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Summary

Nordic consumers purchase 365,000 tonnes of new clothing and home textiles each year. After food, housing and mobility, textiles is the consumption area that causes greatest environmental impacts. Reusing and recycling of used textiles can offset some of these impacts but with an increasing number of options available, government and business need more information to make decisions on which pathways to choose.

The Nordic Council of Ministers commissioned a consortium led by FORCE Technology to carry out an LCA study to compare the environmental impacts and benefits of treatment options of discarded textiles in four Nordic countries. The intention has been to prepare a solid quantitative basis for future political decisions.

We have used a life cycle assessment approach to compare different scenarios for treating one tonne of discarded textiles. A number of findings have emerged that can be important in guiding policy makers and others in creating strategies for discarded textiles:

- 365,000 tonnes of clothing and home textiles are put on the market each year in Nordic countries. Following use, one third is separately collected for reuse and recycling. The remaining two thirds is collected in mixed waste and mostly incinerated with energy recovery. Much of this may be suitable for recycling and reuse.
- Reuse, both in Nordic countries and in other areas of the world, gives by far the greatest environmental benefits compared to recycling and incineration.
- We have assumed that a reused item fully offsets the purchase of a new item of the same type. This is most probably optimistic, but even substitution factors of less than 30% give benefits compared to recycling or incineration.
- Most recycling today is mechanical and constitutes downcycling to a lower quality product. Some fibre-to-fibre chemical recycling processes are under development and can potentially give greater benefits in form of better quality. However, data quality is poor, so results are not robust.

- For all fibres and recycling methods considered, recycling is a better environmental option than incineration, though the relative benefits are moderate compared to the benefits of reuse.
- Wool is the textile fibre where the largest benefits per tonne can be achieved from reuse and recycling. Inventory data are of relatively poor quality, but the benefits are so high, that wool deserves a special focus in future activities. Wool comprises approximately 4% of textiles put on the market in Nordic countries.
- Cotton also gives high environmental gains per tonne, particularly for reuse scenarios and is also the most widespread fibre in Nordic textiles (57% by weight). However, mechanical fibre-to-fibre cotton recycling can currently only be carried out for used textiles of 100% cotton and is therefore not suitable for cotton mixed with other fibres which constitutes a significant market share.
- Polyester fibres are derived from fossil fuels. Therefore, reuse and recycling gives strong benefits compared to incineration specifically for climate change. Benefits in other impact categories are relatively modest compared to cotton and wool. However, with a high share of polyester fibres in today's textiles future efforts should not neglect benefits that can be achieved from reuse in particular.
- Energy use and impacts associated with separate collection, sorting and transport of textiles as the first stages in reuse and recycling are relatively insignificant in the overall picture.
- Discarded Nordic textiles can either be reused in the Nordic region or exported for reuse elsewhere in the world. The benefits from reuse in either case are very similar, despite the large difference in transportation distances.
- Different marginal energy mixes across the Nordic countries give different levels of impacts and benefits from incineration. However, this does not change the overall results when establishing new strategies for collection, reuse and recycling.
- The benefits of incineration will tend to reduce over time as the renewables share in substituted energy sources increases.
- Some of the hazardous chemicals present in textile products remain in the product at the end of their useful life, even if they have been washed several times.
- In mechanical recycling processes, all substances remain in the material and are carried over to the new product.

- In chemical recycling processes, some substances remain in the material and both non-hazardous and hazardous substances may interfere technically with the process.
- Strategies for discarded textiles need to consider the potential exposure to hazardous chemicals of people and the environment from reused and recycled materials.

It is noted that there are significant (and inherent) uncertainties in the results presented. This is unavoidable in all LCA's at this level, but we believe that the results are sufficiently robust for further use.

Summary of the critical review

Reviewers

A critical review according to ISO 14040/14044 was performed by Massimo Pizzol (Danish Centre for Environmental Assessment, Aalborg University) and Jannick H Schmidt (2.–0 LCA consultants).

The review process

The review process was as outlined below:

- A draft goal and scope report was delivered for review on 8th May 2015.
- A phone meeting between Force Technology, NAG and the reviewers was held on 20th May 2015 to address the main concerns based on a draft review document.
- On 21st May 2015, the final review report was delivered.
- The final draft report was delivered for review on 9th December 2015.
- On 15th January 2016, a first full review report was delivered to NAG.
- On 26th April 2016, a revised – final – project report was received and the final review report was delivered to NAG on 26th May 2016.

Final review statement

The LCA report has been reviewed with respect to compliance with the ISO 14040 and 14044 compliance. For most requirements in the ISO standards, the LCA study fulfils the requirements, but there are some elements that fail to comply. These are:

- The LCA is a comparative study intended disclosed to the public. For such studies, the ISO standards require a panel critical review. This has not been performed.
- ISO 14044 presents a hierarchy to model co-products, where the highest options include subdivision of multiple-product-output processes and substitution. Other, less preferable modelling options include allocation. With respect to allocation, the hierarchy has only been followed for the modelling of the foreground system. The background system, which is based on LCI databases, is based on various (non-described) allocation principles.
- The standard requires characterised results to be presented, while normalised results are optional. Even though characterised results are in appendix, the current report only presents the normalised results, which is not strictly in compliance with the standard.
- The ISO 14044 standard requires that an evaluation of sensitivity, consistency and completeness is included in the life cycle interpretation phase. This is not included.

The full critical review can be found in Appendix C.

Preface

The project was carried out in the period from March 2015 to March 2016. The project group was composed of experts from four organisation in three Nordic countries:

- Anders Schmidt and Pia Brunn Poulsen, FORCE Technology, DK.
- David Watson, PlanMiljø, DK.
- Sandra Roos, Swerea IVF, SE.
- Cecilia Askham, Østfoldsforsning, NO.

The work was initiated, funded and followed by NAG (Nordisk Affaldsgruppe), with Marianne Bigum from the Danish EPA as the main coordinator and with input from Yvonne Augustsson from Naturvårdsverket in Sweden and Jon F. Larsen from Miljødirektoratet in Norway.

A critical review was performed by Massimo Pizzol and Jannick H. Schmidt from University of Aalborg/2.–0 Consultants, starting with a review of the Goal and Scope document in May 2015, including a video conference in March 2016 in which the final report was discussed, and ending with a final review.

The project group wants to thank all our colleagues who contributed with their knowledge on the many issues relating to environmental aspects of textile use, reuse and recycling.

Abbreviations

CHP:	Combined Heat and Power Plant.
CMR:	Carcinogenic, Mutagenic, toxic to Reproduction.
EOL:	End Of Life.
EPA:	Environmental Protection Agency.
ILCD:	International Life Cycle Database.
LCA:	Life Cycle Assessment.
LCI:	Life Cycle Inventory.
LCIA:	Life Cycle Impact Assessment.
MJ:	Mega Joule.
mPE:	milli Person Equivalent.
NAG:	Nordisk Affaldsgruppe (Nordic Waste Group).
NCM:	Nordic Council of Ministers.
PE:	Person Equivalent.
PET:	PolyEthyleneTerephthalate (Polyester).
POP:	Persistent Organic Pollutants.
REACH:	Registration, Evaluation, Authorization and Restriction of Chemicals (EU Regulation).
ROW:	Rest Of the World.
SVHC:	Substances of Very High Concern.

1. Introduction and objectives

1.1 Background

Approximately 365,000 tonnes of new clothing and household textiles (including similar textiles in the public and private sector) are sold each year on the Nordic market (Palm *et al.*, 2014a). This corresponds to around 14 kg/capita/year. Purchases of new textiles saw significant growth prior to the economic crisis. In Sweden new textile consumption grew by 40% in volume terms between 2000 and 2009 (Tojo *et al.*, 2012) while Danish household consumption expenditure increased by 36% between 2003 and 2010 (Watson *et al.*, 2014a).

The vast majority of textiles purchased in Nordic countries, and almost all the fibres included in them are imported, mostly from outside Europe. The production of textiles products is associated with significant resource use, and pollution of air, soil and water in producing countries (Beton *et al.*, 2014; Munn, 2011; Muthu, 2014; Slater, 2003). Opportunities for partially offsetting these negative impacts lie in gaining value from used textiles, both via extending active lifetimes of textiles as far as possible, and by making good use of the materials which they contain (Watson *et al.*, 2014b).

Textiles, and in particular, clothing is one of the relatively few product types where there has long existed a healthy separate collection and reuse market both in Nordic countries and globally. Market prices for used textiles have seen significant increases over the past decade (WRAP UK, 2013) Nevertheless, between 80% (Sweden) and 56% (Denmark) of used textiles are disposed of in mixed waste and end their days in incineration, or even in landfill in the case of Finland (Palm *et al.*, 2014a). This is despite a large part of these textiles being directly reusable (Laitala *et al.*, 2012).

Almost all the value of separately collected textiles is derived from resale of the reusable component. Approximately 90% of the reusable collected textiles are exported from the Nordic Region and sold on foreign markets, typically in Eastern Europe, Africa and Asia (Watson *et al.*, 2016; Palm *et al.*, 2014a). The non-reusable component is almost entirely down-cycled e.g. as rags, upholstery filing, insulation etc. or is incinerated. Very little textile-to-textile recycling currently exists mainly due to technical challenges with respect to fibre separation and fibre quality (Palm *et al.*, 2014a).

Downcycling generates little economic value, and existing LCAs indicate that downcycling options give fairly limited environmental benefits due to the types of materials being replaced (Zamani *et al.*, 2014). Efforts have been invested in recent years on developing viable technologies for textile-to-textile recycling. So far, only 100% polyester recycling appears to have reached full maturity, but other technologies focusing on cotton and fibre mixes are under development.

The Nordic Council of Ministers (NCM) and national governments (notably Sweden and Denmark) have begun to focus on textiles as products with high negative environmental and social impacts, but a high potential for mitigating these impacts and creating green Nordic jobs in the process.

One focus area is in reducing and optimising handling of post-consumer textile products. The Nordic action plan for sustainable fashion and textiles – *Well Dressed in a Clean Environment* – launched in April 2015 includes post-consumer elements, including concerns regarding chemicals. There is very little knowledge about which chemicals may be present and in which concentrations, and this lack of knowledge can be of concern to companies planning to use recycled fibres. The legal requirements on chemical content in products apply also to textile products that include recycled fibres.

A wide spectrum of new business models and activities are also emerging in the private sector aimed at gaining greater value from textiles and reducing or offsetting environmental impacts of production e.g. leasing, take-back systems, repair, redesign etc. (Watson *et al.*, 2014b).

With such a wide range of activities underway, it is important to have a solid background of knowledge on which post-consumer treatments can give greatest environmental benefits. The waste hierarchy has not been tested rigorously with respect to textiles. LCAs have been carried out on the production of individual clothing items (e.g. Allwood *et al.* 2006, Roos *et al.*, 2011), but have so far not been carried out for many of the potential end-of-life options, and certainly none of the emerging technologies. It will be useful to directly compare a number of end-of-life options as scenarios in a single or a set of similar LCA-models which not only take account of the actual reuse/recycling option but also collection systems for post-consumer textiles under Nordic conditions. Such a knowledge base will allow environmental gains to be included as one factor in a broader socio-economic evaluation of different options for handling used textiles in Nordic countries.

1.2 Goal of the project

The goal of the project is to generate a solid and well-founded knowledge base for comparing the life-cycle environmental impacts and benefits of various options for handling post-consumer textiles from households and from public and private organisations, including reuse and material and energy recycling.

This information will be used as one of several factors in guiding policy decisions on which types of handling and treatment methods are prioritised in coming years.

The aim is to provide non-LCA practitioners with a toolbox that they can use to estimate the impacts and benefits of a given shift in flows of used textiles from one treatment scenario to another. This might be as a result of a new policy instrument, or the building of new treatment capacity etc.

1.3 Scope and outcomes of the project

The scenarios examined in the report aim at providing an overview of the relative environmental impacts of reuse, recycling and incineration/energy recovery of used textiles. As noted above, this overview can then provide the basis for Nordic governments to evaluate the environmental benefits of various strategies for changing the current patterns of treatment for textiles or by a business/municipality to estimate the benefits of a planned new textile treatment facility.

We do not aim in this project to present results for any specific strategy, nor to evaluate which strategies could be implemented in Nordic countries. That is for future projects to consider using the data provided in this report. However, for illustration purposes we present at the end of this report what the benefits could be of a theoretical shift in treatment of 100,000 tonnes of Nordic textiles from incineration to reuse and recycling.

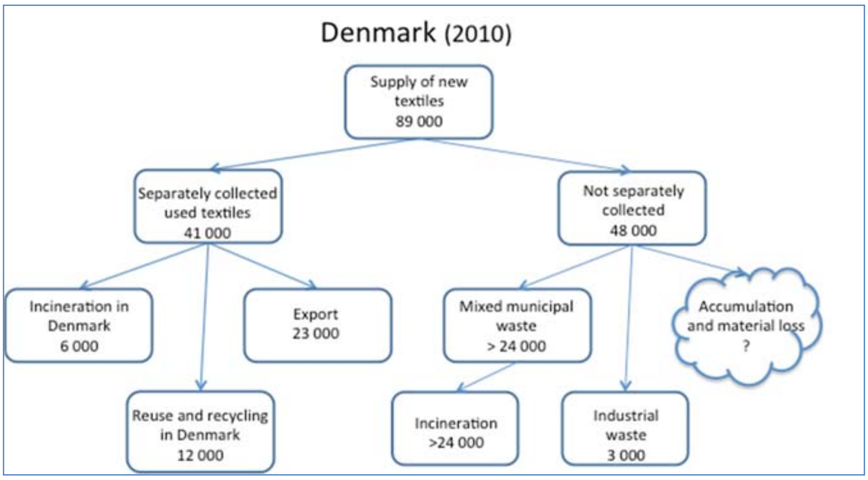
The textiles considered in this report comprise clothing and home textiles such bedlinen, towels, curtains etc. and similar textiles from businesses (e.g. uniforms and hospital bedlinen and patient clothing etc.). It does *not* include carpets, or technical, industrial and agricultural textiles. In formal terms it includes the following 2-digit CN product codes: all of CN code 61 and 62 and most of CN code 63.

2. Overview of flows of textiles in Nordic countries

Flows of new and used textiles in Nordic countries have already been mapped under separate projects both those funded by NCM (Palm *et al.* 2014a; Tojo *et al.* 2012) and by others (Watson *et al.* 2014a; Carlsson *et al.* 2011).

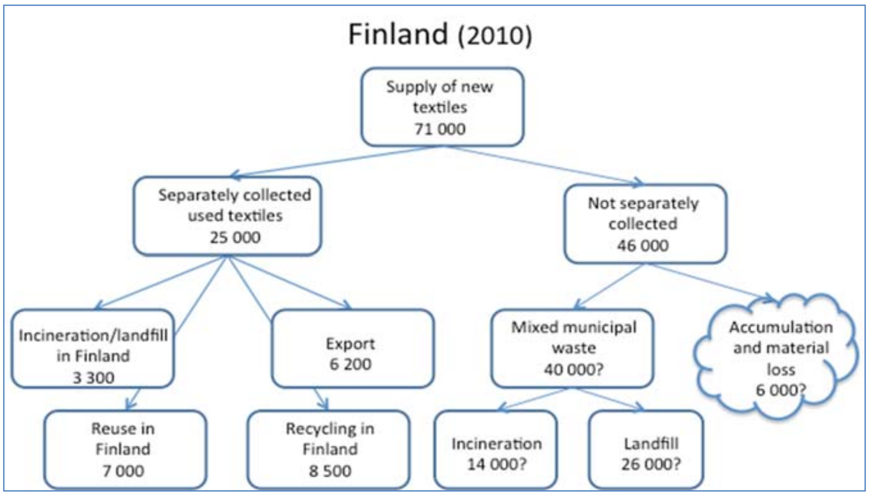
The flows of clothing and household textiles (not including carpets) and similar textiles in business and public organisations (hospitals etc.) for Denmark, Sweden, Norway and Finland are shown in the figures below. These have been adapted from Palm *et al.* (2014a).

Figure 1: Textile flows in Denmark (2010). Amounts are in tonnes



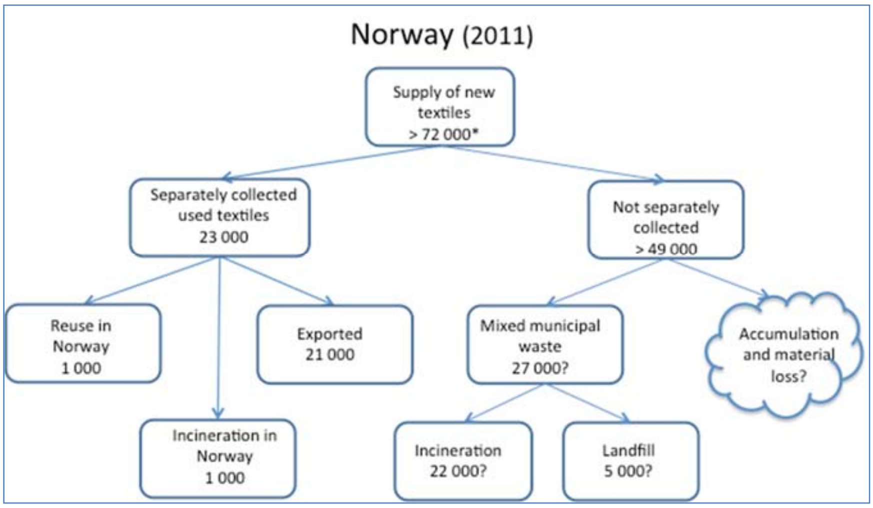
Source: Adapted from Palm *et al.* (2014a).

Figure 2: Textile flows in Finland (2010). Amounts are in tonnes



Source: Adapted from Palm *et al.* (2014a).

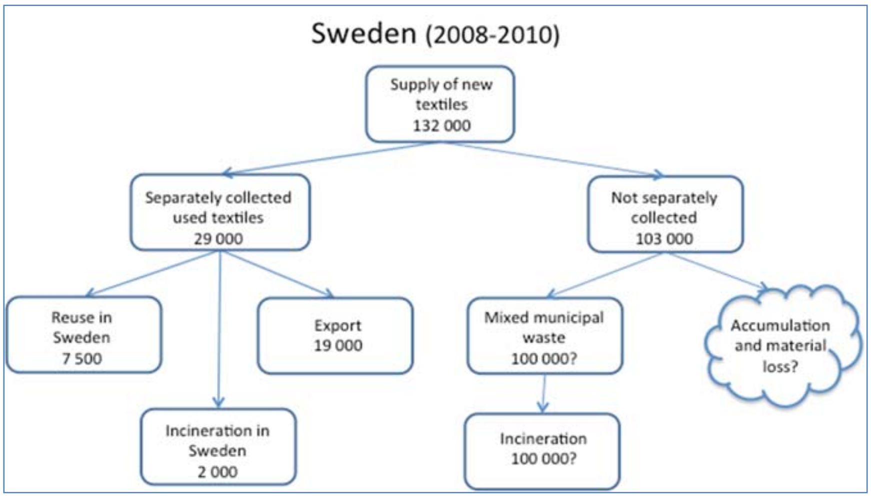
Figure 3: Textile flows in Norway (2011). Amounts are in tonnes



Note: * The supply of new textiles put on the market in Norway is based on clothing only. The volume of household textiles has not been estimated but typically gives an extra 15–25%.

Source: Adapted from Palm *et al.* (2014a).

Figure 4: Textile flows in Sweden (2008–2010). Amounts are in tonnes



Note: In 2013, textiles put on the Swedish market had reduced to 121,000 tonnes, and reuse increased to 8,600 tonnes, with export remaining at 19,000 tonnes (Elander *et al.*, 2014). No figures are available for total separately collected volumes in 2013.

Source: : Adapted from Palm *et al.* (2014a).

Between 22% (Sweden) and 45% (Denmark) of textiles put on the market end up being separately collected, mostly by charities (Palm *et al.* 2014a). Whereas the separately collected quantities are reasonably well quantified, the flows of non-separately collected can only be roughly estimated due to lack of widespread and regular sampling of the composition of mixed waste and bulky waste flows, and lack of knowledge on the quantities of textiles accumulated in households.

The majority can be assumed to end in mixed municipal waste. In Sweden, Norway and Denmark the majority of textiles ending in mixed waste are incinerated with energy recovery. Norway also has some landfill, but landfilling of organic waste, including all textiles of the types we consider here, has been banned since 2009. In Finland about two thirds of textiles in mixed municipal waste is landfilled with the remainder incinerated.[1] However, from 2016 it will be illegal to landfill organic waste in Finland (Fischer, 2013). This means that the majority of textiles wastes will need to be incinerated with energy recovery or recycled.

[1] 45% of municpal waste in Finland is landfilled and 23% incinerated (Fischer, 2013). The remainder is material recycled or composted but this fraction is source segregated prior to collection. It can be assumed that textiles that end in mixed waste are either landfilled (approx. 2/3) or incinerated (approx. 1/3). According to Tojo *et al.* (2012) 73% of textile waste from households is landfilled, and 25% is incinerated, in Finland.

With respect to the separately collected textiles, those charities that have shops in the collection country, typically sort a proportion of collected textiles to skim off the best quality items for resale in these shops. Typically between 10 and 30% of sorted textiles are suitable for domestic resale (Watson *et al.* 2016). At the same time non-textile waste is removed from the sorted shares. The remaining fractions are typically exported along with the unsorted textiles.

Approximately 60% of all used textiles separately collected in the Nordic countries are exported for further processing or resale (Watson *et al.* 2016). Nordic textiles are no longer used directly in humanitarian aid in any significant volume. Instead, they are sold to raise money for charitable operations (or profit in the case of private collectors).

First destinations of exported Nordic textiles are typically European wholesalers with sorting facilities. In 2014, two thirds of all exported textiles from Nordic countries were exported to sorting facilities in Poland, Lithuania, Estonia, Bulgaria and Germany (Watson *et al.* 2016). From here, textiles are sent all over the world.

Humana, which is one of the bigger collection organisations in the four Nordic countries considered in this study, estimates that 80% of used textiles they export from the Nordic region are reused and 16% recycled. The rest is treated as mixed waste. Recycling takes place primarily in Asia (57%) (predominantly India and Pakistan) and Europe (38%). Reuse takes place in Eastern Europe (37%), Africa (36%) and Asia (20%) (Watson *et al.* 2016).

2.1 Recycling options

The economic value of used textiles lies almost entirely in the reusable component. Prices for non-reusables are low and can often barely pay for transport (Palm *et al.* 2014a). The most common forms of recycling today are downcycling as industrial rags, low-grade blankets, insulation materials etc.

Recent intensive focus in European policy on recycling and circular economy will probably lead to improvements over the next decade, but examples of textile-to-textile recycling, either mechanical or chemical, are still sparse. They include 100% polyester closed loop recycling carried out by Teijin for companies in the Ecocircle partnership, and cotton to viscose chemical recycling, which replaces wood fibres. Mechanical recycling of 100% used cotton fabrics is also carried out on a small scale.

High quality products from mechanical recycling (longer fibres without too much colour) can be used in carpets and rugs, furniture and household textiles or clothing, though for the latter it needs to be mixed with virgin fibres. Fibres of lower quality can be used for industrial cleaning, polishing and filling material (upholstery). The main products made in Europe from mechanically recycled textiles are stuffing / wadding/ filling materials for mattresses and upholstery. Other common applications are insulation material or capillary matting products (Zamani, 2011).

Chemical recycling is used for synthetic materials or mixtures of synthetic and natural fibres. The resulting fibre quality is said to be more reliable than for mechanical recycling. The products made are used for car upholstery and household textiles (Valente *et al.* 2014).

Thermal recovery is where textile waste is converted to energy. This can be done using waste incineration with energy recovery, or in other ways, like cutting up cotton textiles into pieces that are pressed and made into pellets for use in boilers. There are also examples of technologies that can turn cotton-based textile waste into biogas or ethanol (Valente *et al.* 2014).

3. Chemicals in used textiles

Textile production processes make use of a vast array of chemicals. The Swedish Chemical Agency has identified 2,400 substances used in textile production whereof 10% are considered to be of potential risk to human health due to carcinogenic, allergenic, endocrine disrupting proeties etc. (Swedish Chemical Agency, 2014).

Some of the textile chemicals may remain in textile products at the end of their useful life, even if they have been washed several times (Swedish Chemicals Agency, 2014). This can have implications for recovery of the material content of the textiles for use in new products, potentially leading to persistent chemicals remaining in products made from recycled materials according to the Swedish Chemicals Agency (2012). People can be exposed to chemicals in recycled textiles by skin contact (especially with chemicals leakage via sweat) or by fibre linting and inhalation. Chemicals that have been added to the original product in a specific purpose risk ending up as contamination in the recycled material with a different exposure route. For example, a plastisol print on a garment, not in skin contact in the original product, may be remelted into recycled fibres that end up in a skin contact textile.

There is very little knowledge about which chemicals may be present and in which concentrations in used textiles (Östlund *et al.* 2015), and this lack of knowledge is of concern to some of the companies planning to use material recycled from used textiles. Life cycle assessments are of little use in this context for the same reason; lack of knowledge about which chemicals are present and in which amounts. In this chapter we take a qualitative approach to the issue, focusing on legal aspects as well as an analysis of the current situation in the Nordic countries.

The legal requirements on chemical content of products apply regardless of whether the product is put on the market for the first time, if it is a second-hand product, or a product using recovered materials. However, companies using recycled materials often wish to market their products with a claim of sustainability, and if the content and kind of chemicals are unknown this can potentially undermine their claims. Further, with respect to chemical recycling processes, the chemical contents of used textiles might react with the process chemicals and cause technical problems, e.g. decreased dyeability (Ecotextile News, 2008) or need for addition of process steps for purification (Östlund *et al.* 2015).

3.1 Legislation concerning chemicals in textiles

When textiles are put on the market today in the EU, several types of chemical contents are restricted according to different relevant legislation such as:

- REACH Regulation No. 1907/2006 – Annex XVII.
  - Azo dyes that by reductive cleavage releases specific aromatic amines.
  - Flame retardants such as PBB, TRIS, TEPA, octaBDE.
  - Certain organocompounds.
  - Dimethylfumarate.
  - Nickel and PAH in metal and plastic parts of textiles.
- Biocidal Products Regulation (BPR) No. 528/2012.
  - Only use of approved biocidal substances for the specific product type (PT9) is allowed.
- "POPs" Regulation No. 850/2004.
  - PFOS.
  - PCB.
  - SCCP.
  - HBCD.

