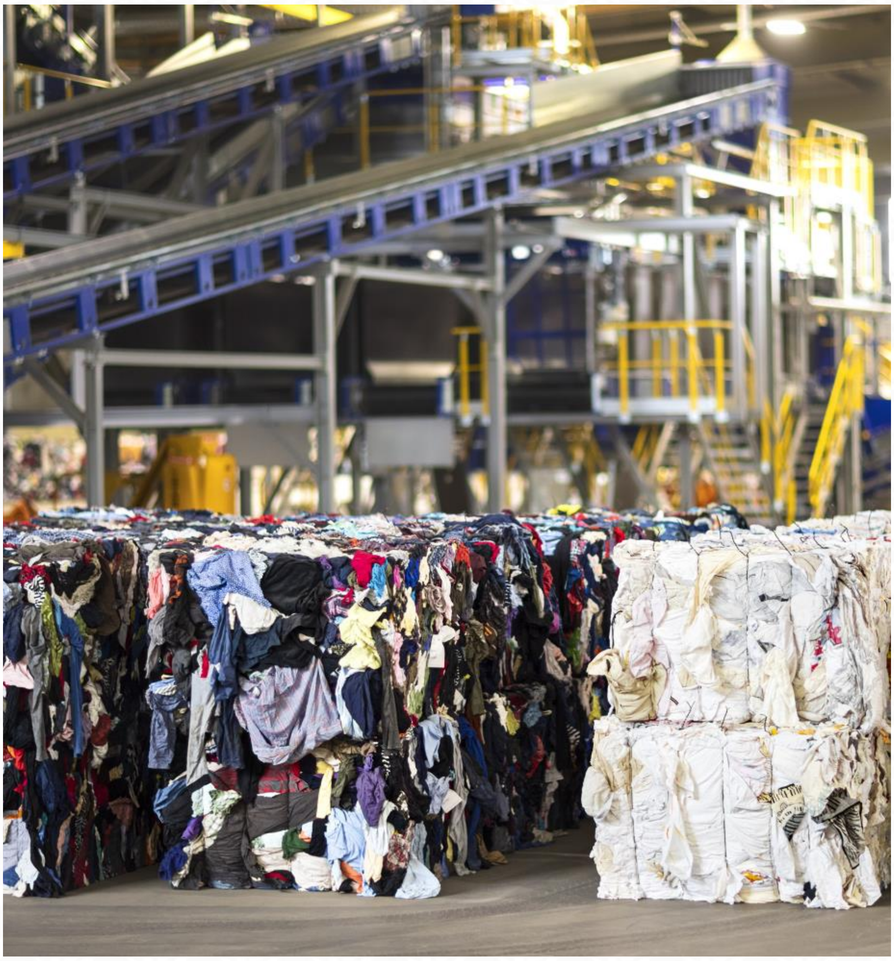

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# Siptex WP5 report: Life cycle assessment of textile recycling products

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# Summary

## Aim of the study

This report presents an environmental assessment of three recycling products of the automated textile sorting plant Siptex in Malmö, Sweden. The three recycling products are sorted fractions of certain fibre content – cotton fractions, polyester, and wool – suitable for recycling. Important is that the input materials to the automatic sorting have been pre-sorted and is not suitable for reuse. So, if not sorted to recycling, there is a high probability that the materials would enter the conventional end-of-life treatment route in Sweden: incineration with energy recovery.

The aim of the environmental assessment is to increase the knowledge of the environmental performance of the Siptex plant, in terms of reducing the incineration of textile waste and in providing the production industries with a new source of material fit for recycling. To fulfil the aim, six research questions are addressed, as outlined below under Conclusions and recommendations.

## Method and scope

The aim is addressed by means of screening life cycle assessments (LCAs) of four garments made of the three recycling products described above:

A. Cotton t-shirt made of 25% recycled and 75% primary cotton.

B. Viscose t-shirt made of 100% chemically recycled cotton.

C. Polyester sports jersey made of 100% chemically recycled polyester.

D. Wool sweater made of 100% mechanically recycled wool.

The LCA covers the full life cycle of each garment: collection of textile waste, pre-sorting, automatic sorting at the Siptex plant, recycling, production into end products, and end-of-life: incineration with energy recovery or collection for reuse or recycling again. Comparisons are made with comparable garments made of 100% primary material.

The results of the four case studies are scaled up to represent the Siptex plant run at full capacity, and the scaled-up model is used as a basis in a so-called consequential LCA to study the effect of large-scale implementation of the Siptex sorting technology in Sweden and Germany.

## Conclusions and recommendations

1. What are the environmental impacts of end products, produced from the three recycling products, in relation to identical end products produced from virgin material?

**The benefits of the recycling scenarios, compared to the benchmark scenarios, are largest in those impact categories where the production of primary material contributes to a large share of the life-cycle impact of the benchmark scenarios**. For case study A, the cotton t-shirt, the benefits are primarily in less arable land use and water deprivation impact, but probably also in less terrestrial and freshwater eutrophication impact. For case study B, the viscose t-shirt, the benefits

are in reduced use of primary energy (mostly renewable) and forest land. For case study D, the wool sweater, the benefits are in all the assessed impact categories.

For case study C, the polyester sports jersey, the benefits of recycling are not as obvious as for the other case studies, but there are likely benefits in freshwater eutrophication impact as well as reduced fossil resource use of about 10% (corresponding to the content of the product) and climate impact, also with about 10%, if considering the avoided incineration at end-of-life.

In general, the results indicate that **the main benefits of recycling arise when the production of primary materials is avoided**, rather than when the usual end-of-life treatment is avoided. This means that benefits rely on the actual substitution of primary materials, which may depend on, for example, the quality of products made of recycled materials and future EU policies.

That the benefits rely on the substitution of primary materials also means that **it is advisable to sort out and recycle materials based on the primary production they can substitute**.

The present report is on Swedish conditions, for countries with less-developed waste infrastructure and treatment, there are likely more benefits also with avoiding the usual end-of-lite treatment.

2. What is the environmental impact of sorting the textile waste so that it can be recycled, in contrast to the end-of-life treatment common in Sweden today: incineration with energy recovery?

**The environmental impact of the collection and sorting of textiles is minor compared to the life-cycle impact of the studied end products.** Even if collection is assumed to be done in a greater area, relying on longer truck transports, its contribution remains low.

The direct impact of incineration is also low compared to the life-cycle impact of textile products, for the assessed indicators. The most obvious direct effect of avoiding incineration is seen in case study C, where avoiding the incineration of the fossil-based primary material reduces the life-cycle climate impact by about 10%. That the effect of avoiding incineration in general is low, underlines the conclusions under research question 1 above, that the greatest differences between the recycling and benchmark scenarios are not related to avoiding incineration, but in avoiding production of primary material.

The assumed collection includes truck and ship transports, but not any car transport of the household discarding the textile. But if the household takes a car to the collection bin, this can significantly increase energy use and climate impact. It will, therefore, be **important to develop a collection system that does not heavily rely on households taking their cars to the collection bin**.

3. Which recycling products can reduce impact the most, and which have a lower or even negative environmental potential?

All assessed indicators showed lower environmental impact for a sweater made of sorted and recycled wool, compared to a sweater of primary wool, and for four of the indicators this benefit was very large, more than 90%. As such, **sorting wool appears to create the largest environmental benefits, per amount of sorted material**. But the availability of discarded wool is small compared to the availability of discarded cotton and polyester. So, in terms of the aggregated benefits of one sorting plant, the potential benefits of sorting other fractions may be greater compared to sorting wool.

After wool, the sorting of cotton to mechanical recycling, case study A, appears to show the greatest environmental benefits, if conventional cotton cultivation is thereby avoided. However, the recycling scenario in case study A relies on input of primary material, in contrast to case studies B and C. This is a potential advantage of case studies B and C, especially in a future where recycling is done at large scale globally, so that the volumes of available recycled and primary materials are comparable.

**None of studied recycling scenarios create a clear increase of the environmental impact**, compared to the benchmark scenarios. Some scenarios show a small increase for some impacts, but within the uncertainty range. Although uncertain whether this is an actual increase, this emphasizes the **need to keep track of the environmental impact when developing the collection system and products made of recycled material**.

4. Which life-cycle stages contribute the most to the life-cycle environmental impact – collection, sorting, recycling, production, use, or end-of-life?

For case studies A-C, **raw material extraction for fibre production is the most important process for water deprivation, land use, and some of the eutrophication indicators**. **For other indicators –** primary energy use, fossil resource use, climate impact – **the subsequent production dominates**, as well as the **use stage**. For case study D, the results pattern is different, as **wool production (primarily sheep grazing) is the dominant life-cycle stage, or one of the most contributing life-cycle stages, for all studied indicators**.

For cotton, viscose and polyester garments, **processes after fibre production contribute to about 75-90% of the climate impact**. This implies that **material recycling is only one of many solutions needed to reduce the climate impact of the textile industry**. Much else is needed, most importantly more use of each garment (e.g., by increased longevity and more reuse), use of low-carbon energy in production, and business models that do not rely on car transports. In addition, sorting plants located in or nearby Sweden can potentially mitigate climate impact by facilitating some of the other changes needed, if it enables subsequent production stages to relocate to or nearby Sweden, where access to low carbon energy is better.

A key observation is that the **direct environmental impact of the Siptex plant is insignificant in comparison to the life-cycle impact of products made of the sorted materials**.

5. By extrapolating to the annual capacity of the Siptex plant, what is an estimate of the environmental benefits (if any) created by the plant each year?

For water deprivation, **the impact of the scaled-up recycling scenarios is 22% lower than the impact of the benchmark scenarios** – a difference that almost solely is accredited to the 25% primary cotton, and associated water deprivation impact, "avoided" in the recycling scenario of case study A. In absolute numbers, **this corresponds to about 10% of the water deprivation impact caused by Swedish clothing consumption** in one year. This figure shall be seen as an indication of the order of magnitude of the potential water deprivation benefits of the Siptex plant. Similar benefits are expected also for the land use indicators.

For use of primary energy resources and climate impact, the differences between the recycling scenarios and the benchmark scenarios using primary materials are much smaller than for water deprivation. Potential climate-impact and energy-resource benefits of cotton and polyester recycling depend on collection and recycling that is efficient and/or powered by low-carbon energy. **That the benefits of cotton and polyester recycling are not more evident for these indicators, is because about 75-90% of the climate impact of clothing made of these materials are not due to the fibre production, but because of later production stages** – and these remain the same regardless of whether primary or recycled materials are used.

6. What are the environmental consequences of implementing the Siptex sorting technology on a large scale?

The consequential outlook underlines the results of the scaled-up model discussed under research question 5 above: **large-scale automatic sorting reduces water deprivation impact as it reduces the need for cotton cultivation**. This benefit is likely to remain even though a lower substitution rate is assumed.

In terms of climate impact and the effects of large-scale implementation of automatic sorting, the consequential outlook indicates that **whether there will be a net climate benefit of large-scale implementation will depend on several factors**. If there are benefits, these benefits are up to about 10% of the life-cycle climate impact of textile products made of the sorted and recycled materials. As mentioned above, other changes are needed for the textile industry to reduce its climate impact in line with the internationally set climate targets.

# 1 Introduction

## 1.1 About this report

This report presents a life cycle-based environmental assessment of three recycling products of the automated textile sorting plant Siptex in Malmö, Sweden. The three recycling products are sorted fractions of textile waste of certain fibre content – cotton, polyester, and wool – suitable for different recycling routes. Important is that the input materials to the automatic sorting have been, in a pre-sorting process, deemed not suitable for reuse. So, if not sorted to recycling, there is a high probability that the materials would enter the conventional end-of-life treatment route in Sweden: incineration with energy recovery.

The overall aim of the environmental assessment is to increase the knowledge of the environmental performance of the Siptex plant, in terms of reducing the incinerating of textile waste and in providing the production industries with a new source of material, fit for recycling.

Two main questions are addressed:

1. What are the environmental impacts of end products, produced from the three recycling products, in relation to identical end products produced from primary material?

2. What is the environmental impact of sorting the textile waste so that it can be recycled, in contrast to the end-of-life treatment commonly used in Sweden today: incineration with energy recovery?

In addition, several sub-questions are addressed, see Section 2.1.

Above questions are addressed by means of screening life cycle assessments (LCAs) of four garments made of the three recycling products. For each case study, the LCA covers environmentally relevant processes in the full life cycles of the garments, from cradle to grave, i.e. from the collection of textile waste, via pre-sorting, automatic sorting at the Siptex plant, recycling, production into end products, to end-of-life: incineration with energy recovery or collection for reuse or recycling again. Comparisons are made with functionally equivalent garments made of primary (virgin) resources.

The screening LCA is based on attributional modelling, which means that the LCA aims to map the share of the global environmental impact that can be attributed to the studied product systems. This is the most common LCA modelling approach and reflects what a manufacturer typically will be able to communicate in terms of the environmental performance of its product, for example in environmental product declarations (EPDs). However, for exploring the environmental *consequences* of implementing the Siptex sorting plant at large scale, consequential LCA modelling is used. Therefore, a screening LCA based on consequential modelling was also carried out. This complements the learnings derived from the four case studies.

The LCA study is primarily intended to be used internally within the Siptex project and within the partners’ organisations.

The work was carried out by IVL Swedish Environmental Research Institute in work package 5 (WP5) of the Siptex project.

## 1.2 What is LCA?

Life cycle assessment (LCA) is a method for assessing the environmental impacts of products in a life-cycle perspective. LCA is a widely used and accepted method for studies of environmental performance of products (goods and services).

The LCA method includes four phases. The first phase is the **goal and scope definition**, in which the intended aims, uses and audiences of the LCA are defined along with the system boundaries, data quality requirements and other aspects of the scope and method of the study. The next phase is the **life-cycle inventory (LCI) analysis**, which includes a mapping of resource use and emissions of all environmentally relevant life-cycle stages, such as raw material extraction, material production, manufacturing, use and maintenance, and end-of-life. These inventory flows are then translated to environmental impacts in the third phase, the **life-cycle impact assessment (LCIA)**, by means of life-cycle impact assessment methods (also called characterisation methods). In the final phase, the **interpretation**, the LCIA results are interpreted by using contribution analysis, sensitivity analysis and other types of analyses to draw conclusions and make recommendations in line with the defined goal and scope. A schematic overview of the LCA method is shown in Figure 1. Notice that the method is iterative, for example, the goal and scope may need to be redefined when doing the inventory analysis due to difficulties in finding LCI data.

The LCA method is defined in the ISO 14040:2006 (ISO 2006a) and ISO 14044:2006 standards (ISO 2006b). The present study consists of four **screening LCAs**, which means that not all requirements of the ISO standards have been fulfilled, for example the different analyses of results to be done in the interpretation phase. This simpler version of LCA was chosen as it was deemed sufficient for the purpose of the study and due to limited time and resources.

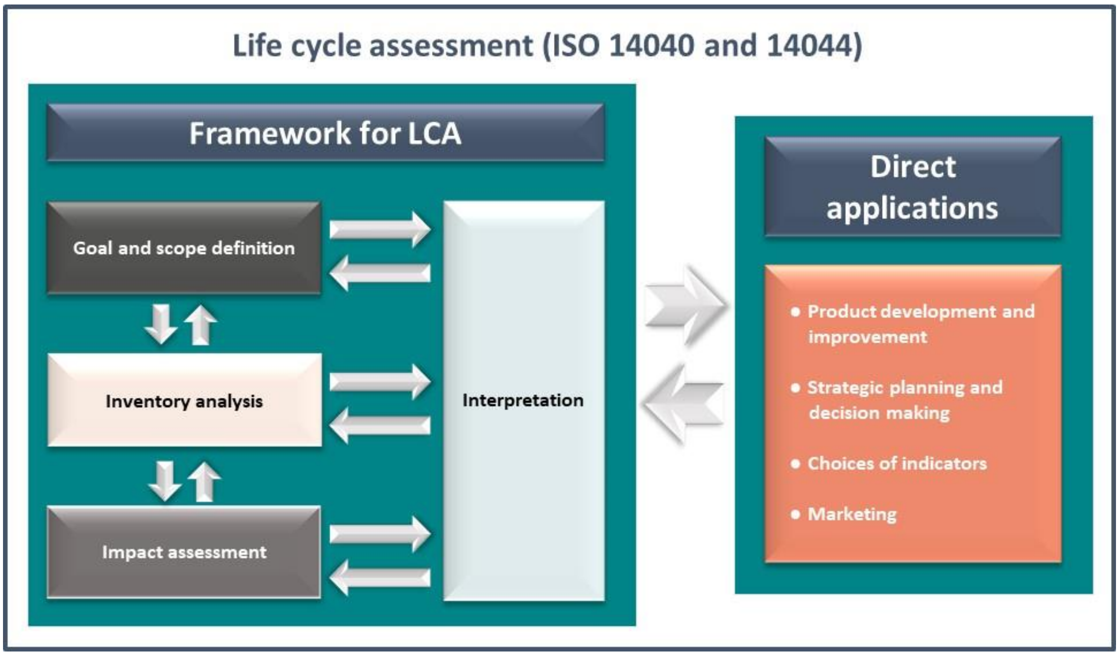

Figure 1: Illustration of the LCA method.

# 2 Goal and scope definition

In this chapter, the goal and scope of the study is defined and explained. The goal and scope definition acts as a guideline for performing the assessment and helps the reader of the report to understand key assumptions, system boundaries, limitations and other aspects influencing the results.

## 2.1 Goal

The study has the main goals of answering the following two questions:

1. What are the environmental impacts of end products, produced from the three recycling products, in relation to identical end products produced from virgin material?

2. What is the environmental impact of sorting the textile waste so that it can be recycled, in contrast to the end-of-life treatment common in Sweden today: incineration with energy recovery?

The questions below are also addressed:

3. Which recycling products can reduce impact the most, and which have a lower or even negative environmental potential?

4. Which life-cycle stages contribute the most to the life-cycle environmental impact – collection, sorting, recycling, production, use, or end-of-life?

5. By extrapolating to the annual capacity of the Siptex plant, what is an estimate of the environmental benefits (if any) created by the plant each year?

Above questions are addressed by means of four LCA case studies (see Section 2.2) using attributional modelling (see Section B). In addition, we use consequential LCA modelling (see Section B) to address the following question:

6. What are the environmental consequences of implementing the Siptex sorting technology on a large scale?

By answering the above questions, the study can, for example, be used to:

- Identify and quantify the environmental benefits and risks **of the project** and **the Siptex sorting plant**.

- As a basis for decisions on what **inbound materials** and **recycling products** to prioritise, and how to **design specific product value chains**.

- For partners to **communicate,** internally and externally, the **environmental benefits** of sorting/recycling.

- Provide an **indication of the environmental effects of large-scale implementation** of the Siptex sorting technology, for example to what extent it can contribute to achieving the politically set climate targets.

Although the report is publicly available, the LCA study is primarily intended to be used internally within the Siptex project and within the partners' organisations. The project and the partners may communicate the public results externally, for example that LCA has been used to assess the Siptex plant and generic products made of the sorted fractions, and what the results indicate. However, as the assessment is based on screening LCAs of preliminary and generic product systems, external communication of specific claims related to specific products shall not be based on the present report.

## 2.2 Studied product systems

The four studied products and their benchmarks are as follows:

A. Cotton t-shirt made of 25% mechanically recycled cotton and 75% primary cotton[1].

   Benchmark: t-shirt of 100% primary cotton.

B. Viscose t-shirt made of 100% chemically recycled cotton.

   Benchmark: t-shirt of viscose made from primary resources.

C. Polyester sports jersey made of 100% chemically recycled polyester.

   Benchmark: Sports jersey of polyester made of primary resources.

D. Wool sweater made of 100% mechanically recycled wool.

   Benchmark: Sweater of primary wool.

In all case studies, the input feedstock (cotton, polyester, or wool) includes a small share of other materials. For example, the cotton fraction to mechanical recycling includes up to 10% of non-cotton materials, which is the maximum content acceptable in the subsequent mechanical recycling process. More on this in the descriptions of each case studies in Section 3.

The case studies were selected to reflect important fractions that are, or can be, sorted out by the Siptex plant, as well as different subsequent recycling routes (chemical as well as mechanical recycling). Fractions of cotton and polyester are frequently sorted out, and wool can potentially be sorted out in the future. Furthermore, common, and relatively simple garments were selected, which are rather similar in their environmental impact to other relatively simple textile articles. For example, the production of t-shirts is similar to the production of simple home textiles made of the same fibre type.

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[1] In earlier versions of the results of this report, which has been communicated for example in the Siptex summary report, the share of recycled material in case study A was 50%. This was changed to 25% as a response to the internal review of the report.

Note that all case studies reflect hypothetical future product systems. As such they do not represent any specific and existing value chains.

In addressing question 7, the four case studies are used as the basis for an exploration of consequences of large-scale implementation of the Siptex technology in two scenarios:

A. Implementation of annual sorting of 50 000 tonnes of mixed textile waste in Sweden, in relation to a business-as-usual scenario.

B. Implementation of annual sorting of 300 000 tonnes of mixed textile waste in Germany, in relation to a business-as-usual scenario.

## 2.3 Type of LCA

The LCAs performed to address questions 1-6 above are based on attributional LCA modelling, also called book-keeping LCA. This means that the modelling aims to estimate the share of the global environmental burdens that can be attributed to each studied product system. Typically, such modelling considers the environmentally relevant processes physically connected to the product under study and models such processes using average data. This is the most common LCA modelling approach and reflects what a manufacturer typically will be able to communicate in terms of the environmental performance of its product, for example in environmental product declarations (EPDs).

However, for exploring the environmental *consequences* of implementing the Siptex sorting plant at large scale, it is suitable to use consequential modelling, which therefore is used to address question 7 of the present study. Consequential modelling aims to estimate how the environmentally relevant physical flows change as a consequence of the studied product or changes done to the product system, for example if it is scaled up. Typically, this also includes processes which are not physically connected to the product but are influenced through market mechanisms (e.g., avoided production). Furthermore, if physically connected processes are not influenced by the studied change, these should be omitted in a consequential study. The consequential model of the present study is further described in the Section 2.11.

Attributional LCA is a reasonable choice in relation to the two main goals of the study. Foremost, it enables the Siptex project and its partners to learn about the life-cycle environmental performance of potential recycling products and subsequent end products. In addition, the results will reflect the environmental performance that manufacturers utilising the sorted fractions will eventually be able to claim in communication of environmental information business-to-business or business-to-consumers. However, the consequential model will complement these results with insights on the effects of large-scale implementation of the Siptex technology.

Note that there is not a universally agreed definition of what an attributional or consequential LCA study is, and many LCAs have elements that can be argued to belong to both types of LCAs (Finnveden et al. 2022). So that we refer to our studies as attributional and consequential, respectively, is a simplification.

## 2.4 Functional unit

A functional unit reflects the function of the studied system and is the unit to which the LCA results are related, i.e., in terms of "X kg $CO_2$ equivalents per functional unit".

