ELSE (Time<=2045, (0.5 + change in future rates -0.2)/ (2045-2024) *(Time-2024) +0.2, 0.5 +change in future rates), 0.2) Units: Dmnl
- (32) SAVEPER =TIME STEP Units: Year [0,?] The frequency with which output is stored.
- (33) Sent for incineration= collection of second-hand clothes + collection in household waste + discarded clothes Units: tons per year

- (34) separate collection of used clothes= DELAY FIXED (supply of new clothes*separate collection rate, lifetime of firsthand use, 0) Units: tons per year
- (35) separate collection rate= IF THEN ELSE (Time>2024, IF THEN ELSE (Time<=2045, (0.95-0.33)/ (2045-2024) *(Time-2024) +0.33, 0.95), 0.33)
Units: Dmnl
- (36) Sorting=separate collection of used clothes-discarded clothes-exports-flowback of second-hand clothes Units: tons per year
- (37) Stocks of clothes in use= INTEG (supply of new clothes + supply of old clothes-collection in household waste-collection of second-hand clothes-separate collection of used clothes, 0) Units: tons per year
- (38) sum of stocks=Stocks of clothes in use/population Units: tons per person
- (39) supply of new clothes=Production Units: tons per year
- (40) supply of old clothes=available clothes to be reused Units: tons per year
- (41) T global emissions S4: INTERPOLATE: Units: **undefined**
- (42) T local emissions S4: INTERPOLATE: Units: **undefined**
- (43) TIME STEP = 1 Units: Year [0,?] The time step for the simulation.
- (44) total imports= conversion Units: **undefined**
- (45) Total Supply=supply of new clothes + supply of old clothes Units: **undefined**
- (46) U emissions S4: INTERPOLATE: Units: tons of CO2 per ton of clothes

Annexure E

- i. Vensim Models
- ii. Emissions Calculations
- iii. Scenario wise analysis

These files are available in <https://odr.chalmers.se/home>



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