The restrictions under REACH apply regardless of whether the product is put on the market for the first time or as a second-hand product unless otherwise specified, which was the case e.g. with the latest restriction on chromium VI compounds (European Commission, 2014). Furthermore, the REACH regulation (European Commission, 2006) include a so-called "information obligation" concerning the content of Substances of Very High Concern (SVHC) on the Candidate list in articles such as textiles (Article 3(3) of REACH).[2]

[2] Textiles are products that are defined as articles under REACH, i.e. as "an object which during production is given a special shape, surface or design which determines its function to a greater degree than does its chemical composition" (Article 3 (3) of REACH).

According to the information obligation, the business-to-business customer must be informed on delivery and, on request, the private consumer must be informed within 45 days of any substances on the Candidate list (SVHC) which exceeds 0.1% by weight of each part of a complex product. The use of such substances is not prohibited, but the information obligation is mandatory. SVHC on the Candidate list, which are relevant to textiles, include phthalates that may be used in plastisol-based printing and trim details such as pullers, buttons, studs etc.

The Biocide Product Regulation (BPR) (European Commission, 2012) has an information obligation to consumers concerning the content of biocides in articles similar to the REACH legislation (Article 58 of BPR), and here no concentration limit applies to trigger the obligation; all content of biocidal active substances must be communicated. The regulation gives the consumer the right to be informed whether an article contains preservatives, bactericides, fungicides etc. for textile products placed on the market.

Finally, the POPs regulation (European Commission, 2004) implements the Stockholm Convention into European legislation and restricts articles with content of persistent organic pollutants. Several textile relevant substances are universally banned by the Stockholm Convention, e.g. HBCD and PFOS.

3.1.1 Implications of legislation for recycling of used textiles

The legislation above also applies for “new” textile products made by remanufacturing, or from recovered textile fibres (including those made partially from recycled fibres). It should be emphasised that REACH does not apply to waste products (according to Article 2 (2) of the REACH Regulation 1907/2006). However, according to the Waste Framework Directive (2008/98/EC), waste must fulfil certain “end-of-waste” criteria in order to be de-classified as waste and be fit for reuse or recycling. One of these four “end-of-waste” criteria is that “the substance or object fulfils the technical requirements for the specific purposes and meets the existing legislation and standards applicable to products” (Article 6 (1c) of Directive 98/2008). This means that textiles being recycled as new textile products must comply with existing product legislation, i.e. the relevant restrictions of REACH Annex XVII, the information duty for articles concerning SVHC (Article 33 of REACH), the BPR regulation and the POPs Regulation.

Knowledge about the content of chemicals in recycled textiles is therefore a key issue when putting recycled textile products on the market again. This implies that recycling of textiles from known sources and known producers (e.g. production waste) is preferable as knowledge about the used chemicals and the presence of chemicals in the textiles ought to be available.

Recycling of post-consumer textiles seems to be more problematic from a legislative point of view as the origin, and thereby content, of chemicals is unknown. There are further no labelling requirements for chemical content in textiles sold to consumers that could encourage disclosure of chemical content in consumer textiles.

However, the risks of contamination can be reduced at the sorting stage of used textiles. Here, types of products such as waterproof outdoor clothing, that are known to include hazardous chemicals (see under section 5.2) can be sorted from other textiles and kept separate from these during any subsequent recycling processes. Trained staff at sorting facilities are adept at sorting used textiles into several hundred different fractions. This will remove much of the risk of for example, waterproofing chemicals ending in baby clothes. However, some hazardous chemicals found for example in dyes that aren't distinguishable purely by colour, cannot be sorted using such methods.

3.2 Literature survey of chemicals in textiles problematic for recycling

A screening literature survey was carried out with the purpose of establishing an overview of current knowledge of the fate of the chemical content of textiles during recycling processes. The scientific database Scopus was used together with searches for "grey" literature via Google and reference searches.[3]

The recently published report from the Swedish Environmental Agency (Östlund *et al.* 2015) gives a description of the state-of-the-art knowledge of the fate of the chemical content of textiles during recycling processes. The report also contains a proposal for a *theoretical model* to assess the possible release of the chemical content during various feasible recycling processes.

It is concluded that in mechanical recycling processes, all substances remain in the material and are carried over to the new product. This

[3] www.scopus.com

means that the material sources need to be chosen with consideration to legal obligations of the end product, for example the consumer's right to know.[4]

In chemical recycling processes, some substances remain in the material (except for depolymerization processes, where distillation or similar separation processes are performed). Both non-hazardous and hazardous substances may interfere technically with the process, but the risk that hazardous substances are carried over to the new product is low.

In the context of providing guidance to actors that recycle or plan to recycle textiles, some general knowledge of which product types that are expected to contain substances that may obstruct recycling are presented in Östlund *et al.* (2015), and further elaborated here:

- Sportswear and underwear, with or without statements about "odor prevention", may contain biocides.
- Workwear, for use in hygiene applications, such as cleanrooms and health sector, may contain biocides.
- Workwear, generic, may contain fluorinated substances and flame retardants.
- Outdoor consumer clothes and equipment, may contain fluorinated substances.
- Outdoor textiles (tents, tarpaulins etc.), may contain heavy metals and perfluorinated substances.
- Curtains and other interior textile products, may contain flame retardants.
- Coated textile products, may contain phthalates, SCCPs and fluorinated products.
- Textiles with prints, may contain phthalates, SCCPs and heavy metals.
- All dyed clothes may contain dyestuff or pigments with hazardous properties.

The Nordic Environmental Protection Agencies/Chemical Agencies have made several studies of the content of hazardous chemicals in textile products (Westerholm *et al.* 2015, Wiberg *et al.* 2014, Poulsen *et al.* 2011, Assmuth *et al.* 2011 and Olsson *et al.* 2009), and also other reports can be found on this topic (Wu, 2012, Kara *et al.* 2010, Luongo, 2015). However,

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[4] The "information duty" in Article 33 of REACH Regulation No. 1907/2006, and Article 58 of Biocidal Products Regulation (BPR) No. 528/2012.

none of these reports addresses the topic of the fate of the chemical content of textiles during recycling processes.

Further, it can be noted that the most cited publications on textile recycling do not discuss the chemical content of textile products (McDonough *et al.* 2003, Farrant, 2008, Shen *et al.* 2012, Zamani *et al.* 2014, Morley *et al.* 2013).

In the scientific literature, 164 publications in Scopus were found that cover the topic of textiles and recycling. When limiting the search the following results were found: 141 when excluding wastewater from the search profile; 7 when including hazardous substances and; 12 when including consumers. When combining the limitations no results were found. Moreover, examination of the seven publications that were found in the search for the topic of hazardous chemicals, revealed that they did not include any information about chemical content of textile products.

In conclusion, it can be stated that the current textile and environment literature either addresses the issue of recycling or the issue of chemicals content in textile products, but with the exception of Östlund *et al.* (2015) no literature has been found that discusses them both.

3.3 Current situation in the Nordic countries

Key persons from the Chemicals Agencies in the Nordic Countries were asked about the current situation in the respective country regarding three issues:[5]

1. Do you have an overall plan to manage the possible risks from chemicals in recycled textiles?
2. What is the plan with inspection and information campaigns for:
   a. Re-used textiles (second hand in stores).
   b. Re-used textiles (second hand between citizens).
   c. Recycled textiles: wiping cloths, insulation, composites, etc. (down-cycling).
   d. Products from mechanical recycling.
   e. Products from chemical recycling.

[5] Denmark: Isabelle Navarro Vinten and Lene Gede, Danish EPA.
Finland: Marilla Lahtinen, Tukes.
Norway: Monika Lahti, Miljødirektoratet.
Sweden: Anne-Marie Johansson and Emma Westerholm, Kemikalieinspektionen.

3. What information do you have regarding the content of hazardous chemicals in recycled products? (from market surveillance, laboratory tests, literature studies, etc.).

3.3.1 Regarding Question 1

Question 1 was answered quite similarly by all the Chemicals Agencies in the Nordic Countries, namely that the most important instrument for controlling the content of hazardous substances in *recycled textiles* is to regulate the content of hazardous substances in *new textiles*. The Nordic Chemicals Agencies all have on-going projects on the topic of chemicals in textiles. In Sweden and Denmark,[6,7] the agencies have led collaboration projects with the industry to increase the awareness of hazardous chemicals in textiles. The issue of recycling has been mentioned in the sense that one good outcome when reducing the unknown chemistry in textiles would be to facilitate recycling.

The basic principle is that recycled products placed on the market shall not contain more unwanted substances than products from virgin materials. The Swedish Chemicals Agency has also highlighted the risks of reintroducing banned substances to material cycles (Swedish Government, 2015) in their response to the proposed policy framework for circular economy by the European Commission (2015), which was not considered in the first writings. The Danish Environmental Protection Agency (EPA) will prospectively address recycling in the surveys they carry out concerning chemicals in consumer products.

3.3.2 Regarding Question 2

Today, the Agencies have a mandate to perform inspection on reused and recycled textile products, though this has not yet occurred. Under current inspections, recycled materials are rarely encountered. Selection of products for chemical analysis can be made based on suspicion of possible hazardous content (Miljødirektoratet 2015). In one inspection in Sweden, one second-hand t-shirt was selected, and phthalates (DEHP) found in the print.

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[6] Textildialogen (Strömbom *et al,* 2015).
[7] Partnerskabet for Kemi i Tekstiler (Danish EPA, 2015).

3.3.3 *Regarding Question 3*

Regarding question 3, information gaps were experienced by all the agencies. Data from own inspections together with reports on textile products' chemicals content are mentioned as the information resources available.

The Danish EPA is planning a publication in 2016, covering how chemicals in consumer products may prevent reuse and recycling.

The Swedish EPA has an ongoing governmental assignment focused on non-toxic and resource efficient resource-cycles which includes the following activities:[8]

- Mapping the waste streams that should be handled in a special way because of the content of particularly dangerous substances and risks of exposure – and if needed, suggest actions with respect to new treatment methods in order to ensure non-toxic resource cycles.
- Make a detailed analysis of how the legislation on waste and chemicals are appiled in practice for recycled materials with respect to both REACH and EU Regulation 1272/2008 on classification, labelling and packaging of substances and mixtures. Also an analysis of when waste no longer is considered as waste (end of waste criteria) in accordance with the waste legislation will be made, and changes to relevant EU legislation may be suggested.
- Strengthen the supervisory guidance regarding waste treatment, focusing on mimimising risks from dangerous substances and phase out of substances of very high concern.

3.4 Future outlook

A future outlook on governmental work on chemicals in textiles includes the EU initiative to use the simplified procedure provided under Article 68.2 of REACH to restrict substances classified as carcinogenic, mutagenic or toxic for reproduction (CMR), which is currently (March 2016) under consultation for textile articles and clothing for consumer use (European Commission, 2015).

[8] http://www.naturvardsverket.se/Miljoarbete-i-samhallet/Miljoarbete-i-Sverige/Regeringsuppdrag/giftfria-och-resurseffektiva-kretslopp/

Further, the Nordic countries under Danish EPA leadership, have commissioned (November 2015), Swerea IVF to perform an analysis of the possibility to enforce requirements to declare any content of hazardous substances in textiles. Future requirements on textile products with regard to knowledge about the chemical content, based on these initiatives, are likely to increase. Whether these requirements will include recycled textiles, and to what extent, remains to be seen.

4. The general framework for the life cycle assessment

The report aims to provide an overview of the relative environmental impacts of reuse, recycling and incineration/energy recovery of used Nordic textiles. This will allow environmental impact comparisons between selected handling and treatment options for used textiles as input to decision-making in Nordic countries.

Life Cycle Assessment (LCA) is a useful tool for this kind of comparison. This section outlines the main elements of the approach taken and some key assumptions used. Chapters 4 and 5 then go on to describe common and individual elements of the reuse and recycling scenarios selected for analysis and assessment.

In any life cycle assessment choices must be made concerning system boundaries, processes and values for a large number of parameters. The present study is no exception, including a range of preconditions and assumptions regarding both the current status and possible future scenarios for the treatment of textiles being discarded by Nordic consumers.

4.1 The functional unit

The functional unit is defined as "Treatment of one tonne of used textiles discarded by households and organisations, from the point of collection until its final grave."

In a number of scenarios, textiles being collected from containers are followed through the broad range of treatment processes that are – or may become – available in the Nordic countries. The different treatment routes have an influence on other product systems like production of heat and energy from waste and production of new textiles.

Processes are throughout the description of models termed as either "induced" or "avoided". Induced processes are those processes which are a direct element of the scenario e.g. production of electricity and heat in incineration scenarios. Avoided processes are indirect processes which no longer occur as a result of the scenario, e.g. a reduced need for production of new textiles within reuse scenarios.

The nature and magnitude of induced and avoided processes vary from one scenario to the other, depending on several variables. For all reuse and recycling scenarios, a system for collection and sorting is induced (see 4.1.1), while energy-related variables used in several scenarios are addressed in specific sections (see 4.1.2). The so-called substitution factors are more or less unique in each relevant scenario, but for practical reasons it has been chosen to address them in a general way which allows for a sensitivity analysis (see 3.2.2).

4.2 The scenarios

The report addresses a wide range of scenarios, looking at treatment of three individual fibre types in single countries as well as treatment of an "average" textile fibre in the Nordic countries in general. The scenarios are presented shortly in Table 1 and in more detail in Chapter 8.

Four groups of scenarios are modelled – one for 100% cotton, 100% polyester and 100% wool respectively, plus one for the Nordic average mix of fibres (see 6.2.1).

Each scenario group includes a reference scenario (incineration) (Scenario A), and two reuse scenarios: one where the textiles are reused in Nordic countries (scenario B) and one where textiles are exported for reuse in the rest of the world (ROW) (scenario C). It is beyond the scope of this study to model reuse in the 115 countries to which Nordic textiles are exported.[9] Instead a single "typical" ROW model has been defined.

The remaining scenarios in each comparison group are those that differentiate the four groups most: key examples of recycling for each fibre type.

All scenarios include LCA processes for collection (and sorting) of used textiles. For the incineration scenarios this is municipal collection of mixed waste – a process that is assumed not to be affected by a shift to reuse or recycling. For reuse and recycling scenarios it includes an average Nordic collection and sorting system, described in some detail in 4.1.1.

Reuse/recycling scenarios also include subsequent transportation of textiles to the point of reuse/recycling. In the case of the ROW reuse scenario a single "typical" transport process has been defined (see section 7.1.1).

[9] Watson et al (2016) uses import export data from the UN to map out exports of used textiles from Nordic countries. Textiles were found to be directly exported to 115 different countries in 2014.

All reuse/recycling scenarios also include a final end-of-life (EOL) stage. This comprises incineration or landfill depending on whether the recycling or reuse has taken place in Nordic countries or ROW.

Table 1: Overview of scenarios, with main induced and avoided processes

No.	Scenario name	Induced processes	Avoided processes
100% Polyester			
1A	Incineration of 100% polyester	Incineration of polyester	Production of marginal energy
1B	Polyester reuse in Nordic countries	Collection, sorting and transport of textiles Incineration EOL	Production of virgin textiles Incineration EOL
1C	Polyester reuse in the ROW	Collection, sorting and transport of textiles Landfilling EOL	Production of virgin textiles Landfilling EOL
1D	Polyester – chemical recycling	Collection, sorting and transport of textiles Chemical recycling	Production of dimethyl terephthalate and ethylene glycol
100% Cotton			
2A	Incineration of 100% cotton	Incineration of cotton	Production of marginal energy
2B	Cotton reuse in Nordic countries	Collection, sorting and transport of textiles Incineration EOL	Production of virgin textiles Incineration EOL
2C	Cotton reuse in the ROW	Collection, sorting and transport of textiles Landfilling EOL	Production of virgin textiles Landfilling EOL
2D	Chemical recycling of cotton	Collection, sorting and transport of textiles Chemical recycling	Production of sulphate pulp
2E	Substitution of virgin cotton yarn	Collection, sorting and transport of textiles Shredding of textiles	Production of baled cotton fibres
2F	Substitution of flax insulation	Collection, sorting and transport of textiles Carding of textiles Incineration of cotton waste from recycling	Production of flax fleece
100% Wool			
3A	Incineration of 100% wool	Incineration of wool	Production of marginal energy
3B	Wool reuse in Nordic countries	Collection, sorting and transport of textiles Incineration EOL	Production of virgin textiles Incineration EOL
3C	Wool reuse in the ROW	Collection, sorting and transport of textiles Landfilling EOL	Production of virgin textiles Landfilling EOL
3D	Recycling of wool	Collection, sorting and transport of textiles Hydroentangling Landfilling	Production of PET fabric Landfilling

No.	Scenario name	Induced processes	Avoided processes
Nordic average fibre mix			
4A	Incineration of mixed fibres	Incineration of mixed fibres	Production of marginal energy
4B	Reuse of mixed fibres in Nordic countries	Collection, sorting and transport of textiles Incineration EOL	Production of virgin textiles Incineration EOL
4C	Reuse of mixed fibres in the ROW	Collection, sorting and transport of textiles Landfilling EOL	Production of virgin textiles Landfilling EOL
4D	Substitution of virgin wipes	Collection, sorting and transport of textiles Washing and drying	Production of cellulose-based tissue

The basic LCA approach is to look at the consequences of a given way of end of life treatment of used textiles discarded by a consumer.

Relevant substituted processes/products/materials – and their life cycle – have been identified for each scenario as outlined in Table 1.

In the incineration scenarios, the substituted processes are the same quantities of heat and electricity, which would have been produced from other energy sources. Since we take a consequential LCA approach here we have developed "marginal energy" assumptions for the avoided process. The details are described in 4.1.2.

In the reuse scenarios, the reused textile product is assumed to replace a new product of the same type. The substituted process is therefore production of 1 tonne of new textile product of the same fibre type. In reality, a reused product might not always offset purchase of new. This replacement rate is called the substitution factor and is discussed in more detail in 3.2.2.

In the recycling scenarios, discarded textiles will undergo a series of processes before they are in a form fit for use in production where they can substitute a virgin material that would otherwise have been used. Avoided impacts from production of the substituted material are subtracted from the impacts of the recycling processes to give an estimation of the overall impacts or benefits of the recycling scenario.

4.2.1 Average Nordic fibre mix

While the first three groups of scenarios are for discarded textiles of single fibres (100% cotton, 100% polyester etc.) the final group consider scenarios for the average fibre mix of textiles collected in Nordic countries i.e. where discarded textiles are not sorted according to fibre type.

We assume here that the average fibre mix of discarded textiles is the same as the fibre mix put on Nordic markets. This has been calculated from data on import, export and domestic production of textiles in the four Nordic countries at a product code level that gives information on fibre content.

The calculations and assumptions are given in Appendix A at the end of this report. The result is the following estimated average fibre mix for textiles collected in Nordic countries:

- Cotton: 57%.
- Polyester: 34%.
- Wool: 4%.
- Other: 5%.

For the LCA models we model Flax as a proxy for the 5% "Other" fibres that are unspecified in the statistical data.

4.2.2 Substitution factors

The substitution factor is an expression of how much of a material/product a given quantity of re-used/recycled textile can replace. In the case of textile reuse, the substitution factor reflects the perceived value of a re-used garment (a societal factor) in comparison to an equivalent new one, while in the case of recycling it reflects the quality, technical or otherwise, of the textile waste derived product as compared to a relevant alternative. The two cases are elaborated in the following paragraphs.

Substitution factor in reuse scenarios

Purchasing of second-hand products can, but does not necessarily, offset the purchase of equivalent new products. A high substitution factor is most likely to be found where the purchase is a result of a direct search for that product due to a concrete need for it. It is also more likely to be high where the buyer purchases second-hand as a result of lifestyle decisions or environmental considerations. The same is the case where the second-hand product is relatively expensive. In contrast, the substitution is likely to be low in those cases where the purchase is spontaneous and/or the price of the second-hand product is perceived to be insignificant by the purchaser.

Because of these factors, the substitution factor will vary from person to person and from purchase to purchase. Due to different composition of demographics it can also vary significantly between countries and regions.

Few studies have been carried out on average substitution rates, and these are based on stated substitutions rather than measured rates, which gives a level of uncertainty in the figures.

Farrant (2008) carried out a limited questionnaire survey of people purchasing second-hand items Estonia, Sweden and Denmark. By scaling up results to country demographics the study estimated displacement rates of 60% in Sweden/Denmark and 75% in Estonia. A more recent study by WRAP (2013) showed a large range of displacement rates between regions in the UK of 11% to 52% with an average of 29%. The study was broader than Farrant's with over 10 times as many interviews. However, it was not carried out in a Nordic country. For simplification, and in the absence of reliable data, the EU Joint Research Centre used a substitution factor of 1 in their calculation of the environmental improvement potential for textiles (Beton *et al.* 2014).

For similar reasons, the present project also uses a substitution factor of 1 as the default, supplementing with a sensitivity analysis examining the results emerging with substitution factor of 0.33 and 0.66. The lower factor represents a conservative view of the environmental benefits of reuse.

The uncertainty caused by the wide range in potential substitution factors is addressed in more detail when interpreting the results. There is an almost linear relationship between the substitution factor and the environmental benefits from reuse, i.e. the higher the substitution rate, the higher the benefits. However, benefits from reuse occur even at very low substitution factors (0.1 or even lower), simply because the induced impacts from collection and distribution for reuse are very small compared to impacts that are avoided because new textiles need not be produced.

An additional factor introducing uncertainty in relation to substitution factors is the so-called rebound effect. In practice, the money saved by purchasing second hand garments instead of new will often be used for other purposes, some of which may have a higher impact per Euro and some a lower impact. However, prices of garments vary significantly and it is beyond the scope of this project to map out prices of both second-hand and new garments in the Nordic countries, in Eastern Europe and in Africa. It is also beyond the scope to map spending patterns in the same regions. The rebound effect is therefore not considered further in the study.

Substitution factors in recycling scenarios

In the recycling scenarios, a main challenge is to identify the point of substitution, i.e. the point where the output from a recycling process can substitute an alternative product produced in a different way.

If technical properties are important there is often a need for more recycled material (measured by weight) to achieve the same functionality as if virgin materials are used. An example of this is that secondary (re-spun) fibres do not have the same strength as virgin fibres. Nevertheless, secondary fibres can (and do) substitute virgin fibres in a 1:1 ratio in some products. They cannot substitute the full amount of virgin fibres without compromising the quality of the product, but as much as 20% recycled fibres are being used in products that are considered to have the same functionality as products made entirely from virgin fibres (see 5.6.3).

Even though the substitution ratio is assumed to be 1:1, losses in the recycling process must also be taken into account. When shredding fibres, some will inevitable lose their functionality and have to be discarded as waste. Typically one kg of fibres for recycling will only yield 0.8 kg for further processing and can, accordingly, only substitute 0.8 kg of virgin fibres. The remaining 0.2 kg is assumed to be incinerated with energy recovery in Europe.

In the project, we have used a pragmatic assumption that recycled fibres after processing substitute virgin materials 1:1 on a weight basis. This assumption will in many cases favour the results for recycling, but on the other hand it gives a good indication of the benefits that can be achieved by a given recycling scenario. For specific applications, e.g. when using recycled fibres for high quality thermal or acoustic insulation, more details are needed in order to determine the actual benefits. Standards and requirements in national building regulations describe in detail the technical properties needed, and it is up to the individual suppliers to demonstrate compliance. Collection of such information is outside the boundaries of the present study.

4.2.3 Background data

The GaBi databases from thinkstep^{ts} are used to include processes that are not a part of the foreground system, e.g. with respect to production of virgin textiles, transportation, waste incineration, etc. The modelling principles follow the ISO 14040 series concerning multifunctionality, using the hierarchy of subdivision, system expansion and allocation (PE International, 2014). How this is done in specific processes can be found by searching the website for documentation of GaBi-processes.[10]

It is noted that the foreground data, e.g. with respect to induced and avoided energy consumption, are based on consequential modelling, according to the wishes of the project owner (the Nordic Waste Group).

[10] http://www.gabi-software.com/index.php?id=8323&L=1

4.2.4 *Cut-off criteria*

No formal cut-off criteria have been defined. In practice, all known processes have been included, but it must be acknowledged that most of the recycling processes are included as black-box processes with limited details on specific material and energy flows.

It is noted that capital goods and services are not considered, nor is infrastructure in the form of e.g. vehicles.

4.3 Life Cycle Impact Assessment methodology

Life Cycle Impact Assessment (LCIA) addresses a wide range of potential impacts, using different approaches. Several methods are available, but the methods selected – in accordance with NAG – for this report are those recommended in the EU ILCD handbook (Hauschild *et al.* 2011) and subsequently modified in the development of the framework for Product Environmental Footprint (PEF).[11]

The method addresses 15 impact categories, including calculations of global warming potential with and without biogenic carbon being integrated in the calculations. Addressing the wide range of impact categories is not a problem in the advanced GaBi6-software that was used for the calculations. We added an extra indicator, total energy consumption (in MJ), to the impact assessment.

The 15 impact categories all have different units, and for many people it is difficult to use the broad range of categories in a focused analysis of the results and, eventually, in a strategic decision-making process. It was therefore decided to benchmark the result in each impact category according to the annual impacts caused by an average citizen. Thus all impacts can be expressed in the same unit, i.e. in Person Equivalents (PE) or milli-Person Equivalents (mPE) which is one thousandth of a PE. The normalisation step is a useful process in order to see the relative size of impacts in relation to existing emission levels. However, the reader should not confuse this with any form of weighting, that would be the result of a judgment of how important specific impacts were in relation to each other (e.g. whether climate impacts are more important than toxicity impacts).

The PE for each impact category have been calculated by Benini *et al.* (2014) for use in the development of the upcoming EU-method for Product Environmental Footprints. For practical reasons it has been assumed

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[11] http://ec.europa.eu/environment/eussd/smgp/product_footprint.htm

that the normalisation factors (the PE) found in GaBi are accurate reflecting the most recent updates of the method.

It is noted that the most recent PEF method includes biogenic carbon in its default calculations of the contribution to climate change. The PEF framework, however, aims at assessing the cradle-to-grave impacts of products and not only the EOL treatment as is the case in the present study. When the default method is applied to EOL treatment as the only life cycle activity, biogenic carbon will contribute to climate change in the same way as fossil carbon. In this case, the basic assumption that bio-based products have an uptake of carbon during the production stages similar to the emissions at the EOL stage, is "forgotten". This results in climate change impacts from incineration of cotton and wool being higher when biogenic carbon is included compared to when biogenic carbon is excluded. When interpreting the results in this project, the focus is on the results excluding biogenic carbon as we believe that this choice is most relevant when looking at EOL scenarios.