The functional unit for the attributional LCA of the four case studies is **one garment**. Note that one cotton t-shirt is not comparable with a polyester sports jersey or a wool sweater since they provide different functions – so the results per garment shall not be compared across case studies.

Note that in LCAs of clothing, we generally recommend "one use of a garment" as the functional unit, as this allows you to see the influence of prolonging the number of uses before the final disposal – which is one of the most powerful ways to reduce the environmental impact of clothing (Sandin et al. 2019a). But as the focus of the present study is not on the use stage, and we do not explore reuse or other scenarios for prolonging the number of uses, we chose "one garment" as the functional unit as it is easier and more intuitive to understand.

The functional units for consequential outlook, in which we look at the future large-scale implementation of the Siptex technology, are for the two scenarios outlined Section 2.2:

A. Automatic sorting of 50 000 tonnes mixed textile waste.

B. Automatic sorting of 300 000 tonnes mixed textile waste.

## 2.5 System boundaries

The study has a cradle-to-grave perspective. This means that in the attributional LCA of the four case studies, all environmentally relevant processes from the collection of textile waste (or raw material extraction, for the benchmarks) to the end-of-life of the end product are included.

Figure 2 shows a generic overview of the studied product systems. Retailing has been excluded as it has been found to be insignificant in terms of environmental impact (Sandin et al. 2019a). Note that the figure is not fully representative for all case studies, for example there is no fibre production in case of mechanical recycling, i.e., in case studies A and B. In the benchmarks, the collection and sorting is replaced by raw material extraction, which is cotton cultivation (case A), forestry (case B), extraction and refinement of petroleum products (case C), and sheep farming (case D). Also, note that the processes in Figure 2 are so-called foreground processes; there are also background processes included in the model: production of energy and materials used in the foreground processes.

More specific system diagrams for each case study, including the benchmarks, are included in Section 3.

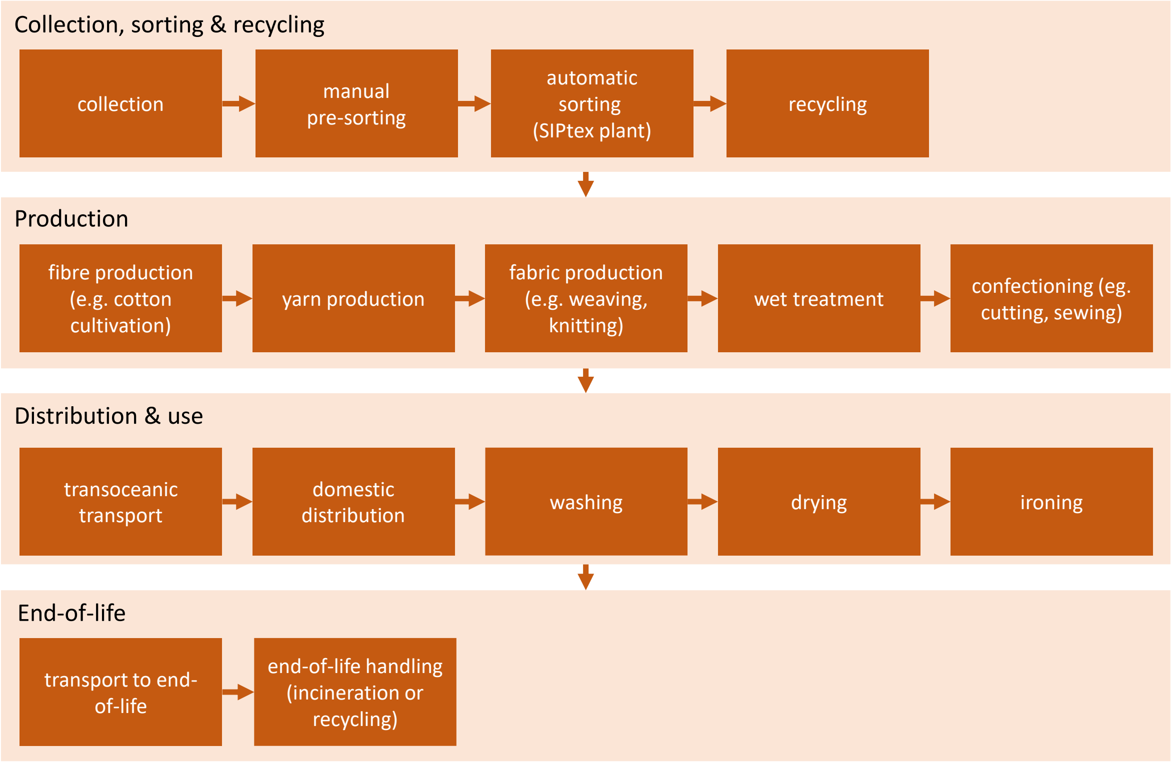

**Figure 2. A generic overview of the processes of the studied product systems. Some case studies deviate from this figure, as described in Section 3.**

Collection of textile waste is the starting point of the product system because this is when the input material has its lowest economic value, and therefore is the first process to be assigned to the product system using the textile waste according to the chosen allocation method (Section 2.6). Depending on scenario, end-of-life here refers to either waste incineration with energy recovery, or the point at which the user disposes of the product before it is collected to be sorted and subsequently reused or recycled again (i.e., the point right before the starting point of the product system using the recycled material). Section 2.8 describes the scenarios in greater detail.

In the consequential LCA, the system boundaries are different, see Section 2.11.

### 2.5.1 Boundaries towards nature

The inventory flows are tracked from "the cradle" where natural resources (e.g. crude oil or wood) are extracted, until "the grave", where emissions are emitted to soil, air (e.g. emissions from combustion of fuels) or water (e.g. water emissions from wastewater treatment).

### 2.5.2 Geographical boundaries

The choices of geographical system boundaries in production are chosen to represent generic and common clothing in Sweden. Since this is a screening LCA, we sometimes make simpler choices than done in the study on Swedish clothing consumption from which much of the LCI data is taken: Sandin et al. (2019a). For example, instead of yarn, fabric, and garment production in several Asian countries, we assume production only in China. This is, however, deemed to not influence the results much, as the main difference between countries is the energy sources used, and the dominating textile-producing countries all have relatively carbon-intensive electricity mixes.

The geographical boundaries are described in more detail below.

The collection of the textile waste occurs in the south of Sweden in one scenario and in a greater part of Sweden, or neighbouring countries, in another scenarios. The manual pre-sorting is located in Lithuania and the automatic sorting, i.e., the Siptex plant, is located in Malmö, Sweden.

The recycling of cotton is assumed to take place in Southern Europe, the recycling of cotton to viscose in Sweden, the recycling of polyester in China, and the recycling of wool in India.

The production of the yarn, fabrics and garments is assumed to occur in China for all case studies, except for case study D where the production takes place in India.

The use of each garment is assumed to take place in Sweden, and this is where the end-of-life scenarios are assumed to take place as well.

For the primary feedstock of the benchmarks, cotton cultivation in case study A is assumed to take place globally (i.e., the dataset reflects a global average, which accounts for conditions in four large cotton-producing countries: Australia, China, India and USA), forestry and conventional pulp production in case study B are assumed to take place in Sweden, the primary EG and PTA production in case study C is assumed to take place in China, and the primary wool production, including sheep grazing, in case study D, is assumed to take place partly in Australia and partly in India.

For one of the scenarios of the consequential outlook, the geographical boundaries differ, as the collection and sorting are assumed to occur in Germany.

More information on geographical boundaries can be found in Section 3 and Appendix B.

### 2.5.3 Temporal boundaries

The product system models of case studies A-D aim to represent the situation today, so in selecting data we have chosen as recent data as possible, while still reflecting the desired technology and geographical scope.

The exception is the consequential outlook, in which the scenarios studied are deemed to be realistic sometime in the years 2030 to 2040 – but as a simplification, data on current technologies were assumed to represent future marginal technologies. More information on this is provided in Section 2.11 and Section 3.6.

More information on the chosen LCI data sets, their geographical scopes, reference years and original sources can be found in Appendix B.

### 2.5.4 Boundaries towards other technical systems

As there are inputs from other technical systems in terms of textile waste, there is a need to define the boundaries between these systems and the studied system. In the attributional LCA of the four case studies, allocation is handled with the cut-off method, as is described in Section 2.6. The method used in the consequential LCA is outlined in Section 2.11.

## 2.6 Allocation methods

An important allocation problem for systems using recycled textile material as input is the allocation of the environmental impact of the original resource extraction and material production as well as the collection, sorting, and recycling processes. In the four case studies, the cut-off method for modelling allocation is used. This is sometimes called simple cut-off, the recycled content approach or the 100/0 method (Ekvall et al. 2020). The method makes a cut-off at some point in the material flow and allocates all environmental burdens of processes before this point to the product system generating the waste, and all environmental burdens of processes after this point to the user of the waste/recycled material. The cut-off point can for example be set at the point when all the criteria for the end-of-waste state have been fulfilled, as outlined by the EU Waste Framework Directive (EC 2021a), or when the material has the lowest value (which may be when it has reached the end-of-waste state).

The cut-off method was chosen as it (i) aligns with the attributional LCA modelling approach of the four case studies, (ii) is a common method in LCAs of recycling systems (e.g. in EPDs), and (iii) is a straightforward method to apply from a modelling perspective (an important aspect in screening LCAs). Furthermore, the point when the material has its lowest value has been chosen as the cut-off point, which is when the user discards the material, i.e., right before the material is transported to a collection bin or a collection facility. The cut-off method means that the recycled material is considered free of environmental burden from its previous life cycles, i.e., it does not come with a rucksack of environmental impact. In addition, the method means that all environmental impact of subsequent transporting and processing of the material is 100% allocated to the product system utilising the material.

At the end-of-life of each garment, two scenarios are considered: the garment is sent to incineration with energy recovery or is once again collected for sorting and subsequent reuse or recycling. In both these scenarios, cut-off allocation is applied. In the latter scenario, the system boundary to the next product system is placed when the user discards of the garment, i.e., at the same place as it was placed in the beginning of the product life cycle. In the former scenario, the “polluter pays” principle is applied, which means that the cut-off is placed where the waste material ceases to be waste, which is typically after the incineration. In other words, (i) environmental impact of incineration is assigned to the product system generating the waste, i.e., the four studied product systems; (ii) the recovered energy (electricity and heat) leaves the studied product systems without environmental burden, i.e., from the perspective of the user of this energy, the energy is free of environmental impact; and (iii) credits for the use of the recovered energy (e.g., that it replaces some other means of energy production) is not assigned to the studied product systems.

The interested reader may read more about the cut-off method and alternative allocation methods in Ekvall et al. (2020). An important alternative method described by Ekvall and colleagues is the Circular Footprint Formula (CFF) used in EU’s Product Environmental Footprint (PEF) method (EC 2021b). This method is a more complex method that will probably have considerable impact on future EU legislation, and therefore how environmental benefits of recycling should or shall be allocated within the EU. The CFF considers, for example, the quality of recycled materials in relation to the quality of primary materials (and the balance between supply and demand for such materials). The latter balance between supply and demand is expressed in the material-specific A factor, which can be set to 0.2, 0.5 or 0.8. For textiles, the A factor is 0.8, which means that recycled textiles carry 20% of the burden of the primary material production. So if the CFF would have been applied, instead of the cut-off method, the benefits of recycling would be lower than assessed in the present study. It would be interesting to study the effect of applying the CFF on textile products made of recycled materials in a future study.

For allocation method used in the consequential LCA, see Section 2.11.

## 2.7 Limitations and key assumptions

Below is a summary of key assumptions made in the LCA. These assumptions, and their expected influence on results, are elaborated on in other parts of the report. For more key assumptions on the scaled-up model or the consequential outlook, see Sections 3.5 and 3.6.

- Environmental impact of retailing, as well as infrastructure and capital goods of the foreground system[2] (e.g., the building of production plants), are excluded in all case studies.
- Some potentially relevant environmental impacts are not considered, such as toxicity. And even though several indicators of land use (arable, pasture and forest land) are considered, the environmental impacts of land use, for example on biodiversity, has not been quantified.
- In comparing the recycling and benchmark scenarios, a substitution rate of 1:1 is assumed, i.e., that a garment made of recycled material replaces an equivalent garment made of primary material. This is also assumed in the consequential outlook.
- To allocate the environmental impact of the input textile waste, the cut-off method is applied. This means that the material comes without any environmental burden from previous life cycles, but the entire environmental burden of collection, sorting and recycling are allocated to the product system utilising the recycled material.

The assumptions made, and the fact that this is a screening LCA, make it necessary to be cautious in interpreting the results. Particularly, it is important not to generalise to specific product systems based on the results of the generic system models of the present study.

## 2.8 Scenario and sensitivity analysis

To address the second goal of the study, two end-of-life scenarios (scenario 1 and 2) are explored for each case study:

1. Incineration with energy recovery[3]. This is currently the common end-of-life treatment of textile waste in Sweden and shall thus be considered the baseline scenario.
2. Recycling, i.e., the discarded garment is once again sorted and sent to reuse or material recycling.

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[2] Infrastructure and capital goods are included in some of the LCI datasets used to model the background systems.

[3] Note that although energy is recovered, this has no influence on the results because of the allocation method applied, see Section 2.6, except for in the consequential outlook, see Section 2.11.

An alternative collection scenario is also explored – scenario 3 – to test the influence of extended collection routes. In the default collection, which is assumed in scenario 1 and 2 above, collection takes place in Skåne in southern Sweden. In scenario 3, an additional 500 km truck transport is added in collection, which represents a scenario in which collection is done in a greater part of Sweden or in neighbouring countries (e.g., Denmark or northern Germany). This scenario is only added for case study A. In this scenario, the end-of-life stage is modelled according to scenario 1 above.

For scenarios of the consequential LCA, see Sections 2.11 and 3.6.

## 2.9 Data collection

The models are based on a mix of primary data, selected generic data from literature and databases, and proxy data from literature and databases.

Primary data have been collected for the foreground processes of collection, pre-sorting, and sorting based on the actual situation of the Siptex plant and its supply chain in 2021.

Selected generic data from literature and databases have been collected for most of the subsequent life-cycle stages: from recycling to end-of-life. This is data that are deemed to be technologically, geographically, and temporally representative for the processes of the four case studies. For case studies A-C, most of the foreground data for these life-cycle stages are from a report carried out in the research programme Mistra Future Fashion on the environmental impact of Swedish clothing consumption (Sandin et al. 2019a). For case D, most of the foreground data for these life-cycle stages are from the literature (Wiedemann et al. 2020, 2022; Martin and Herlaar 2021). The main source of data for the background processes is the Gabi Professional database (version 2022.1) provided by Sphera (2022), complemented by data from the Ecoinvent database (version 3.8) provided by Ecoinvent (2022), when no representative data were available in the Gabi Professional database.

For some processes, especially the recycling processes, there is a lack of available, fully representative data, and therefore proxy data are used. This is data on similar processes that are, for the purpose of the study, deemed to be sufficiently representative in terms of their environmental impact. Each choice of proxy data is described and justified in Section 3.

Data collection and the collected data are further described in Section 3.

## 2.10 Selected impact categories

The selected impact and resource use indicators and their characterisation methods are presented in Table 1. The indicators are chosen as they represent important environmental issues of the textile industry: climate change, eutrophication, water deprivation, and the use of scarce resources: land, energy, fossil fuels. The characterisation methods are chosen because they are commonly used in LCA. For example, the three methods for characterising eutrophication impact are used in PEF (EC 2021b) and in EPDs (EPD International 2022).

For land use, three indicators are used, considering how much of arable, pasture/grassland and forest land that is used – but the environmental impacts of these land uses are not considered. There are more advanced methods available to assess land use, such as the LANCA method advocated by PEF, based on five indicators on soil quality. No such advanced method is used because the LCI data are deemed not to be robust enough to support such an impact assessment.

For the land use indicators, we show results only for the land type(s) that is/are most relevant for the foreground processes of each case: arable land use for case A, forest land for case B, and pasture/grassland for case D. If all land indicators were shown for all cases, there would be very small numbers for some land use types for some cases, and differences between scenarios would be due to the selection of datasets for the background systems (e.g., variations in small inputs of bioenergy), rather than real differences in the foreground systems.

Toxicity is perhaps the most important environmental issue not covered at all by this study. The most viable alternative to assess toxicity today is the USEtox method, which is advocated by PEF to characterise ecotoxicity and human toxicity impact. USEtox is not included in this study since the impact assessment methods and the available LCI data are deemed not robust enough to yield meaningful results.

Because of above reasons, LANCA and USEtox are not mandatory to declare in EPDs, and if included they shall be accompanied with a disclaimer stating the uncertainty of results and that the indicators shall be used with care (EPD International 2022). Out of the indicators included in the present report, water deprivation must be accompanied with the same disclaimer – so the water deprivation results are carefully interpreted in the present report.

For future studies, especially full LCAs, it is recommended to consider developments in land use and toxicity impact assessment methods and the underlying LCI data. If methods and data have improved, a more elaborate assessment of these impact categories is recommended.

A description of each impact and resource use category are found in Appendix A.

**Table 1 . Selected impact and resource use indicators.**

| Impact and resource use categories | Methods [unit] |
|---|---|
| Climate change | Global warming potential (GWP) baseline model of 100 years of the IPCC (based on IPCC 2013) [kg CO2eq.], excluding biogenic $CO_2$ |
| Eutrophication, marine | EUTREND model (Struijs et al, 2009) as implemented in ReCiPe [kg N eq.] |
| Eutrophication, freshwater | EUTREND model (Struijs et al, 2009) as implemented in ReCiPe [kg P eq.] |
| Eutrophication, terrestrial | Accumulated Exceedance (Seppälä et al. 2006, Posch et al. 2008) [mol H+ eq.] |
| Land use | Area and years of land use [m2*a]. Separating between arable, pasture and forest land. |
| Resource use, fossils | CML 2002 (Guinée et al. 2002 and van Oers et al. 2002) [MJ] |

| | |
|---|---|
| Water deprivation | Available WAter REmaining (AWARE) as recommended by UNEP (2016) [$m^3$ world eq.] |
| Energy use | Primary energy demand from ren. and non ren. resources (gross cal. value) [MJ] |

## 2.11 Consequential outlook

In the consequential outlook, we study the effect of future, large-scale implementation of the Siptex automatic sorting technology in Sweden and Germany, respectively. This is done by looking at the consequences of changing from a linear textile system to the circular textile system enabled by the Siptex technology. In contrast to the attributional LCA models of the four case studies, the consequential outlook considers effects beyond the system boundaries – for example, when the textile wastes are redirected from incineration with energy recovery to recycling, the energy that is no longer recovered is assumed to be replaced by other energy sources, which in turn cause environmental impact.

It shall be stressed that the consequential outlook is associated with larger uncertainties than the four attributional case studies, as some fundamental assumptions are uncertain (e.g., that sorting and recycling of a material leads to the substitution of an equal amount of primary material, or what the future marginal sources of heat and electricity in Sweden and Germany will be). As such, the results of the outlook are cautiously interpreted, and the focus is not on the numbers as such, but the learnings in terms of what the long-term consequences *could be* and what *parameters* that appear to determine these consequences. The model can be seen as a starting point for increasing the understanding of the environmental effects of large-scale implementation of the Siptex technology and increased textile recycling in general, and as a basis for more elaborate, future studies of the matter.

More details on the modelling of the consequential outlook can be found in Section 3.6.

## 2.12 Review procedure

This study and report have been internally reviewed and approved in accordance with IVL's audited and approved management system. Review has also been done by an LCA expert of one of the Siptex project partners. No other third-party review has been performed.

# 3 Life cycle inventory analysis

This section describes each case study, including the modelling of each life-cycle stage: the selection of data and main assumptions made. Modelling of the product systems has been done using the LCA software GaBi (version 10.6.2.9). More details on the data selected, including the specific LCI datasets used, are presented in Appendix B.

Although life-cycle stages of the four case studies are named in the same way, the processes they include, and their outputs, may differ. Most importantly, the recycling stage includes all processes for transforming the sorted textile materials into a material that can enter the regular textile production value chain, which then starts in the production stage. This means that for case D, recycling includes yarn spinning, whereas yarn spinning is part of production in cases A-C. This means that all processes after recycling are identical between the recycling scenarios using secondary feedstock from the Siptex plant, and their respective benchmark scenarios using primary feedstock.

Most LCI data used do not specify the location of water use. To calculate the water deprivation results, the chosen data thus had to been corrected, as described in the description of the water deprivation impact category in Appendix A.

There are some processes in the life cycles that are excluded in all case studies. First, retailing (e.g. heating for offices and stores and travelling of personnel) is excluded in all case studies as it has been found to contribute negligible to the life-cycle impact of clothing (Sandin et al. 2019a). Moreover, the construction of infrastructure (e.g. buildings) and capital goods (e.g. machinery used in manufacturing) are excluded, unless included in LCI datasets used for background processes (e.g., the construction of power plants is often included in the LCI datasets on electricity). This is common practice in LCAs of consumer goods, where the use of material and energy in manufacturing are often considerably higher than what was used to produce the infrastructure and capital goods used in manufacturing. If infrastructure and capital goods would be included, it should be included the recycling as well as the benchmark scenarios – and it is not expected to differ considerably between the scenarios. Related to this, it can be mentioned that the current Siptex plant is located in an old building, so no new building has been constructed. If a new building is constructed for a future plant for automatic sorting of textiles, it is recommended to make an LCA of the new building to assess its potential environmental impact in relation to the potential environmental benefits of the textile sorting thereby enabled.

## 3.1 Case A: Cotton T-shirt

In this case, a white, 110 g cotton t-shirt is produced, either from 25% recycled cotton via mechanical recycling and 75% primary cotton (recycling scenario), or from 100% primary, conventional cotton (benchmark). The definition of the garment and all processes after recycling are based on the cotton t-shirt model of Sandin et al. (2019a) – the t-shirt on which that model was used in shown Figure 3. Sections 3.1.1 to 3.1.6 detail the modelling of the recycling scenario, and Section 3.1.7 describes the benchmark model and how this differs from the recycling scenario.

The assumption of 25% recycled and 75% primary material in the recycling scenario is based on the fact that mechanically recycled cotton has lower quality than primary cotton, creating a need to blend with primary cotton (or other fibres) to achieve comparable quality of the end product as if only using primary material. How different shares of recycled materials influence the results is discussed in Section 4.1.

Figure 3. T-shirt on which the LCA model is based on (figure from Sandin et al. 2019a).

Figure 4 and Figure 5 show system diagrams of case study A, for the recycling scenario and the benchmark scenario. Transports between life-cycle stages are not shown in the figure.

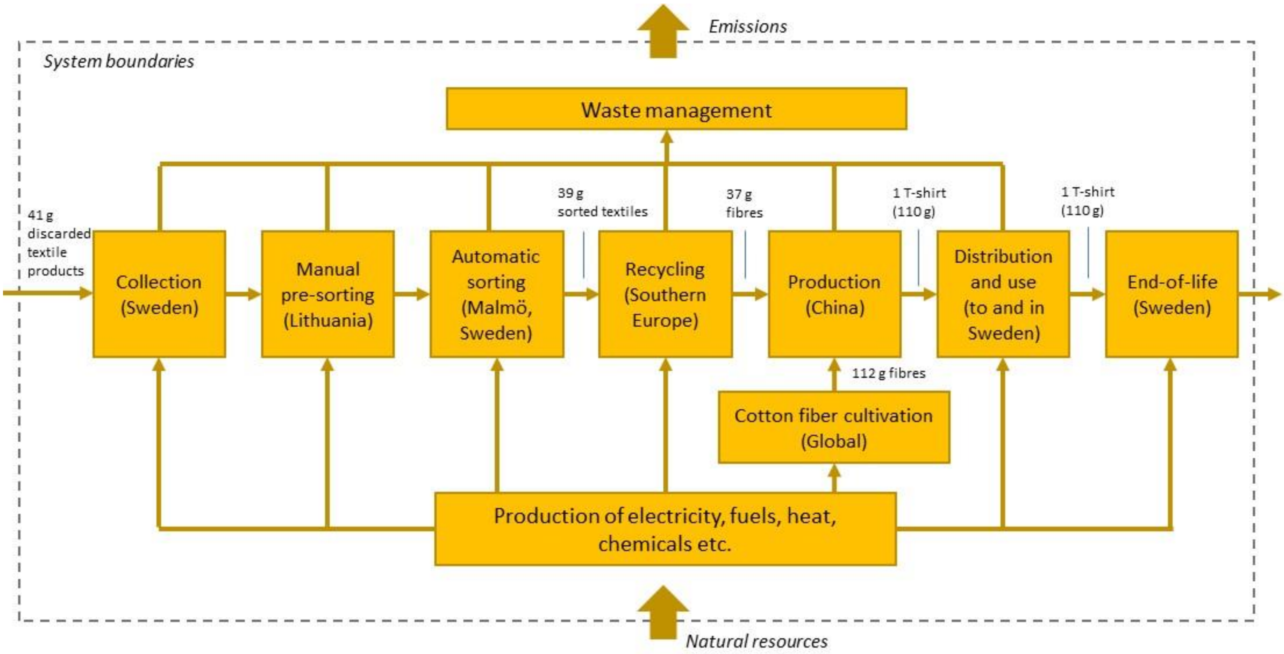

Figure 4. System diagram of the recycling scenario of case study A, a T-shirt made 25% recycled and 75% primary cotton.

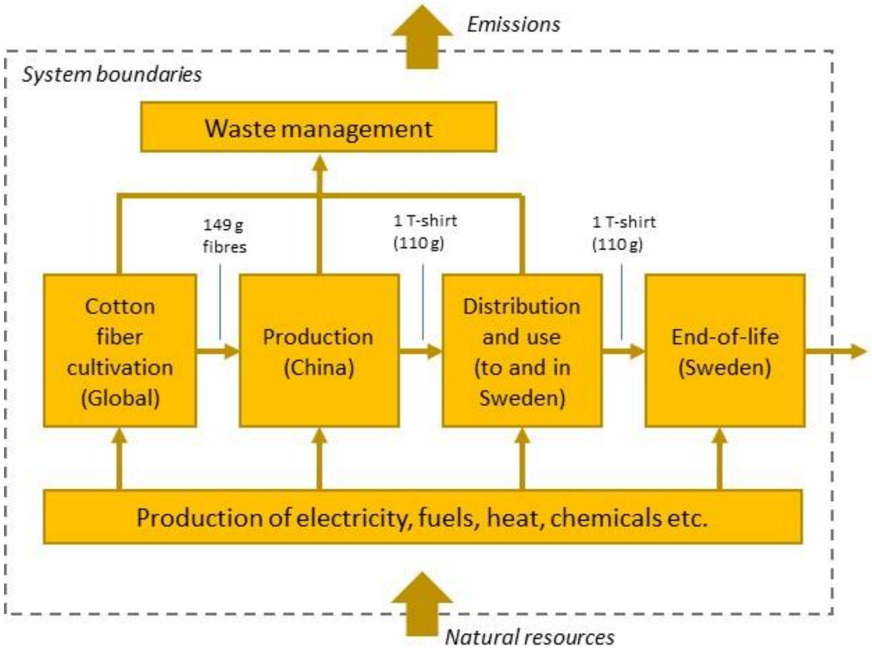

**Figure 5. System diagram of the benchmark scenario of case study A, a T-shirt made of primary cotton.**

### 3.1.1 Collection and sorting

The discarded textile product materials are, in this study, assumed to be collected at municipal recycling centres ("återvinningscentraler" in Swedish) in Sweden. As such, these flows consist primarily of post-consumer textiles from households. This is today common source of input textiles to the Siptex plant, that is expected to be common also in the future. However, input textiles can come from other sources, including pre-consumer textiles and more uniform post-consumer flows, such as discarded workwear from a specific company, as well as from other countries. For these situations, the present models on collection and pre-sorting may not be representative.

In the baseline scenario, collection takes place in the Skåne region of southern Sweden. Thereafter, the material is packaged (including a rough sorting), transported by truck to a harbour in Karlshamn, transported by ship to Vilnius, Lithuania, and finally by truck to Klapeida, Lithuania, which is the location of the pre-sorting facility. Transport distances, types of vehicles, filling degree, losses, and packaging materials are based on primary data provided by personal communication with Sysav as well as Klaus Rosinski in early 2022, representing practices of actual material collected for sorting in the Siptex plant in 2021.

In an alternative scenario, an additional 500 km truck is added to the collection, to reflect a situation in which textiles are collected in a greater part of Sweden – this is done to study the influence of transport distance. Results for this scenario is only shown for case study A, but the results and conclusions are valid also for the other case studies. This scenario should be representative also in case collection involves neighbouring countries close by, such as Denmark and northern Germany.

Note that collection is not assumed to include any user transport, i.e., for example a potential transport of the previous user of the t-shirt to deposit the garment at a municipal recycling centre or some other site for collection bins. Only the truck transport *from* the collection bin, and later ship transports to the sorting facilities, are included. In one of the end-of-life scenarios, however, a user transport to a collection bin is included, see Section 3.1.6.

In the manual pre-sorting, in Lithuania, textiles are sorted out to various fractions. Apart from fractions suitable for automatic sorting, these may be clothing suitable to reuse, textiles deemed to be directly suitable for a specific recycling route, or textiles that are of such poor quality that they go to incineration with energy recovery. We have allocated the environmental impact of the pre-sorting, as well as previous processes (packaging and transports from collection to pre-sorting), to the different outputs based on mass.

Site-specific data on the manual pre-sorting in Lithuania were not collected. Instead, we used literature data from Spathas (2017), on manual textile sorting aided by machinery in the Netherlands. Spathas states electricity use of 0.0260 MJ and heat use of 0.0003 MJ for sorting 0.426 kg used textiles, which translates to 16.9 kWh electricity and 0.70 MJ heat per tonne sorted/pre-treated textiles. The only other data source on manual sorting found was Bodin (2016), which states 12.5 kWh electricity use per tonne sorted textiles. The higher number of Spathas (2017) was chosen as a conservative estimate; but the number from Bodin confirms that the order of magnitude of the figure from Spathas is reasonable.

Following pre-sorting, the textiles are transported back to the Siptex plant by the same truck and ship that were used in the other direction, however with a slightly different load factor (based on communication with Sysav).

All truck transports within Sweden are assumed to run on diesel following the greenhouse gas reduction mandate for 2022 (“reduktionspliktsdiesel” in Swedish), and the truck transports outside of Sweden are assumed to run on diesel including 6% FAME (fatty acid methyl ester), as this is a common truck fuel in Europe outside Sweden.

For sorting at the Siptex plant, site-specific data on energy use, losses and packaging were provided by personal communication with Sysav. This data is based on the situation at the plant in 2021. The output from the Siptex plant is, in case A, a cotton-rich fraction consisting of, at maximum, 10% other fibres. The sorted fraction of case A is not defined in more detail in the present study, as the product system has been modelled to represent a generic cotton-rich fraction and its subsequent recycling and further life cycle, as this is sufficient for the aims of the study.

See appendix B for more details.

### 3.1.2 Recycling

The model of mechanical recycling of cotton is based on a confidential LCA report provided by a recycler in Southern Europe. Due to confidentiality, the present report cannot disclose the LCI data, which recycler the data is from, or any details about the process. A general description of the process is, however, given below.

The recycling process tolerates up to 5% of non-cotton materials (which means that a fraction sorted by Siptex is a viable input), the process includes adding low amounts of chemicals, removing unwanted elements and shredding of the textiles into a purer textile fraction that is ready to be subsequently spun into yarn (the yarn spinning and subsequent processes can then be identical to those processes in a value chain based on primary materials).

The data represent a commercial-scale process and primary data has been collected on site and represents production in the year 2021. The primary data includes chemicals, water and energy (electricity and fuels) used in the process, as well as material losses through waste generated, where some are assumed to be incinerated (textiles) and others are recycled (metals, plastics etc.).

For waste going to recycling, the cut-off method has been used. Datasets for background processes have been selected by us (i.e., they are not the same as selected in the original model in the confidential LCA report). Here, we have used the most representative datasets in the Gabi Professional and Ecoinvent databases, in technical and geographical terms. A change from the original model is that for electricity used, the consumption mix of the country of the recycling facility has been assumed, instead of specific electricity used at the recycler's facility, as backed up by Guarantees of Origin for renewable energy. This was done because country-based consumption mixes are used for all electricity used in all case studies in the present study, which in turn is done to reflect generic, and not specific, value-chains. Data from the confidential report on transport of input textile waste has been replaced by our own assumption on transport (distances and means of transport) from the Siptex plant to Southern Europe.

The datasets chosen for the background datasets are not identical to the datasets chosen in the confidential LCA report, so although the model is based on data from a specific recycler, it shall not be considered to represent any specific recycler but rather a generic mechanical recycler of cotton in Europe.The recycling stage also includes the transport of sorted textiles from the Siptex plant in Sweden to the recycling facility in Southern Europe, by ship and truck. The same type of truck (run on diesel with 6% FAME) and ship has been assumed as in the collection and sorting stage.

See appendix B for more details.

### 3.1.3 Cotton cultivation

The dataset used for conventional cotton cultivation represents a global average, including all processes from raw material production to ginning. See Appendix B for more details. The same dataset has been used for the benchmark scenario, see Section 3.1.7.

### 3.1.4 Production

The production stage includes:

- yarn spinning, including opening, carding, combing, drawing, ring-spinning, twisting and winding;
- fabric production, including knitting by a circular knitting machine;
- wet processing, including bleaching, opening, drying and fixation; and
- confectioning, including cutting, sewing (10 minutes sewing time is assumed), ironing and packaging.

The modelling of these production processes is based on the t-shirt model in Sandin et al. (2019a), but with more up-to-date selection of background datasets. Production has been assumed to take place in China. The model in Sandin et al. (2019a) and the additional assumptions were done to represent the production of a generic t-shirt purchased and used in Sweden. Transports from recycling in Southern Europe to yarn spinning in China, and between the subsequent processes, are also included in the production stage. See Sandin et al. (2019a) and Appendix B for more details.

### 3.1.5 Distribution and use

The distribution and use stage include the transport of the t-shirt from production in China to the retailer in Sweden, by trucks and ship. This stage also includes the user's transport back and forth to the store as well as the residential laundering (washing, drying, ironing) of the t-shirt. All these processes are based on the t-shirt model in Sandin et al. (2019a), but with more up-to-date selection of background datasets. The model of Sandin et al. (2019a) and the additional assumptions were done to reflect average Swedish conditions. Among others, the model assumes a user transport to and from the store of 8.5 km per kg garment in each direction, whereof 50% by car and 50% by bus, and that the t-shirt is used 30 times before being discarded. Moreover, the t-shirt is assumed to be subjected to 15 washing cycles in 40°C and is tumble-dried in 35% and ironed in 15% of the washing cycles. See Sandin et al. (2019a) and Appendix B for more details.

### 3.1.6 End-of-life

In the baseline scenario, the end-of-life stage includes transportation of the discarded t-shirt to a municipal waste incineration plant, and the subsequent incineration with energy recovery[4]. This is the most common means of textile waste management in Sweden. This stage has been modelled based on the t-shirt model in Sandin et al. (2019a), but with more up-to-date selection of background datasets.

For the energy recovered, the cut-off allocation method has been used. This means that the environmental impact of further distribution and use of this energy is allocated to the product system that uses the energy, and no environmental credits of this use (e.g., the benefits of substituting some other type of energy) has been allocated to the t-shirt.

In an alternative scenario, the discarded t-shirt is assumed to instead be collected to once again be sorted and reused or recycled. Also in this scenario, the cut-off allocation method has been applied, so that the system boundaries end right before the first collection transport – i.e., the first process in the present system model, so this scenario represents a closed material loop. This allocation method was described in Section 2.6. Note that although the alternative scenario assumes reuse or recycling again, this does not reflect a scenario with a fully closed material loop, as there are (i) inevitably material losses all the way from collection to the purchase of the garment (which needs to be compensated by primary materials), and (ii) mechanically recycled materials need to, in each loop, be blended with materials with the same quality as primary material (that can be primary materials or chemically recycled materials) to achieve sufficient quality in the end product.

See Appendix B for more details.

### 3.1.7 Benchmark

The benchmark scenario is identical to the recycling scenario, except that conventional cotton is 100% of the input to yarn spinning, instead of 75%. The dataset used for conventional cotton cultivation is the same as in the recycling scenario, see Section 3.1.3.

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[4] Note that the energy recovered does not influence the results of the attributional case studies A-D, as the allocation method used does not account for any credits of the produced energy. The effect of the recovered energy is, however, considered in the consequential outlook, see Section 3.6

## 3.2 Case B: Viscose T-shirt

This case uses the t-shirt modelled in case A as the basis for the model. But instead of cotton, the garment is made of viscose produced from dissolving pulp made of recycled cotton via chemical recycling (recycling scenario), or from viscose made from dissolving pulp made of primary wood feedstock (benchmark). The viscose t-shirt is assumed to have the same weight as the cotton t-shirt of case A, and all processes after fibre production (from yarn spinning to end-of-life) are assumed to be identical to case A – this is a simplification which was sufficient for the goal of this study.

Sections 3.2.1 to 3.2.5 detail the modelling of the recycling scenario, and then the benchmark model – and how this differs from the recycling scenario – is described in Section 3.2.6.

Figure 6 and Figure 7 show system diagrams of the case study, for the recycling scenario and the benchmark scenario. Transports between processes are not shown in the figure.

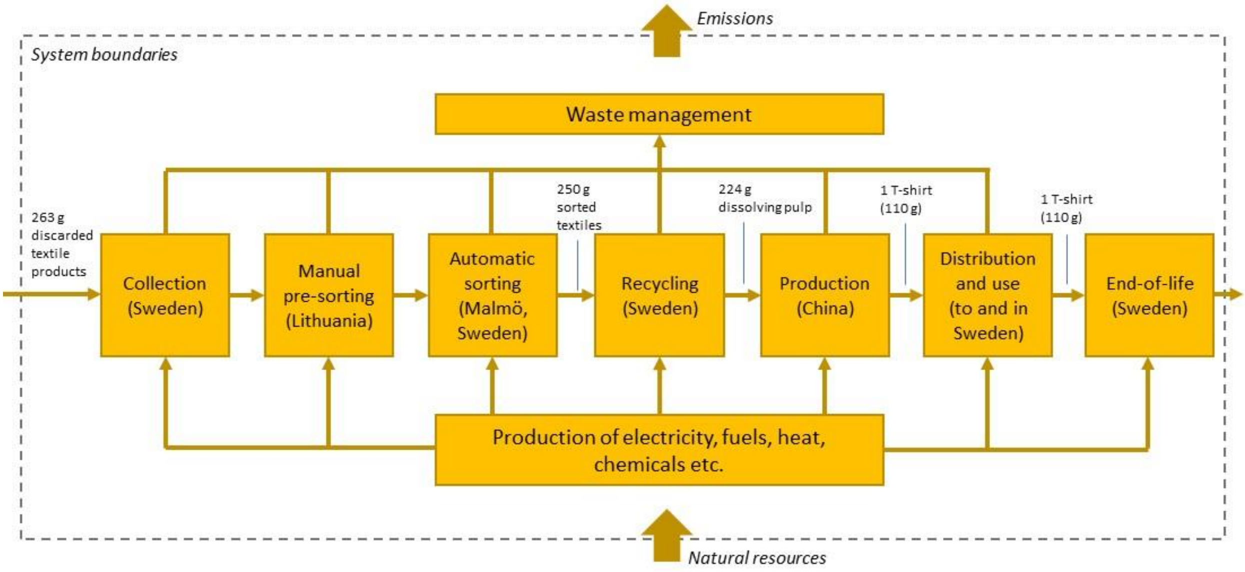

**Figure 6. System diagram of the recycling scenario of case study B, a viscose T-shirt made of recycled material.**

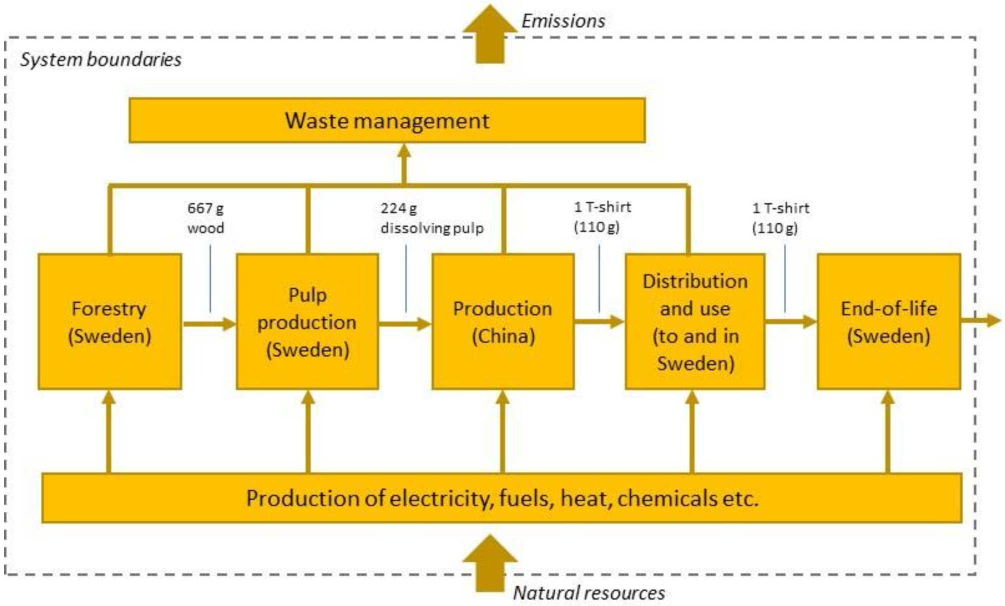

**Figure 7. System diagram of the benchmark scenario of case study B, a viscose T-shirt made of primary material.**

### 3.2.1 Collection and sorting

Modelled in the same was as in case study A, see Section 3.1.1.

### 3.2.2 Recycling

In case B, chemical recycling is used to turn the cotton-rich Siptex-sorted fraction (at least 90% cotton) into dissolving pulp, which then is sent to regular production of man-made cellulose fibres (MMCF), in our case: viscose fibres. The recycling stage consists of the transport of sorted material from the Siptex plant to the recycling plant, which in turn consists of mechanical shredding, cellulose processing and drying and forming. There are several processes for such recycling, for example the process developed and commercialised by Renewcell, one of the partners of the Siptex project, or the processes by Södra (the OnceMore process), the Infinited Fiber Company, Circ and others.

There is a lack of publicly available LCI data on large-scale chemical recycling of cotton into dissolving pulp. There is also a lack of publicly available LCI data on production of dissolving pulp from primary resources (most often wood). Therefore, in the present study, a modified LCI dataset on paper pulp production from the Ecoinvent database (version 3.8) is used to model both the dissolving pulp production from recycled material and the dissolving pulp production from primary resources. The Ecoinvent dataset has been modified in a parallel LCA project, managed by IVL Swedish Environmental Research Institute, to better reflect a Swedish mill, and it was assumed that the modified dataset was relevant to use in the present project as well. The only differences between the recycling and benchmark scenarios are the feedstock used and the transports of this feedstock to the production site. This is a simplified modelling approach that we deemed to be sufficient for the present screening LCA, and which shows the influence of the main difference between the recycling scenario and the benchmark: the change of feedstock. Below paragraphs outline a justification for this modelling choice.

Available LCA studies on MMCF, which primarily are Shen and Patel (2010), Shen et al. (2010) and Schultz and Suresh (2017), do not display LCI data. Moreover, Schultz and Suresh (2017) use a simplified model on dissolving pulp production from primary resources. This model combines LCI data on chemical use, waste outputs and water use in paper pulp production from the Ecoinvent database with energy use data on dissolving pulp production from the RISI Mill Asset database, as well as data from an unnamed Chinese man-made cellulose fibre production database. The latter two LCI data sources are not available for the present LCA study.

The climate impact results of Schultz and Suresh (2017) for MMCF produced from primary sources are substantially higher than the results of Shen and Patel (2010), or the results generated by using the Ecoinvent data on paper pulp production, also when accounting for differences in methodology used (Schultz and Suresh 2017 uses unconventional methods for assessing the climate impact). It seems that data used by Schultz and Suresh (2017) to model MMCF produced from primary resources consist of high energy use and/or $CO_2$-intensive energy sources – much higher than, for example, Shen and Patel (2010). Furthermore, Schultz and Suresh (2017) present climate impact results for MMCF produced from recycled feedstock, which is much lower than for MMCF from primary resources – indicating that the high impact of MMCF from primary resources is due to production of dissolving pulp rather than the MMCF production. However, the contribution from dissolving pulp production is in the study by Schultz and Suresh (2017), much higher than the contribution from dissolving pulp production in the study presented in Shen and Patel (2010) and Shen et al. (2010) (although the results of this study are difficult to interpret, as the results of pulp and fibre production are not separated). Furthermore, the results of Schultz and Suresh (2017), as well as Shen and Patel (2010) and Shen et al. (2010), indicate large differences in results between different MMCF production sites. All this suggests that (i) the high climate impact results from some of the scenarios of dissolving pulp production from primary resources in Schultz and Suresh (2017) are highly uncertain, (ii) it is questionable whether these scenarios are representative for such production in general, and (iii) there are large differences in climate impact between MMCF production sites. The last point is supported by the mapping of sources of LCI data for fibre production done by Sandin et al. (2019b).