The normalisation factor for energy consumption was calculated using a simplified methodology using Eurostat figures as reported by EEA (2013).[12,13]

4.4 Reporting the results

In dialogue with NAG it was decided to present the normalised results as the main output of the calculations for the treatment of one tonne of used textiles. With a common unit it is easier to identify the more and less significant impacts in terms of magnitude, and to compare across relevant scenarios.

In addition, normalised results are useful for non-LCA experts and decision makers on whom the results of this report are focussed. Such stakeholders can use the normalised results directly to calculate the potential benefits of particular collection, reuse and recycling scenarios or policies that affect these.

When assessing the benefits of a given treatment of discarded textiles it is important to remember that in practice, a shift is made from current

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[12] The unit reported is tonne Oil Equivalent (TOE) a unit defined and used by OECD to report aggregated figures for consumption of different fuels, e.g. coal, crude oil, natural gas, biodiesel, etc. (OECD, 2006). The EEA has calculated the per capita final energy consumption in 2009 to 2.3 TOE or 96.3 GJ, and with one TOE equalling 41.868 GJ the per capita consumption in EU-27 can thus be calculated to 96.3 GJ https://stats.oecd.org/glossary/detail.asp?ID=4109

[13] http://www.eea.europa.eu/data-and-maps/figures/final-energy-consumption-million-toe-3

practice (primarily incineration) to an alternative treatment (reuse or recycling). To calculate the full effect of a change, the impacts and benefits from incineration shall therefore be subtracted from impacts and benefits related to the new treatment route. In some cases this means that the overall benefits become smaller, while in other cases may be larger. It is noted in this context that when reporting the results for 15 different impact categories they will not all show the same trend.

The characterised results (with different units) are presented in Appendix B containing links to excel-compatible files with the results for all basic scenarios in all four Countries and the Nordic average.

The results for alternative treatment scenarios are also used to present some indicative estimates of benefits that could be gained across the Nordic region by diverting given quantities of textiles from incineration to other treatment types.

4.5 Limitations of the calculations

The core output of the report is the calculation and comparison of the environmental impacts of various treatment methods for one tonne of discarded textiles. Such calculations include a number of sources of uncertainty. Many of these are well known to the LCA-society but are presented briefly below.

In the project a number of sensitivity analysis are performed for relevant scenarios. Obviously, it is not possible to cover the full range of possibilities in the calculations and the decision-maker or others using this report are encouraged to interpret the results in an appropriate perspective.

4.5.1 Uncertainties related to geographical boundaries

The changes in energy production that follows a decrease in waste incineration are modelled using knowledge and data for each of the four Nordic countries. However, substituted fibre production in reuse and recycling scenarios is modelled using data as available in the commercial GaBi databases, which is mostly limited to processes in industrialised countries.

This can be a source of error and uncertainty. An example of this is that reduced production of polyester fibres has been modelled using European conditions, despite the affected production occurring in countries all over the world, and mostly in Asia. The importance of this apparent mismatch cannot be determined with our current knowledge and data availability.

Uncertainties in substitution factors

As described in 3.2.2, the substitution factor (how much of a material/product a given quantity of re-used/recycled textile can replace) is very important for the results.

In the project, it has been decided to use a substitution factor of 1 in all reuse and recycling scenarios, with the results reflecting the highest benefits achievable. A supplementary sensitivity analysis is used to illustrate a realistic range of the benefits, and in a practical application of the results in decision-making the full range of potential benefits should be kept in mind.

4.5.2 Impact assessment method uncertainties

The methods for LCA impact assessment have been continuously developed during the past 25 years. The scientific society has put a lot of effort into improving the precision and prediction power of each of the many methods that are in use. Most focus has been applied to global warming and ozone depletion – because of the visibility of the impacts and their global scope – and today we can calculate the contribution to these impacts with a high certainty. Regional impacts like acidification, eutrophication and photochemical ozone formation are also addressed with a relatively high certainty. On-going improvements of the methods focus on pinpointing and operationalising the relationship between emissions taking place in one region while the impacts takes place in another, but this approach is not yet operational.

When it comes to modelling toxicity impacts on human health and ecosystems the uncertainty is much higher. A main reason for this is that the impacts are highly dependent on local exposure pathways for substances emitted in to the environment. Modelling this is a complex and demanding task, and although several thousand chemical substances are modelled in the USEtox method, the characterization for each chemical may have an uncertainty factor of 1,000.

Secondly, life cycle inventories for processes may often be incomplete with respect to emissions of toxic substances. For textiles, it is questionable whether emissions to air, water and soil of spinning oils, detergents, softeners, dyestuffs, etc. are included in the inventories. Moreover, processes differ from one fibre type to the other as well as within a specific fibre type. The terms “cotton” and “polyester” are therefore mostly an umbrella term for a very large number of products with very different profiles with respect to their potential for impacts on human health and ecosystems.

4.5.3 Uncertainties in technology description

The descriptions of some of the material recycling processes inventoried in this report are based on the small-scale facilities that are currently on the market or in the process of starting up industrial production. There has been a reluctance to give away information and assumptions have had to be made based on available public sources and technical knowledge. There is thus an uncertainty in that the technologies are adequately described, both in terms of coverage of resource use and emissions, and further in that there might be scaling effects if large-scale facilities are implemented.

5. Common elements in all or most scenarios

As indicated in 3.1, the LCAs include induced and avoided processes by making use of processes and variables that are common to several scenarios. These processes and their relative importance are described in detail in the following sections and will not be repeated later in the report.

5.1 Collection, sorting and distribution of sorted textiles

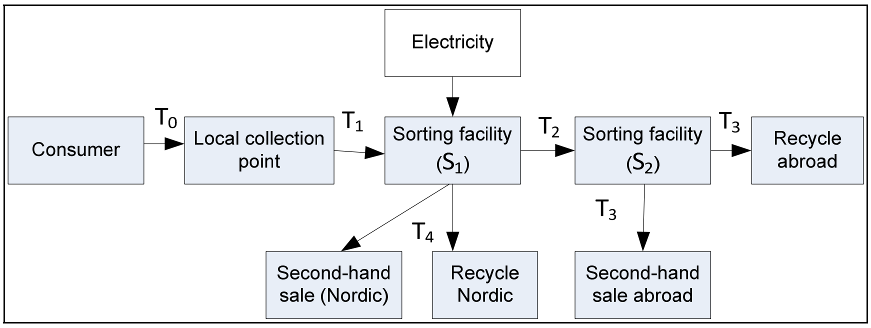
A simplified scenario modelled for post-consumer collection, sorting and transport of sorted textiles is outlined in Figure 5, below. The consumer transports their textiles to a local collection container, in conjunction with another errand (e.g. shopping, T_0). This collection container is emptied and the textiles transported (T_1) to a sorting facility (S_1) where textiles to be sold in second-hand shops within that Nordic country are selected, and the remaining textiles bailed and transported to reuse or recycling in Europe or Asia/Africa.

Routes for collected textiles differ widely from collector to collector. One or two collectors carry out full sorting in the collection country and sell the sorted fractions on the international market. The majority of textiles collected in Nordic countries, though, are either exported completely unsorted (so called original) or are exported after removal of higher quality textiles for domestic sales for further sorting elsewhere (Watson *et al.* 2016).

The business model chosen by the collector affects the relative values of transport distances. However, it is only the total transport distance that is important for the LCA prior to and following the sorting. It is of little significance how far along the transport chain the sorting comes. Therefore, the basic model shown in Figure 5, where sorting is carried out domestically, should suffice for our needs.

This assumption has one weakness: around 5% of the volumes collected in containers is non-textile waste that is removed during sorting and managed in the sorting country. This means that where sorting is carried out in Poland or the Baltic countries (most common for Nordic textiles according to Watson *et al.* 2016) rather than domestically, the non-textile waste fraction will have been transported further and have a different EOL treatment. In our model, however, it is reasonable to ignore this non-textile waste since it is not part of the functional unit.

Figure 5: Basic activities in collection and sorting of used textiles



5.1.1 *Overview of the collection system*

Different ways of collecting textiles for reuse and recycling are described in detailed elsewhere, e.g. in Palm *et al.* (2014b). The following paragraphs outlines the basic container collection system used for the calculations in the present report.

Collection containers are typically located next to supermarkets, in municipal car parks, at waste collection sites owned by municipalities or at recycling sites. The textiles are collected from the containers and transported to central sorting or bagging locations for either local second hand use, or for export to sorting companies in other countries. This kind of collection gives an average quality of collected textile with less quality than in-store collection, but is assumed to be more efficient with respect to the amounts of textiles that potentially will be collected.

5.1.2 *Data for collection and sorting of textiles*

The following data have been used in the calculations of impacts related to collection and sorting of post-consumer textiles:

- T_0: The consumer brings the textile to the collection point in conjunction with another errand and thus 0 km is allocated to textile collection.

- T_1: Transport to a Nordic sorting facility. Data from Nielsen, Fretex:[14,15] Vehicle size used for collection: 15 tonne or 7.5 tonne gross weight. Amount of textiles collected: 2 tonnes on average. Distance driven: 20 km (variation from 10 to 150 km is possible). Modelled in GaBi using data for a 12–14 tonne truck with 10-ton capacity and an utilisation rate of 0.2. The distance is set to 150 km.
- S_1 and S_2: Sorting facilities. A typical sorting process involves conveyor transport, with largely manual sorting, followed by bailing (Trasborg 2015). S_1 energy consumption is approximately 70 kWh electricity per tonne of clothes sorted (Fretex 2015b), equal to 0.25 MJ/kg. Electricity consumption in a second sorting facility is not included in the calculations but will in relevant cases be of the same magnitude.
- T_2: Transport to second sorting facility in Europe. Data from Nielsen, Fretex: Vehicle size used for collection: 15–19 tonne (load weight of clothes. Distance driven: 1,600 km (Drammen-Krakow, Poland assumed). Modelled in GaBi using data for a 20–26 tonne lorry with 17.9-ton capacity and an utilisation rate of 0.4. Distance driven is 1,600 km.
- T_3: Transport to reuse/recycling in ROW. Same truck and distance as for transport to Poland in T_2. Additionally, a transport with a container ship is assumed (distance = 12,000 km, using Pakistan as an example country). This is the scenario used when addressing ROW scenarios, giving the most conservative estimate for transport-related impacts.
- T_4: Transport to Nordic second-hand shop or recycling. Vehicle size used for distribution: 15 tonne or 7.5 tonne gross weight. Amount of textiles collected: 2 tonnes on average. Distance driven: 150 km (variation from 10 to 150 km is possible). Modelled in GaBi using data for a 12–14 tonne truck with 10-ton capacity and an utilisation rate of 0.2.

The transportation scenarios are illustrated in Figure 6, Figure 7 and Figure 8.

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[14] Nielsen, F, Fretex (2015a). E-mail communication to Cecilia Askham, 29/4/2015.
[15] Nielsen, F, Fretex (2015b). E-mail communication to Cecilia Askham, 12/5/2015.

Figure 6: Transport scenario for Nordic reuse and recycling

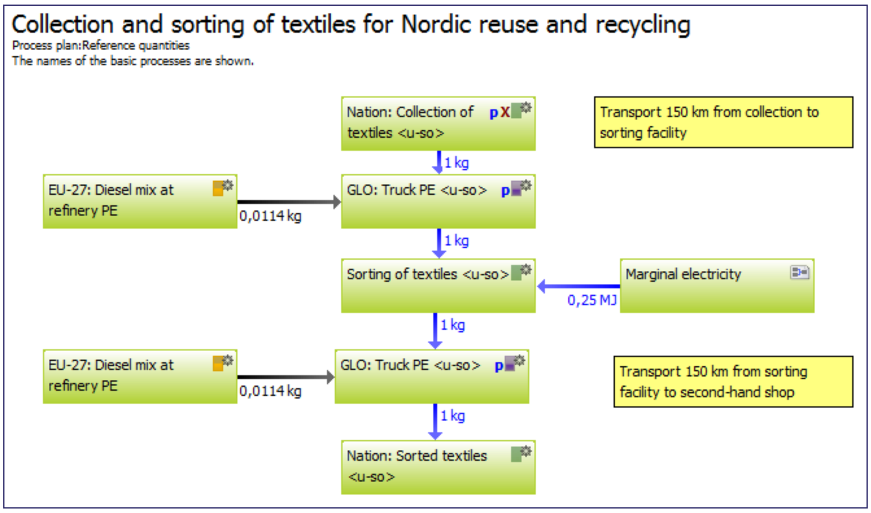


Figure 7: Transport scenario for ROW reuse and recycling

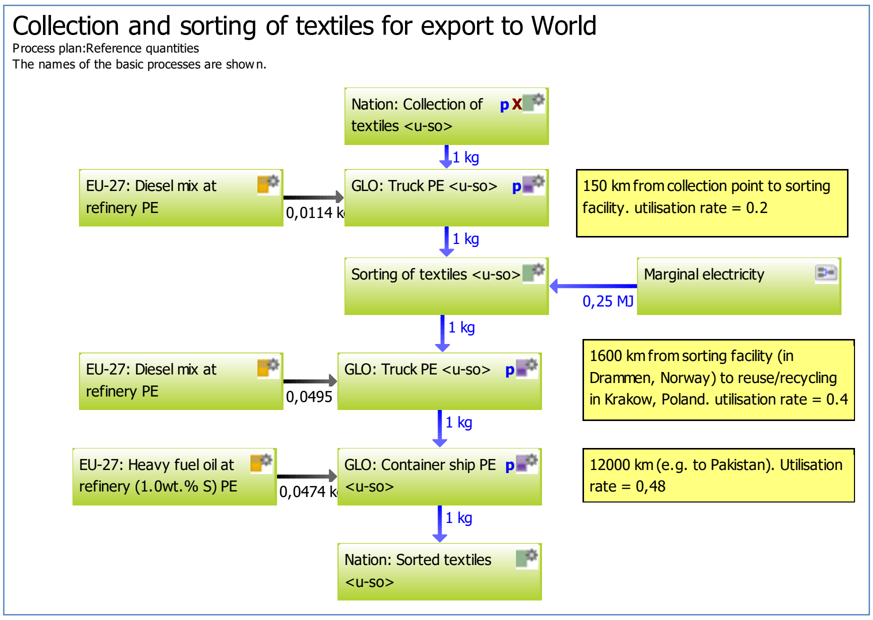
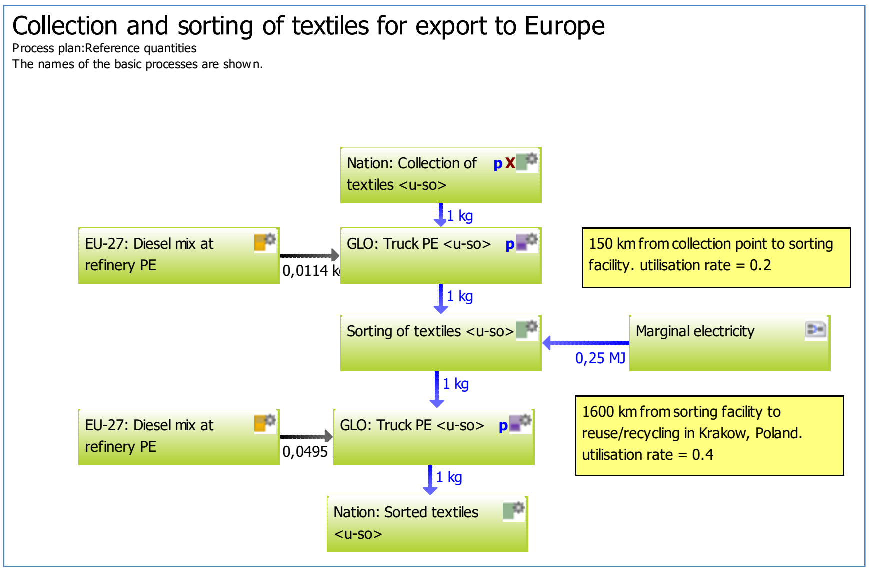


Figure 8: Transport scenario for reuse and recycling in Europe



5.1.3 *Energy consumption in collection and sorting scenarios*

A screening of the energy consumption in the three reuse/recycling scenarios (T_2, T_3 and T_4) was conducted at an early stage in order to identify the need for refinement, if any.

The results of the screening is summarised in Table 2.

Table 2: Energy consumption in collection, sorting and transportation in Nordic, European and Worldwide reuse or recycling scenarios

Scenario	Energy consumption (MJ/kg textiles)
T_2: Reuse or recycling "Europe"	4.09
T_3: Reuse or recycling "ROW"	6.2
T_4: Reuse in Nordic second-hand shops	2.14

It appears from Table 2 that about 2 MJ/kg is the basic energy requirement for collecting and sorting textiles delivered by consumers to collection containers. The energy consumption also includes subsequent transportation (up to 150 km) to second-hand shops in Nordic countries.

If the textiles after sorting are sent to reuse or recycling in a European country (e.g. Poland, Ukraine, or Germany), the total amount of energy needed for this increases with about 100% to about 4 MJ/kg, due to the longer transportation by truck (1,600 km). When reuse or recycling takes place in distant regions (Africa or Asia), the additional transport by ship adds a consumption of about 2 MJ/kg (caused by long-distance transport by ship), totalling about 6 MJ/kg.

The energy consumption for collection and sorting is at most about 50% of the energy that potentially can be recovered from incineration of mixed textiles, and far less than the energy that can be saved by their reuse.

The screening thus shows that collecting, sorting and distribution of sorted textiles gives a visible, though not significant contribution to environmental impacts. This finding is an integral part of the more detailed discussion of the many scenarios addressed in the report.

5.1.4 Washing and drying of textiles for reuse and recycling

Washing and drying of separately collected textiles has not been included as an induced impact. It may be relevant for some garments but it is judged from the descriptions of well-established sorting facilities that it is not a general activity. It is estimated the washing and drying in relevant cases will cause an energy consumption of about 0.65 kWh, increasing the consumption of primary energy with about 5 MJ/kg.

5.2 Marginal energy considerations

NAG has requested a consequential LCA approach is taken in this study. Therefore, for incineration scenarios, we have used a marginal energy approach to substituted energy. The following sections describe how this is done in practice.

5.2.1 Efficiency in waste incineration

In the four Nordic countries waste incineration yields electricity and heat, although with differences in efficiency and proportions between electricity and heat. All incineration plants are classified as R1 in the EU classification system for waste incineration plants, indicating that their efficiency is sufficient to characterise the incineration process as energy recovery.

For Finland, Norway and Sweden, country reports to CEWEP (CEWEP, 2014) have been used to calculate the overall efficiency and the relative amounts of electricity and heat being produced. Denmark has not delivered similar data to CEWEP, but corresponding figures have been established in several projects, most recently in Møller *et al.* 2013.

The national efficiencies and distribution between electricity and heat are shown in Table 3.

Table 3: Data on the efficiency of waste incineration in four Nordic countries

Year	Country	Incinerated amount (ton)	LHV (GJ/t)	Total energy (GJ)	Recover electricity (GJ)	Recovered heat (GJ)	Efficiency	% elec	% heat
2012	Norway	1,612,000	10.4	16,764,800	1,296,000	12,744,000	0.84	9.2%	90.8%
2013	Sweden	5,280,000	10.8	57,024,000	6,444,000	49,536,000	0.98	11.5%	88.5%
2013	Finland	600,000	10.4	6,240,000	496,800	3,330,000	0.61	13.0%	87.0%
2015	Denmark		10.4				0.95	23.1%	76.8%

It is noted that the lower heat value of waste for incineration is assumed to be 10.4 MJ/kg for Denmark, Finland and Norway. For Sweden, a value of 10.8 MJ/kg has been reported from waste incineration (Haraldson and Holmström, 2012). It is also noted that waste incineration with energy recovery is less common in Finland than in the other three countries.

5.2.2 Marginal electricity

According to Schmidt *et al.* (2010) the long-term marginal electricity suppliers in a country are defined as the national mix of planned/predicted new installation during a specified period of time. We have assumed that the changes will take place between 2020 and 2030, giving decision-makers four years to develop their recommendations and implement them in practice.

The changes were identified using data from the LIBEMOD model developed by the Norwegian Frischcenteret and based on the IEA Electricity Information Database.[16] The website describes the considerations behing the model in some detail,[17] and it is possible to download the full technical documentation.

A spreadsheet describing the predicted installed capacity in 2020 and 2030 was kindly provided by Rolf Golombek on 11th April 2015 to Cecilia Askham in the project group. The 2020 reference scenario spreadsheet is based on Aune *et al.* (2016) while the 2030 scenario is based on Aune *et al.* (2015).

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16 LIBEMOD (LIBEralization MODel for the European Energy Markets). Described at http://www.frisch.uio.no/ressurser/LIBEMOD/

17 http://www.frisch.uio.no/ressurser/LIBEMOD/About%20the%20model/

The data in the spreadsheet was used to derive the predicted increase in installed capacity (equal to the electricity marginal) between 2020 and 2030 in the four Nordic countries, distinguishing between five technologies that are relevant in one or more of the countries. Based on this information it was calculated that the increase in electricity demand in the four countries will be met by the technologies outlined in Table 4.

Table 4: Distribution of technologies used to produce marginal electricity in four Nordic countries. In percent, 2020 to 2030

	Bio power	Nuclear power	Hydro power	Gas power	Wind power
Denmark	49.8			18.6	31.6
Finland	5.2	42.3	0.03		52.3
Norway			5.8		94.2
Sweden	34.8		2.2		63.0

Ideally, the same approach should be used to identify the (marginal) electricity used in the production of those fibres that will be affected by a change in their EOL treatment. In the extreme, this would require information about which countries export each of the fibre types and manufacture products, which is not readily available. However, the data structure in GaBi does not give the possibility to use this information if it becomes available in the future, so it is underlined that there are different approaches used to calculate the induced and the avoided impacts that are a consequence of a change in end-of-life treatment.

For each country, a marginal electricity profile was established combining the above percentages in Table 4 with appropriate electricity generating technologies as available in GaBi. It is noted in this context that GaBi contains information on each of the technologies on the level of individual Nordic countries.

It is noted here that there are several other approaches to identification of the electricity in future scenarios. Lund *et al.* (2010) describes an approach for Denmark, in which the full energy system (electricity and CHP) is addressed. The paper forms the basis of a generalised methodology which is described in Schmidt *et al.* (2011) and used to establish a number of national scenarios in a crowd-funding project, the Energy Club.[18] The Danish EPA has asked the Danish Technological Institute to establish and describe a similar approach, but the reports are not yet available (T. Fruergaard, Danish EPA, pers comm. 290216). Finnveden

[18] http://lca-net.com/projects/show/energy-club/

(2008) addresses the issue of marginal electricity in consequential LCA in a paper in which the EU quota system plays a role.

It is outside the scope of this report to compare the different approaches and their results. It is only noted that both the LIBEMOD approach and the work by Schmidt *et al.* (2011) points towards renewable energy (wind, biomass, hydropower) being the most prominent source of marginal electricity in 2020 and onwards. It must, however, be acknowledged that prediction of future scenarios are inherently uncertain, being influenced by variables such as geopolitics, technological advancements and national policies.

5.2.3 Marginal thermal energy

The marginal production of thermal energy (used for district heat) has not been considered to the same extent in the scientific literature, and it has not been possible to find a consistent model and database for the calculations.

Instead, it has been chosen to use an approach as applied by the Danish EPA in recent Danish projects on reuse, recycling and recycling of waste from households and industry, with some modifications.

For Denmark, the projected Danish production of district heat in 2020, as described in e.g. Miljøprojekt 1458 (Møller *et al.* 2013) has been used as the basis. It has, however, been decided to exclude heat from waste incineration from the calculations of the marginal, simply because it does not make sense to decrease the amount of heat from waste incineration (because of increased reuse and recycling) and at the same time include an increase in the amount of heat from waste incineration to compensate for the decrease.[19]

For Sweden (Swedish Energy Agency, 2012) and Norway (Statistics Norway, 2014), the current mixture of energy sources in production of district heat has been used to establish the future marginal, using the same approach as for Denmark.

For Finland, the marginal energy source for production of heat is assumed to be biomass. This choice is based on the reference scenario developed by EREC (European Renewable Energy Council) and Greenpeace in a report from 2012, using policy scenarios published by the International Energy Agency (IEA) in World Energy Outlook 2011 (Teske *et al.* 2012). It appears from the report (p.60/61) that the use of fossil fuel for production of heat remains at the same level while biomass is used in increasing amounts.

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[19] This assumes that the fossil carbon content of textiles sent for incineration ios the same as the average fossil carbon content of municipal waste.

This finding is confirmed by modelling done by Goep (2012), who used the TIMES model to establish three different scenarios.

The technologies for production of marginal district heat are summarised in Table 5.

Table 5: Distribution of technologies used to produce marginal heat in four Nordic countries. In percent, 2020–2030

	Biomass	Oil	Gas	Coal	Peat	Heat pumps	Electricity	Biogas
Denmark	39	9	26	20				6
Finland	100							
Norway	34	3	8	8	6	16	24	
Sweden	64	5	7	7	5	12		

5.2.4 Energy recovery from incineration of fibres

Four fibre types are included in the calculations of impacts and benefits associated with incineration of textiles. The relative share in an average Nordic fibre mix (see 6.2.1) and the lower heat value of the fibre types is as follows:[20]

- Cotton (57%): 20.2 MJ/kg.
- Polyester (34%): 21.2 MJ/kg.
- Wool (4%): 23.2 MJ/kg.
- Flax (5%): 20.2 MJ/kg.

Using the arithmetic mean for incineration efficiencies in the Nordic countries in Table 3, the amount of energy that can be recovered from one kg of the average fibre can be calculated to 2.5 MJ electricity and 13.2 MJ thermal energy. Both energy types are assumed to be substituted by the Nordic mean average marginal energy technology.

[20] Calculated using the method described by Reimann, D.O. and Hammerli in "Verbrennungstechnik für Abfalle in Theorie und Praxis". H. Bamberg (Zürich), 1995.

6. Modelling of scenarios for treatment of textile waste

The overall scope of the project is described in and elaborated in 3.2. This chapter provides more detail about each scenario, including figures showing material and energy flows in the basic settings using a Nordic average.

It must be acknowledged that the scenarios give a simplified picture of the actual implications for each scenario. Other choices, e.g. with respect to geographical settings and substitution factors, could be equally relevant, but it is our best judgement that the choices made in this project gives a representative picture of the range of reuse and recycling scenarios existing today. Alleged major uncertainties have been examined by applying a sensitivity analysis, but it is not possible to do this for all variations that may occur in practical recycling and reuse activities.