The climate impact of pulp calculated using the chosen LCI dataset is similar to the lower range of the climate impact of scenarios of Shen and Patel (2010) and Shen et al. (2010), and similar to the climate impact calculated in a preliminary and confidential LCA study conducted by IVL (including one of the authors of the present study) for Renewcell in 2020-2022 (insert reference). Data on the yield of the recycling process (i.e., the quantity of Siptex-sorted input needed per quantity of produced dissolving pulp) was however taken from the LCA study done for Renewcell (with the permission from Renewcell). The losses are assumed to be incinerated, which is modelled by LCA data on incineration of animal and plant-based textiles. Moreover, the location of the plant was based on Renewcell's plant, i.e., it was assumed to be located in Northern Sweden. The assumed location in Northern Sweden influences the transport distance of incoming feedstock, the transport distance for dissolving pulp to fibre production, and the assumed electricity mix used: the average Swedish consumption mix, which causes relatively low $CO_2$ emissions. The model shall not be interpreted to be representative of Renewcell's operations but shall be seen as a proxy for a generic process for chemical recycling of cotton.

Note that using paper pulp data to model dissolving pulp production is in general an underestimation, as the dissolving pulp needs more chemicals and energy per mass output compared to paper pulp. This is because dissolving pulp has higher cellulose and lower hemi-cellulose content, i.e., more of the hemi-cellulose must be removed when producing dissolving pulp, so the yield is lower. This underestimation will influence the results of the recycling as well as the benchmark scenario, so its influence on the comparison between the two scenarios is limited.

See Appendix B for more details on the modelling of the recycling stage.

### 3.2.3 Production

The production stage includes the transport from the recycling stage to the viscose fibre production plant, which is assumed to be located in China. Viscose production is modelled using a generic dataset on viscose fibre production from the Ecoinvent database (version 3.8). Background datasets (e.g. for input chemicals) have been selected to reflect global or European average production. In reality, there are large differences in the environmental impact of different viscose production plants, which will be considered when interpreting the results.

The subsequent production, from yarn to garment, is modelled the same way as in case study A, see Section 3.1.3.

### 3.2.4 Distribution and use

Distribution and use are modelled in the same was as in case study A, see Section 3.1.5.

### 3.2.5 End-of-life

End-of-life is modelled similarly as in case study A, see Section 3.1.6, but with the difference that another LCI dataset for incineration is used, reflecting incineration of animal and plant-based textiles in general. See Appendix B for more details.

### 3.2.6 Benchmark

The benchmark scenario is identical to the recycling scenario from dissolving pulp production and onwards. The difference is the feedstock used to produce dissolving pulp: primary hardwood is used instead of discarded textiles. More specifically, we assumed a Ecoinvent 3.8 dataset on birch harvested in Sweden, which is a common source of wood for producing dissolving pulp suitable for viscose. See, for example, the Södra purple grade dissolving pulp (Södra 2022). Since the same model was assumed as for the recycling scenario, also in the benchmark the pulp mill is assumed to be in Sweden with availability to energy with low $CO_2$ emissions.

See Section 3.2.2 for why the same LCI data on pulp production were used for the recycling and the benchmark scenarios. This means that dissolving pulp production is assumed to occur in Sweden for the benchmark scenario as well. It should however be noted that there are many different types of primary feedstock used for viscose production, and other variations in dissolving pulp and viscose production that significantly influences its environmental impact: location, whether pulp and fibre production are integrated, how advanced the water and chemical management is, whether renewable or fossil energy is used, etc. (Shen et al. 2010, Schultz and Suresh 2017, Sandin et al. 2019b). This will be considered in the discussion of results for the benchmark in case study B.

## 3.3 Case C: Polyester sports jersey

This case study is about a black, 104 g polyester sports jersey produced either from polyester made of recycled material via chemical recycling (recycling scenario), or from polyester made of primary resources (benchmark). The definition of the garment is based on an actual sports jersey of the Siptex project partner Stadium (see Figure 8). The LCA model is, however, not based on primary data of Stadium's supply chain, but on data from Sandin et al. (2019a). As such, the model represents a generic polyester sports jersey that can be made either from recycled or primary materials, rather than the specific jersey of Stadium.

Sections 3.3.1 to 3.3.5 detail the modelling of the recycling scenario, and Section 3.3.6 describes the benchmark model and how this differs from the recycling scenario.

Figure 9 and Figure 10 show system diagrams of the case study, for the recycling scenario and the benchmark scenario. Transports between processes are not shown in the figure.

Figure 8. Sports jersey on which the LCA model is based on (photo from the authors).

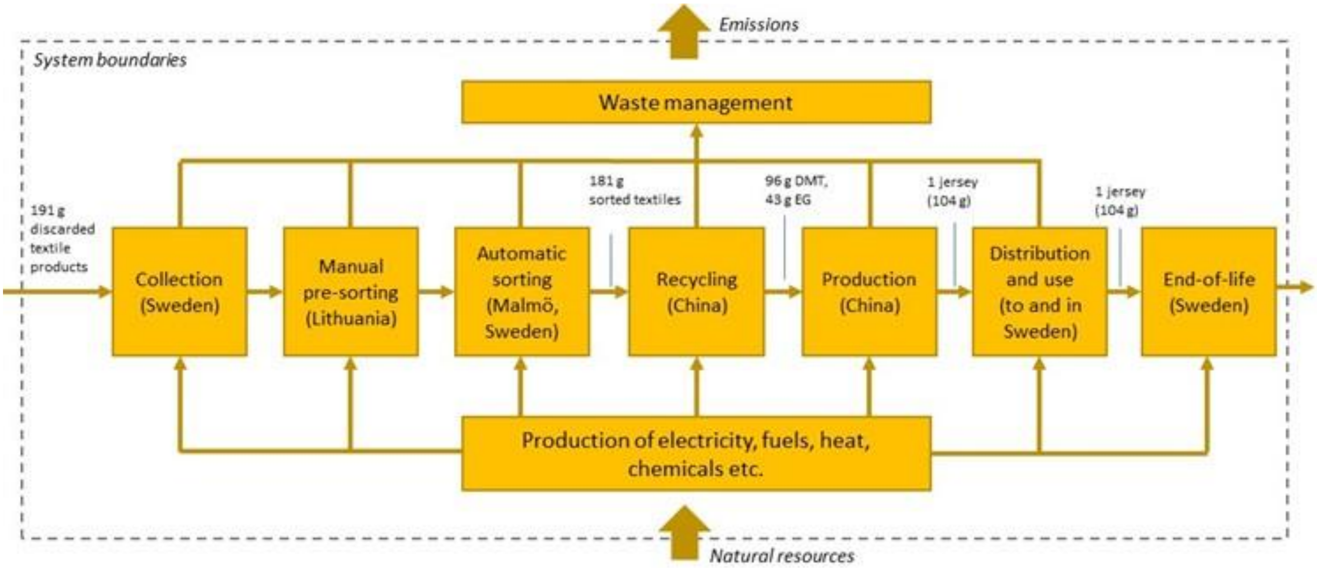

Figure 9. System diagram of the recycling scenario of case study C, a polyester sports jersey made of recycled material.

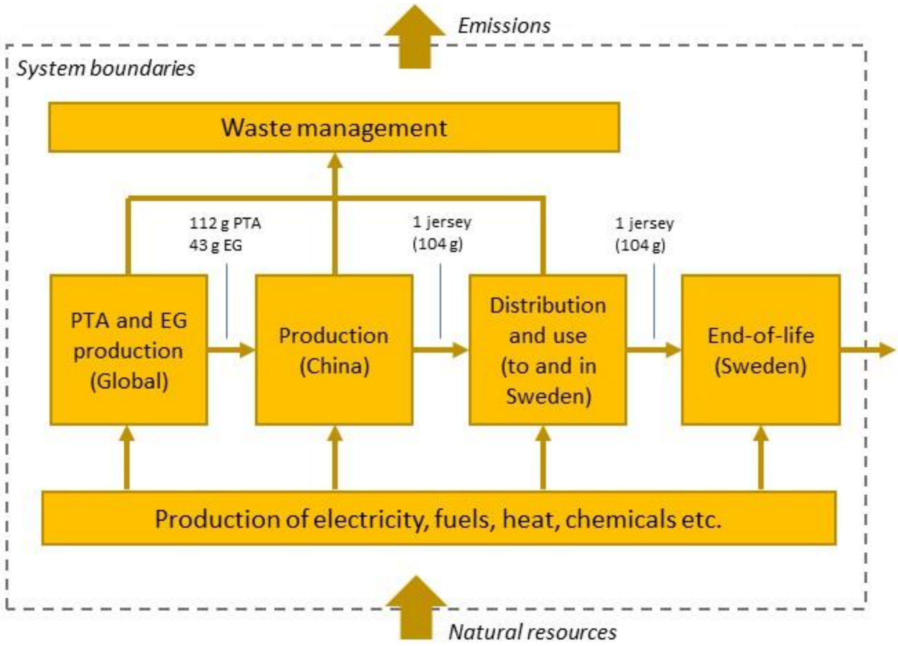

**Figure 10. System diagram of the benchmark scenario of case study C, a sports jersey made of primary material.**

## 3.3.1 Collection and sorting

Collection and sorting are modelled in the same way as in case study A, see Section 3.1.1, but instead of a cotton-rich output, we here assume a polyester-rich output (5% other fibres has been assumed for the recycling process).

## 3.3.2 Recycling

The LCI data on chemical recycling of polyester is based on data from Schmidt et al. (2016), which in turn is based on data from the polyester recycling plant of Teijin Ltd, Japan. The process consists of cutting, washing, and dissolving the discarded polyester in ethylene glycol (EG), methanol and sodium carbonate ($NaCO_3$), so that the polyethylene terephthalate (PET) is depolymerised first into bis-hydroxyl ethylene terephthalate (BHET) and then into EG and dimethyl terephthalate (DMT), which then are purified. EG and DMT can then be used to produce new PET granulates used for polyester production.

Although the data is originally from a Japanese manufacturer, the recycling process is assumed to be located in China in our study. This was done to increase comparability with the benchmark scenario and to make sure that we primarily compare recycling and conventional production, and not different locations of production.

In addition to the data in Schmidt et al. (2016), a loss of non-polyester materials has been added to the recycling stage. The end-of-life treatment of this loss has been modelled using a dataset for incineration of cotton.

See Appendix B for more details on the modelling of the recycling stage.

### 3.3.3 Production

The production stage consists of the following processes;

- production of polyethylene terephthalate (PET) granulates from the EG and DMT coming from the recycling process;
- staple fibre production;
- staple yarn spinning, including opening, combing, drawing, ring-spinning, twisting and winding;
- fabric production, including knitting by a circular knitting machine;
- wet processing, including jet-dyeing, opening, drying and fixation; and
- and confectioning, including cutting, sewing (10 minutes sewing time is assumed), ironing and packaging.

In addition, the transports from the recycling process to PET production and in between subsequent processes are included.

The LCI data on production on PET granulates is based on the input of purified terephthalic acid (PTA) and EG, instead of DMT and EG. PTA is increasingly common to use instead of DMT as input to PET production. To assume the same process, although the inputs are different, is based on the fact that repolymerization via the PTA/EG and DMT/EG routes have the same energy requirements (Shen et al. 2010). The stochiometric relations between PTA and EG, and DMT and EG, have also been assumed to be the same. This is based on the fact that the stochiometric relation between DMT and EG is stated to be 76:24 by weight by Shen et al. (2010), that Schmidt et al. (2016) say it can vary but assumes 69:31 by weight, and that the dataset on PET granulates states a PTA and EG ratio of 72:28 by weight – right in between the DMT and EG ratios.

The remaining production processes are based on selected datasets from Sandin et al. (2019a). The selection was done based on the technical properties of the sports jersey of Stadium (dtex of the yarn, likely dyes used, etc.).

See Appendix B for more details.

### 3.3.4 Distribution and use

Distribution and use are modelled in the same way as the t-shirts of case studies A and B, see Section 3.1.5, except that it has been assumed that the polyester jersey is not ironed. This means that the jersey is assumed to be used 30 times and washed every second time. We have accounted for the lower weight of the jersey, which means less transportation and less energy use in washing and drying of one garment, compared to the t-shirts. See Appendix B for more details.

### 3.3.5 End-of-life

End-of-life is modelled similarly as in case study A, see Section 3.1.6, but another LCI dataset for incineration has been used, reflecting the fact that the polyester is produced from fossil resources, which among others means that fossil $CO_2$ is released at incineration. See Appendix B for more details.

### 3.3.6 Benchmark

The benchmark scenario is identical to the recycling scenario from the PET granulate production and onwards. The difference are the feedstocks used to produce the PET granulates: PTA and EG made from primary (petroleum) feedstock instead of DMT and EG from recycled polyester. See Appendix B for more details.

## 3.4 Case D: Wool sweater

This case concerns a 300 g lightweight wool sweater, produced either from recycled wool via mechanical recycling (recycling scenario) or from primary wool (benchmark scenario). The definition of the garment and the modelling of all processes from recycling to the use stage are based on the wool sweater models of Wiedemann et al. (2020) and Wiedemann et al. (2022). Sections 3.4.1 to 3.4.5 detail the modelling of the recycling scenario, and Section 3.4.6 describes the benchmark.

Note that we have assumed 100% recycled wool in the scenario, although recycled wool is commonly blended with primary material. For example, Wiedemann et al. (2022) has assumed the recycled wool is blended with 10.5% polyester. As a simplification we have assumed 100% recycled wool. This simplification is based on the fact that there are fabrics made of 100% mechanically recycled post-consumer wool being part of marketed products[5]. Having said this, note that in the recycling scenario in which the wool is sorted again at end-of-life, for reuse or recycling (the scenario denoted "scenario 2"), the material will most probably have to be blended with primary material if there is a second recycling loop, as the fibre length is decreased in each cycle of production and use.

Figure 11 and Figure 12 show system diagrams of the case study, for the recycling scenario and the benchmark scenario. Transports between processes are not shown in the figure.

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[5] An example is a wool coat by Asket: https://www.asket.com/us/mens/outerwear/wool-coat-charcoal-melange (Accessed October 2022).

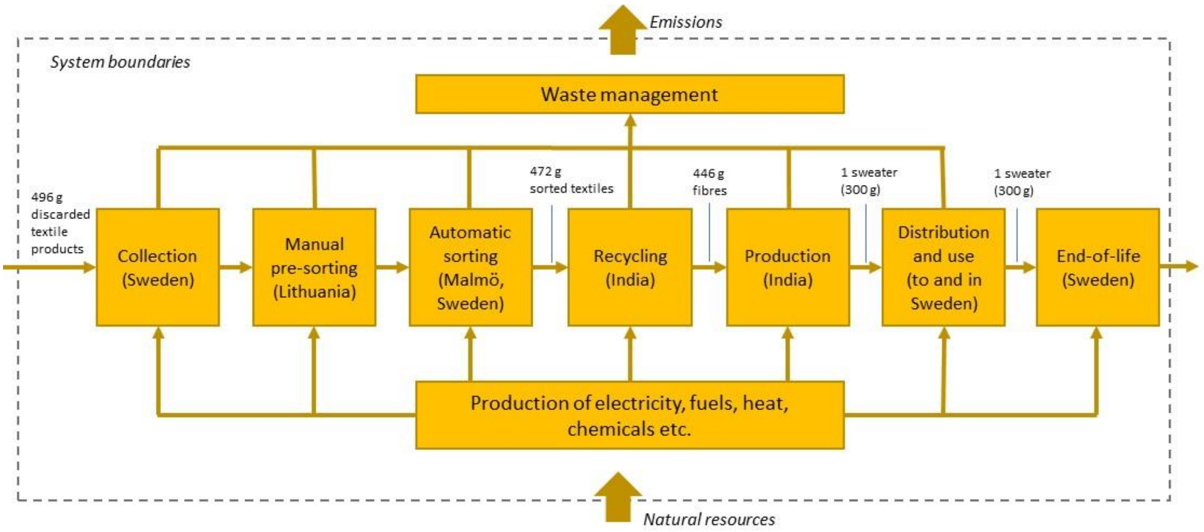

**Figure 11. System diagram of the recycling scenario of case study D, a wool sweater made of recycled material.**

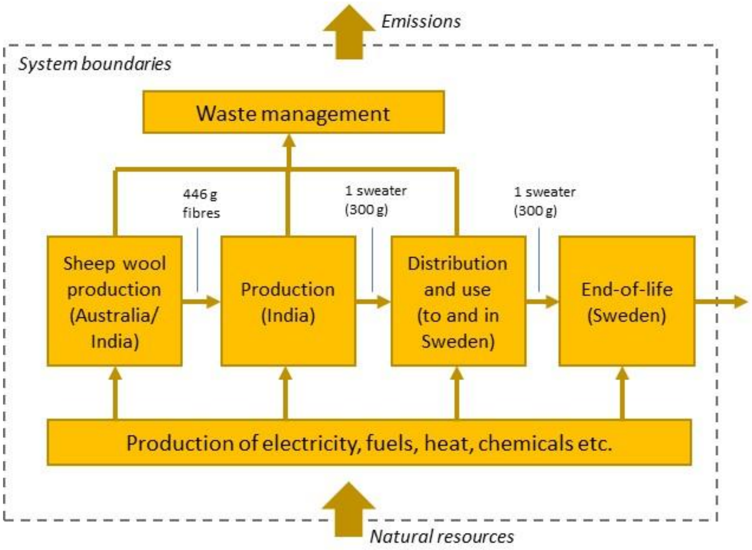

**Figure 12. System diagram of the benchmark scenario of case study D, a wool sweater made of primary material.**

### 3.4.1 Collection and sorting

Collection and sorting are modelled in the same way as in case study A, see Section 3.1.1, but instead of a cotton-rich output, we here assume a wool-rich output (with no more than 10% other fibres).

Note that until today (October 2022), no wool fraction has been sorted at the Siptex plant. As such, the sorting of wool is a hypothetical, future activity of the sorting machine.

### 3.4.2 Recycling

The modelling of mechanical recycling of wool is based on data from Wiedemann et al. (2022), which in turn is based on surveys of industrial closed-loop recycled-wool processors in Panipat, India and in Italy. For conservative reasons, we assume that the recycling and the production are located in India (which has more carbon-intensive electricity mix than Italy). The process consists of a pre-treatment process, which among others includes shredding of the material. The recycling stage also includes a transport by truck and ship from the Siptex plant to India. See Appendix B for more details.

### 3.4.3 Production

The production stage has been modelled based on the wool sweater model of Wiedemann et al. (2022), which includes over-dyeing, yarn spinning (including carding, blending, spinning and spooling), knitting, finishing (mechanical and chemical treatment), and garment make-up (i.e., confectioning). Approximately 82% of the recycled wool is pre-dyed and does not go through the over-dyeing process. The rest, 18%, of the recycled wool is not pre-dyed and hence goes through an over-dyeing process before the yarn spinning. In Wiedemann et al. (2022), the yarn consists of 10.5% polyester and 89.5% recycled wool – as a simplification we have assumed 100% wool.

Data from over-dyeing until finishing is from Wiedemann et al. (2022). For garment make-up, Wiedemann et al. (2022) refer to Wiedemann et al. (2020) which in turn do not present separate data for garment make-up. Therefore, we modelled confectioning based on the model of confectioning of a t-shirt from Sandin et al. (2019a) that is used in case studies A-C. This was deemed reasonable as the wool sweater is, just as the t-shirts and the sports jersey, a relatively simple garment construction-wise. As the data on confectioning in Sandin et al. (2019a) scales with weight, the data on sewing of the wool sweater corresponds to a sewing time of almost 30 minutes, compared to the 10 minutes assumed for the t-shirts and the sports jersey.

Case studies A-C contain a confectioning process, which has been added to case study D as well, based on Sandin et al. (2019a). As all case studies are relatively simple garments construction-wise, it is assumed that the confectioning process is the same for all case studies.

All processes of production are assumed to take place in India.

In addition to the above processes, the production stage includes transports from the recycling to production as well as in between the production processes.

See Appendix B for more details on.

### 3.4.4 Distribution and use

The distribution includes transport from the production in India to the retailer in Sweden, by trucks and ships. The transport by the user to the store and back is modelled in the same was as in case studies A-C, see Setion 3.1.5. The use stage includes washing of the sweater, machine wash and hand wash, and dry cleaning, based on Wiedemann et al. (2020). The data in Wiedemann et al. (2020) is based on an online consumer survey done in the UK by the Nielsen Company in 2018. Based on the survey, the sweater is assumed to be used 109 times before disposal and used 5.2 times between each washing cycle. Also based on the survey, washing is assumed to be done by machine (63% of the time), hand (27%), and dry-cleaning (10%). The modelling of the use stage was adjusted to reflect Swedish conditions. See Appendix B for more details.

### 3.4.5 End-of-life

The end-of-life for the wool sweater is modelled similarly as case study A, except that another LCI dataset for incineration is used, reflecting incineration of animal and plant-based textiles in general. See Appendix B for more details.

### 3.4.6 Benchmark

The benchmark scenario is identical to the recycling scenario from yarn spinning and onwards, i.e., the difference is the input of primary wool instead of recycled wool.

For sheep wool production, we used the LCI dataset "sheep production, for wool" from Ecoinvent (version 3.8), the version reflecting a global average (adjusted from data collected for the US in 2001-2006). The dataset represents the inputs to (fertilisers, feedstuffs, pesticides, irrigation, machine infrastructure etc.), and direct emissions of, husbandry of one average sheep during a year, on 20% intensive and 80% extensive pastureland. This produces 4.2 kg of sheep fleece in the grease (i.e., wool) and 7.85 kg of sheep for slaughtering. The environmental impact of the process has been allocated based on the price (i.e., revenue) of wool and sheep, respectively, which means that 55.3% was allocated to wool and 44.7% was allocated to sheep for slaughtering. There are other allocation methods available that generates other results than shown in the present study. For example, a biophysical method based on the protein content is commonly used. In Wiedemann et al. (2015), different methods are compared, showing (i) that the biophysical methods yield roughly the same climate-impact results as the method applied in the LCI dataset used in the present study, and (ii) that results using economic allocation can vary a lot between different countries, depending for example on whether the focus is on meat or wool production – the results in the present study are between the lowest and highest of those results. The effect of allocation method for primary wool production is not further explored in the present study.

A transport of 100 km with truck was added between the wool production and the scouring. The LCI data for the scouring is based on a report by Martin and Herlaar (2021).

To calculate transportation from scouring to the subsequent production in India, it is assumed that 50% of the wool is sourced in India, and the remaining 50% is imported from Australia. These countries are two of the largest wool producers globally. Because of this, two scouring processes were modelled, one representing Indian energy mix and the other Australian energy mix. The Australian wool was assumed to be transported by ship and truck from New South Wales in Australia, and the Indian wool was assumed to be transported with truck from Rajasthain in India to the subsequent production in Panipat, India.

See Appendix B for more details.

## 3.5 Scaling up to 1 year of sorting

In scaling up the model to represent 1 year of sorting at the Siptex plant, we have assumed an annual sorting of 19 500 tonnes. This is, according to Sysav, a reasonable annual capacity of the current plant, assuming three-shift operation.

Each case study is assumed to represent a certain share of the annual sorting capacity. To estimate this share, we considered three data sources:

1. Data on the fibre composition of textile residential waste in Sweden. Here we found a study by Hultén et al. (2016), which by composition analysis concluded that 58% of the material consisted of pure cotton and the remaining 42% were mainly mixed fractions. The report does not provide further information on fibre composition of the mixed fractions.

2. Global fibre production, which states that polyester is 52%, cotton is 23%, and wool is about 1% of the annual global fibre production, by mass (Textile Exchange 2020).

3. The current inbound flows to the Siptex plant, which according to Sysav is heavily dominated by cotton due to the current demand of outbound flows.

Based on above, and an assumption that cotton and wool are more common on the Swedish market compared to the global average market, we assume that case studies A-C represent 32% each of sorted annual capacity of the plant, and case study D the remaining 4%. In terms of fibres, this means that the cotton case studies (A and B) represent 64% of the sorting capacity, and the polyester (C) and wool (D) case studies represent 32% and 4%, respectively. Note that these percentages are based on the quantity of sorted materials used as input to the case studies. In terms of the number of garments produced, the shares are different. Case study A will have a larger share in terms of number of garments, as each garment contains only 25% recycled materials. Similarly, case study D has a share that is smaller than 4% in terms of number of garments, as the case study concerns a heavier garment that needs more recycled material per garment. Table 2 shows the scaling-up exercise in numbers[6].

**Table 2. How much each case study contributes to the scaled-up model.**

| | **Quantity of Siptex-sorted material per garment** | **Share of scaled-up model, in terms of sorted material** | **Number of garments produced from sorted material, in scaled-up model** |
|---|---|---|---|
| Case study A: 110 g cotton T-shirt | 39 g | 32% | 160 000 000 |
| Case study B: 110 g viscose T-shirt | 250 g | 32% | 41 879 194 |
| Case study C: 104 g polyester jersey | 181 g | 32% | 34 475 138 |
| Case study D: 300 g wool sweater | 468 g | 4% | 1 666 667 |

A source we did not consider on the matter of scaling up, which also may be of interest in a future more in-depth study, is the Swedish national statistics of imports and exports of textile articles

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[6] Some of the numbers in the table may seem unrealistic but remember that each garment represent a range of possible garments made of each sorted fraction.

available at SCB (2022). The most refined classification (the eight-digit combined nomenclature code) is based on articles but separates each article into three fibre categories: cotton, animal fibres (including wool), and synthetic fibres ("konstfibrer" in Swedish, which includes oil-based fibres such as polyester as well as regenerated cellulose fibres such as viscose). Although this does not give the full answer of the fibre composition of the textile waste streams suitable for automatic sorting, it provides an indication of what is available. However, extracting this data on national statistics was deemed too time-demanding for the present project.

In the scaling-up exercise we focus on climate impact and water deprivation only, as the results of these impact categories were, in the four attributional case studies, shown to follow very different patterns.

The scaled-up results provide an indication of the environmental benefits of the Siptex plant over 1 year, assuming it runs at full capacity. If this exercise is repeated in the future, when the plant has been in full operation for at least 1 year, we recommend it to be based on the actual sorted fractions over 1 year.

The results of the scaled-up scenario can be found in Section 4.5.

## 3.6 Large-scale implementation – consequential outlook

The consequential outlook focuses on the consequences of large-scale implementation of the Siptex technology, by looking at the difference between a scenario with multiple Siptex plants and a baseline reflecting the conventional way of disposing and producing textiles. This is assessed in two different countries, at two different scales: sorting of 50 000 tonnes of textiles in Sweden (scenario A) and sorting of 300 000 tonnes of textiles in Germany (scenario B). Both these scenarios can be seen as reflecting a future – perhaps realistically in 2030-2040 – in which the Siptex automatic sorting technology (or equivalent technologies) have been implemented at large scale to take care of a significant share of the non-reusable textile waste, not only in Sweden but also in continental Europe.

This outlook, and these scenarios, are highly speculative. Nevertheless, it provides learnings about what the long-term consequences *could be* and which *parameters* that are likely to determine these consequences. Therefore, the results of this outlook shall be cautiously interpreted.

This outlook focuses on climate impact and water deprivation only, as the results of these impact categories were, in the four attributional case studies, shown to follow very different patterns.

Some life-cycle stages are assumed not to be influenced by the sorting and recycling enabled by the sorting: production (excluding recycling and those parts of conventional production influenced by increased fibre recycling, e.g., raw material extraction), distribution, use, and end-of-life. For these stages, the consequences of large-scale implementation are therefore assumed to be zero.

Other stages, however, will be influenced by the implementation of sorting: there will be added impact due to collection, sorting and recycling, and avoided impact of incineration and primary fibre production (assuming sorting and recycling leads to the substitution of primary materials). There will also be consequences beyond the system boundaries: added production of heat and electricity to compensate for the energy recovered from the avoided incineration – this is the only effect not covered at all in the scenarios of case studies A-D.

That end-of-life is assumed not to be influenced may come as a surprise. Alternatively, one could have assumed two scenarios: one in which the material is sorted and recycled once, and one in which it is sorted and recycled again. However, the second scenario would mean that 200 000 tonnes and 1 000 000 tonnes (for Sweden and Germany, respectively) would be sorted in the two scenarios, so this would change the basis of the comparison. Therefore, we only consider the consequences of one round of sorting.

Table 3 shows how the modelling has been done, including the life-cycle stages that are assumed to be influenced by large-scale implementation of the Siptex technology. Note that there are a few main assumptions behind the modelling, as described below the table.

**Table 3. Modelling of the consequences of large-scale implementation of Siptex sorting.**

| **Life-cycle stage** | **Scenario A** | **Scenario B** |
|---|---|---|
| Collection and sorting | Same as in case studies A-D. In an alternative scenario, no wool is assumed to be sorted. | As in scenario A, but:<br>(i) ship transport removed, and truck transports reduced by 40% (as Germany is almost twice as densely populated as Skåne).<br>(ii) electricity in automatic sorting changed to German consumption mix. |
| Recycling | Same as in case studies A-D. In an alternative scenario, no wool is assumed to be recycled. | Same as in case studies A-D (i.e., sorted textiles assumed to be exported to the same plants as textiles sorted in Sweden). |
| Avoided incineration (with energy recovery) of discarded textiles, including transports | The LCI datasets used to model end-of-life incineration and transports in case studies A-D. | As in scenario A, but for incineration, other LCI datasets from the Gabi Professional database were chosen for viscose, polyester, and wool to better reflect conditions in Germany:<br>For wool and viscose: "DE: Textile (animal and plant based) in waste incineration plant"<br>For polyester: "DE: PET in waste incineration plant" |
| Avoided processes in fibre recycling | Same as the processes assumed for fibre production in the benchmarks of case studies A-D. In an alternative scenario, no wool is assumed to be avoided. | Same as the processes assumed for fibre production in the benchmarks of case studies A-D. In an alternative scenario, no wool is assumed to be avoided. |
| Compensation for loss of energy recovered | Today's average Swedish electricity consumption mix (LCI dataset from Gabi Professional database; climate impact of 0.04 kg $CO_2$ eq./kWh) and district heating mixes (LCI dataset provided by IVL; climate impact of 0.04 kg $CO_2$ eq./kWh). | Using LCI datasets from the Gabi Professional database on today's average German electricity consumption mix (climate impact of 0.51 kg $CO_2$ eq./kWh) and the average EU-28 district heating mix (0.02 kg $CO_2$ eq./kWh). |

The four attributional models of case studies A-D serve as a basis for the consequential outlook, and each case has been assumed to represent the same share of total sorted quantity as was assumed in the scaled-up model of Section 3.5. In reality, many other types of textiles will be sorted if 50 000 tonnes are sorted annually in Sweden, or 300 000 tonnes are sorted annually in Germany. The assumed fibre composition of input materials is therefore a simplification. As presented in section 4.5, wool contributes much to the climate-impact results of the scaled-up model, and therefore an alternative scenario is tested, in which no wool is sorted.

There are several assumptions concerning the modelling of the future energy used in collection (transportation), sorting and recycling; the future heat and electricity production influenced by reduced incineration of textile waste; and the future primary fibre production influenced by reduced demand. In consequential modelling, the marginal technology is normally considered, i.e., the technology with the highest marginal cost, as that is the technology affected by a change in demand. In terms of energy production, the marginal technologies are often those with the highest environmental impact. Assuming the climate targets set in Europe will be reflected in future energy technologies, it is reasonable to assume that the environmental impact of the *average* energy used in Sweden and Germany when the sorting has been implemented at large scale (in 2030-2040) will be lower than today. However, as marginal energy production can be expected to have higher environmental impact, we have approximated the future marginal energy production with the current average production. This is a rough approximation, sufficient for the purpose of the present study. The actual future technologies influenced by large-scale sorting and recycling may have higher or lower environmental impact than the technologies assumed in the present study. Note that also the collection, sorting and recycling may have lower environmental impact in the future than what is assumed in the present study; this has not been accounted for either.  Even if more elaborate estimates of the future marginal energy technologies are used, this kind of analysis always relies on a high degree of speculation and results will remain an estimate of potential future consequences.

Finally, an important assumption is that sorting, and recycling, of a material leads to the substitution of production of an equal amount of primary material. In reality, a share of the increased supply of recycled material may contribute to a net global growth of the total supply of materials. To what extent primary material production is substituted will depend on, for example, the future policy on recycling and primary material production in the EU, as well as decisions made by big textile product retailers.

Because of above assumptions, the results of the consequential outlook shall be cautiously interpreted, and the numbers as such are less important – more important are what parameters that appear to influence the results, and whether there are any differences in the patterns between the two studied impact categories (climate change and water deprivation). As such, the model can be seen as a starting point for increasing the understanding of the environmental effects of large-scale implementation of the Siptex technology and increased textile recycling in general, and as a basis for more elaborate, future studies on the matter.

The results of the consequential outlook can be found in Section 4.6.

# 4 Results and discussion

Below subsections present results for the four case studies, the scaling-up exercise, and the consequential outlook. When reading the results, remember that this is a screening LCA which, by necessity, is based on some rough assumptions (see Section 3 for more details). This means that precise numbers are not very important – more important is the relative contribution of different life-cycle stages and processes. In addition, differences between scenarios below about 20% shall not be seen as real differences, unless there is a known reason for why there is a difference.

For the case studies, the results are normalised to the results of the benchmark with incineration at end-of-life ("Benchmark 1"). This means that the results of this scenario are set at 100% and the results of the other scenarios are expressed as percentages of these results. Visualising the results in this way – instead of showing the results in absolute numbers in the different units of the impact categories – makes sense since it is important to see the differences between scenarios and which life-cycle stages contribute, but less important to communicate the absolute results.

Sometimes there is a need to blend the sorted materials in a way not reflected in the case studies, due to the quality of the sorted materials, for example in terms of fibre content, fibre quality or colour. For example, mechanically recycled cotton will most often have to be blended with more primary material than what is assumed in case study A. For such cases, the results will be somewhere in between the results of the recycling and benchmark scenarios as shown below. It is important to remember that for two garments to be compared on a fair basis, they must be of similar quality. If the recycled material is of insufficient quality – in itself, or together with primary material in a blend – a product made of this material cannot be expected to be used the same number of times before disposal as a product made of 100% primary material. An assumption of similar quality in benchmark and recycling scenario is thus fundamental to any of the conclusions below. To study the effect of the potentially lower quality of mechanically recycled materials is an interesting topic for a future study.

Related to above, for the scaling-up exercise or the consequential outlook, it is not very important for the results whether a million garments are made of 100% recycled material, or four million garments are made of 25% recycled materials – as an example.

## 4.1 Case A: Cotton T-shirt

Figure 13 shows the results of case study A. The results are discussed below the figure.

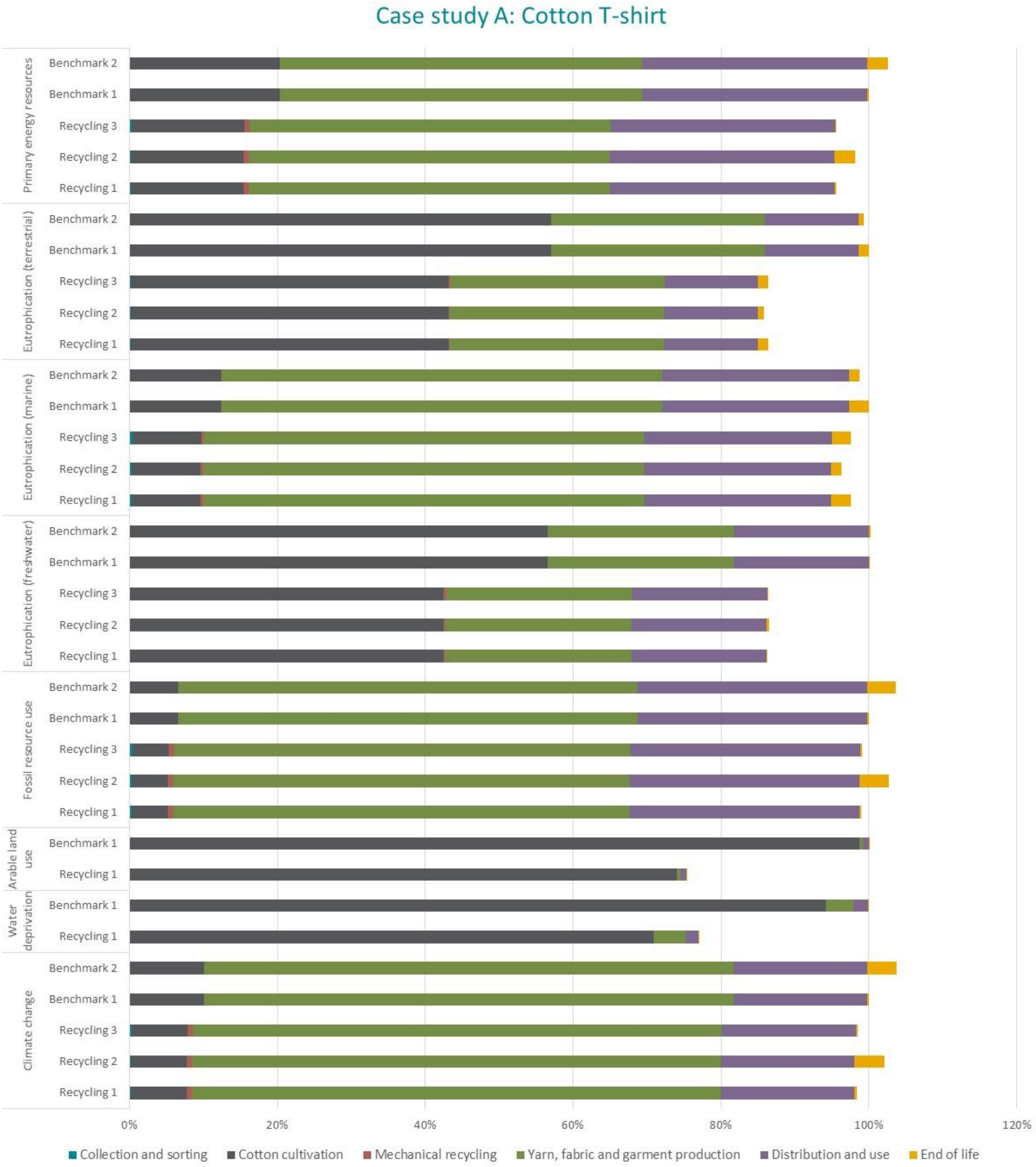

**Figure 13. Results of case study A, for the recycling scenarios with 25% recycled and 75% primary input materials and the benchmark scenarios with 100% primary input materials, and sub-scenarios 1 (incineration at end-of-life), 2 (recycling after end-of-life), and 3 (collection in a greater part of Sweden, instead of only in Skåne). Results are normalised to benchmark scenario 1.**

The most contributing life-cycle stages are yarn, fabric and garment production (which also includes wet treatment); distribution and use (here mainly the user’s transport back and forth to the store contributed); and cotton cultivation. Among others, this means that:

- The contribution of collection and sorting (including the automatic Siptex sorting) to the life-cycle environmental impact of a t-shirt made of 25% recycled cotton is low, regardless of impact categories. For more complex garments, the contribution is expected to be even lower, as garment production usually has a higher contribution for such garments. This is because there is, in this case study, relatively small amount of energy use in collection (i.e., transports) and sorting compared to the energy use in other life-cycle stages. It is the energy use, primary fossil energy use (for heat and electricity), that is the main driver of environmental impacts in textile production. For the collection and sorting, it is important to stress a few things:
    - The collection scenario does not include any user transport, i.e., for example a potential transport of the previous user of the t-shirt to deposit the garment at a municipal recycling centre or some other site for collection bins. Only the truck transport *from* the collection bin, and later ship transports to the sorting facilities, are included. A user transport is, however, part of the end-of-life stage of the scenarios marked with "2" – here it is assumed that the user in average takes a car to the collection bin, 4 km per kg discarded textiles. What can be observed by comparing scenarios "1" and "2", is that this user transport increases the life-cycle impact by up to a few percentages – more than the impact of the collection and sorting stage in the recycling scenarios. This means that a collection that system relies on increased user transports, can make up a significant share of the life-cycle impact of some impact categories. Note that the transport of 4 km per kg was assumed to test this influence. In reality, the transport can be longer and thereby fully offset the potential benefits of recycling, at least in impact categories where the benefits are small, such as in the impact categories of fossil resource use and climate change. So how the collection is organised can influence the environmental viability of textile recycling.
    - In scenario "recycling 3", textiles are assumed to be collected in a greater part of Sweden, or in neighbouring countries, by adding a 500 km truck transportation. This has negligible influence on the results, which indicates that it is not, from an environmental viewpoint, important whether textiles are collected locally or regionally – unless this affects the need for user transports (see below bullet point).
    - The results reflect a Swedish context. In other contexts, with longer or less clean transports or other energy mixes used in sorting, the importance of collection and sorting can be larger.
- The contribution of end-of-life to the life-cycle environmental impact of a cotton t-shirt is low, regardless of impact categories. However, if end-of-life management depends on the user transporting the garment to a collection bin (seen in scenario "recycling 3") or to disposal (not seen in any scenario), this can influence the results, see discussion above.

Within the dominating process – yarn, fabric and garment manufacturing – it is energy use that is the dominant contributor to all impact categories. Mostly, electricity from fossil resources, but also to some extent heat from fossil resources, which is used to heat water in the wet treatment processes. This life-cycle stage, as well as the distribution and use stage, are not in focus in the present study. For further information on what contributes to the impact of these life-cycle stages, we refer to the source used to model them: Sandin et al. (2019a).

In terms of the comparison between the recycling scenarios and the benchmark scenarios, one can observe considerable benefits in the recycling scenarios in those impact categories where cotton cultivation dominates, especially terrestrial and freshwater eutrophication[7], arable land use, and water deprivation. In arable land use and water deprivation, the benefits are almost exactly as large the share of recycled material in the t-shirt, as cotton cultivation contributes with almost all impact in these impact categories. So, if recycling can reduce the need for primary cotton, it will help to mitigate the environmental impact of cotton cultivation.

There appears to be benefits in the recycling scenarios also in terms of primary energy use, marine eutrophication, fossil resource use, and climate change – but these benefits are less than 10% and are therefore within the uncertainty range of the comparison between the recycling and benchmark scenarios. For example, it is known that the climate impact of cotton cultivation can vary more than 100% between sites or regions, as can estimates of the average climate impact of cotton cultivation globally (Sandin et al. 2019b). That there are not necessarily climate-impact benefits of recycling cotton versus growing cotton, is because the climate impact of cotton cultivation is, in general, not very high, compared to other fibres or other parts of the textile life cycle. Because of this, it is important that the system of collection, sorting and recycling of cotton is efficient and is powered by energy with low $CO_2$ emissions – not to risk that recycling increases the climate impact.

It is important to remember that the benefits, *per garment*, of recycling cotton will increase if the share of recycled material increases. For example, if the t-shirt consists of 30% recycled material, there will be almost another 5% reduction of arable land use and water deprivation impact, compared to a t-shirt of 100% primary cotton. But, as mentioned in the introduction to section 4, in terms of the environmental benefits created by sorting and recycling *in absolute terms*, it is of little relevance whether a million textile products are made of 100% recycled cotton, or four million textile products are made of 25% recycled cotton. This holds if the recycling of material actually substitutes primary material production, i.e., it is important that increased content of recycled material does not reduce the quality, and thus the life span, of the end product.

Related to the above comparisons, it shall be emphasized that for allocating the environmental burden of the incoming textile waste, the cut-off method has been applied. This means that the textile waste is allocated to environmental burden from its initial production. As mentioned in Section 2.6, this allocation may be handled by other methods, such as the Circular Footprint Formula (CFF). With the CFF, textile waste would carry 20% of the environmental burden of its initial production, and the benefits seen in the present study would be smaller or, for some indicators, non-existent. This is worth studying in more detail in future studies of textile recycling.

## 4.2 Case B: Viscose T-shirt

Figure 14 shows the results of case study B. The results are discussed below the figure.

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[7] Here the difference is lower than 20%, but as this difference can be explained by an actual difference between recycled and primary material, we consider it to be significant. With a higher share of recycled material in the cotton T-shirt in the recycling scenario, for example 35%, the difference would be larger than 20%.