6.1 Guidance for readers

Before moving into the detailed models of each scenario we would like to give the reader some guidance on how to read the scenarios and the diagrams provided to represent the processes in each scenario.

6.1.1 Numbering of scenarios

The scenarios cover a wide range of fibre types, recycling technologies and geographical elements that are combined in different ways. It is not possible to establish a fully consistent numbering, but the following bullet points may help the reader:

- Scenarios are numbered from 1 to 4, with a fixed relation between number and fibre type:
  - 1 = Polyester.
  - 2 = Cotton.
  - 3 = Wool.
  - 4 = Average Nordic fibre mix.

- Each number is followed by a letter, where the following assignments apply to all fibre types:
  - A = Incineration.
  - B = Reuse in the Nordic countries.
  - C = Reuse in rest of world (ROW) (e.g. Eastern Europe, Asia and Africa).
  - D, E, F = Recycling (differs between fibre types).

As an example, scenario 1A regards incineration of polyester, while scenario 2B regards reuse of cotton in the Nordic countries.

6.1.2 Scenario diagrams

Each scenario is illustrated with a diagram depicting the primary flows of material and energy between the processes/activities being assessed. The diagrams are copied from the LCA-software used to build them, and need some explanation to make them understandable to readers.

Process boxes
The LCA processes in a scenario include both processes that are directly induced within the scenario and processes that are avoided when a given treatment route for discarded textiles is used. These processes are illustrated by boxes: induced processes are olive-coloured while yellow boxes indicate *avoided* processes.

Process box names and abbreviations
Each process box has a name, given by the database developer or by us, which refers to the process it represents. The boxes also contain abbreviations and graphical icons. These are inherent to GaBi and cannot be removed and should be ignored by the non-technical reader. The icons and abbreviations are primarily used by the LCA-practitioner to give a quick overview of the plan he is developing, and the interested reader is referred to the technical GaBi-manuals for details.[21]

Dummy processes
Some boxes are named according to so-called "dummy" processes (e.g. "electricity dummy"). These refer to sub-systems where the modeller can switch between alternative processes e.g. between national scenarios for

[21] http://www.gabi-software.com/fileadmin/gabi/Welcome_to_GaBi_4.4.pdf

marginal energy. As such, they contain no specific information but point to subsets of data related to specific countries or scenarios. Again, the interested reader is referred to the technical manuals for GaBi.[22]

Flows, arrows and quantities

Arrows (blue or red) show flows of material and energy from one process/activity to the next. Neither the colour nor the shape of the arrows is of importance. The flow of materials in the figures (measured in kg) are the same ("generic") in all scenarios. When energy flows (in MJ) are shown, they relate to average Nordic conditions across the region as a whole, and this is indicated in the caption for the figure. If the model was applied to a specific country the diagram would stay the same but the energy flows would change since marginal energy is different from country to country.

The amounts in the figures relate to handling of one kg of discarded textiles. However, the results presented in tables and graphs presents the results as calculated for one tonne of discarded textiles.

6.2 Scenarios 1A, 2A, 3A, 4A: Incineration of textile fibres: 1) 100% polyester, 2) 100% cotton, 3) 100% wool and 4) average Nordic fabric mix

The reference scenario for end of life treatment of textiles in the Nordic countries is assumed to be incineration with energy recovery. The impacts and benefits from the current situation is examined through calculations for the average fibre mix on the Nordic market as well as for three individual fibre types.

The incineration processes used in the calculations are standard GaBi processes for incineration of specific or comparable fibre types (e.g., flax is regarded as similar to cotton in this respect) in average EU municipal incineration plants. It must be acknowledged that specific emission profiles depends on flue gas cleaning technologies, but the EU Waste incineration Directive (2000/76/EC) ensures that all plants must fulfil the same basic set of requirements. The uncertainty in our approach is, therefore, assumed to be of low importance in the overall picture.

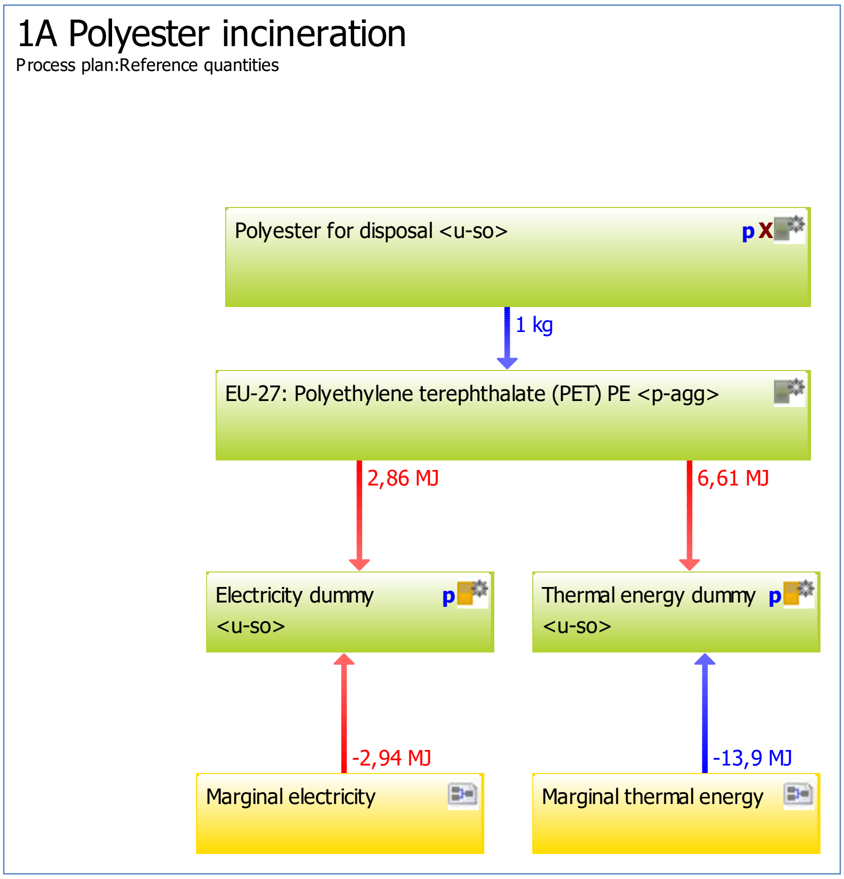
The amount of energy being recovered in incineration is described in detail in 4.1.2, as is the substituting marginal energy technologies.

[22] http://www.gabi-software.com/fileadmin/gabi/Modelling_Principles/GaBi_Modelling_Principles_2014.pdf

6.2.1 Scenario 1A: Incineration of polyester

The reference scenario for polyester textiles is incineration with energy recovery in a Nordic country. The processes addressed in this scenario are shown in Figure 9.

Figure 9: Elements in the assessment of impacts and benefits from incineration of polyester



The incineration process is a standard GaBi process for average incineration of polyester in the EU, with a lower heat value of 21.5 MJ/kg. The amount of energy recovered in the four Nordic countries is shown in Table 6. The output from the standard GaBi process is changed in the "dummy processes" in order to reflect the actual efficiency in each of countries.

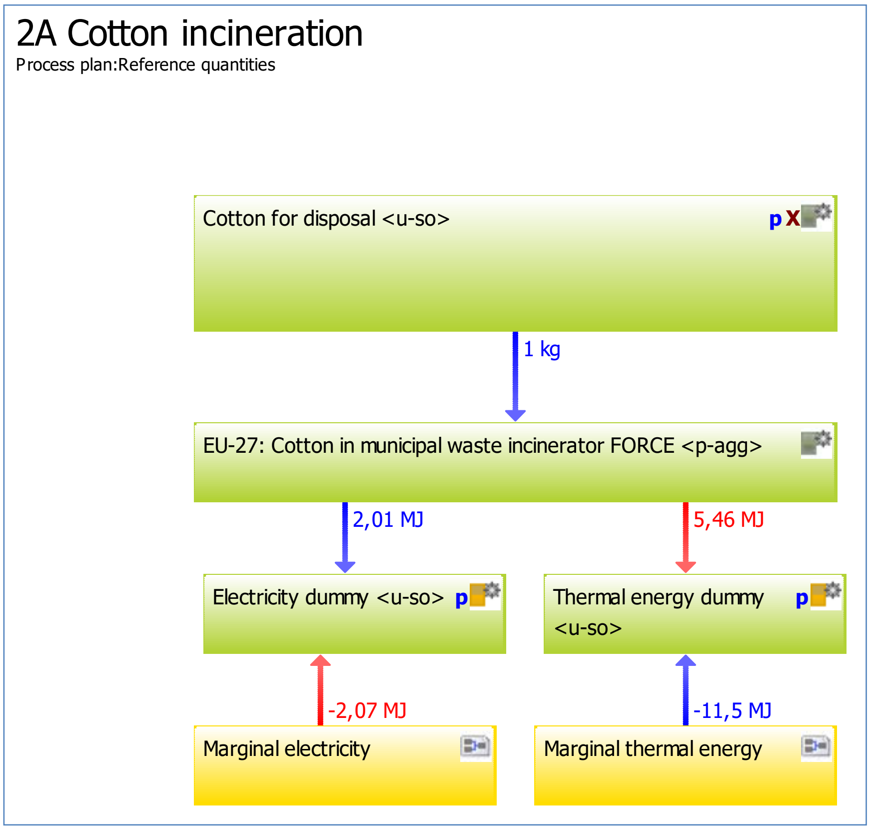
Table 6: Energy recovered by incineration of polyester in the four Nordic countries

	Unit	Denmark	Finland	Norway	Sweden
Electricity	MJ/kg	5.3	1.4	2.5	2.7
Thermal energy	MJ/kg	15.0	7.9	15.0	17.8

6.2.2 *Scenario 2A: Incineration of cotton*

The base-case scenario for polyester textiles is incineration with energy recovery in a Nordic country. The processes addressed in this scenario are shown in Figure 10.

Figure 10: Elements in the assessment of impacts and benefits from incineration of cotton



The inventory for incineration of cotton is based on the general GaBi inventory for incineration of textiles in EU municipal waste incinerators. The inventory has been changed in two ways, reflecting on the one hand that only CO_2-emissions from auxiliary materials are regarded as fossil (45.6 g/kg cotton, similar to emissions from incineration of paper), and on the other that the lower heat value is 17.0 MJ/kg, which is a little less than the value used for “textiles” in GaBi.

The amount of energy actually recovered varies between the Nordic countries as shown in Table 7. The marginal energy scenarios are described in 4.1.2.

Table 7: Energy recovered by incineration of cotton in the four Nordic countries

	Unit	Denmark	Finland	Norway	Sweden
Electricity	MJ/kg	3.7	1.0	1.7	1.9
Thermal energy	MJ/kg	12.4	6.5	12.4	14.7

6.2.3 Scenario 3A: Incineration of wool

The scenario for incineration of wool is similar to that for incineration of cotton, with the exception of the lower heat value,; estimated as 23.2 MJ/kg for wool. The emissions of carbon dioxide for wool is also assumed to be primarily biogenic, with small amounts of fossil CO_2 coming from auxiliary materials.

Figure 11: Elements in the assessment of impacts and benefits from incineration of wool

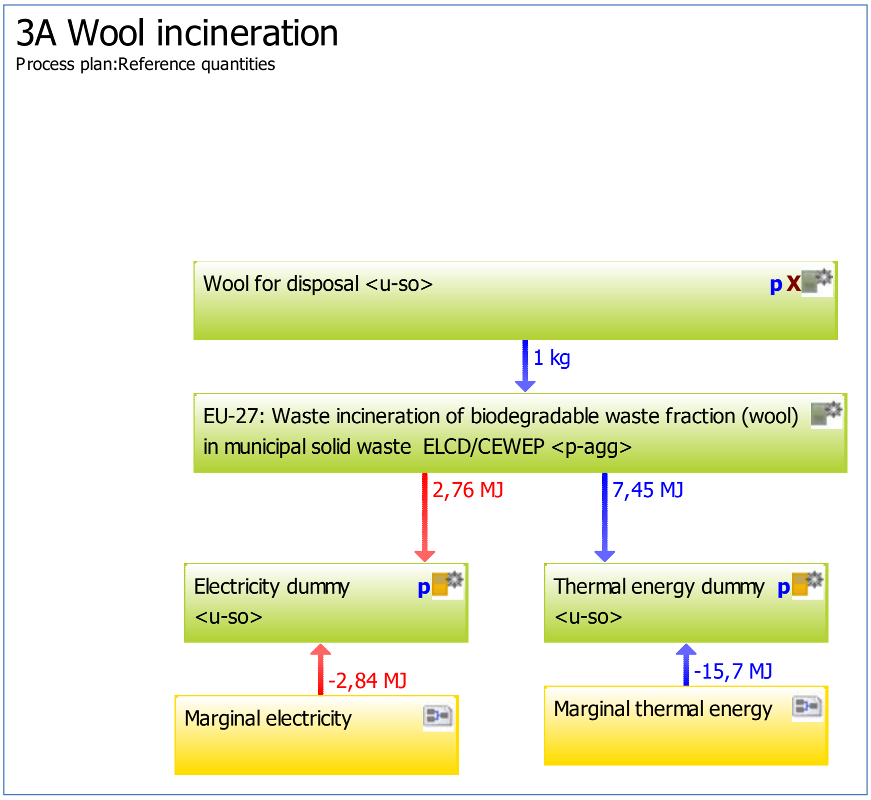


Figure 11 gives an overview of the processes and flows included in the calculations for the average Nordic scenario. The amount of energy recovered in the four Nordic countries is shown in Table 8.

Table 8: Energy recovered from incineration of wool in the four Nordic countries

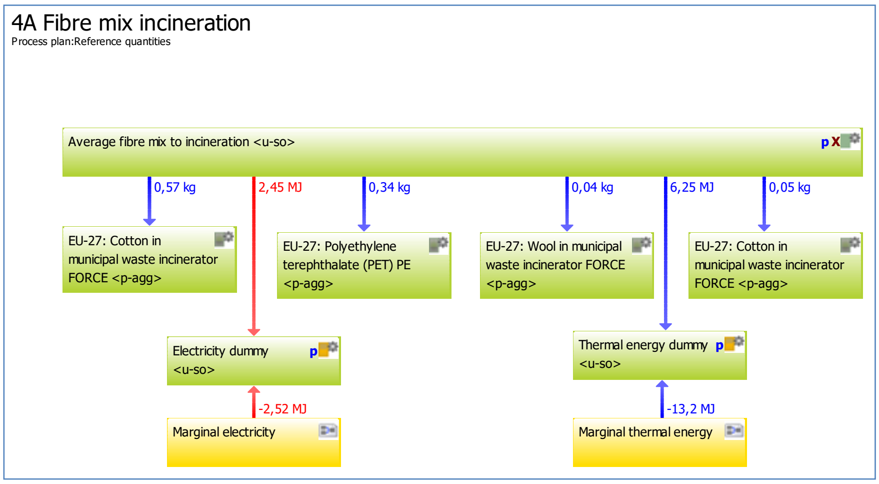
	Unit	Denmark	Finland	Norway	Sweden
Electricity	MJ/kg	5.1	1.3	2.4	2.6
Thermal energy	MJ/kg	17.0	8.9	16.9	20.1

6.2.4 Scenario 4A: Fibre mix incineration

The composition of the average Nordic Fibre mix is calculated in Appendix A.

The reference scenario for the average fibre mix (see Section 6.2.1) is modelled as outlined in Figure 12.

Figure 12: Elements in the calculation of the impacts and benefits from incineration of the average Nordic fibre mix



The amount of energy that can be recovered from incineration of one kg of the average fibre mix in the Nordic countries is shown in Table 9. Both energy types are assumed to be substituted by the Nordic mean average marginal energy technology as described in 4.1.2.

Table 9: Energy recovered from incineration of one kg of average fibre mix

	Unit	Sweden	Denmark	Norway	Finland	Nordic average
Electricity	MJ	2.11	4.10	1.92	1.07	2.3
Thermal energy	MJ	15.28	12.89	12.83	6.75	11.9

6.3 Scenarios 1B, 2B, 3B & 4B: Reuse of textile products in Nordic countries substituting new products from 1) 100% polyester, 2) 100% cotton, 3) 100% wool average Nordic fabric mix and 4)) average Nordic fabric mix

6.3.1 Introduction to Nordic reuse scenarios

Buying second-hand extends the active lifetime of textile products and offsets (see Section 6.2.2) purchases of new textiles thus giving an environmental benefit by offsetting the production of the new textiles.

Four scenarios have been established, examining the benefits and impacts of re-using 100% cotton, polyester and wool products as well as for re-using products with an average fibre mix as collected in the Nordic countries.

6.3.2 Avoided processes: Production of new textile products

The benefits of reuse are achieved through avoided production of new textile products. In practice, the avoided production basically consists of three activities, i.e. production of new fabric, cutting and sewing into new products (or knitting in the case of wool), and transport to the consumer.

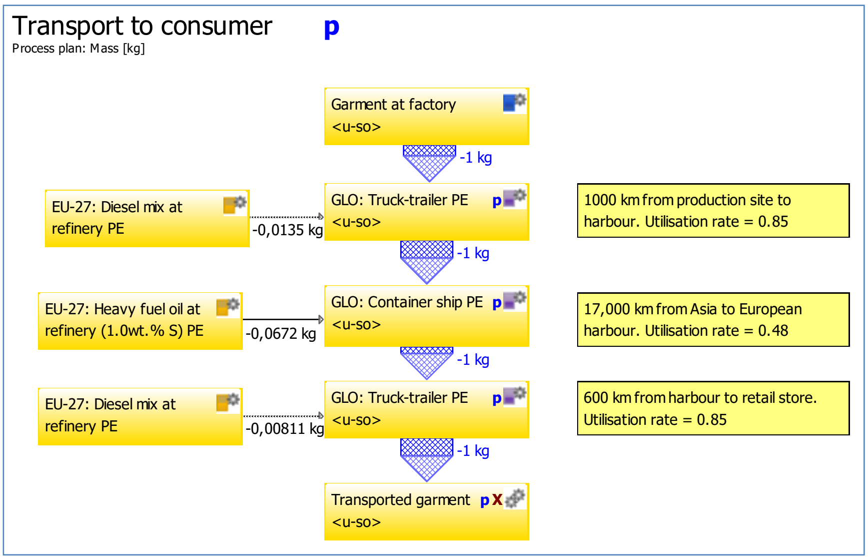
It is assumed in each scenario that the reused product replaces a product of the same fibre type and weight.

Production of new fabric is addressed by using standard GaBi processes for polyester and cotton, while the (avoided) production of woollen garments is addressed using information available in ecoinvent (ver. 2.2), GaBi and EU BREF documents.

Cutting and sewing of garments is assumed to cause a loss of material of 15% in average, calculated from Table 18 in Beton *et al.* 2014. Woollen products in general are knitted with no cutting and therefore involves insignificant material losses.

The transport from production of textiles to the consumer is assumed to involve a truck transport in both ends of the chain (1,000 km and 600 km, respectively) as well as a transport with a container ship (17,000 km). See Figure 13 for a graphical presentation of the transportation scenario.

Figure 13: Elements in avoided transportation of new garments to Nordic countries



The distances are believed to give a fair representation of the transport associated with distribution of virgin textiles. Obviously, there are potentially large differences depending on actual production sites, but transport impacts are of low importance for all reuse scenarios. This statement is based on the calculations made for sorted textiles for reuse being distributed to different markets, see section 4.1.1, together with calculations made in the basic reuse scenarios, where the avoided production of textiles is assumed to affect production in Asia.

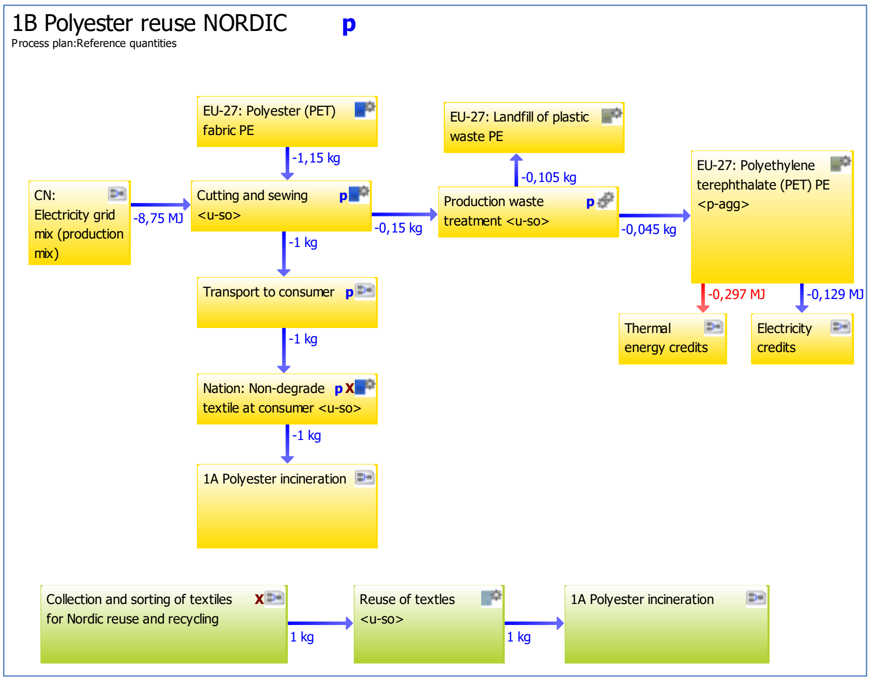
6.3.3 Induced processes: Collection and sorting of textiles for Nordic reuse

The basic elements in collection and sorting of all types of textiles for Nordic reuse are described in 4.1.1 and presented graphically in Figure 6. In short, the transportation to the collection point is assumed to take place together with other activities and no impacts are allocated to this. Transport to a sorting facility and afterwards to a domestic second-hand shop is addressed using fairly conservative estimates for distance and utilisation rate. More details can be found in 4.1.1.

6.3.4 *Scenario 1B – Nordic reuse of 100% polyester products substituting equivalent new products*

Substituted products made of 100% polyester are assumed to have the life cycle outlined in Figure 14 for the Nordic countries.

Figure 14: Elements in the assessment of impact and benefits from reuse of polyester textiles in the Nordic countries



The inventory for the avoided production of polyester fabric reflects the average polyester fabric produced from granulate in the EU. It is thus assumed that the fabric can be produced with similar impacts in China, which is one of the main suppliers to the EU market. The fabric is cut and sewn into garments in China and subsequently transported to the EU market as outlined in 5.3.2. 70% of the waste generated in the manufacturing process (15% of output) is assumed to be landfilled and the remaining 30% is incinerated with energy recovery (44% efficiency).

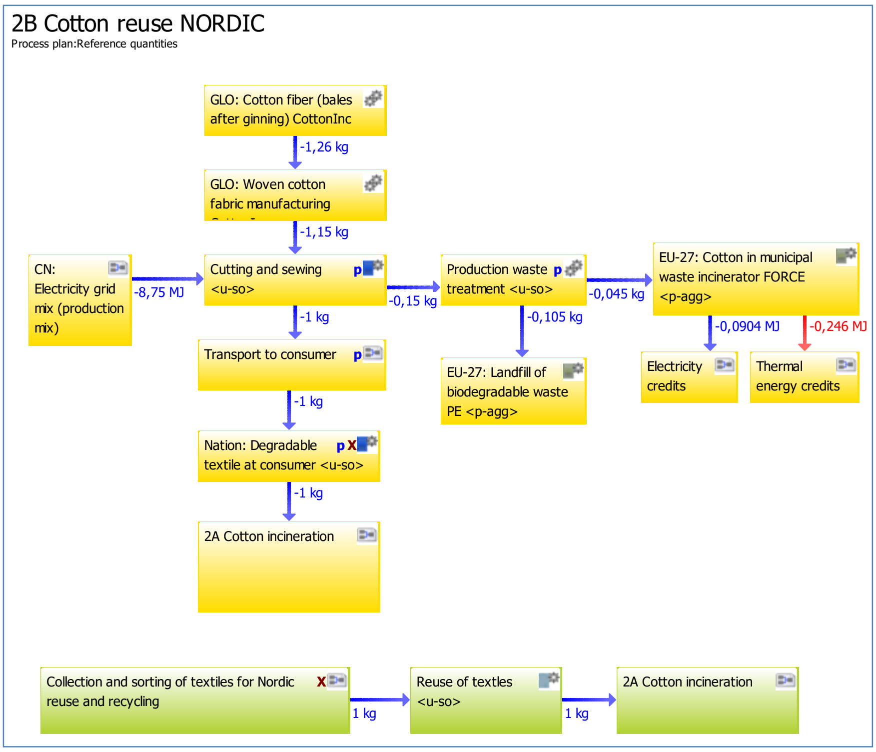
In both the avoided process and in the induced reuse process the textile is incinerated at EOL in one of the Nordic countries, assuming energy recovery as outlined in 5.2.1. The collection and sorting system is similar to that described in 5.3.3.

It is noted that there may be significant differences in the efficiency with which polyester fabric is produced in different regions of the world. Also, production of energy is often associated with larger impacts in Asia than in Europe. It is, however, outside the scope of the present report to investigate this in any detail. It is also noted that the transport of sewn fabric products differ significantly, depending on the geographical location of the sequence of manufacturing processes. The avoided impacts from manufacturing and transport processes may therefore very well be higher than those reported here.

6.3.5 *Scenario 2B – Nordic reuse of 100% cotton products substituting equivalent new products*

Substituted products made of 100% cotton are assumed to have the life cycle outlined in Figure 15.

Figure 15: Avoided and induced processes in reuse of 100% cotton in Nordic countries



The inventory for the avoided cotton fabric production reflects the average cotton fabric on the EU-27 market, using an average for production in China, India and the US as available in GaBi. It is assumed that the fabric is cut and sewn in China and subsequently transported to the EU market as outlined in 5.3.2. Again a 15% fabric waste is assumed in the production process. 70% of this is assumed to be landfilled and the remaining 30% to be incinerated with energy recovery (44% efficiency).

Again in both the avoided process and in the induced reuse process the textile is incinerated at EOL in one of the Nordic countries, assuming energy recovery as outlined in 5.2.2.

It is noted that the production of cotton fibres takes place in a broad range of countries all over the world. The manufacturing processes may also take place in many countries, and very often a garment will be transported to separate processes in several countries before it reaches a retail shop. The avoided impacts from manufacturing and transport processes may therefore very well be higher than those reported here.