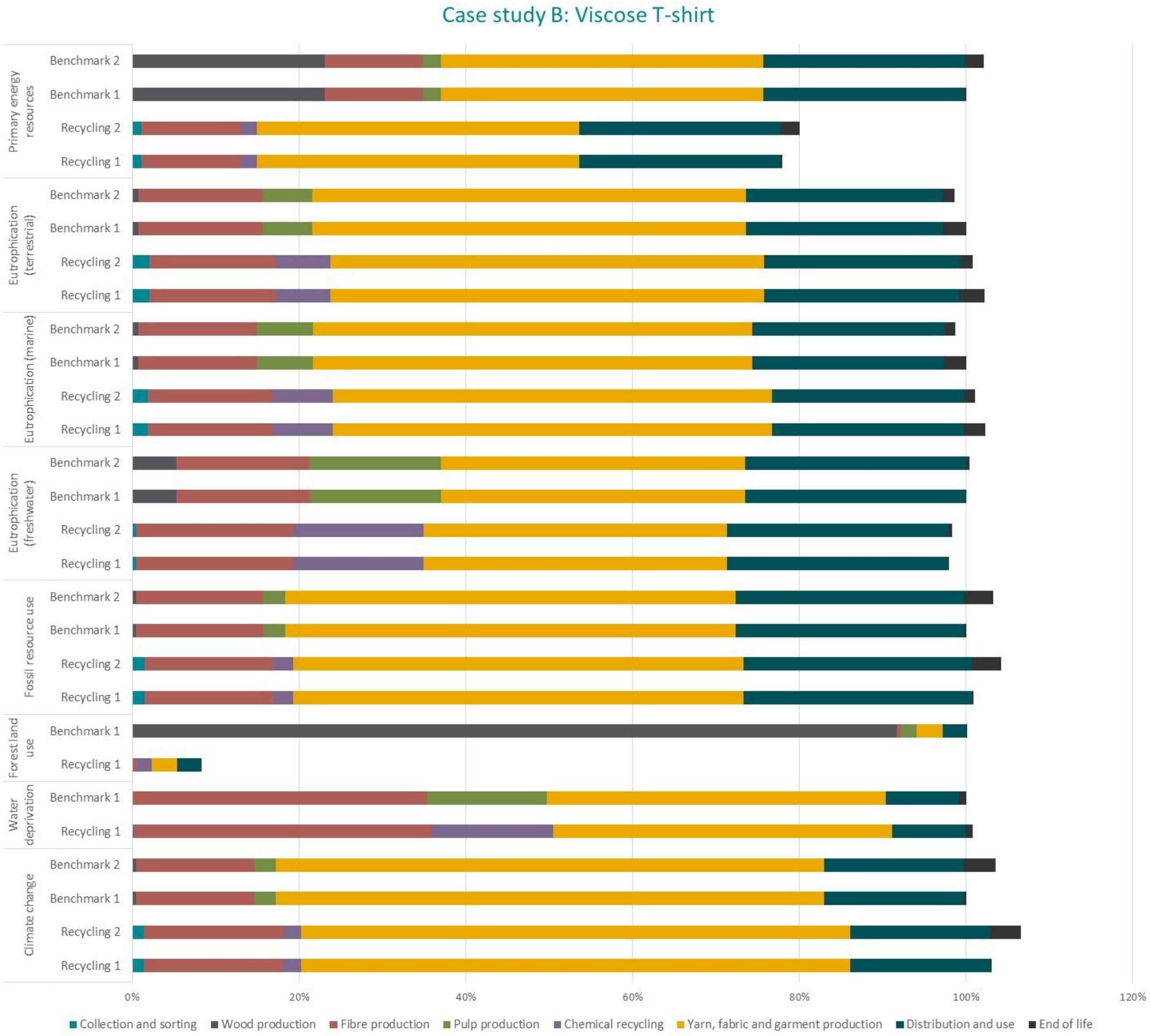

**Figure 14. Results of case study B, for the recycling scenarios with 100% recycled input materials, and the benchmark scenarios with 100% primary input materials, and sub-scenarios 1 (incineration at end-of-life) and 2 (recycling after end-of-life). Results are normalised to benchmark scenario 1.**

The most contributing life-cycle stages are yarn, fabric, and garment production (which also includes wet treatment); distribution and use (here mainly the user's transport back and forth to the store contributed); fibre (viscose) production; and pulp production (for the benchmark scenarios) and chemical recycling (for the recycling scenarios). Note that the process "chemical recycling" is also a pulp-producing process and that it has been modelled with the same dataset used to model pulp production in the benchmark scenarios (see more in Section 3.2.2). For the benchmark scenarios, also wood production (i.e. forestry) is important for primary energy use and forest land use.

The discussion of case study A on collection and sorting, and the end-of-life stage, is valid also for case study B. See Section 4.1.

The main differences between the recycling and the benchmark scenarios concern the reduced use of primary energy (mostly renewable) and forest land when recycled cotton is used instead of primary wood to produce dissolving pulp and viscose. All other differences between the recycling and the benchmark scenarios are within the uncertainty range.

Note that we have not studied the potential environmental benefits of reduced use of renewable energy and forest land. Potential benefits, for example in terms of biodiversity, depend greatly on location and the specific land management practices. Therefore, such aspects are difficult to assess in a representative and fair manner in a study on generic product systems. Additionally, such aspects are not well-covered by today's LCI data on forestry and the available impact assessment methods. However, the reduced need for land and renewable primary energy is likely to, in general, mitigate the environmental impacts associated with land use. This is probably where the main benefits are in replacing viscose made of primary resources.

Important to remember is that wood harvested in Sweden is the assumed feedstock in the benchmark scenarios. If the feedstock is assumed to be grown in more arid parts of the world, it may contribute more to the impact category of water deprivation, which in turn means that recycling will reduce the water-deprivation impact for this case study as well.

## 4.3 Case C: Polyester sports jersey

Figure 15 shows the results of case study C. The results are discussed below the figure.

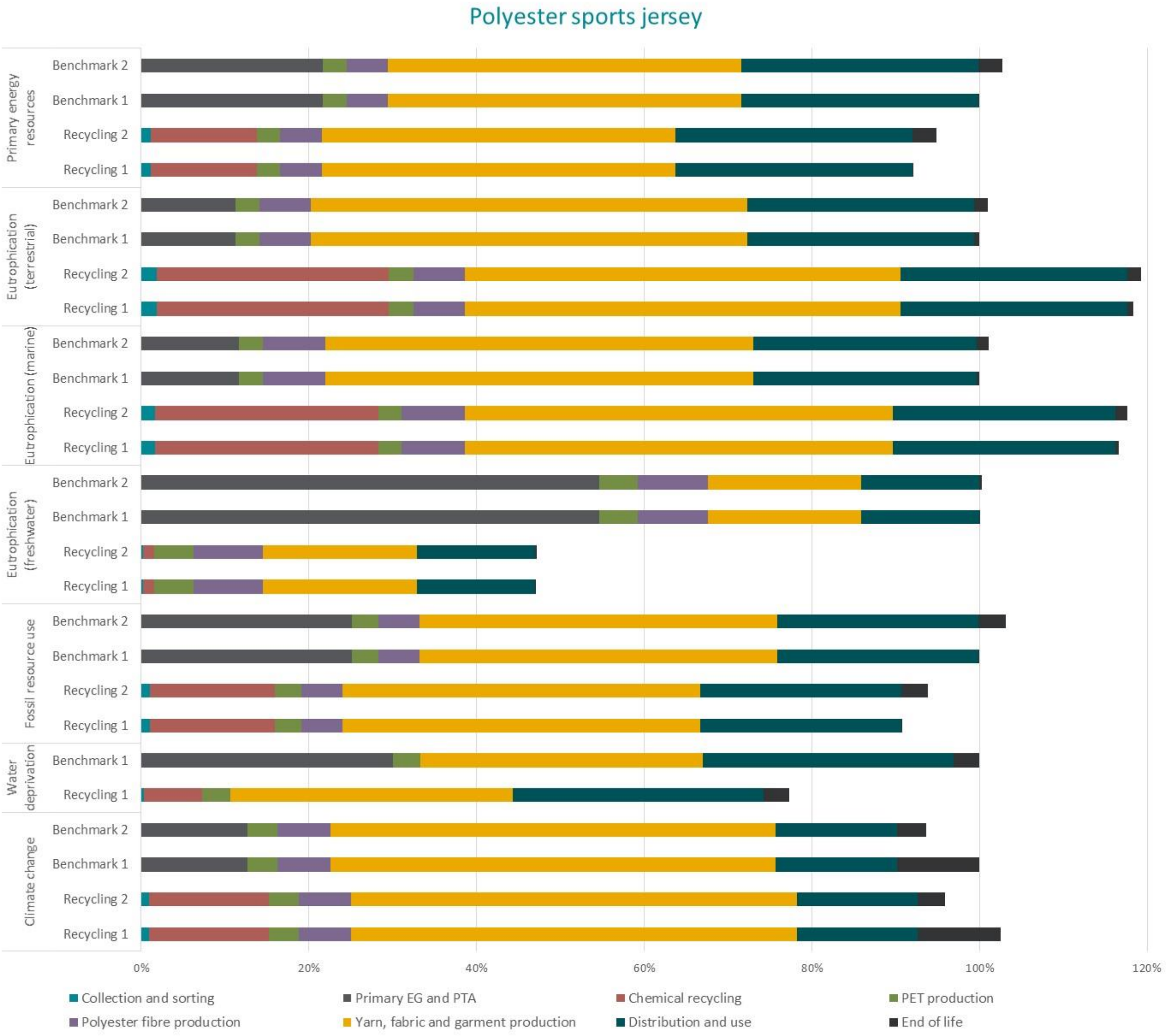

**Figure 15. Results of case study C, for the recycling scenarios with 100% recycled input materials, and the benchmark scenarios with 100% primary input materials, and sub-scenarios 1 (incineration at end-of-life) and 2 (recycling after end-of-life). Results are normalised to benchmark scenario 1.**

The most contributing life-cycle stages for the jersey made of chemically recycled polyester are yarn, fabric, and garment production; distribution and use; chemical recycling (for the recycling scenarios); and production of primary EG and PTA (only for the benchmark scenarios). Regarding the results of collection and sorting; yarn, fabric and garment production; and the end-of-life stage, the discussion in Section 4.1 is valid for the results of case study C as well.

The recycling scenarios have considerably lower freshwater eutrophication impact compared to the benchmark scenarios, since the production of primary EG and PTA contributes with more than 50% of the impact to a jersey made of primary material – an impact avoided in the recycling scenarios. The PTA production has a larger contribution to the environmental impact than the EG production. As this is a screening LCA, we have not looked further into what part of PTA production, or which type of emissions, that contribute to this.

For the other indicators, it is difficult to clearly say that there are differences. Potentially there is an increase for terrestrial and marine eutrophication for the recycling scenarios, which is mainly due to $NO_x$ emissions from the ships transporting the sorted textiles from Sweden to China (also the transportation of primary EG and PTA inputs in the benchmark scenarios have been accounted for, but this reflects transports of EG and PTA available to the average customer on the global market, which assumes shorter distances). This difference will thus depend on the location of the recycling facility in relation to the automatic sorting, as well as the future development of NOx emissions from transoceanic shipping. Moreover, there may be a decrease in water-deprivation impact in the recycling scenarios, compared to the benchmark scenarios. However, the water deprivation impacts of case study B are very low in absolute terms, compared to the impact of the cotton t-shirt in case study A, which suggests these results and the differences between scenarios are of little relevance. The water deprivation results are about 90% lower than for the cotton t-shirt made of 100% primary material, and about 85% lower than the cotton t-shirt made of 25% recycled material.

The recycling scenarios have about 10% lower fossil resource use, compared to the benchmark scenarios, because of the fossil resources not having to be extracted when the material is recycled. Although this difference is small, it can be considered significant as it can be derived from an actual difference between the recycling and benchmark scenarios, that is not influenced by the uncertainty within each scenario. The reason for the difference not being larger is that about 90% of the fossil resources are used for energy purposes in production and are not related to the material feedstock. The same is seen in the impact category of climate change. Noteworthy is also that end-of-life scenarios denoted with "2" (recycling 2, benchmark 2), in which the jersey is assumed to be sorted and reused or recycled again at end-of-life, reduce the climate impact with about 10%. So, the main effect on climate impact of recycling polyester is to avoid, or postpone, the incineration of the material. But to fully address the climate impact of products made of polyester, other changes are needed: use of low-carbon energy in production or avoiding production altogether by, for example, using each garment more before disposal.

## 4.4 Case D: Wool sweater

Figure 16 shows the results of case study D. The results are discussed below the figure.

**Figure 16. Results of case study D, for the recycling scenarios with 100% recycled input materials, and the benchmark scenarios with 100% primary input materials, and sub-scenarios 1 (incineration at end-of-life) and 2 (recycling after end-of-life). Results are normalised to benchmark scenario 1.**

This is the only case study for which the results are lower for the recycling scenarios for all the assessed indicators, compared to the benchmark scenarios. The main reason to this is that wool production and scouring (mainly sheep grazing) is the dominant life-cycle stage, or one of the dominant life-cycle stages, for all the assessed indicators.

For the recycling scenarios, it is the yarn, fabric and garment production that contributes most to all indicators, and the contributions from collection to sorting are relatively small.

Noteworthy is that the dataset for the sheep production for wool reflects a global average, but there are great variations in the environmental impact of different sheep farms due to variations in local conditions and farming practices (Sandin et al. 2019b). Thus, specific garments made of primary wool may have considerably lower as well as higher impact than shown in our results. We do not go further into these variations and dependencies in the present report.

## 4.5 Scaling up to 1 year of sorting

Figure 17 shows results for water deprivation, for the life cycles of clothing made of the material sorted in one year of full-capacity sorting at the Siptex plant, compared to an equivalent amount of clothing made of 100% primary materials (cotton, viscose, polyester, and wool). Note that 32% of the materials sorted at Siptex are assumed to be cotton that go to mechanical recycling, which subsequently is blended with primary cotton. So primary cotton cultivation constitutes a substantial part of the scaled-up recycling scenarios. Primary cotton cultivation is also the main contributor to the overall water-deprivation results of these scenarios. However, the overall impact of the scaled-up recycling scenarios is 22% lower than the impact of the benchmark scenarios – a difference that almost fully can be attributed to the 25% primary cotton "avoided" in case study A, in the recycling scenario compared to the benchmark scenario.

In absolute numbers, the potentially avoided water deprivation, due to the recycling enabled by one year of sorting at the Siptex plant, is about 700 million $m^3$ world equivalents. This corresponds to about 10% of the water deprivation impact caused by Swedish clothing consumption in one year according to Sandin et al. (2019). Many assumptions are behind this number – in the modelling of the four case studies and their benchmarks, in the scaling up to one year of sorting, in the figure provided by Sandin et al. (2019). The results shall therefore be seen as an indicator of the order of magnitude of water deprivation benefits that the Siptex plant can give rise to. Similar benefits of the scaled-up recycling scenario are expected also for the land use indicators.

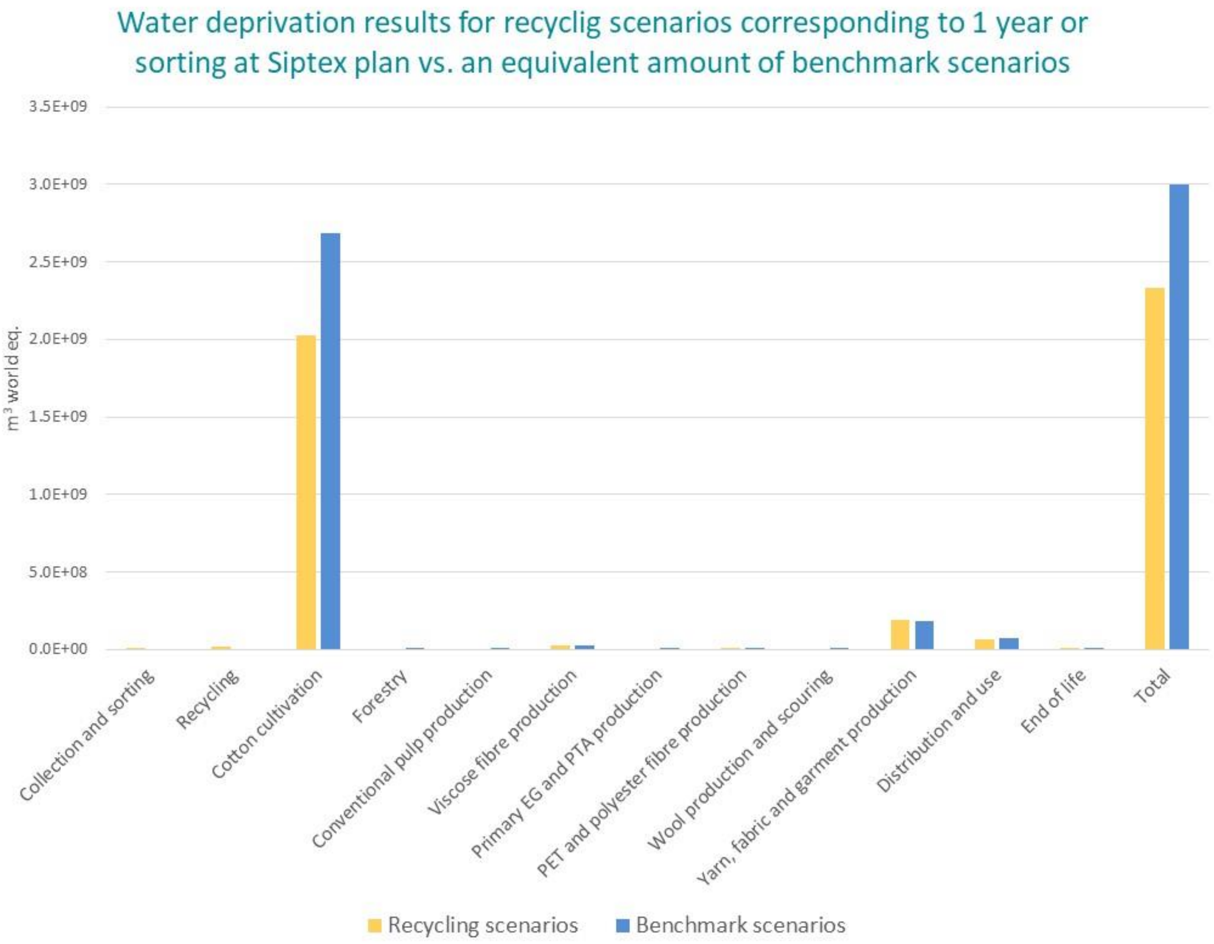

**Figure 17. Results for the impact category of water deprivation, from the scaling up of case studies A-D to one year of sorting at the Siptex plant compared to an equivalent amount of clothing made of primary materials.**

Figure 17 and Figure 18 show the scaled-up results for use of primary energy resources and climate impact, respectively. The pattern of results is very different compared to that of water deprivation, as it is production of yarn, fabric, and garment including wet treatment, instead of cotton cultivation, that contribute most to these impact categories. Therefore, the differences between the recycling scenarios, which rely on Siptex-sorted materials, and the benchmark scenarios using primary materials, are much smaller than for water deprivation. Sorting and recycling seem to reduce primary energy use with about 11%, because less energy is – in the studied scenarios – used in collection, sorting and recycling compared to primary material production (cotton cultivation, forestry, EG and PTA production). For climate impact, the difference is about 7%. In absolute numbers, this corresponds to about 4.5 kg $CO_2$ eq. per capita in Sweden, corresponding to the burning of a couple of litres of fossil gasoline or diesel. Although one automatic sorting plant with the capacity of the current Siptex plant cannot handle all textile waste in Sweden, this gives an indication of the order of magnitude of the potential climate benefits, and the need not to rely on people taking their car to dispose of their textiles (the scenarios on which the scaled-up model assumes no such transports). The logistics setup in collection is therefore important for the environmental viability of sorting and recycling. The consequential outlook in Section 4.6 looks further into this, for a scenario with several sorting plants in Sweden.

The main differences between results of resource use and climate impact are because:

- forestry is less important for climate impact – although it uses quite a bit of primary energy, this is to a large extent low-carbon, renewable energy (here we have used dataset representing Swedish conditions);

- the use stage is less important for climate impact – although it uses quite a bit of primary energy, much of this is, in our model, assumed to be the Swedish electricity mix used for washing, drying and ironing, which has relatively low climate impact; and

- wool production is more important for climate impact, due to the methane emissions of sheep grazing.

Furthermore, it is important to note that the scaled-up model was based on 4% sorting of wool. If this share is reduced, so is the climate benefit seen in Figure 18. If no wool would be sorted, the climate-impact difference between the recycling and benchmark scenarios would be negligible and within the uncertainty range. However, in the scaled-up results, the benefit of avoiding burning the fossil-based polyester material at end-of-life is not considered, as incineration is assumed at end-of-life both for the recycling and benchmark scenarios (for an assessment of avoiding incineration, see the consequential outlook in Section 4.6). In other words, potential climate benefits of cotton and polyester recycling are highly dependent on collection and recycling being efficient and/or powered by low-carbon energy. That the climate benefits of cotton and polyester recycling are not more evident, is because about 75-90% of the climate impact of clothing made of these materials are not due to the fibre production, but because of later production stages – and these remain the same regardless of whether primary or recycled materials are used.

There may be other, long-term effects of enabling access to a textile feedstock in Sweden, beyond what is captured in our LCA study. For example, having access to a feedstock locally, may make it more likely and economically feasible to – in the long run – have also subsequent production stages in Sweden or nearby. And as there is – at least today and realistically in the coming decade – better access to low-carbon energy in Sweden and Europe, than in the currently dominating production countries in Asia. Thus, a local large-scale supply of textiles may help in reducing the climate impact of other parts of production. It will certainly be interesting to follow the textile value chains that are created around the materials sorted at the Siptex plant, and the environmental performance of these value chains. The present study has been on envisioned products made of Siptex-sorted materials, reflecting how clothing purchased in Sweden today are produced and used *in general*, using *generic data*. A suggestion for future studies is to study specific items of clothing, or other textile products, made of Siptex-sorted materials. Such a study may reveal environmental advantages and disadvantages of sorting and recycling not seen in the present report.

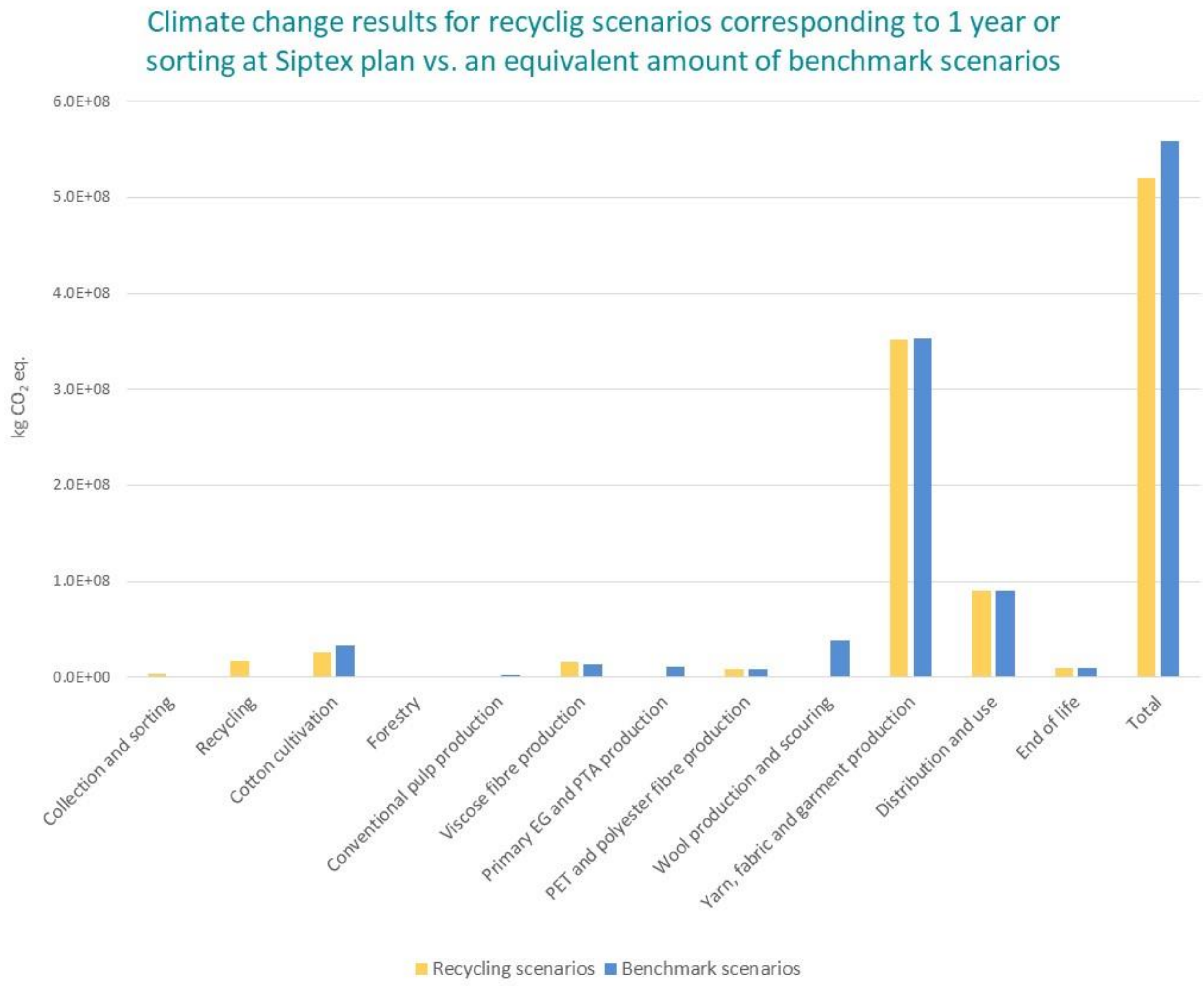

**Figure 18. Results for the impact category of climate change, from the scaling up of case studies A-D to one year of sorting at the Siptex plant compared to an equivalent amount of clothing made of primary materials.**

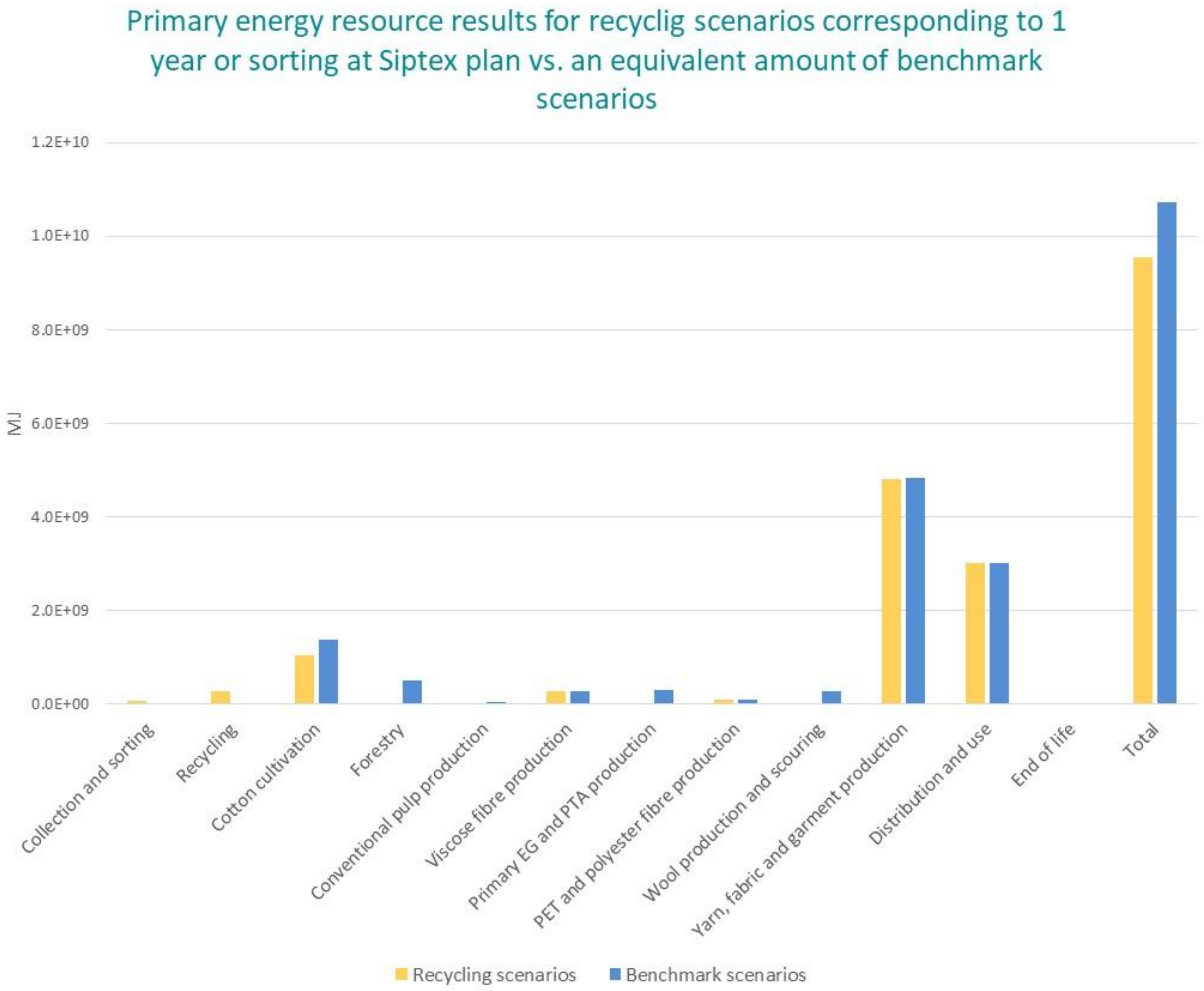

**Figure 19. Results for the impact category of primary energy resources, from the scaling up of case studies A-D to one year of sorting at the Siptex plant compared to an equivalent amount of clothing made of primary materials.**

## 4.6 Consequential outlook – effects of large-scale implementation of automatic sorting

Figures 19 to 24 show results for the consequential outlook, i.e., the potential environmental consequences, in terms of water deprivation and climate impact, of future annual automatic textile sorting of 50 000 tonnes in Sweden and 300 000 tonnes in Germany.

For water deprivation, these results emphasise the results of case study A in Section 4.1 and the scaled-up model in Section 4.5: that it is by avoiding cotton cultivation that the greatest benefits are created. As this impact category is so clearly driven by cotton cultivation, a benefit will most likely remain if recycling of cotton does not lead to the substitution of an equal amount of conventional primary material, but to a lower rate of substitution. As mentioned in Section 3.6, to what extent primary material production is substituted will depend on, for example, the quality of textile products made of recycled materials, the future policy on recycling and primary material production in EU, as well as decisions made by big textile product manufacturers and retailers.

For climate impact, **whether the net climate impact decreases or increases depend on more factors**. Avoiding primary fibre production seems to be the main contributor, but as the results of the scaled-up model in Section 4.5 indicate that this is highly influenced by the 4% wool assumed to be sorted and recycled, and that this then replaces primary wool, we created a modified consequential outlook, without sorting of wool, see Figures 23 and 24. In these figures, the total results are also negative (indicating climate-impact benefits). However, these negative figures are small compared to the positive and negative bars contributing to the net total – bars which are based on several rough assumptions and thus are uncertain. Therefore, we cannot say that there are definite climate-impact consequences of large-scale implementation of the Siptex plant in Sweden or in Germany, unless the sorting covers materials with high climate impact, such as wool. And if there are benefits, these are rather small compared to the life-cycle climate impact of textile products made of the sorted and recycled materials, as was discussed in Section 4.5. For perspective, the climate benefits shown in Figures 21 and 23, reflecting sorting in Sweden, correspond to about 10 and 1 kg $CO_2$ eq. per capita, respectively. In other words, equivalent to saving half a litre, or a few litres, of fossil gasoline or diesel per person annually – emphasising the fact that a textile collection system should not rely on people driving their car to a collection bin.

Moreover, in terms of climate impact, it is interesting to note that the loss of energy recovered when recycling textiles instead of incinerating them – that is compensated with increased energy (heat and electricity) production elsewhere in the energy system – is a rather small effect. In the Swedish scenario, this effect roughly corresponds to the relatively small climate impact of collection and sorting. In the German scenario, the effect is slightly larger because the electricity consumption mix assumed to compensate for part of the lost energy (the other part is assumed to be compensated by the national district heating mix) causes much higher $CO_2$ emissions per kWh compared to the Swedish consumption mix. Still, this effect is smaller than the direct emissions avoided due to the avoided incineration, and the effect is still relatively small in a life-cycle perspective.

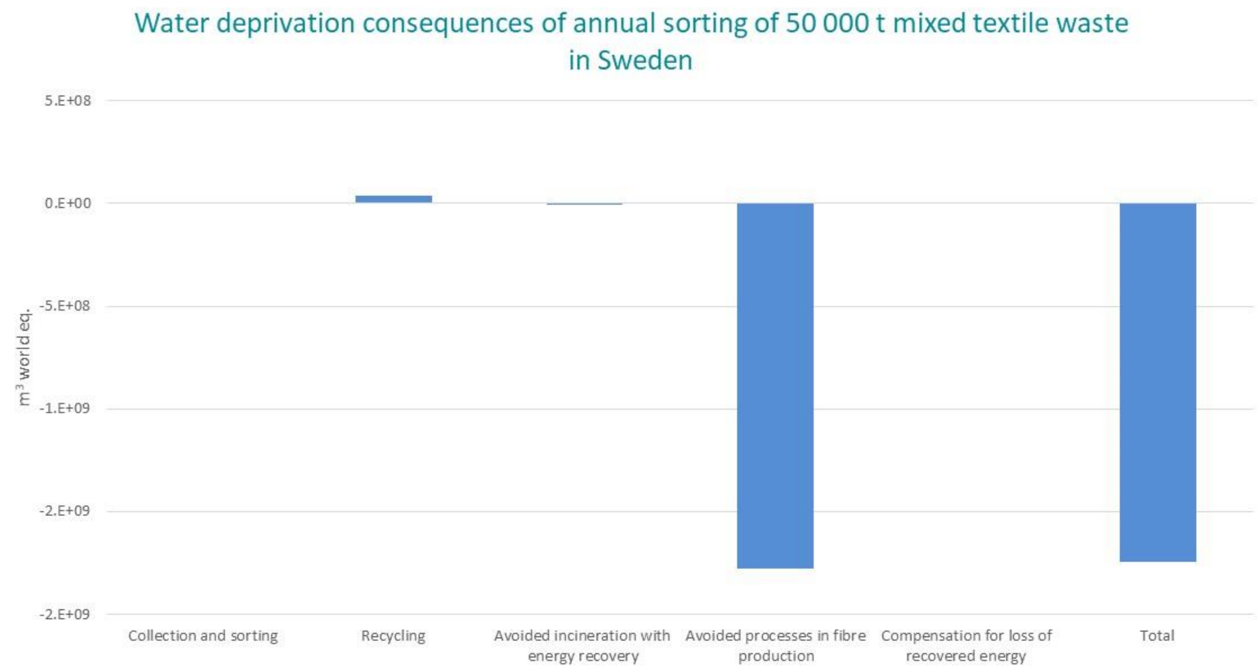

**Figure 20. Results for impact category of water deprivation, for the consequential outlook, for the case of sorting of 50 000 tonnes mixed textiles in Sweden.**

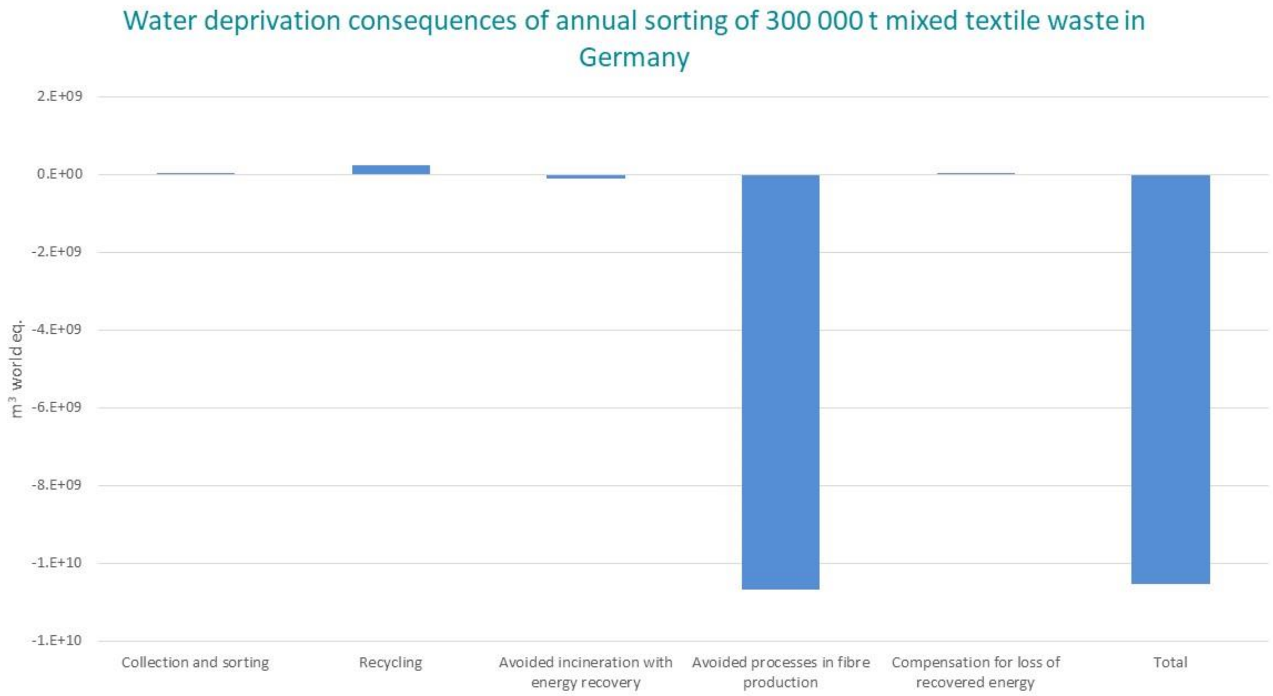

Figure 21. Results for impact category of water deprivation, for the consequential outlook, for the case of sorting of 300 000 tonnes mixed textiles in Germany.

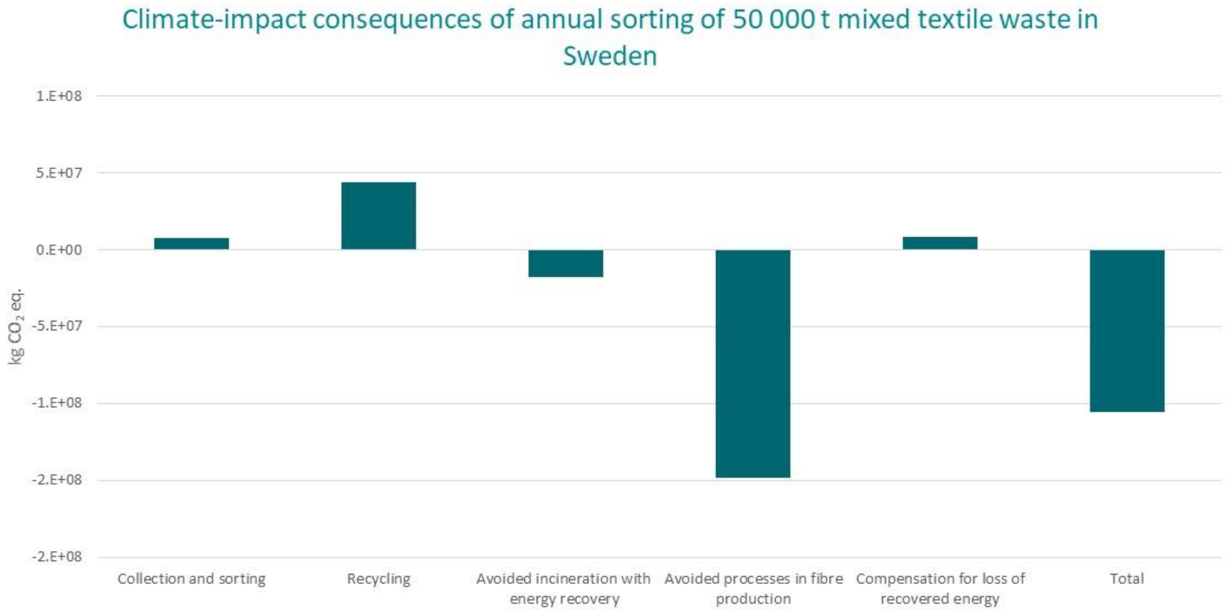

Figure 22. Results for impact category of climate change, for the consequential outlook, for the case of sorting of 50 000 tonnes mixed textiles in Sweden.

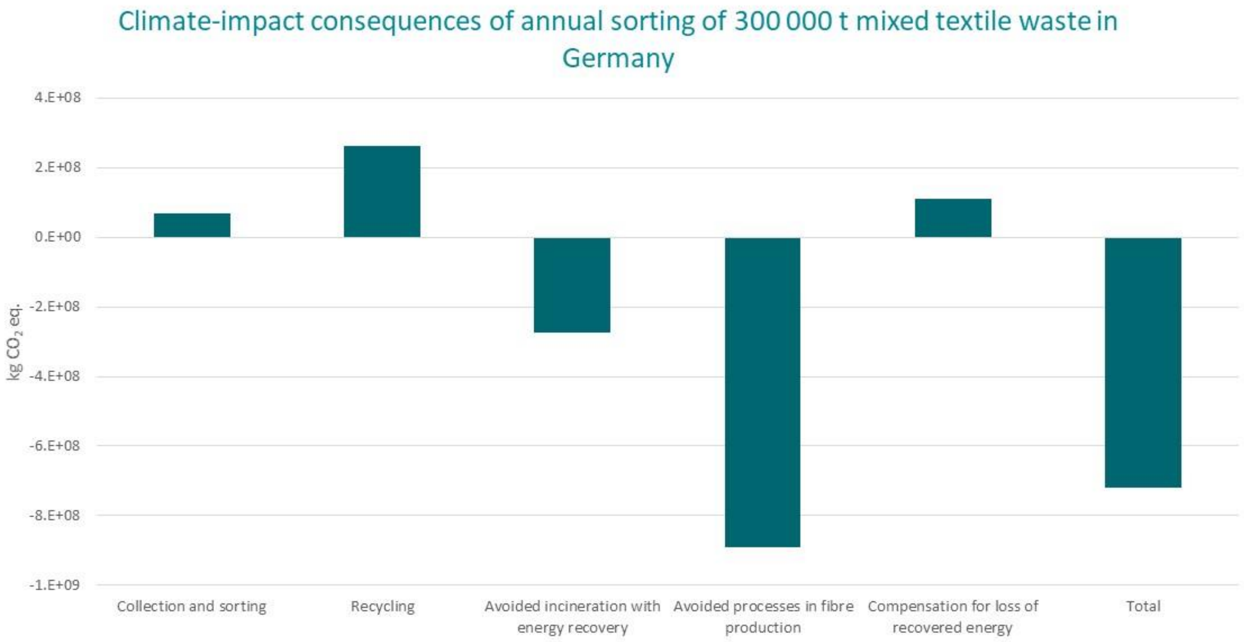

Figure 23. Results for impact category of climate change, for the consequential outlook, for the case of sorting of 3000 000 tonnes mixed textiles in Germany.

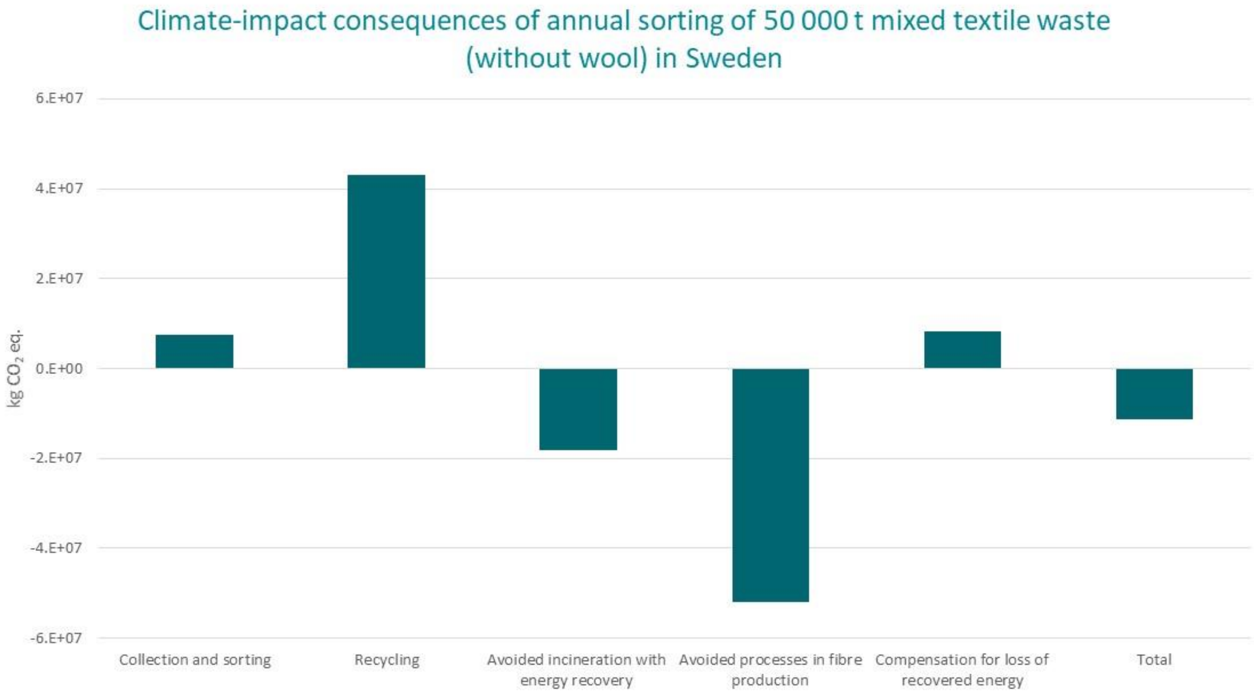

Figure 24. Results for impact category of climate change, for the consequential outlook, for the case of sorting of 50 000 tonnes mixed textiles, but not including wool, in Sweden.