6.3.6 Scenario 3B: Nordic reuse of 100% wool products substituting equivalent new products

Calculations of the impacts and benefits from recycling of wool are associated with high levels of uncertainty. The main reason for this is that sheep's wool is a co-product, with meat production. The various existing data sources have applied very different assumptions and methods when establishing valid datasets. In New Zealand for example, especially merino wool is considered as the primary product with lamb and mutton as by-products (Barber and Pellow, 2006). For UK wool production the opposite assumption is made, i.e. the wool is of very limited economic value (Murphy and Norton, 2008). The IWTO (International Wool Textile Organisation) is aware of this issue (see Henry, 2011). The geographic location – and the related traditions and technologies – also plays a significant role with respect to both yields and manufacturing processes.

In short, there is no such thing as an average wool process, and neither GaBi nor ecoinvent datasets aim at establishing data for a well-defined, but limited, geographical area. Ecoinvent focus on co-production of meat and wool in the US, while GaBi has transformed a dataset established for the New Zealand wool industry to be used in LCA's of seat covers produced in Germany.

In the calculations in the present report, the ecoinvent (version 2.2) data for production of wool in New Zealand has been used as the basis for the avoided production. It is noted that ecoinvent (version 3.1) presents an update of this dataset, with a significantly higher impact per kg wool at farm than in the earlier version. The difference is not readily explained as the dataset information from ecoinvent clearly states that the dataset was not individually updated during the transfer to ecoinvent version 3.

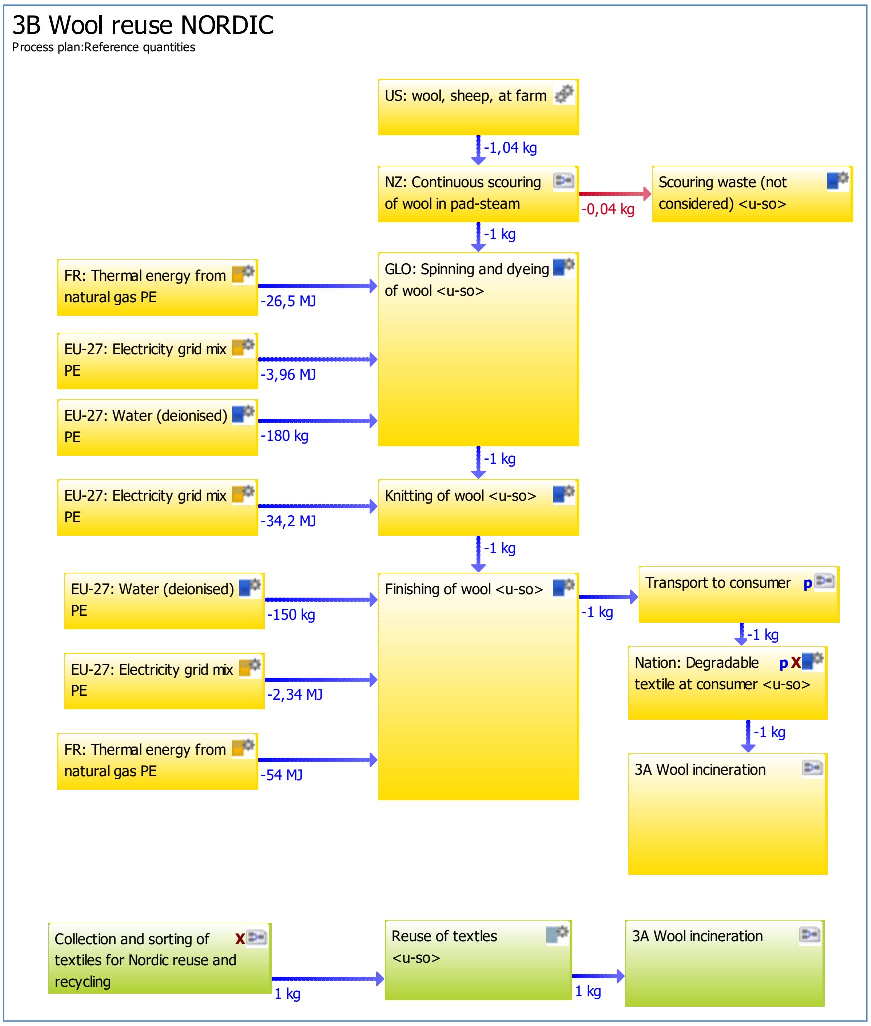
It is equally difficult to find and use representative datasets for the avoided manufacturing processes following shearing of the sheep. Available reports show that scouring of the wool, followed by spinning, dyeing, knitting and finishing are commonly used processes, but again there are large differences from one manufacturer to the other. This is evident from the EU BREF document for textiles, section 3.3.1.2, 3.3.2.4, and 3.3.3.3 (European Commission, 2003), showing that the ranges for energy and water consumption are very broad where more than one site is investigated:

- Scouring of wool: 10.8 MJ/kg (Italian data from GaBi).
- Spinning and dyeing: 6–17 kWh/kg.
- Knitting: 3.5–17 kWh/kg.
- Finishing: 18.8 kWh/kg (only one site included).

Obviously, the very large differences between geographical and technological scenarios means that the (avoided) impacts from production of wool textiles are determined with a corresponding high degree of uncertainty. It is, however, evident that reuse of wool is very beneficial from an environmental point of view, simply because the manufacturing processes from scouring of wool to a final garment is sold in a shop are very demanding in terms of consumption of energy, chemicals and water as well as in terms of related emissions. Furthermore, the potentially avoided breeding of sheep could add significant extra benefits, especially where wool and not meat is the primary product of sheep raising.

An overview of the avoided and induced processes for wool being reused in the Nordic countries are seen in Figure 16.

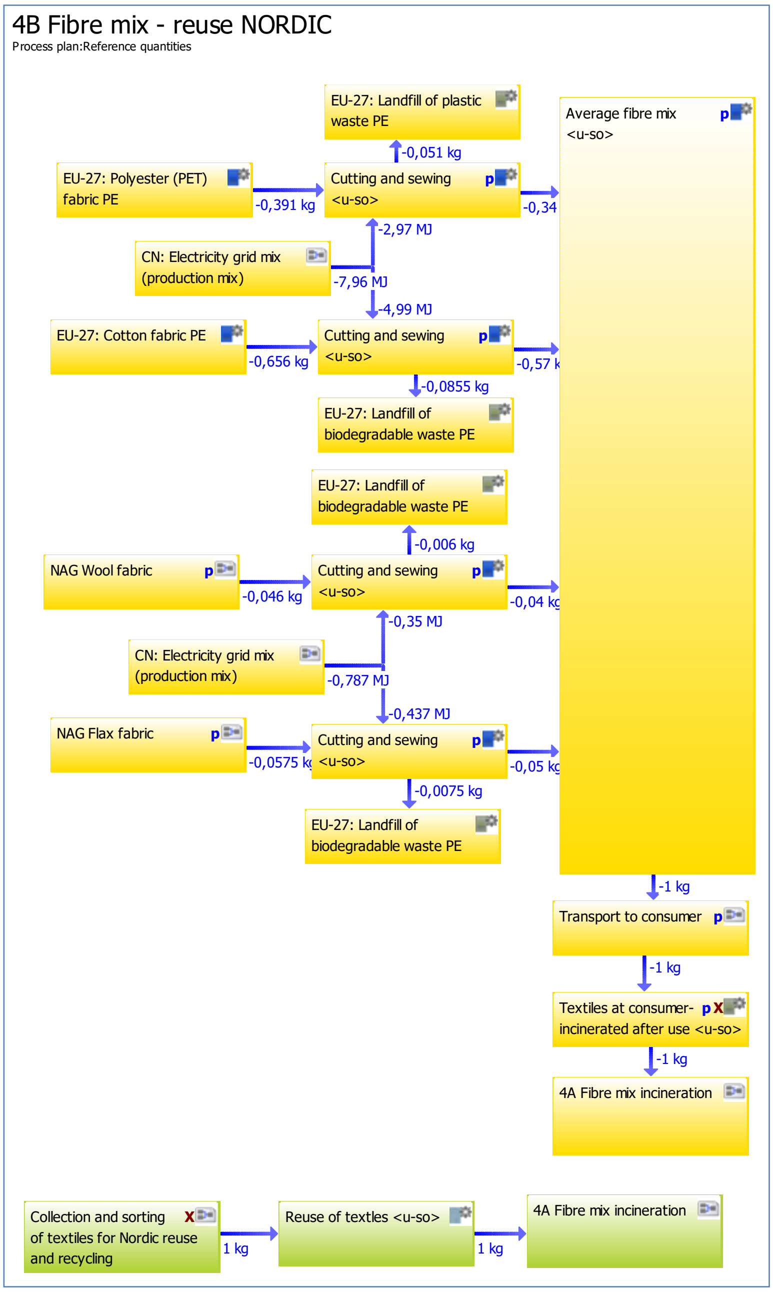
Figure 16: Avoided and induced processes in reuse of 100% wool in Nordic countries



6.3.7 *Scenario 4B: Nordic reuse of "average textile fibre mix" products substituting equivalent new products*

This scenario aims at giving an overview of the benefits than can be gained from reuse of one kilogram of used textiles of average Nordic fibre mix collected in a container. The life cycle of the average fibre mix being substituted by reuse is outlined in Figure 17.

Figure 17: Elements in the assessment of impact and benefits from reuse of average textile fibres in the Nordic countries



The life cycles of the four fibre types addressed in the average fibre mix are described in the previous sections. The incineration scenario at the end of the useful life is similar to that described in 5.2.4.

6.4 Scenarios 1C, 2C, 3C and 4C: Reuse of textile products in the ROW substituting new products from 1)100% polyester, 2) 100% cotton 3) 100% wool and 4) average Nordic fabric mix

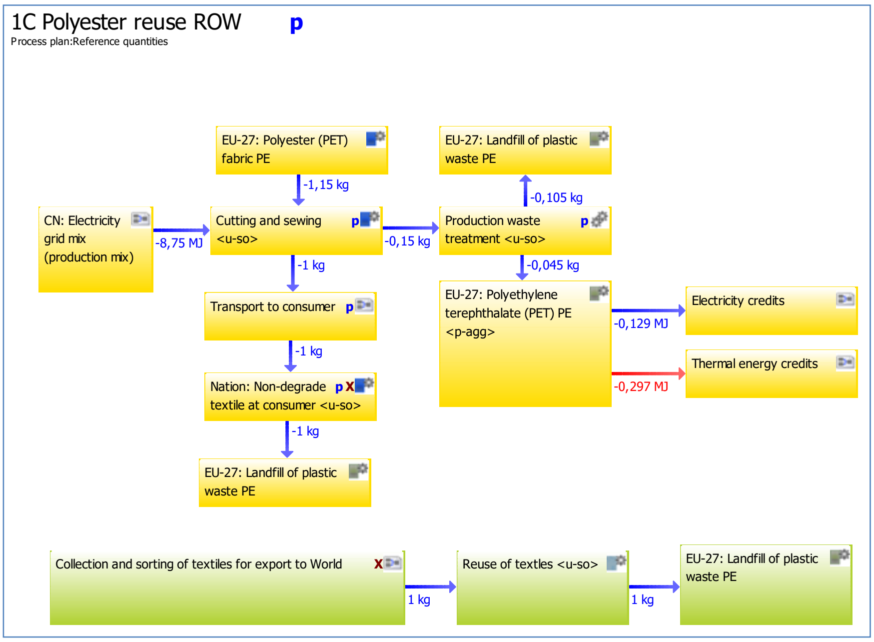
The scenarios for ROW reuse of textiles are very similar to the scenarios for reuse in the Nordic countries. There are, however, two exceptions. Firstly, it is assumed that in the induced processes, the textiles will be landfilled after their second use in ROW instead of being incinerated with energy recovery. The basis for this assumption is that waste incineration with or without energy recovery remains very limited in the receiving countries in Eastern Europe, Asia or Africa. GaBi-processes for landfilling in the EU have been used in the calculations (plastics waste for polyester, biodegradable waste for cotton and wool), however without utilisation of landfill gas.

Secondly, the transportation distances for sorted textiles is significantly longer. This was already discussed in 4.1.1.

6.4.1 Scenario 1C: ROW reuse of 100% polyester products substituting equivalent new products

The processes for reuse in the ROW of a textile product from polyester in Figure 18 is very similar to reuse in Nordic countries (Figure 14) with the changes described above.

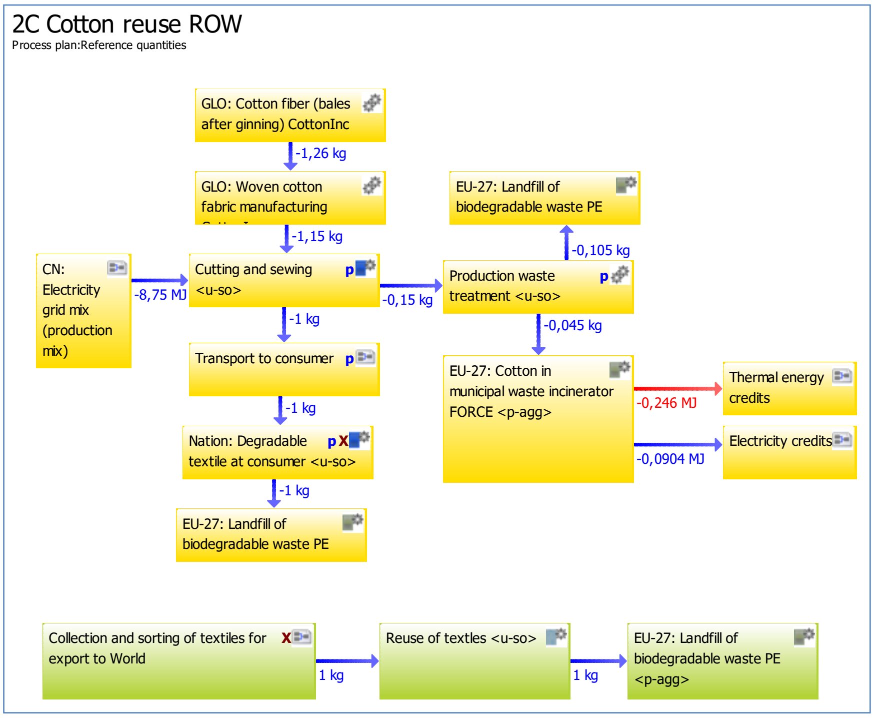
Figure 18: Elements included in the assessment of impacts and benefits from reuse of polyester in the ROW



6.4.2 *Scenario 2C: ROW reuse of 100% cotton products substituting equivalent new products*

Again, the processes for reuse in the ROW of a textile product from cotton in Figure 19 is very similar to reuse in Nordic countries (Figure 15) with the changes described above.

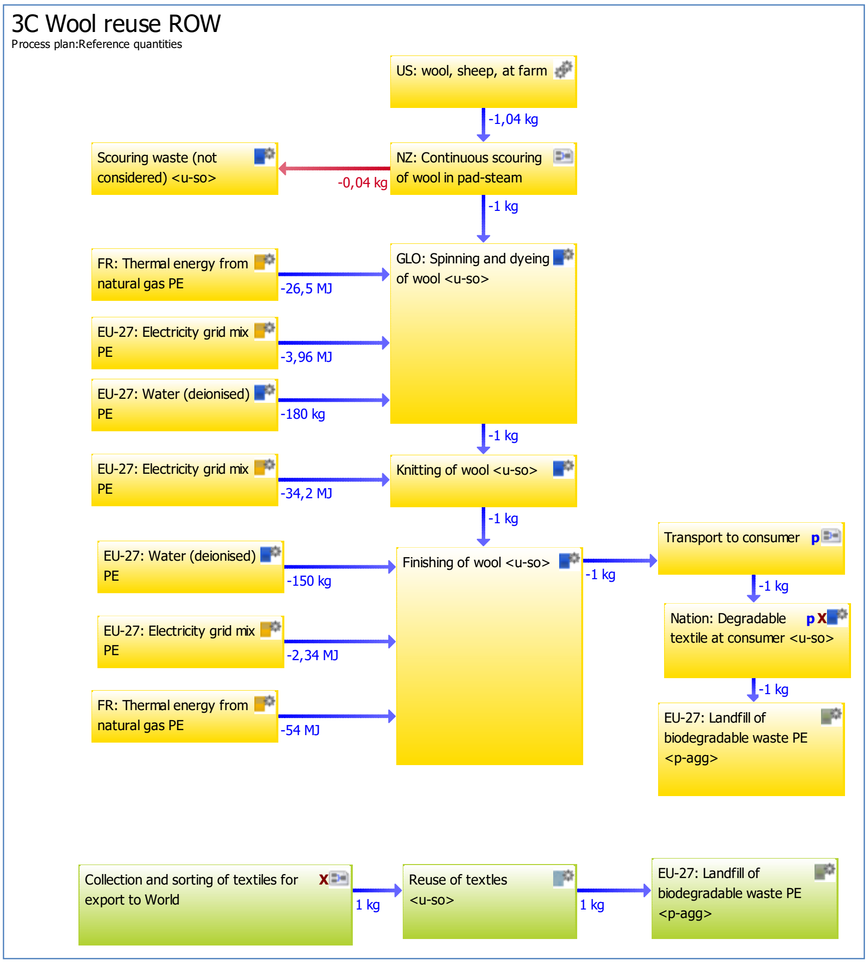
Figure 19: Elements included in the assessment of impacts and benefits from reuse of cotton in the ROW



6.4.3 Scenario 3C – ROW reuse of 100% wool products substituting equivalent new products

The elements in the ROW scenario for reuse of wool are outlined in Figure 20.

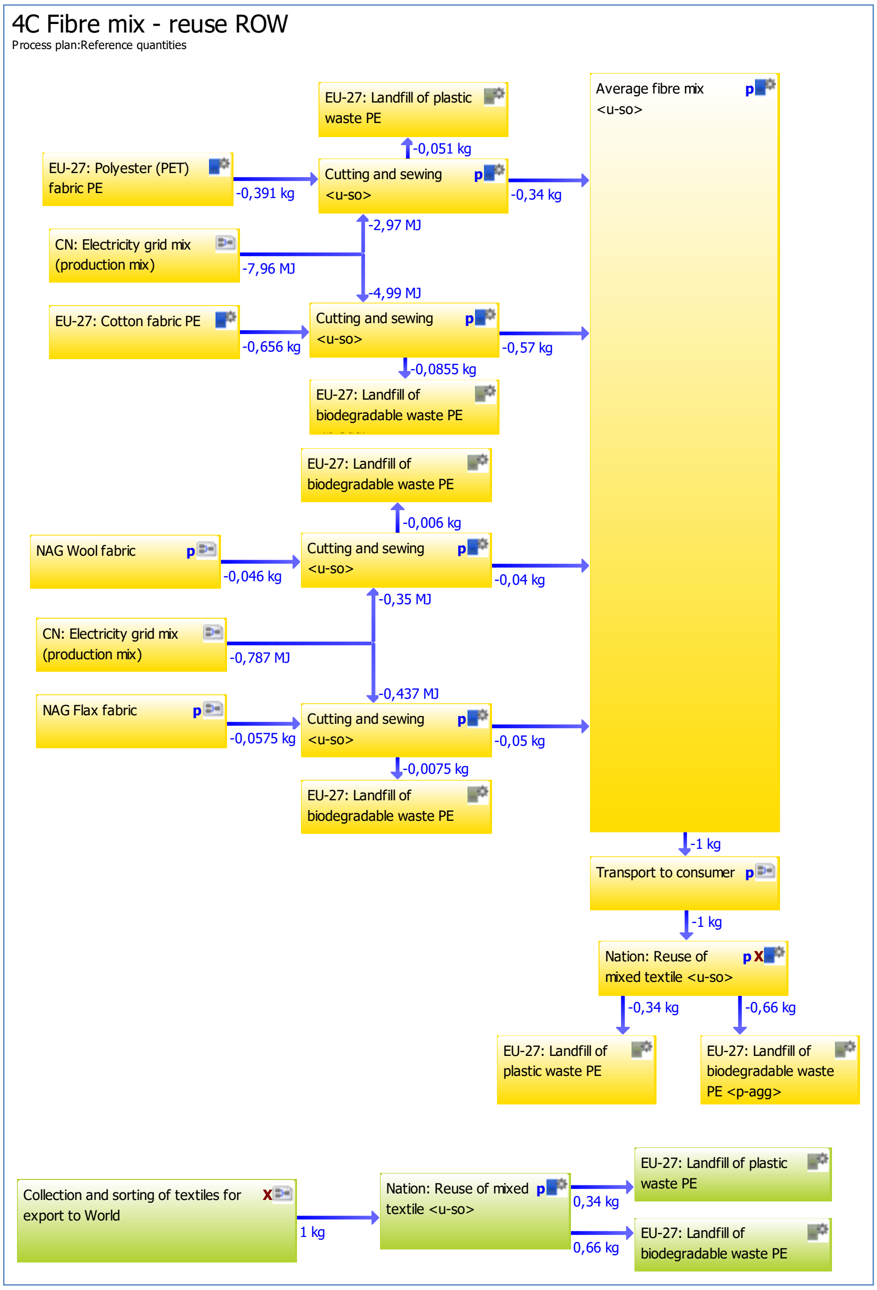
Figure 20: Elements included in the assessment of impacts and benefits from reuse of wool in the "ROW"



6.4.4 *Average Nordic fibre mix products substituting equivalent new products*

The processes for reuse in the ROW of a textile product from mixed fibre in Figure 21 is very similar to reuse in Nordic countries (Figure 17) with the changes described above.

Figure 21: Elements included in the assessment of impacts and benefits from reuse of average fibre mix in the ROW



6.5 Scenario 1D: Polyester recycling

The global polyester fibre production was estimated at over 40 million tonnes in 2013 with China as the main polyester fibre producer. Textile polyesters are commonly produced from DMT (dimethyl terephthalate) and EG (ethylene glycol). The dominating raw material for DMT is fossil petroleum while EG is sometimes made from biobased material, e.g. in the Sorona fibres.[23]

6.5.1 Scenario 1D. Chemical recycling substituting production of virgin DMT and EG

The induced and avoided processes are shown in Figure 23 and explained in some detail in the following paragraphs.

Induced processes
Polyesters can be chemically recycled by depolymerising the polymer into its monomers (chain scission) isolation and subsequent monomer–oligomer valorisation (Jbilou *et al.*, 2015). The only commercially available process today is performed at the Teijin plant in Japan, where a closed-loop recycling system named "ECO CIRCLE" was started along with apparel and sportswear manufacturers (e.g. Patagonia).[24] The production capacity of the plant was estimated to 62,000 tonne DMT/Year in 2006. However, it is not clear whether this capacity refers to recycled DMT.[25] At Teijin, polyethylene terephthalate (PET) is converted to its ingredients: dimethylterephthalate (DMT) and ethylene glycol (EG). The stoichiometric relation can vary but is reported by Teijin to be 69% DMT and 31% EG.[26]

Teijin's route includes that the material is cut, washed and then compounded/dissolved in EG at its boiling point under pressure of 1 bar to depolymerize to bishydroxyethyl terephthalate (BHET) which is later reacted with methanol in an autoclave equipment to produce DMT and EG by ester exchange reaction at the boiling point of methanol (Venkatachalam *et al.*, 2012). The DMT and EG are then purified, probably via distillation at 200°C, see Figure 22 below.

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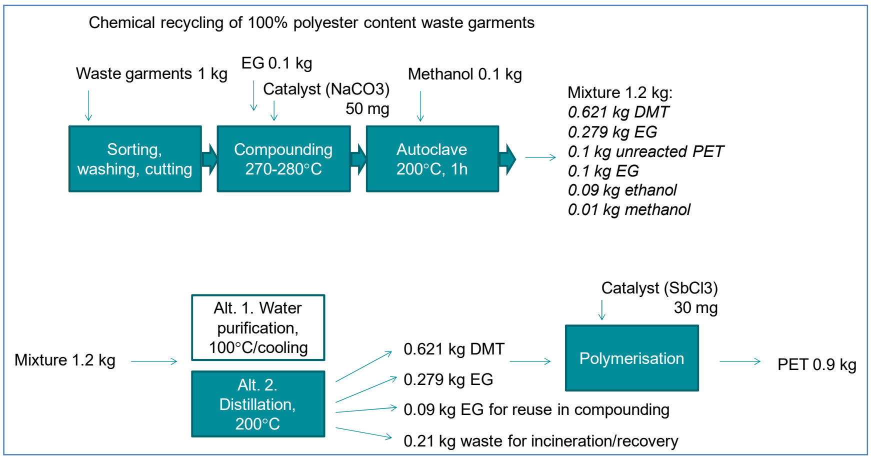
[23] http://www.dupont.com/products-and-services/fabrics-fibers-nonwovens/fibers/brands/dupont-sorona.html
[24] http://www.teijin.com/solutions/ecocircle/
[25] Patagonia (2006) Common Threads Garment Recycling Program, http://www.patagonia.com/pdf/en_US/common_threads_whitepaper.pdf
[26] Email conversation with Tomomi Okimoto, Teijin, August 2015.

Figure 22: Mass balance for chemical recycling process for polyester (PET)



The figure on energy use from the Patagonia report 11,962 GJ per tonne "produced DMT fibre" has been assumed to cover only the production and purification of the DMT fraction from the depolymerisation.[27] Upscaling the figure results in recycling of 1 tonne PET with a yield of 621 kg DMT and 279 kg EG will demand an energy consumption of 17.3 GJ. This value is used in the basic calculations. Because of the uncertainty related to figures given in the Patagonia report it has been chosen to make a sensitivity analysis of the low energy consumption of 11,962 GJ/ton, which appears as a key information in the report. This low value can be regarded as a theoretical best-case scenario while the basic scenario presented in the result tables is regarded as realistic with today's technological efficiency.

It has been chosen to assume that the recycling process will take place at Teijin's premises in Japan. If and when the process becomes more commonly used, new recycling facilities may be established closer to the Nordic countries. For now, however, the following transportation scenario has been assumed:

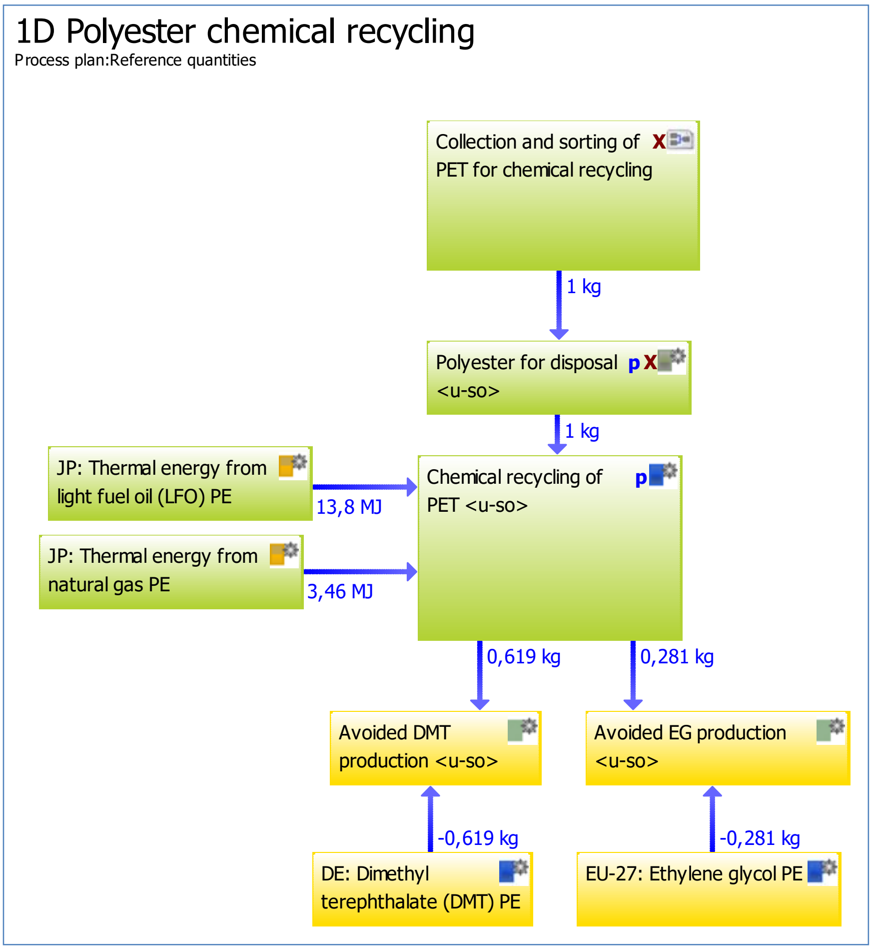
- 150 km by truck from collection point to sorting facility.
- 600 km by truck to (German) harbour.
- 21,624 km by container ship from German harbour (Hamburg) to Japan (Matsuyama).

[27] Whether purification of DMT is included is however questionable as this is an energy consuming process. Contacts twith Teijin has not helped resolve this question.

Avoided processes

The DMT and EG resulting from the recycling process is assumed to replace corresponding virgin qualities. For this purpose, data from GaBi are used, reflecting German production of DMT and average EU-27 production of EG, respectively. It has not been possible to investigate potential differences to production of the chemicals in Japan, which must be assumed to be the actual substitution scenario for the time being.

Figure 23: Elements in the assessment of impacts and benefits from recycling of polyester in Japan



6.6 Scenarios 2D, 2E, 2F – Recycling of cotton, substituting cellulose pulp, virgin cotton and flax

6.6.1 Introduction to cotton recycling scenarios

This section examines scenarios for chemical and mechanical recycling of cotton using a variety of processes, of which the mechanical processes have been in use for years while the chemical recycling process is still in a development stage.

The main challenge in defining the recycling scenarios is to find a "point of substitution" where the recycled material has the same technical properties as the (virgin) material it is substituting. The scenarios described in this report for cotton are very basic in the sense that the discarded textiles are subjected to one or a few relatively simple processes where after it can be further processed into a new fibre-based product using the same processes as for the substituted virgin material.

The processes examined can thus be regarded as true recycling rather than downcycling. It may also be possible to prepare some of the textiles, e.g. by repairing the garments and selling them for reuse. This is most probably done for some of the textiles sorted out for reuse, but since it requires manual labour it is seldom an economically viable process in the Nordic countries. It is therefore not examined further, but it is suggested to use the results from direct reuse as a good indicator for the environmental benefits that could be achieved in this way.

6.6.2 Scenario 2D – Chemical recycling of cotton, substituting virgin cellulose pulp

Around 3.5 million tonnes of regenerated cellulosic fibres are produced globally each year, of which the main part is viscose. Regenerated cellulosic fibres are made from dissolving pulp, which can be produced from a variety of cellulose sources, such as spruce, beech, bamboo, eucalyptus, cotton lint – or – recycled cellulosic fibres.

Today, no commercial production of regenerated fibres from waste cotton fibres exists, but a lot of research and investments focus on realising this possibility Östlund (2015). Several technical tracks are explored; including cold alkaline extraction (Palme, 2015), acid hydrolysis,[28] ozone

[28] http://www.swerea.se/nyheter/pilotanlaggning-for-vatspinning-av-textilfibrer-pa-swerea-ivf

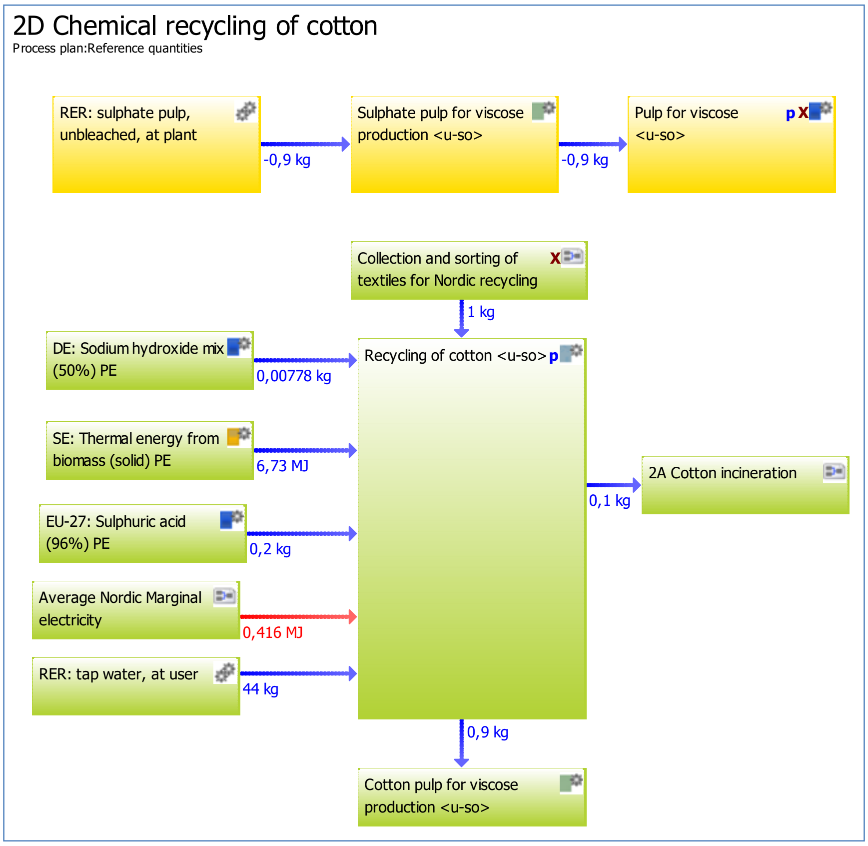
pretreatment and dissolution in ionic liquids (Ottewell, 2014)[29] (the latter process creates ioncell fibres, similar to lyocell fibres, in contrast to the others that produce viscose fibres).

In all cases, the waste cotton textiles are sorted, washed and shredded and then pretreated where cotton fibres are cleaved in order to reduce the molecular weight. In the example for this report, dissolving pulp that is suitable for viscose wet spinning is assumed to be produced via acid hydrolysis pretreatment. Data for this process has been collected from the pilot plant at Swerea IVF and complemented with literature data.[30]

After pretreatment, several cleaning steps are needed to remove the acid. Drying the pulp before transportation to viscose factory is necessary if not an integrated facility is used. An energy estimation model was developed to evaluate the energy demand in dilute acid pretreatment processes (Mafe *et al.*, 2015). The majority of the energy required was found to be from the heating stage of biomass and water for the pretreatment reaction. Solid loading rate was found to be a key factor in influencing the energy use. A dissolving process for virgin pulp production requires 0.416 kWh electricity per kg according to Hischier (2007). Input is 1 kg of cotton garments, sorted, shredded and washed. The output is 0.9 kg dry dissolving pulp suitable for viscose fibre production and 0.1 kg of cotton waste, which is assumed to be incinerated with energy recovery (national marginal energy scenarios).

[29] http://renewcell.se/hem/the-process.html
[30] Personal communication with Dr. Carina Olsson, fibre expert at Swerea IVF.

Figure 24: Elements included in the assessment of impacts and benefits from chemical recycling of cotton producing pulp for viscose production



6.6.3 Scenario 2E – Recycled cotton fibres substituting virgin cotton fibres for production of yarn

There is fairly limited experience with respect to recycling of used cotton textiles into fibres that subsequently can be used in the production of new textiles after spinning, weaving, dyeing, etc. However, it is known that some companies such as H&M and G-Star Raw are making use of recycled cotton fibres in new products along with virgin fibres.

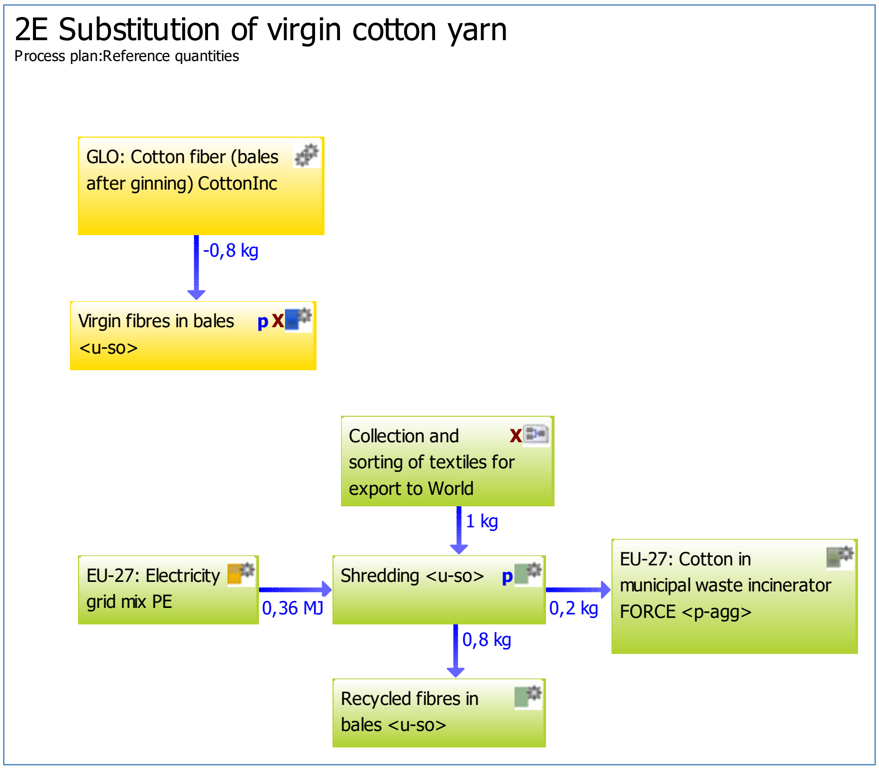
This need to mix recycled fibres with new fibres is a result of a shortening of fibres during wear and laundering of the original textile product and further during the recycling process. It is, therefore, currently not possible to achieve a high quality textile product using only recycled fibres. In practice, the recycled fibres are blended with virgin fibres at some point in the production process. This can happen during spinning, but it can also take place in weaving with up to 20% of the finished product being produced from recycled yarn as is the case for H&M and G-Star Raw producing denim products like jeans with 20% recycled cotton content.[31] There is also a third part assured global standard for inclusion of recycled cotton in new garments (Textile exchange, 2014).[32] In the mechanical recycling process, the cotton waste is sorted by type and colour, cut into small pieces, passed through a rotating drum and finally turned into fibres. The physical quality of the fibres produced using this method is low due to the shortened fibre lengths. One way to improve the quality of this product is to mix these fibres with virgin fibres and blend them into yarns (Zamani, 2014).

In the calculations it has been assumed that the substitution factor is 1, in recognition of the fact that an economically satisfactory market already exists for secondary cotton fibres and that the resulting products with up to 20% recycled cotton are of as good quality as products entirely from new cotton fibres.

The elements in this scenario are shown in Figure 25. It is noted that it is assumed that the collected cotton is transported to Asia for processing. If this type of recycling takes place in Europe, the environmental benefits will be marginally higher.

[31] http://www.itma.com/docs/default-source/news/itma_sustainability_bulletin_issue_1_2014_en.pdf?sfvrsn=2
[32] http://textileexchange.org/upload/Integrity/Standards/GRS/GRS%20v3%20Implementation%20Manual.pdf

Figure 25: Elements included in the assessment of impacts and benefits from substituting virgin cotton with secondary cotton in "the ROW"



It is also noted that only the basic processes in (avoided) production of virgin cotton fibres and (induced) recycling into secondary fibres are included. In practice, it is assumed that cotton collected for recycling after shredding into loose fibres can substitute virgin cotton fibres in bales 1:1 (w/w).

If more processes than shredding are needed to give the secondary fibres qualities ready for spinning, this will decrease the benefits accordingly. Mechanical processes, however, are not very demanding in the overall picture. The basic shredding process used in the calculations thus only requires 0.18 MJ of electricity per kg, based on information from a producer of textile shredders.[33] As this process initially produces down-sized textiles, it has been chosen to double the energy consumption to allow for a subsequent pulling process, yielding loose fibres that are suitable for spinning. A 20% loss of material has been assumed for the process. This loss is assumed to be incinerated without energy recovery. The material balance thus shows that for one tonne of cotton being collected, 800 kg of recycled fibres are

[33] http://www.cmg-america.com/fiber-textile-recovery

produced and 200 kg incinerated. The 800 kg of recycled fibres can substitute 800 kg of virgin cotton in bales.

The EOL treatment of virgin and recycled fibres is identical and therefore not included in the calculations.

6.6.4 *Scenario 2F – Mechanically recycled cotton fibres substituting flax insulation in Europe*

Many different types of fabrics are used in cars for many purposes. Insulation – both acoustic and thermal – is an application where fabrics are commonly used, but seldom visible or identifiable as fabrics. If visible, the appearance is determined by colouring of the plastic matrix of the composite material. According to O'Dell (2011), a wide range of materials are suitable for the purpose: "Acoustic and thermal insulation uses needle-punched nonwoven composites made with natural fibres (kenaf, jute, waste cotton, flax) in blends, often with PP and PET, for floor covering, door panels, headliners, trunk liners and parcel shelves". Pure fractions of recycled cotton and polyester can be used in the same type of applications, and also blends of wool and polyester are reported to be used in the production of fleece and fabric with noise-reducing properties, e.g. by Recytex (Recytex.com) in Germany.

It is noted that the use of recycled textile materials in cars is not limited to insulation products. A company like Rando (Rando.com) designs random air laid-down manufacturing systems for production of headliners, sun shades, acoustical pads and door panels, using cotton, cotton shoddy, synthetic shoddy, recycled fibre, reclaimed material, carbon, and fiberglass as fibres in a composite.

Of the many possibilities for recycling of fabrics in cars it is chosen to investigate the consequences of substituting virgin flax with mechanically recycled cotton waste in car insulation.

It has not been possible to map the actual use of different fibres in this type of applications. It is therefore assumed that recycled cotton fibres after shredding and carding can substitute flax fibres 1:1 (w/w).

It is noted that a similar substitution also is possible with regard to upholstery of chairs in cars and home furniture.[34]

The elements in this scenario are shown in Figure 26.

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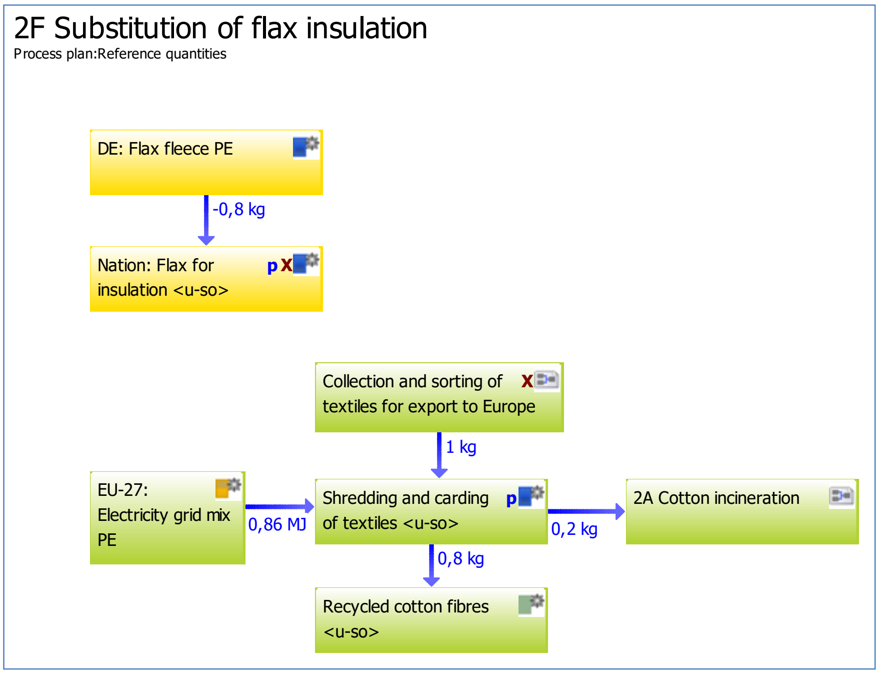
[34] See e.g. http://www.swicofil.com/products/003flax.html for examples on the use of flax in different applications.

Figure 26: Elements included in the assessment of impacts and benefits from substituting flax insulation with secondary cotton in Europe



The cotton recycling processes include shredding and carding, two processes that combined requires 0.238 kWh/kg, based on information in Östlund *et al.* (2015). The loss in shredding and carding is estimated to be 20%, the full amount of this is assumed to be incinerated with energy recovery in an average municipal incineration plant in the EU as defined in the GaBi dataset.

The EOL treatment of virgin flax and recycled cotton fibres is the same, irrespective of their application. If the EOL treatment involves incineration, this may cause very small differences with respect to impacts and benefits, related to the chemical composition of the cellulosic fibres. There is, however, not specific processes available in GaBi for incineration of flax and cotton, and the potential differences in impacts from this stage of the life cycle are therefore not considered in the calculations.

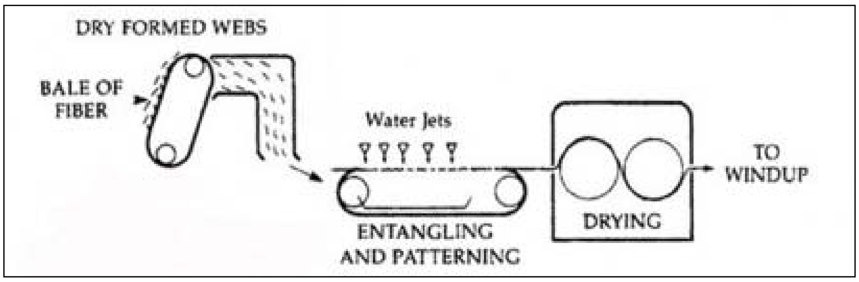
6.7 Scenario 3D Recycling of wool

6.7.1 Scenario 3D – Mechanical unravelling of wool to low grade wool yarn as a substitute for polyester fibres in blankets

Wool recycling is a term that is used both for processing of wool from sheep farmers that dispose of the wool as residual waste against payment (Laitala *et al.* (2012), Patnaik *et al.* (2015)) and for recycling of waste wool fabrics, either post industrial waste or post consumer garments Morley *et al.* (2006).

Morley *et al.* (2006) describes how recovered acrylic/wool blended garments are recycled into a thermal insulation layer for emergency blankets and IWTO (2012) how post-consumer woollen clothing is converted to for a diversity of industrial uses, including mattress, furniture and automotive components. Woollen fabrics are in both cases shredded and then turned into non-woven, e.g. via hydro-entanglement/ spunlacing, see Figure 27 below.

Figure 27: Hydroentanglement using water jets



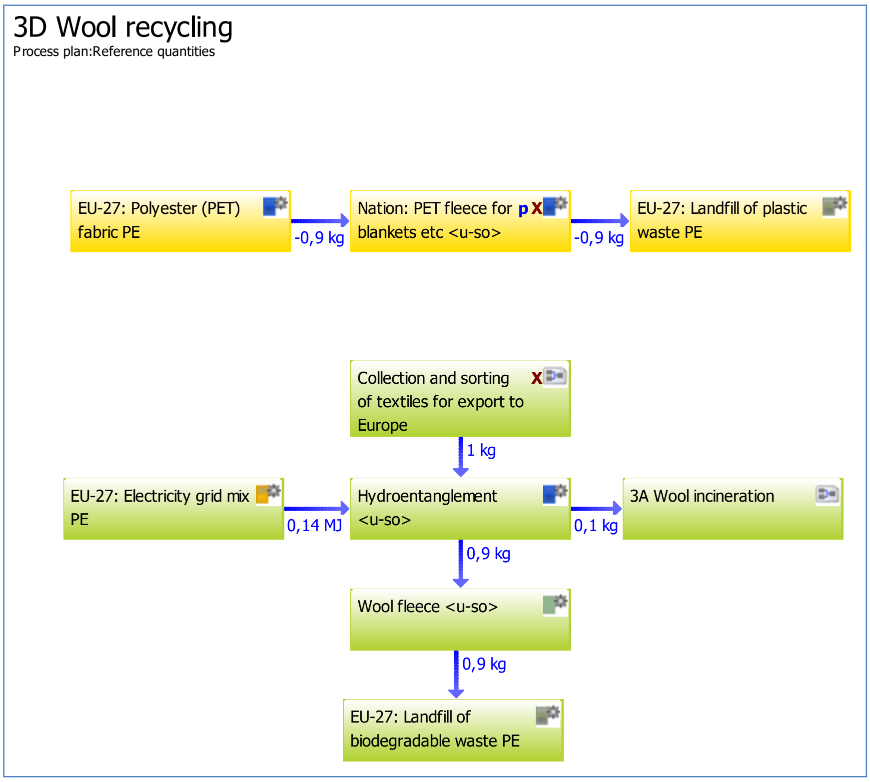
The non-woven fabric can be used as such or be combined with other fabrics to produce a multi-layer construct.

In the present calculations it has been assumed that the recycled wool substitutes polyester fabric product based on virgin materials (Figure 28). It is noted that production of fleece rather than fabric probably have different requirements to consumption of energy and water, but it has not been possible to investigate this in any detail.

It is also noted that the results when using virgin polyester fabric as the substituted material are very favourable for recycling. If the same substitution scenario as in 5.6.4 (flax insulation) was chosen, the results would be very similar to this scenario. On the other hand, if the wool is respun into yarn, the benefits would be even higher than in the present results. In this case, the recycled wool will substitute the initial and demanding production steps.

For both the induced and avoided product it is assumed that the EOL fate is landfilling since it is assumed that the blankets will mostly be used in developing countries.

Figure 28: Elements included in the assessment of impacts and benefits from substituting polyester fabric with recycled wool



6.8 Scenario 4D and 4E Recycling of mixed fibres as a substitution for cellulose-base industrial wipes and low-quality flax-based filling material

6.8.1 Scenario 4D: Production of industrial wipes from used mixed textiles as a substitution for new cellulose based wipes

Industrial wipes are known under various names, for example:

- Textile rental cloth.
- Industrial wiping cloth.
- Industrial cleaning cloth.
- Reusable shop towel.

Industrial wipes from virgin materials can be both single use products and multi use products. Wipes for single use are commonly cellulose or polyester based non-wovens, while reusable wipes are cotton/polyester blends. Reusable wipes are collected and laundered before reuse, which is not the case for wipes from used mixed textiles. Since single use cellulose based wipes has a similar type of use pattern to wipes from used mixed textiles this type has been selected as an example of substituted material/product.

Several companies market industrial wipes from used mixed textiles, e.g. SOEX (www.soexgroup.com) and ERC Wiping Products Inc. (www.ercwipe.com) in the US, from where the picture below is taken.

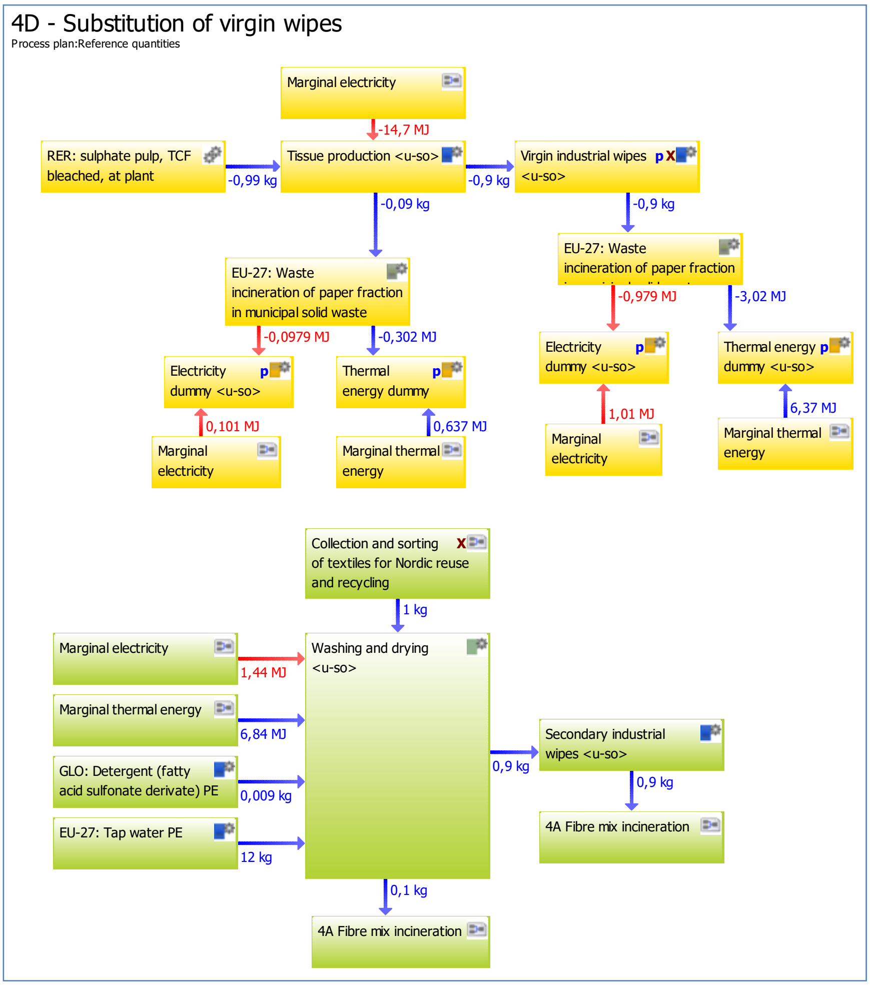
Figure 29: Industrial wipes from used mixed textiles

The avoided and induced processes are shown in Figure 30. The used mixed textiles are washed and dried and cut into wipe size. This has been modelled using data from a Swedish hospital laundry and data from Thompson *et al.* (2012), assuming a per kg electricity consumption of 0.4 kWh, thermal energy consumption of 6.84MJ, detergent consumption of 0.009 kg and 12 kg of tap water. A loss of 10% is assumed to be incinerated with energy recovered, using national efficiencies and substitution scenarios.