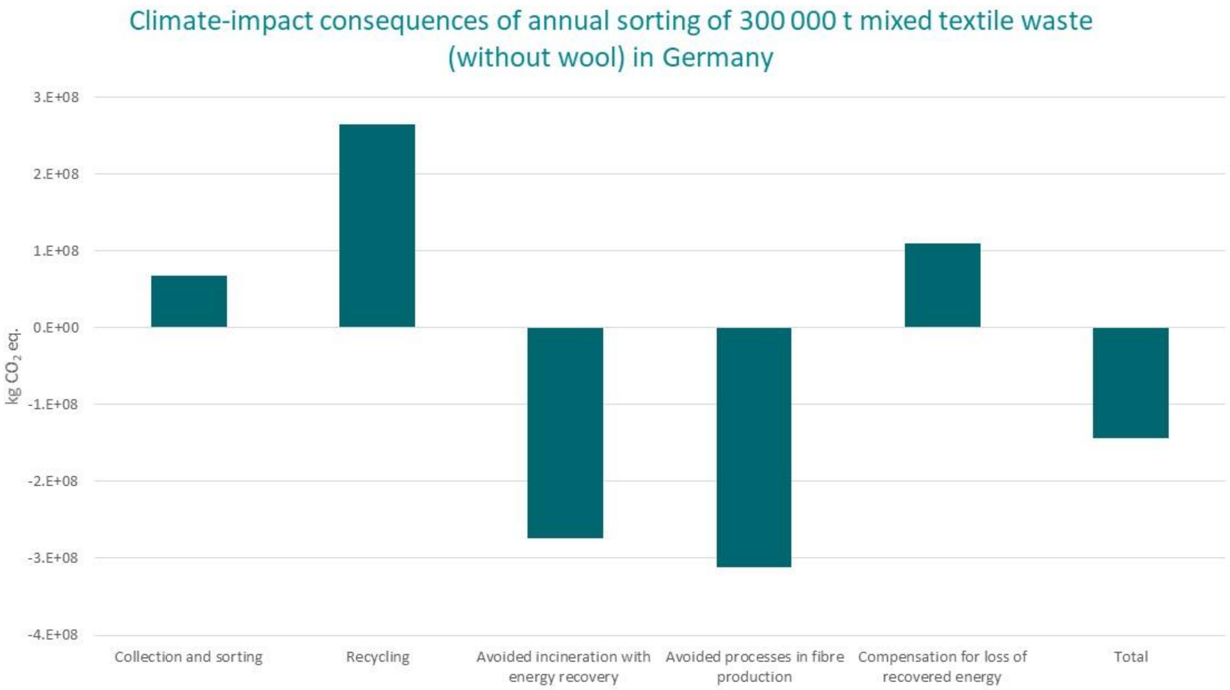

**Figure 25. Results for impact category of climate change, for the consequential outlook, for the case of sorting of 300 000 tonnes mixed textiles, but not including wool, in Germany.**

# 5 Conclusions and recommendations

In this section, we summarize the main conclusions of the study, based on the results and discussion in Section 4, in relation to the research questions outlined in Section 2.1. In the end, there is also a paragraph summarizing the identified research needs.

Before reading the conclusions, note that this study is on the automatic sorting and recycling of materials that are not fit for reuse. Reuse, or other ways of prolonging the use of existing textile products, is often the impact-reduction measure that creates the largest environmental benefits across all impact categories (Sandin and Peters 2019). Therefore, the conclusions below shall not be used to advocate increased recycling on the expense of reuse.

1. What are the environmental impacts of end products produced from the three recycling products, in relation to identical end products produced from virgin material?

**The benefits of the recycling scenarios, compared to the benchmark scenarios, are largest in those impact categories where the production of primary material contributes to a large share of the life-cycle impact in the benchmark scenarios**. For case study A, the cotton T-shirt, the benefits are primarily in terms of arable land use and water deprivation, but probably also in terms of terrestrial and freshwater eutrophication. For case study B, the viscose T-shirt, the benefits are in terms of reduced use of primary energy (mostly renewable) and forest land. For case study D, the wool sweater, the benefits are in all the assessed indicators.

For case study C, the polyester sports jersey, the benefits of recycling are not as obvious as for the other case studies, but there are likely benefits in freshwater eutrophication as well as reduced fossil resource use of about 10% (corresponding to the content of the product) and climate impact, also with about 10%, if considering the avoided incineration at end-of-life.

In general, the results indicate that **the main benefits of recycling arise when production of primary materials is avoided**, rather than when the usual end-of-life treatment – which in Sweden is incineration with energy recovery – is avoided. This is further emphasised by the consequential outlook, see conclusions under research question 6 below. This means that the benefits rely on the actual substitution of primary materials – this study has relied on an assumption of 100% substitution, but the actual substitution rates may be lower. In the end, the substitution rates may depend on, for example, the quality of products made of recycled materials as well as future policy decisions made in EU related to the use and production of recycled and primary materials. That the benefits rely on the substitution of primary materials also means that **it is advisable, from an environmental viewpoint, to sort out and recycle materials based on the primary production that they can substitute**. Having said this, remember that the present report was on Swedish conditions. For countries with less-developed waste infrastructure and treatment, there are likely more benefits also with avoiding the usual end-of-lite treatment (or lack thereof).

Above conclusions concern the *direct* effects of enabling large-scale automatic sorting in Sweden, but there may also be *indirect* effects beyond what is captured in our LCA study, as discussed in Section 4.5. For example, enabling access to a textile feedstock in Sweden may, in the long run, enable more parts of the subsequent production stages to relocate to Sweden or nearby, with, for example, better access to low-carbon energy and wastewater management. It is recommended to study such potential effects in future studies.

2. What is the environmental impact of sorting the textile waste so that it can be recycled, in contrast to the end-of-life treatment common in Sweden today: incineration with energy recovery?

**The environmental impact of the collection and sorting of textiles is minor compared to the life-cycle impact of the studied end products.** Particularly, the direct contribution from the Siptex plant is low, because of low energy use combined with low-carbon energy (the greatest part of the energy use is here assumed to be provided by the Swedish electricity mix). Even if the collection is assumed to be done in a greater area, by adding a 500 km truck transport, its contribution remains low.

For the assessed indicators the direct impact of incineration is also generally low compared to the life-cycle impact of textile products. The most obvious direct effect of avoiding incineration is seen for materials made of fossil resources, as in case study C, which reduces the life-cycle climate impact of about 10%. The generally low effect of avoiding incineration underlines the conclusions under research question 1 above, i.e., that the greatest differences between the recycling and benchmark scenarios are not related to avoiding incineration, but in avoiding production of primary material.

A potential effect of avoiding incineration with energy recovery, not covered in the attributional LCA models of case studies A-D, is that the energy generated is compensated by some other type of energy production. For more on this, see Section 4.6 and below conclusions under research question 6.

Note that the collection stage includes truck transports from the collection bin, and a subsequent ship transport, but not any previous transport of the household discarding the textile. However, in end-of-life scenario 2, in which the garment goes to sorting and reuse or recycling again at end-of-life, it is assumed that the average household drives a car to the collection bin, in average 4 km per kg discarded textiles. This increases the life-cycle climate impact of a few percentages, which is non-negligible in relation to the small climate-impact difference between the recycling and benchmark scenarios in case studies A-C. This indicates that **how collection is organised can influence the environmental viability of the textiles sorted at the Siptex plant** (or any sorting plant), particularly in terms of climate impact and associated impact categories. Specifically, it will be **important to develop a collection system that does not heavily rely on households taking their cars to the collection bin**. This means that the environmental viability of collection for sorting and recycling may differ depending on geographical factors such as the average distance from households to the collection bin.

3. Which recycling products can reduce impact the most, and which have a lower or even negative environmental potential?

All assessed indicators showed lower environmental impact for a sweater made of sorted and recycled wool, compared to a sweater of primary wool, and for four of the indicators this benefit was very large, more than 90%. As such, **sorting wool appears to create the largest environmental benefits, per amount of sorted material**. However, two things need to be emphasized:

- There are impact categories not covered by this study, such as toxicity, which may show a different picture in terms of the relative benefits and impact of the different sorted fractions.

More impact categories will have to be accounted for to say, with greater certainty, which sorted fraction that creates the greatest environmental benefits.

- The availability of discarded wool is small compared to the availability of discarded cotton and polyester. In terms of the aggregated benefits of one sorting plant, the potential benefits of sorting other fractions may therefore be greater compared to sorting wool. For more on this, see conclusions under research question 5 below, concerning the scaled-up LCA model.

After wool, the sorting of cotton to mechanical recycling (case study A) appears to show the greatest environmental benefits, if conventional cotton cultivation is thereby avoided. However, the recycling scenario in case study A relies on input of primary material, in contrast to case studies B and C. This is a potential advantage of case studies B and C, especially if recycling is done at such a scale that the access to recycled material becomes comparable to the access to primary material.

**None of studied recycling scenarios create a clear increase, compared to the benchmark scenarios relying on 100% primary materials, in any of the environmental impact indicators assessed**. Some scenarios show a small increase, for example for eutrophication and climate impact, but within the uncertainty range. That small increases can be seen, emphasizes the **need to keep track of the environmental impact when developing the collection system** (as discussed above) **and products made of sorted and recycled material**.

4. Which life-cycle stages contribute the most to the life-cycle environmental impact – collection, sorting, recycling, production, use, or end-of-life?

For case studies A-C, **raw material extraction for fibre production is the most important process for some of the indicators**: water deprivation, land use, some eutrophication indicators. **For other indicators** – primary energy use, fossil resource use, climate impact – **the subsequent production dominates**, as well as the use stage (primarily the user's transport to the store and back), **which is driven by fossil energy use**. For case study D, the results pattern is different, as **wool production (primarily sheep grazing) is the dominant life-cycle stage, or one of the most contributing life-cycle stages, for all studied indicators**.

For cotton, viscose and polyester garments, **processes after fibre production contribute with about 75-90% of the climate impact**. This implies that **material recycling is only one of many solutions needed to reduce the climate impact of the textile industry**. Much else is needed, most importantly more use of each garment (e.g., by increased longevity and more reuse), use of low-carbon energy in production, and business models that do not rely on car transports (Sandin et al. 2019). Sorting plants located in, or nearby, Sweden can potentially help also in some of the other changes needed, as concluded under research question 1 above.

A key observation is that the **direct environmental impact of the Siptex plant is insignificant in comparison to the life-cycle impact of products made of the sorted materials**. This means that it can be worthwhile, from an environmental viewpoint, to use some extra energy at the plant (e.g., by letting the material go through the sorting plant another round) if this improves the sorted material, i.e., if its fibre content and/or colour thereby is more consistent. This can increase the likeliness that the material is used to a high-quality end product that is more likely to replace a product made of primary material. The downside of this is, however, that less material will then be sorted per day, if the sorting machine is running at full capacity. So, there may be a trade-off between the quality and volume of sorted materials – both are important to create environmental benefits.

5. By extrapolating to the annual capacity of the Siptex plant, what is an estimate of the environmental benefits (if any) created by the plant each year?

In the scaled-up model, we looked at water deprivation, climate impact and use of primary energy resources. See Section 4.5 for results and discussion.

For water deprivation, **the impact of the scaled-up recycling scenarios is 22% lower than the impact of the benchmark scenarios** – a difference that is almost fully because of the 25% primary cotton, and associated water deprivation impact, "avoided" in the recycling scenario of case study A. In absolute numbers, **this corresponds to about 10% of the water deprivation impact caused by Swedish clothing consumption** in one year. This figure shall be seen as an indication of the order of magnitude of the potential water deprivation benefits of the Siptex plant. As such, it implies clear and considerable water deprivation benefits made possible by the Siptex plant. Similar benefits are expected also for the land use indicators, although not shown for the scaled-up model in this report.

For use of primary energy resources and climate impact, the results are very different compared to the results for water deprivation, as it is production of yarn, fabric, and garment, including wet treatment, that contribute most to these impact categories – instead of cotton cultivation. Therefore, the differences between the recycling scenarios, which rely on Siptex-sorted materials, and the benchmark scenarios relying on primary materials, are much smaller than for the impact category of water deprivation. Sorting and recycling seem, according to the results shown in Section 4.5, to reduce the use of primary energy resources and climate impact with about 10%, respectively. Regarding sorting and recycling, it is important to stress two things. First, if collection of textiles would rely on people driving their car to discard textiles, the energy and climate benefits of recycling would be reduced and could potentially disappear. **The logistics setup in collection is therefore important for the climate impact and energy resource viability of sorting and recycling**. Secondly, the scaled-up model was based on 4% sorting of wool and if this share is reduced, so is the climate benefit. If no wool would be sorted, the climate-impact difference between the recycling and benchmark scenarios would be negligible and within the uncertainty range. However, it should be noted that the scaled-up results do not consider the effect of avoiding burning the fossil-based polyester material at end-of-life, as incineration is assumed at end-of-life both for the recycling and benchmark scenarios (for conclusions of avoiding incineration, see below research question 6 below). In other words, potential climate and energy resource benefits of cotton and polyester recycling depend on efficient collection of discarded textiles and efficient recycling powered by low-carbon energy. **The benefits of cotton and polyester recycling are not more evident for these indicators, is because about 75-90% of the climate impact of clothing made of these materials are not due to the fibre production, but because of later production stages that remain the same regardless of whether primary or recycled materials are used**.

6. What are the environmental consequences of implementing the Siptex sorting technology on a large scale?

In the consequential outlook, we looked at the effects of large-scale implementation of the Siptex sorting technology in terms of water deprivation and climate impact. See Section 4.6 for results and discussion.

The result of the consequential outlook emphasises the results of the scaled-up model discussed under research question 5 above: **large-scale automatic sorting reduces water deprivation impact as it reduces the need for cotton cultivation**. This benefit is likely to remain even if a lower substitution rate is assumed.

In terms of climate impact and the effects of large-scale implementation of automatic sorting, the consequential outlook indicates that **whether there will be a net climate benefit of large-scale implementation depends on several factors**. Avoiding primary fibre production seems to be a main contributor, but this depends much on the materials replaced – if wool is replaced, the benefits are clearer and increases. Other influencing factors, such as the substitution rate, were mentioned under the other research questions above. If there are benefits, these are up to about 10% of the life-cycle climate impact of textile products made of the sorted and recycled materials. As previously discussed in Section 4.5, other changes, beyond recycling, are also needed for the textile industry to reduce its climate impact in line with the internationally set climate targets.

Finally, we summarize a few research needs identified in the work with this report:

- It would be valuable to study a range of actual clothing items produced from the Siptex-sorted materials, with specific data on, for example, production. In this type of study, it could for example be explored whether producers purchasing recycled materials are more likely to also reduce subsequent production stages. In addition, it would be interesting to study a case in which a local supply of recycled materials has enabled production stages located in Sweden or nearby, and what this means for the life-cycle impact of the garment compared to the life-cycle impact of a conventionally produced garment (made of primary material, produced in Asia). Additionally, it would be interesting to study the effect of quality in such a study, for example the potentially lower quality of mechanically recycled materials.
- It would be valuable with a more refined scaled-up model of the Siptex plant, for example based on actually sorted fractions in one year, possibly including other fibres than those covered by the present study.

- It would be valuable with data on the substitution rate of recycled textile materials, preferably divided per fibre type. Based on this, an update could be made of the comparisons between recycling and benchmark scenarios, and the consequential outlook, of the present screening LCA.

- In a future study, it would be interesting to study the effect of applying another method for allocating the environmental burden of the initial production of textile fibres, to the textile waste input to the recycling scenarios. In this study, the cut-off method has been applied, which means that textile waste comes free of environmental burden, but it carries all the burden from collection and recycling. In particular, it would be interesting to test the effect of instead using the Circular Footprint Formula (CFF) – as this may influence future LCA practices in the EU – which is expected to allocate a larger environmental burden to recycled materials. See Section 2.6 for more details.

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# Annex A: Impact and resource use categories

The impact and resource use categories studied in the present study are described below.

## Climate change

Global climate change is a problem for many reasons. One is that a higher average temperature in the seawater results in flooding of low-lying, often densely populated coastal areas. This effect is aggravated if part of the glacial ice cap in the Antarctic melts. Global warming is likely to result in changes in the weather pattern on a regional scale. These can include increased or reduced precipitation and/or increased frequency of storms. Such changes can have severe effects on natural ecosystems as well as for the food production.

Global warming is caused by increases in the atmospheric concentration of chemical substances that absorb infrared radiation. These substances reduce the energy flow from Earth in a way that is similar to the radiative functions of a glass greenhouse. The category indicator is the degree to which the substances emitted from the system investigated contribute to the increased radiative forcing. The characterisation factor stands for the extent to which an emitted mass unit of a given substance can absorb infrared radiation compared to a mass unit of $CO_2$. As the degree of persistence of these substances is different, their global warming potential (GWP) will depend on the time horizon considered, such as 20, 100 and 500 years. In this study, a time horizon of 100 years has been applied. The time scale 100 years is often chosen as a “surveyable” period in LCAs and discussions regarding global warming.

In this project, a GWP-indicator is used that excludes biogenic $CO_2$. If biogenic $CO_2$ would have been included, there would be equal amounts of uptake and emissions within the system boundaries – as the full life cycle from raw material extraction to end-of-life is included – so that there would be net-zero influence of biogenic $CO_2$ on the GWP results. But since some datasets have an incomplete balance of uptake and emission of biogenic $CO_2$, it is easier to exclude it altogether.

## Eutrophication (nutrient enrichment)

When the nutritional balance in the soil and waters is disturbed, it is called eutrophication (when the amount of nutrition is increased). In aquatic systems, this leads to increased production of biomass, which may lead to oxygen deficiency when the biomass is subsequently decomposed. The oxygen deficiency, in turn, kills organisms that live in or near the bottom of the lakes or coastal waters. It also makes the reproduction of fish more difficult.

In terrestrial systems, deposition of nitrogen compounds leads to increased concentrations of nitrogen, which in turn leads to a change in the growing conditions. The nitrogen may leak into water systems and cause increased levels of nitrogen in the aquatic systems. The effects in aquatic systems depend on the recipient. Different terrestrial and aquatic systems have different sensitivity to eutrophying and oxygen depleting substances. Phosphorous-containing substances increase biomass production where the availability of phosphorous limits the growth. In other case, biomass production is increased through emissions of nitrogen-containing substances.

Oxygen depletion in aquatic systems is caused not only by emissions of nutrients that stimulate the biomass production, but also by direct emissions of organic material that is decomposed in the water. These emissions can be measured in terms of BOD (biological oxygen demand), COD (chemical oxygen demand) or TOC (total organic carbon).

## Water deprivation

Freshwater resources, among others including surface water flows and groundwater flows and stocks, are increasingly under stress due to human interventions. This has consequences for humans (e.g., through less water available for agriculture) and for ecosystems. Water stress also makes society and ecosystems less resilient to other environmental impacts. For example, resilience to changed weather patterns is reduced due to climate change (e.g., less rainfall) and nutrient pollutants.

In this study, water deprivation is considered by using the AWARE method for water deprivation (Boulay et al. 2018). In the AWARE method, the freshwater removed from a catchment is considered, and this water use is then multiplied by a factor between 0.1 and 100 that reflects the scarcity of water in that catchment. If the exact catchment area is unknown or not specified, an average AWARE factor for the considered region is used (this may be a country or a larger area).

In the present study, most water use of the LCI datasets used, is not specified with regards to geography. Therefore, results (as derived from the LCA software) for the life-cycle stages contributing the most to the results were corrected with geography-specific AWARE factors from WULCA (2022) and from Boulay et al. (2019). The latter study provides crop-specific AWARE factors for different countries and these factors were therefore used for cotton cultivation. If a process is assumed to take place in several countries (for example, cotton cultivation is assumed to occur in Australia, China, India, and USA), the average of the AWARE factors of the contributing countries was used. For remaining water use with unspecified location of use, we used the average factor for OECD and BRICS countries (which is of the same order-of-magnitude as the country-specific AWARE factors used, except for water used in the use stage in Sweden, which has a much lower AWARE factor).

## Energy use

The energy use indicator reflects a concern about the limited availability of (renewable and non-renewable) energy resources and its unequal sharing between various needs in society. The energy use indicator is relevant because it is a driver behind environmental impacts, and it can be used to identify processes of the product system with a potential for energy savings, irrespective of whether the energy in the present system comes from renewable or non-renewable resources.

## Land use

The land use indicators reflect a concern about the limited availability of land and its unequal sharing between various needs in society. Land use also cause environmental impacts such as erosion, loss of fertile topsoil, water quality, biodiversity loss, etc., which can impact ecosystem services, for example water purification, cycling of nutrients, provision of food, feed and other materials used in society.

In the present study, three rough indicators are used. These indicators consider how much of arable, pasture and forest land that is used, but not the environmental impact of these land uses. There are more advanced methods available, such as the LANCA method advocated by PEF, based on five indicators on soil quality. Such advanced method was not used since the LCI data used in the present study were deemed not robust enough to support such an impact assessment

## Fossil resource use

The fossil use indicator reflects a concern for the reliance and fair use of a limited resource. Fairness relates to the question on how to distribute the fossil resources that can still be used within the carbon budget set to achieve the global targets for reducing climate impact. The indicator also reflects a concern for the environmental impact caused by fossil resource use, climate change (see above) as well as other effects of mining or burning fossil fuels, such as particle matter formation and acidifying pollutants.

# Annex B: Detailed LCI description

Data used in the study is presented as an electronic appendix, in the form of an Excel file, see attachment below. See Table 4 for information on the different tabs in the Excel file.

**Table 4. Guidance to the tabs in electronic appendix.**

| | |
|---|---|
| A1. Cotton | The processes included in the production of the cotton T-shirt benchmark scenario. Some processes are referred to that are in other tabs in the Excel file. |
| A2. Cotton | The processes included in the production of the cotton T-shirt recycling scenario. Some processes are referred to that are in other tabs in the Excel file. |
| B1. Viscose | The processes included in the production of the viscose T-shirt benchmark scenario. Some processes are referred to that are in other tabs in the Excel file. |
| B2. Viscose | The processes included in the production of the viscose T-shirt recycling scenario. Some processes are referred to that are in other tabs in the Excel file. |
| C1. Polyester | The processes included in the production of the polyester sports jersey benchmark scenario. Some processes are referred to that are in other tabs in the Excel file. |
| C2. Polyester | The processes included in the production of the polyester sports jersey recycling scenario. Some processes are referred to that are in other tabs in the Excel file. |
| D1. Wool | The processes included in the production of the wool sweater benchmark scenario. Some processes are referred to that are in other tabs in the Excel file. |
| D2. Wool | The processes included in the production of the wool sweater recycling scenario. Some processes are referred to that are in other tabs in the Excel file. |
| Collection_Sorting | The processes related to the collection and sorting, applicable for all four case studies. |
| Confect. (A-C) | The confectioning process for case studies A-C. |
| Distribution | The distribution of the garments from the production site to Sweden and the stores. One process for case studies A-C and one process for case study D. |
| Use (A-B) | The processes included in the use stage of case studies A and B applicable for both the benchmark and recycling scenarios. |
| Use (C) | The processes included in the use stage of case study C applicable for both the benchmark and recycling scenarios. |
| EoL 2 | The processes related to the end-of-life scenario 2 for all four case studies. |
| CLCA | The processes of the case studies A-D adjusted in the consequential outlook, i.e., the processes concerning collection and sorting. |

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