The substituted cellulose based industrial wipes are modelled as produced from sulphate pulp using ecoinvent data, and production data from Pullman *et al.* (1997) and Ekstrom (2012).

A functional equality between the two types of wipes is assumed. Potential differences in absorption rates are thus not considered, the main argument being that the full absorption capacity of a wipe is seldom utilized. Differences in weight between wipe qualities can also cause uncertainties in a comparison, but it has not been possible within the time and budget frames of the project to investigate the wiper market in any detail. The scenario investigated in therefore that one tonne of recycled mixed fibres results in 900 kg secondary wipes for industrial use, replacing 900 kg of virgin cellulose-based industrial wipes. The loss of 100 kg fibres in the process is assumed to be incinerated in the Nordic countries with energy recovery.

Figure 30: Induced and avoided processes in mixed fibre substitution of cellulose-based wipes



6.8.2 *Scenario 4E: Recycling of mixed fibre as non-woven filling material substituting flax-based filling material*

The elements in this scenario are similar to Scenario 2F, except for incineration of the waste from shredding and carding of recycled fibres. This difference is judged to be without importance in the overall picture, and the results from Scenario 2F are accordingly also representative for mixed fibres.

7. Results

All results presented relate to EOL treatment of one tonne of textile fibres. The unit of the normalised results is in all cases “Person Equivalents” (PE), see 3.4. Negative values indicate a benefit resulting from the treatment method following discarding by the first user, while a positive value indicates an (unwanted) impact of the treatment method.

The tables presents the results in all impact categories, while figures for the main scenarios include selected global and regional impacts and the figures used in the sensitivity analysis are limited to the constribution to climate change and consumption of primary energy. The main aim of the figures is to provide an easier overview than that found in the tables, nut it is underlined that only the tables present the full overview as defined in ILCD.

7.1 Fibre scenarios

The impacts and benefits are calculated for each of the four groups of fibres, including four to six scenarios for each group. The project uses the Nordic average marginal energy scenario as the key condition, while the national marginal energy scenarios are used to illustrate similarities and differences as found relevant.

The interpretation of the results follows a corresponding structure by first presenting and discussing the Nordic average and – after presentation of the national scenarios – discuss differences where there are assumed to be interesting for the primary target group of the report, i.e. decision-makers in the Nordic countries. Where relevant, additional sensitivity analysis are used to elucidate these differences.

7.2 Polyester fibres

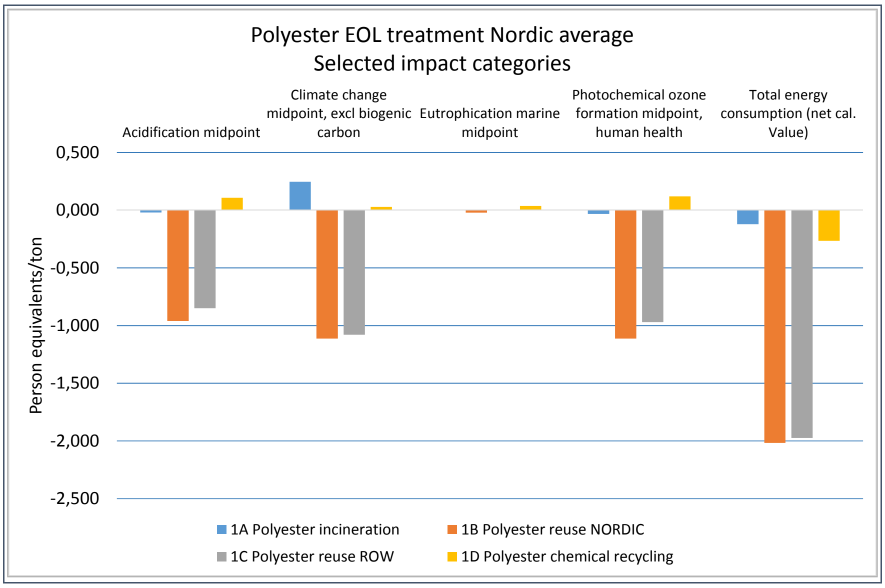
7.2.1 Treatment of discarded 100% polyester textiles – Nordic average marginal energy

The Nordic average impacts and benefits from treatment of discarded 100% polyester textiles are shown in Table 20.

Table 10: Impacts and benefits from different treatment routes for discarded polyester textiles. Nordic average marginal energy

ILCD impact categories	Unit	1A Polyester incineration	1B Polyester reuse NORDIC	1C Polyester reuse ROW	1D Polyester chemical recycling
Acidification midpoint	PE/ton	-0.021	-0.960	-0.849	0.108
Climate change midpoint, excl biogenic carbon	PE/ton	0.246	-1.113	-1.079	0.028
Climate change midpoint, incl biogenic carbon	PE/ton	0.245	-1.122	-1.089	0.027
Ecotoxicity freshwater midpoint	PE/ton	-0.001	-0.169	-0.163	-0.004
Eutrophication freshwater midpoint	PE/ton	0.000	-0.036	-0.035	0.000
Eutrophication marine midpoint	PE/ton	0.000	-0.022	0.003	0.037
Eutrophication terrestrial midpoint	PE/ton	-0.017	-0.679	-0.554	0.142
Human toxicity midpoint, cancer effects	PE/ton	-0.008	-2.140	-2.090	0.059
Human toxicity midpoint, non-cancer effects	PE/ton	-0.042	-7.004	-6.972	-0.024
Ionizing radiation midpoint, human health	PE/ton	-0.054	-0.374	-0.373	-0.017
Ozone depletion midpoint	PE/ton	0.000	0.000	0.000	0.000
Particulate matter/Respiratory inorganics midpoint	PE/ton	-0.008	-1.168	-1.121	0.034
Photochemical ozone formation midpoint, human health	PE/ton	-0.033	-1.112	-0.970	0.119
Resource depletion water, midpoint	PE/ton	0.008	-0.650	-0.649	-0.045
Resource depletion, mineral, fossils and renewables, midpoint	PE/ton	-0.005	-0.094	-0.093	-0.008
Total energy consumption (net cal. Value)	PE/ton	-0.121	-2.017	-1.974	-0.265

Figure 31: Contribution to selected impacts in the polyester scenarios



It appears readily from Table 10 and Figure 31 that reuse is the most favourable treatment route for discarded polyester textiles. There is one small exception from this general finding, namely that incineration appears to be the better solution than reuse in the rest of the World when assessing the contribution to marine eutrophication. This is due to the fact that incineration of polyester in the Nordic countries is beneficial for the environment for this category, while the ultimate fate of the polyester textile after reuse in ROW is landfilling, which is associated with a small impact in the category. The difference is, however, judged to be without importance in the overall picture.

Reuse is associated with significant benefits when compared to the currently prevailing treatment route, incineration with energy recovery. For climate change, reuse leads to saved emissions (negative contribution) rather than an unwanted contribution from the incineration process, and for other impact categories the benefits are 20–100 times higher.

In the basic scenario it is assumed that the reuse substitution factor is 1 when the reuse takes place in the Nordic countries as well as in the ROW. With this assumption, the benefits from Nordic recycling are a few percent higher than for ROW. The main reason for this is that there is less transportation in the Nordic scenario, and the final fate of the textiles after reuse (incineration/landfill) also plays a role.

The chemical recycling scenario appears to be better than incineration when addressing climate change, water consumption and total energy consumption but performs worse with respect to eutrophication and photochemical ozone creation potential. It is noted here that the documentation for the recycling process is of poor quality, and the results shall therefore primarily be used as an indication of which types of environmental impacts are affected by the process – and how. The poor data quality in this scenario primarily concerns the input of energy in relation to the output of recovered chemicals (DMT and EG). A sensitivity analysis has been conducted, comparing the "realistic" scenario shown in Table 10 with the assumed best case for chemical recycling (assuming a smaller input of energy for production of the same output of chemicals for substitution), see 6.2.4.

7.2.2 Sensitivity analysis – Marginal energy scenarios in Nordic countries (polyester)

It is an integral element of the systems examined that the impacts and benefits from reuse and recycling scenarios are the same in all Nordic countries. The small differences relating to national transportation distances are not considered in the calculations, but the nature and amount of energy produced in the reference scenario (incineration) is substituted by different technologies in the Nordic countries, leading to national differences in the incineration scenarios. This is illustrated in Table 11, depicting the impacts and benefits from incineration in the Nordic countries.

It can be seen from Table 11 that the differences are significant, at least when looking at incineration as an isolated process. When the impacts and benefits from incineration are compared to those from reuse and recycling (Table 10), the national differences seems to be less important. The ranking of the scenarios is in general the same in all countries, but as an example it can of course be argued that increasing the reuse of Finnish textiles will be better for the environment than increasing the reuse of Danish textiles. The very simple explanation for this is that incineration of polyester in Denmark has a better environmental profile than incineration in Finland, and the Danish benefits from increased reuse or recycling are correspondingly lower.

A finding and interpretation of this nature is probably irrelevant for future decision-making. The real benefits should be examined by looking at the difference between scenarios on the national level. In practice, this is done by subtracting the reference scenario from the “new” scenario (re-use or recycling), resulting in an overview of the net benefits and impacts to be obtained by a change in EOL treatment.

Table 11: Impacts and benefits from incineration of polyester in four Nordic countries – and an unweighted average

ILCD impact categories	Unit	NORDIC average	DK	FI	NO	SE
Acidification midpoint	PE/ton	-0046	-0.088	-0.021	-0.030	-0.056
Climate change midpoint, excl biogenic carbon	PE/ton	0.204	0.153	0.246	0.200	0.193
Climate change midpoint, incl biogenic carbon	PE/ton	0.204	0.153	0.245	0.200	0.191
Ecotoxicity freshwater midpoint	PE/ton	-0.004	-0.005	-0.001	-0.003	-0.009
Eutrophication freshwater midpoint	PE/ton	-0.005	-0.006	0.000	-0.004	-0.014
Eutrophication marine midpoint	PE/ton	-0.014	-0.018	0.000	-0.010	-0.037
Eutrophication terrestrial midpoint	PE/ton	-0.034	-0.068	-0.017	-0.016	-0.042
Human toxicity midpoint, cancer effects	PE/ton	-0.017	-0.022	-0.008	-0.010	-0.031
Human toxicity midpoint, non-cancer effects	PE/ton	-0.073	-0.074	-0.042	-0.055	-0.130
Ionizing radiation midpoint, human health	PE/ton	-0.045	-0.002	-0.054	-0.041	-0.030
Ozone depletion midpoint	PE/ton	0.000	0.000	0.000	0.000	0.000
Particulate matter/Respiratory inorganics midpoint	PE/ton	-0.020	-0.034	-0.008	-0.017	-0.028
Photochemical ozone formation midpoint, human health	PE/ton	-0.055	-0.100	-0.033	-0.028	-0.065
Resource depletion water, midpoint	PE/ton	-0.003	-0.001	0.008	-0.017	-0.004
Resource depletion, mineral, fossils and renewables, midpoint	PE/ton	-0.006	0.000	-0.005	-0.008	-0.005
Total energy consumption (net cal. Value)	PE/ton	-0.234	-0.265	-0.121	-0.257	-0.289

Basically, Table 11 shows that the benefits from incineration appear to be highest in Denmark and lowest in Finland. The Nordic average, however, gives a good indication of the benefits in general, taking into consideration that the marginal energy scenarios for individual countries is determined with some uncertainty (see 4.1.2).

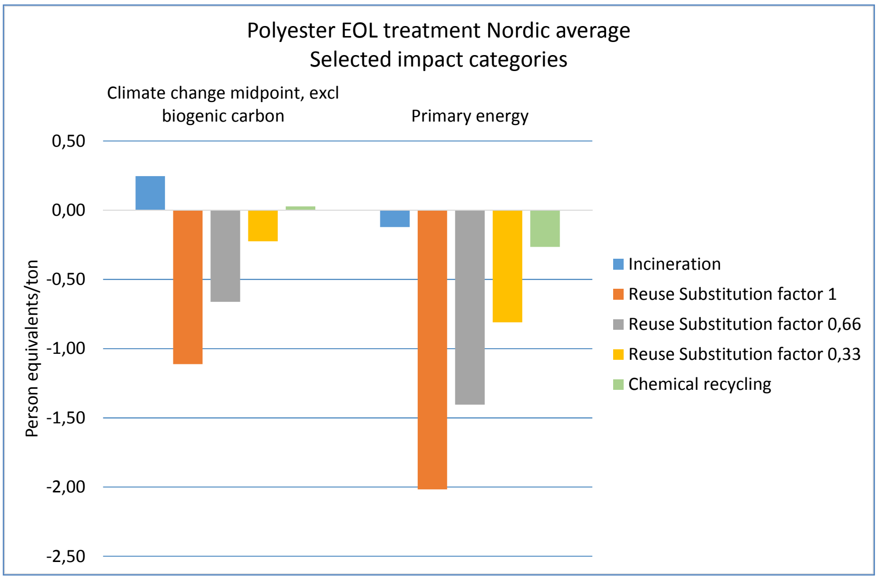
It is noted that for polyester (a synthetic fibre), incineration in all cases induces a contribution to climate change, because the carbon in the polymer is fossil-based. There is a benefit from a reduced need for marginally produced energy, but as this energy in the not-so-far future is based on renewables, there is not a corresponding benefit from avoided use of fossil carbon.

7.2.3 Sensitivity analysis: Substitution factor for polyester reuse, incineration and recycling

Figure 32 shows the relationship between the substitution factor and selected environmental impacts (climate change and consumption of primary energy).

As described in 3.2.2, it is not realistic to achieve a substitution factor of 1 when textiles are reused. This value is used in the calculation of the basic scenarios and in order to examine the importance of the substitution factor, a sensitivity analysis using 0.66 and 0.33 as factors has been conducted. It has been chosen to include the reference scenario (incineration) as well as the chemical recycling scenario in the calculations, thereby creating a better overview of the potential impacts and benefits from treatment of discarded polyester textiles in the Nordic countries, see Figure 32.

Figure 32: Impacts and benefits from different treatment routes for discarded polyester textiles in the Nordic countries



Firstly, the figure shows that there is an almost linear relationship between environmental benefits and the substitution factor. This finding applies to all impact categories examined in the study, and it is also valid for reuse in the ROW.

Furthermore, the figure demonstrates clearly that reuse is much more beneficial for the environment than incineration and chemical recycling. Even a low substitution factor of 0.33 provides significantly more benefits than incineration and recycling.

Finally, the figure shows that chemical recycling is more beneficial for the environment than incineration in the two selected impact categories. The finding, however, is not consistent in all impact categories as is evident from Table 10.

7.2.4 Sensitivity analysis: Increased energy efficiency in chemical recycling of polyester

As described in 5.5.1 there is some uncertainty regarding the output of the chemical recycling process taking place at Teijin in Japan. We have not been able to get a clear answer from the responsible person at Teijin, and in the basic scenario it was therefore chosen to use a conservative approach, assuming a low yield of the process. The Patagonia report indicates a somewhat higher yield, and it was therefore decided to examine the difference in a sensitivity analysis.[35] The results of this are presented in Table 12.

Table 12: Sensitivity analysis: Importance of yield from chemical recycling of polyester

ILCD impact categories	Unit	1D Polyester chemical recycling – basic scenario	1D Polyester chemical recycling – energy efficient scenario	Difference (in %)
Acidification midpoint	PE/ton	0.108	0.091	18
Climate change midpoint, excl biogenic carbon	PE/ton	0.028	-0.019	-248
Climate change midpoint, incl biogenic carbon	PE/ton	0.027	-0.020	-238
Ecotoxicity freshwater midpoint	PE/ton	-0.004	-0.011	-61
Eutrophication freshwater midpoint	PE/ton	0.000	0.000	6
Eutrophication marine midpoint	PE/ton	0.037	0.037	0
Eutrophication terrestrial midpoint	PE/ton	0.142	0.128	10
Human toxicity midpoint, cancer effects	PE/ton	0.059	-0.060	-198
Human toxicity midpoint, non-cancer effects	PE/ton	-0.024	-0.033	-29
Ionizing radiation midpoint, human health	PE/ton	-0.017	-0.024	-32
Ozone depletion midpoint	PE/ton	0.000	0.000	-1
Particulate matter/Respiratory inorganics midpoint	PE/ton	0.034	0.029	20
Photochemical ozone formation midpoint, human health	PE/ton	0.119	0.098	21
Resource depletion water, midpoint	PE/ton	-0.045	-0.046	-1
Resource depletion, mineral, fossils and renewables, midpoint	PE/ton	-0.008	-0.009	-15
Total energy consumption (net cal. Value)	PE/ton	-0.265	-0.330	-20

It appears from Table 12 that the higher yield from the process is reflected by a significantly smaller impact in most impact categories. For climate change, the increased efficiency means that there is a net benefit instead of an impact. The same finding is seen for human toxicity, cancer effects. For other impact categories the increased efficiency gives a corresponding decrease in impacts – or increase in benefits.

[35] Patagonia (2006) Common Threads Garment Recycling Program, http://www.patagonia.com/pdf/en_US/common_threads_whitepaper.pdf

The sensitivity analysis is an example of the importance of collecting and using data of good or high quality. In the example, the basis for building the scenario was a report from one of the stakeholders, Patagonia. However, the report did not fully comply with the requirements in the ISO LCA standard (ISO 14044) and contact via e-mail was therefore taken to both Patagonia and Teijin in order to get more precise information. Patagonia never answered the e-mails, while a repeated dialogue with Teijin did not produce clarity, probably because of language barriers.

The only conclusion that was made with respect to chemical recycling is, therefore, that it as a general rule appears to beneficial for the environment, compared to incineration, also with a low yield from the process. The benefits may very well be higher – or become higher in the future – but better data is needed to demonstrate this.

A final remark to this analysis is that the benefits under all circumstances are small, compared to those that can be obtained from reuse.

7.3 Cotton fibres

7.3.1 *Treatment of discarded 100% cotton textiles – Nordic average marginal energy*

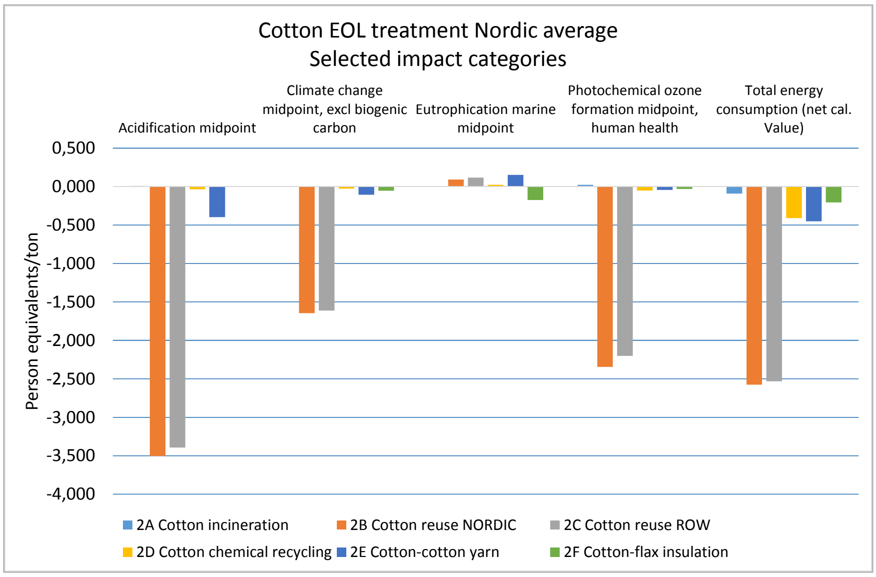
The Nordic average impacts and benefits from treatment of discardedcotton textiles are shown in Table 13 and Figure 33.

Table 13: Impacts and benefits from different treatment routes for discarded cotton textiles. Nordic average marginal energy

ILCD impact categories	Unit	2A Cotton incineration	2B Cotton reuse NORDIC	2C Cotton re-use ROW	2D Cotton chemical recycling	2E Cotton-cotton yarn	2F Cotton-flax insulation
Acidification midpoint	PE/ton	0.010	-3.505	-3.394	-0.035	-0.397	-0.002
Climate change midpoint, excl biogenic carbon	PE/ton	0.003	-1.646	-1.612	-0.027	-0.106	-0.054
Climate change midpoint, incl biogenic carbon	PE/ton	0.140	-1.422	-1.389	0.265	0.052	0.110
Ecotoxicity freshwater midpoint	PE/ton	0.000	-4.786	-4.780	-0.327	-2.794	-0.040
Eutrophication freshwater midpoint	PE/ton	0.000	-0.436	-0.436	-0.146	-0.230	-0.142
Eutrophication marine midpoint	PE/ton	0.000	0.091	0.117	0.022	0.153	-0.176

ILCD impact categories	Unit	2A Cotton incineration	2B Cotton reuse NORDIC	2C Cotton reuse ROW	2D Cotton chemical recycling	2E Cotton-cotton yarn	2F Cotton-flax insulation
Eutrophication terrestrial midpoint	PE/ton	0.023	-2.379	-2.254	-0.016	-0.460	0.000
Human toxicity midpoint, cancer effects	PE/ton	0.001	-1.266	-1.216	-0.947	-0.002	0.003
Human toxicity midpoint, non-cancer effects	PE/ton	0.020	-2.642	-2.610	-0.065	-0.347	-0.053
Ionizing radiation mid-point, human health	PE/ton	-0.038	-1.486	-1.485	-0.107	0.002	-0.031
Ozone depletion mid-point	PE/ton	0.000	-0.002	-0.002	-0.003	0.000	0.000
Particulate matter/Res-piratory inorganics mid-point	PE/ton	-0.004	-4.687	-4.640	-0.302	-0.196	-0.013
Photochemical ozone for-mation midpoint, human health	PE/ton	0.021	-2.344	-2.201	-0.053	-0.045	-0.032
Resource depletion water, midpoint	PE/ton	0.009	-5.823	-5.822	-88.13	-3.370	-0.035
Resource depletion, mineral, fossils and renewables, midpoint	PE/ton	-0.004	-3.342	-3.341	-0.353	-0.101	-0.011
Total energy consump-tion (net cal. Value)	PE/ton	-0.091	-2.575	-2.533	-0.409	-0.452	-0.206

Figure 33: Contribution to selected impact categories in the cotton scenarios



Similarly for polyester, the benefits from reuse of cotton textiles are much higher than from incineration and recycling. In most impact categories, the difference between reuse (Nordic or ROW) and incineration/recycling is a factor 10 or more. The available inventory data does not allow for a very detailed examination of which (avoided) processes that are most important, but it can be seen that the avoided manufacturing steps are about five times as important as the avoided production of virgin cotton fibres.

The impacts and benefits from incineration are modest. This is not surprising, because cotton in the context is regarded as a renewable fuel, the incineration of which to a large extent will be substituted by other renewable fuels in a not-so-distant future.

The impacts and benefits from chemical recycling (for substitution of sulfate pulp) and mechanical recycling for substitution of flax in insulation are also modest, although with mechanical recycling emerging as the better of the two treatment routes. Both these recycling routes are advantageous in most impact categories when compared to incineration, and it must be kept in mind that especially the chemical recycling process is at an early stage of development. The apparent benefits with respect to water savings in chemical recycling are related to the avoided production of sulfate pulp for viscose production. The water consumption in the recycling process is high (about 44 litre/kg), but the amount of water consumed in the (avoided) production of sulfate pulp is much higher, about 8,000 litres according to the ecoinvent 3.1 dataset used. Most of this water is "Cooling water, unspecified natural origin" and "Water, unspecified natural origin", and both types may very well also be used in the recycling process – but not included in the material balance established in the project. It is therefore doubtful whether the water-related benefits can be achieved in practice when the process is running in industrial scale. It is remarked here that some of the reservations related to data quality issues described in the sensitivity analysis of polyester (see 5.5.1 and 6.2.4) very well may be applicable also to this scenario (2D).

Recycling of cotton fibres into yarn that is used in the production of new fabric appears to be the recycling process with the highest benefits. The process is mechanical and simple, assuming that the fluff resulting from shredding can be spun into yarn in a process similar to that for baled cotton fibres. The recycled cotton fibres can then substitute virgin fibres to some extent, about 20%. It must be acknowledged that fabrics with a content of recycled fibres cannot be expected to have the same quality as cotton made from 100% virgin fibres, but big retail companies do not seem to have quality problems using recycled fibres in their design strategies.

7.3.2 *Sensitivity analysis – Marginal energy scenarios in Nordic countries (cotton)*

The impacts and benefits from incineration of cotton are shown in Table 14. On the general level the picture is similar to that found for polyester in Table 11, namely that the differences between the Nordic countries is small and that the calculated Nordic average is representative for the Nordic region.

It is noted that incineration of cotton – in contrast to polyester – gives a negative/avoided contribution to climate change in Sweden, Norway and Denmark. The avoided contribution is relatively small in absolute figures (0.3–0.6 kg CO_2-equivalents per kg cotton incinerated, see the detailed figures in the links in Appendix B), but it is still more than 0.15 kg avoided in chemical recycling.

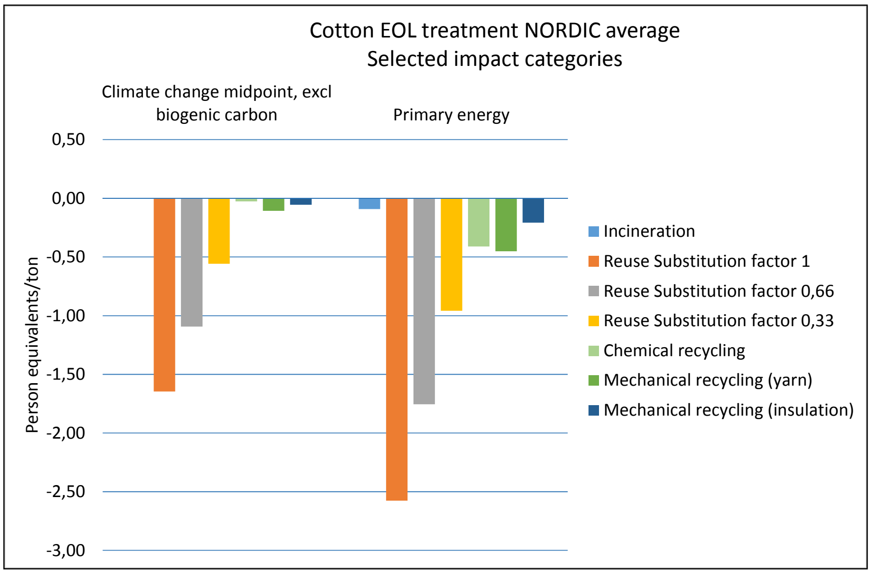
Table 14: Impacts and benefits from incineration of cotton in four Nordic countries – and an unweighted average

ILCD impact categories	Unit	NORDIC average	DK	FI	NO	SE
Acidification midpoint	PE/ton	-0.011	-0.043	0.010	0.002	-0.019
Climate change midpoint, excl biogenic carbon	PE/ton	-0.031	-0.072	0.003	-0.035	-0.040
Climate change midpoint, incl biogenic carbon	PE/ton	0.106	0.066	0.140	0.102	0.096
Ecotoxicity freshwater midpoint	PE/ton	-0.003	-0.004	0.000	-0.002	-0.007
Eutrophication freshwater midpoint	PE/ton	-0.004	-0.005	0.000	-0.003	-0.011
Eutrophication marine midpoint	PE/ton	-0.010	-0.013	0.000	-0.008	-0.030
Eutrophication terrestrial midpoint	PE/ton	0.009	-0.017	0.023	0.024	0.003
Human toxicity midpoint, cancer effects	PE/ton	-0.006	-0.010	0.001	-0.001	-0.018
Human toxicity midpoint, non-cancer effects	PE/ton	-0.005	-0.004	0.020	0.009	-0.051
Ionizing radiation midpoint, human health	PE/ton	-0.033	-0.001	-0.038	-0.033	-0.024
Ozone depletion midpoint	PE/ton	0.000	0.000	0.000	0.000	0.000
Particulate matter/Respiratory inorganics midpoint	PE/ton	-0.015	-0.025	-0.004	-0.012	-0.021
Photochemical ozone formation midpoint, human health	PE/ton	0.003	-0.031	0.021	0.025	-0.004
Resource depletion water, midpoint	PE/ton	0.000	0.002	0.009	-0.012	-0.001
Resource depletion, mineral, fossils and renewables, midpoint	PE/ton	-0.004	0.000	-0.004	-0.006	-0.004
Total energy consumption (net cal. Value)	PE/ton	-0.180	-0.201	-0.091	-0.201	-0.226

7.3.3 *Sensitivity analysis: Substitution factors for cotton reuse, incineration and recycling*

Figure 34 shows the relationship between the substitution factor and selected environmental impacts (climate change and consumption of primary energy). The figure also includes incineration and the three recycling scenarios examined for cotton, giving a graphical overview of the results for two selected impact categories.

Figure 34: Impacts and benefits from different EOL treatment routes for cotton in the Nordic countries



The picture for avoided impacts as a function of substitution factor is similar to that for polyester seen in Figure 32, i.e. there is an almost linear relationship. It is worth noting, however, that the benefits are much higher for cotton than for polyester, measured in person equivalents as well as in absolute figures for the individual impacts categories (see the links in Appendix B for detailed results). The obvious explanation of this is that it is more demanding for the environment to produce cotton and the benefits from avoided production are, accordingly, much higher.

It is mentioned that the sensitivity analysis identifies one exception from this general finding, i.e. the contribution to marine eutrophication is higher in the reuse scenarios than in the incineration and chemical recycling scenarios. This is due to an input of nitrate as an “inorganic emission to fresh water” in the production of cotton, and the ILCD method subsequently accounts for this as an avoided emission of nitrate to marine waters.

Since this emission is not avoided in reuse, the contribution becomes positive, reflecting an unwanted consequence of reuse. It is outside the scope of the report to go into further details regarding this finding.

The high benefits from avoided production of cotton is also reflected in the mechanical recycling (yarn) scenario, although with less significance than reuse. This can be seen when comparing the "yarn scenario" to the "insulation scenario". In the yarn scenario, growing and ginning of cotton is avoided by a mechanical recycling process, while in the insulation scenario an almost identical mechanical process leads to avoided production of short flax fibres.

All three cotton recycling scenarios appears to have larger benefits than incineration, at least in the two impact categories shown in Figure 34. A closer examination of the data shows that this finding is consistent, with very few exceptions that are related to the inventory data used.

7.3.4 Sensitivity analysis: The importance of transportation in reuse and recycling

It was indicated in 4.1.1 that collecting and transporting fibres for reuse and recycling is of limited importance. The results in Table 15 adds some details to this.

Table 15: Impacts from collection and transport of textiles, in comparison with the benefits achieved by selected treatment routes

ILCD impact categories	Unit	Collection and sorting of textiles for export to World	2C Cotton reuse ROW	2D Cotton chemical recycling	2E Cotton-cotton yarn
Acidification midpoint	PE/ton	0.123	-3.394	-0.035	-0.397
Climate change midpoint, excl biogenic carbon	PE/ton	0.043	-1.612	-0.027	-0.106
Climate change midpoint, incl biogenic carbon	PE/ton	0.043	-1.389	0.265	0.052
Ecotoxicity freshwater midpoint	PE/ton	0.008	-4.780	-0.327	-2.794
Eutrophication freshwater midpoint	PE/ton	0.001	-0.436	-0.146	-0.230
Eutrophication marine midpoint	PE/ton	0.039	0.117	0.022	0.153
Eutrophication terrestrial midpoint	PE/ton	0.140	-2.254	-0.016	-0.460
Human toxicity midpoint, cancer effects	PE/ton	0.065	-1.216	-0.947	-0.002
Human toxicity midpoint, non-cancer effects	PE/ton	0.048	-2.610	-0.065	-0.347
Ionizing radiation midpoint, human health	PE/ton	0.003	-1.485	-0.107	0.002
Ozone depletion midpoint	PE/ton	0.000	-0.002	-0.003	0.000
Particulate matter/Respiratory inorganics midpoint	PE/ton	0.050	-4.640	-0.302	-0.196
Photochemical ozone formation midpoint, human health	PE/ton	0.148	-2.201	-0.053	-0.045
Resource depletion water, midpoint	PE/ton	0.002	-5.822	-88.131	-3.370
Resource depletion, mineral, fossils and renewables, midpoint	PE/ton	0.001	-3.341	-0.353	-0.101
Total energy consumption (net cal. Value)	PE/ton	0.061	-2.533	-0.409	-0.452

It can be seen from the table that the impacts from transport reduces the benefits from reuse in ROW with 2–3% in most impact categories. In recycling, the impacts from transportation are much higher, simply because the benefits are smaller. It is, nevertheless, evident that recycling is beneficial for the environment, even if you have to transport the collected textiles to Asia for recycling into yarn as is assumed in Scenario 2E. It is noted in this context that the impacts from transportation are included in the calculation of the net benefits reported in the scenarios shown in the table. The relative importance is thus smaller than it appears.

7.4 Wool fibres

7.4.1 Treatment of discarded 100% woollen textiles – Nordic average marginal energy

The Nordic average impacts and benefits from treatment of discarded wool textiles are shown in Table 16 and Figure 35.

Table 16: Impacts and benefits from different EOL treatment routes for wool. Nordic average marginal energy

ILCD impact categories	Unit	3A Wool incineration	3B Wool reuse NORDIC	3C Wool reuse ROW	3D Wool recycling
Acidification midpoint	PE/ton	-0.016	-14.410	-14.299	-0.232
Climate change midpoint, excl biogenic carbon	PE/ton	0.002	-3.505	-3.472	-0.576
Climate change midpoint, incl biogenic carbon	PE/ton	0.070	-2.767	-2.734	-0.558
Ecotoxicity freshwater midpoint	PE/ton	-0.001	-2.356	-2.350	-0.067
Eutrophication freshwater midpoint	PE/ton	0.000	-4.280	-4.279	0.050
Eutrophication marine midpoint	PE/ton	0.000	-7.111	-7.085	0.038
Eutrophication terrestrial midpoint	PE/ton	-0.009	-16.457	-16.331	-0.115
Human toxicity midpoint, cancer effects	PE/ton	-0.010	-9.320	-9.270	-1.260
Human toxicity midpoint, non-cancer effects	PE/ton	-0.044	-2.421	-2.389	-5.202
Ionizing radiation midpoint, human health	PE/ton	-0.054	-1.561	-1.561	-0.286
Ozone depletion midpoint	PE/ton	0.000	-0.013	-0.013	0.000
Particulate matter/Respiratory inorganics midpoint	PE/ton	-0.009	-4.624	-4.578	-0.148
Photochemical ozone formation midpoint, human health	PE/ton	-0.023	-1.714	-1.572	-0.327
Resource depletion water, midpoint	PE/ton	0.002	-17.357	-17.356	-0.409
Resource depletion, mineral, fossils and renewables, midpoint	PE/ton	-0.008	-0.748	-0.748	-0.069
Total energy consumption (net cal. Value)	PE/ton	-0.129	-3.977	-3.935	-1.312

Figure 35: Contribution to selected impact categories in the wool scenarios

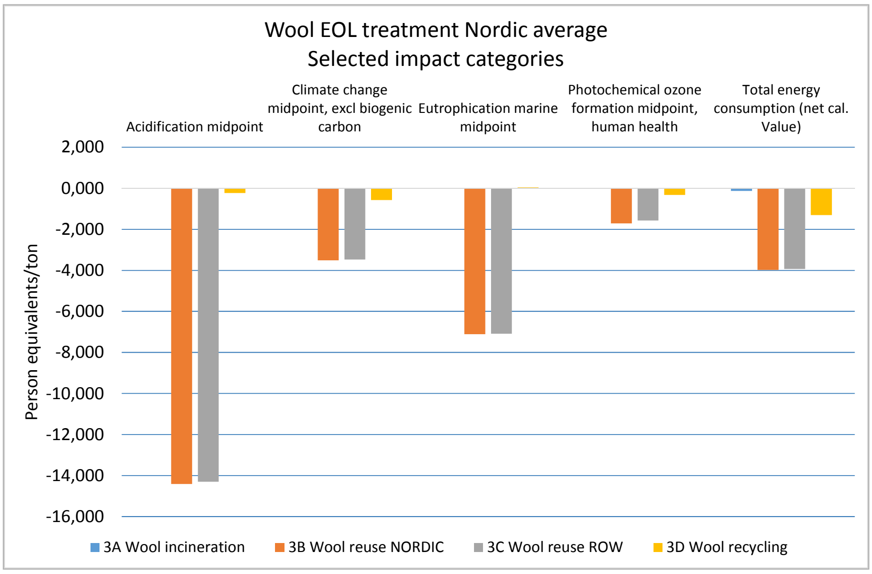


Table 16 and Figure 35 shows a picture for wool similar to that seen for polyester and cotton, i.e. that reuse gives very high benefits for the environment compared to incineration and recycling. The high benefits are related to savings throughout all steps in the production, from raising of sheep over spinning and knitting to the final finishing. The data quality for wool production is not optimal (see 5.3.6) – and the variation between different production routes is significant – but high benefits can be achieved for all types of reuse of wool.

The recycling process assumes that polyester fabric is substituted by non-woven woollen products, e.g. emergency blankets. The benefits from this are most probably lower than those that can be achieved if production of virgin wool can be avoided. This judgment is based on the fact that raising of sheep alone accounts for more than 50% of the climate change impacts in the life cycle of wool and about a third of the energy consumption. These impacts are avoided if collected wool is carded and spun into new yarn, with the possibility that more benefits can be achieved further down the production line.

The incineration process gives results that are very similar to those seen for cotton, which also is a material based on renewable resources. Although the lower heat value for wool is slightly higher than for cotton, the benefits are also in this case smaller than those calculated for recycling.

The per tonne benefits of reuse and recycling are much higher for wool than for both cotton and polyester, measured in person equivalents as well as in absolute figures for the individual impacts categories (see the links in Appendix B for detailed results). The obvious explanation of this is that it is more demanding for the environment to produce wool and the benefits from avoided production are, accordingly, much higher.

7.4.2 Sensitivity analysis – Marginal energy scenarios in Nordic countries (wool)

The impacts and benefits from incineration of wool in the Nordic countries are shown in Table18. On the general level the picture is similar to that found for polyester in Table 11 (and cotton in Table 14), namely that the differences between the Nordic countries is small and that the calculated Nordic average is representative for the Nordic region.

It is noted that incineration of wool – in contrast to polyester – gives a negative/avoided contribution to climate change in Sweden, Norway and Denmark. The avoided contribution is small in absolute figures (0.5–0.9 kg CO_2-equivalents per kg cotton incinerated (see the detailed figures in the links in Appendix B) but this is significantly less than the about 5 kg avoided in the recycling process examined in the project.

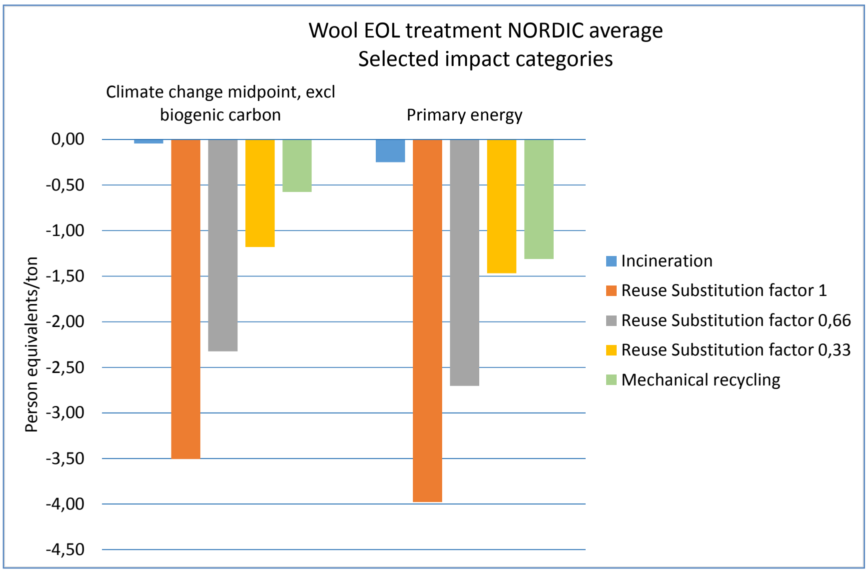
Table 17: Impacts and benefits from incineration of wool in four Nordic countries – and an unweighted average

ILCD impact categories	Unit	NORDIC average	DK	FI	NO	SE
Acidification midpoint	PE/ton	-0.044	-0.088	-0.016	-0.026	-0.055
Climate change midpoint, excl biogenic carbon	PE/ton	-0.044	-0.100	0.002	-0.050	-0.057
Climate change midpoint, incl biogenic carbon	PE/ton	0.024	-0.031	0.070	0.018	0.009
Ecotoxicity freshwater midpoint	PE/ton	-0.004	-0.005	-0.001	-0.003	-0.010
Eutrophication freshwater midpoint	PE/ton	-0.005	-0.006	0.000	-0.004	-0.015
Eutrophication marine midpoint	PE/ton	-0.015	-0.019	0.000	-0.012	-0.041
Eutrophication terrestrial midpoint	PE/ton	-0.029	-0.065	-0.009	-0.009	-0.038
Human toxicity midpoint, cancer effects	PE/ton	-0.019	-0.024	-0.010	-0.012	-0.035
Human toxicity midpoint, non-cancer effects	PE/ton	-0.078	-0.077	-0.044	-0.059	-0.140
Ionizing radiation midpoint, human health	PE/ton	-0.048	-0.004	-0.054	-0.047	-0.035
Ozone depletion midpoint	PE/ton	0.000	0.000	0.000	0.000	0.000
Particulate matter/Respiratory inorganics midpoint	PE/ton	-0.023	-0.036	-0.009	-0.019	-0.031
Photochemical ozone formation midpoint, human health	PE/ton	-0.047	-0.094	-0.023	-0.018	-0.058
Resource depletion water, midpoint	PE/ton	-0.010	-0.008	0.002	-0.026	-0.011
Resource depletion, mineral, fossils and renewables, midpoint	PE/ton	-0.009	-0.004	-0.008	-0.012	-0.009
Total energy consumption (net cal. Value)	PE/ton	-0.250	-0.279	-0.129	-0.278	-0.313

7.4.3 Sensitivity analysis: Substitution factors for wool reuse, incineration and recycling

Figure 34 shows the relationship between the substitution factor and selected environmental impacts (climate change and consumption of primary energy). The figure also includes incineration and the recycling scenario examined for wool, giving a graphical overview of the results for two selected impact categories.

Figure 36: Impacts and benefits from different EOL treatment routes for wool in the Nordic countries



The picture for avoided impacts as a function of substitution factor is similar to that for polyester and cotton seen in Figure 32 and Figure 34, i.e. there is an almost linear relationship. It is, however, worth noting that when the substitution factor is reduced to 0.33, mechanical recycling begins to compete with reuse in terms of environmental benefits.

It also appears from the figure that recycling gives far more benefits than incineration, and as described in 6.4.1 the benefits will probably be even higher if the recycled wool substitutes virgin wool.

7.5 Mixed fibres

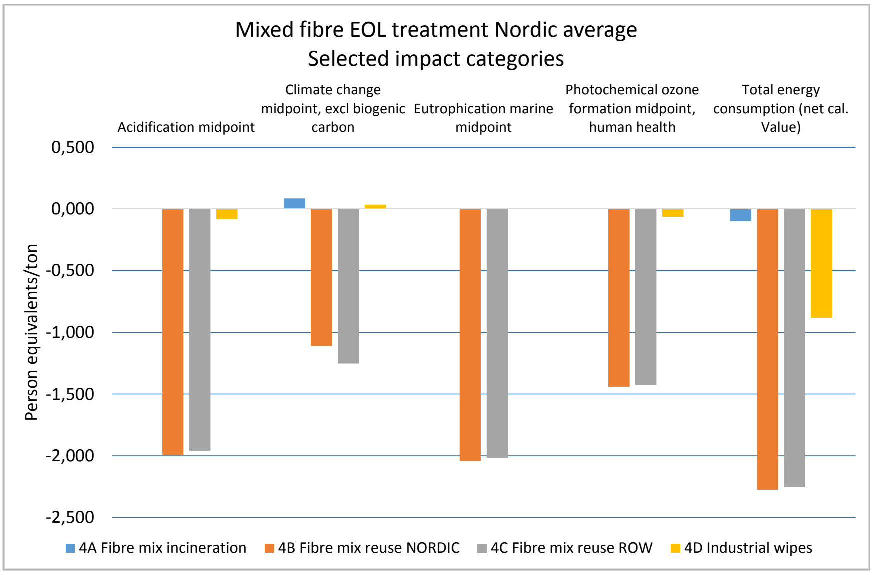
7.5.1 Treatment of discarded textiles of mixed fibres – Nordic average marginal energy

The Nordic average impacts and benefits from treatment of discarded textiles of average Nordic mixed fibres are shown in Table 18.

Table 18: Impacts and benefits from different EOL treatment routes for mixed fibres. Nordic average marginal energy

ILCD impact categories	Unit	4A Fibre mix incineration	4B Fibre mix reuse NORDIC	4C Fibre mix reuse ROW	4D Industrial wipes
Acidification midpoint	PE/ton	0.000	-1.994	-1.959	-0.081
Climate change midpoint excl biogenic carbon	PE/ton	0.086	-1.110	-1.254	0.035
Climate change midpoint incl biogenic carbon	PE/ton	0.176	-0.615	-1.080	0.281
Ecotoxicity freshwater midpoint	PE/ton	0.000	-0.490	-0.485	-0.380
Eutrophication freshwater midpoint	PE/ton	0.000	-1.434	-1.433	-0.176
Eutrophication marine midpoint	PE/ton	0.000	-2.042	-2.018	0.000
Eutrophication terrestrial midpoint	PE/ton	0.010	-1.845	-1.823	-0.020
Human toxicity midpoint cancer effects	PE/ton	-0.002	-4.108	-4.079	-1.151
Human toxicity midpoint non-cancer effects	PE/ton	0.000	-3.669	-3.766	-0.035
Ionizing radiation midpoint human health	PE/ton	-0.042	-0.500	-0.506	-0.672
Ozone depletion midpoint	PE/ton	0.000	-0.001	-0.001	-0.004
Particulate matter/Respiratory inorganics midpoint	PE/ton	-0.005	-1.706	-1.668	-0.366
Photochemical ozone formation midpoint human health	PE/ton	0.004	-1.441	-1.426	-0.064
Resource depletion water midpoint	PE/ton	0.008	-5.178	-5.210	-98.122
Resource depletion mineral, fossils and renewables midpoint	PE/ton	-0.004	-0.218	-0.218	-0.445
Total energy consumption (net cal. Value)	PE/ton	-0.098	-2.276	-2.254	-0.882

Figure 37: Contribution to selected impact categories in the mixed fibre scenarios



The results in Table 18 and Figure 37 represent the (theoretical) situation where one tonne of textiles from mixed fibres is either incinerated. reused or recycled. In other words, in each scenario all fractions of the mixed fibres (Nordic average composition. See 5.3.7) are assumed to follow the same treatment route after collection. It is acknowledged that this will never be the case. In practice, the collected textiles will be sorted where after the sorted fractions follow the treatment route with the largest economical profit. The results in the table can, however, give an indication of the potential environmental benefits that can be achieved on the national level.

7.6 Upscaling of results – an example

Bearing in mind the uncertainties of the calculations for the individual scenarios, the results can be upscaled to indicate the environmental benefits that potentially can be achieved on the national level by an increased collection and subsequent EOL treatment of the textiles that currently are being incinerated in the reference scenario.

For Sweden, the amount of textiles that currently are not collected separately amount to about 100,000 tonnes per year (see chapter 4). Instead of being incinerated, the following treatment routes after separate collection may be theoretically viable in a not-so-distant future:

- Cotton (57%, equal to 57,000 ton), of which:
  - Incinerated: 50%, equal to 28,500 ton.
  - Reuse in Nordic countries: 10%, equal to 5,700 ton.
  - Reuse in ROW: 20%, equal to 10,400 ton.
  - Chemical recycling: 10%, equal to 5,700 ton.
  - Mechanical recycling to yarn: 10%, equal to 5,700 ton.
  - Mechanical recycling to car insulation: 10%, equal to 5,700 ton.
- Polyester (34%, equal to 34,000 ton), of which:
  - Incineration: 50%, equal to 17,000 ton.
  - Reuse in Nordic countries: 10%, equal to 3,400 ton.
  - Reuse in ROW: 20%, equal to 6,800 ton.
  - Chemical recycling in Japan: 20%, equal to 6,800 ton.
- Wool (4%, equal to 4,000 ton), of which:
  - Incineration: 20%, equal to 800 ton.
  - Reuse in Nordic countries: 30%, equal to 1,200 ton.
  - Reuse in ROW: 30%, equal to 1,200 ton.
  - Recycling to blankets: 20%, equal to 800 ton.
- Other (5%, equal to 5,000 ton), of which:
  - Incineration 50%, equal to 2,500 ton.
  - Recycling as wipes: 50%, equal to 2,500 ton.

The above distribution of textiles assumes that the fibre mix composition of textile waste is similar to the textiles purchased by consumers in the Nordic countries – and that the fibres are pure. The distribution between EOL treatment routes shall be regarded as an example, where a main assumption is that 50% of the textiles now collected separately are not suitable for neither reuse nor recycling and therefore must be incinerated.

Table 19: Environmental benefits from collection of 100,000 tonne textiles, followed by an improved EOL treatment

ILCD impact categories	Unit	Current situation	Increased collection	Difference
Acidification midpoint	PE	-3.353	-105.602	102.248
Climate change midpoint excl biogenic carbon	PE	4.250	-46.241	50.490
Climate change midpoint incl biogenic carbon	PE	12.649	-33.891	46.539
Ecotoxicity freshwater midpoint	PE	-827	-107.581	106.754
Eutrophication freshwater midpoint	PE	-1.204	-21.535	20.332
Eutrophication marine midpoint	PE	-3.264	-16.407	13.143
Eutrophication terrestrial midpoint	PE	-1.500	-87.263	85.763
Human toxicity midpoint cancer effects	PE	-2.311	-71.910	69.599
Human toxicity midpoint non-cancer effects	PE	-8.243	-132.501	124.258
Ionizing radiation midpoint human health	PE	-2.643	-35.737	33.094
Ozone depletion midpoint	PE	1	-88	89
Particulate matter/Respiratory inorganics midpoint	PE	-2.418	-106.111	103.693
Photochemical ozone formation midpoint human health	PE	-2.806	-54.291	51.485
Resource depletion water midpoint	PE	-245	-670.366	670.121
Resource depletion mineral fossils and renewables midpoint	PE	-442	-62.885	62.444
Total energy consumption (net cal. Value)	PE	-25.166	-93.452	68.286

It appears from Table 19 that significant benefits can be achieved by an increased separate collection of textiles, followed by an optimised treatment of discarded textiles. It is underlined that the benefits in the table refers to an increased collection of 100,000 ton, which is the total amount of textiles assumed to be incinerated in Sweden today. It is hardly realistic to collect all 100%, and in the other Nordic countries, the amounts of textiles not collected separately are only about 50% of this figure. As such, the table, provides a first indication of the order of magnitude of the potential benefits, but it is underlined that the example is based on a number of assumptions, each of which is open for discussion.

With the assumptions and uncertainties outlined above, the changes in treatment of 100,000 tonnes of discarded textiles would lead to estimated annual savings of:

- 466 thousand tonnes of CO2-equivalents.
- 54 million cubic metres of water.
- 6,600 TJ of energy.
- 9 tonnes of acidification emissions (mole of H+ equivalents).

7.6.1 Sensitivity analysis

With the given distribution of treatment routes for the individual fibre types the main benefits are related to reuse of textiles (primarily cotton) in the Nordic countries and/or the rest of the world. It does not seem unrealistic that 30% of the cotton textiles not being collected separately today, can be reused by consumers somewhere in the world. The full picture shall, however, also include a view to the substitution factor. The above calculations assume a substitution factor of 1, but the benefits from an increased collection will in practice be lower because a factor of 1 is unrealistically high.

A very basic sensitivity analysis is thus that the benefits are reduced by 75% if only half of the 100,000 tonnes is collected and the substitution factor is set at 0.5. More precise calculations can be made by using the result tables found in the files that are lunked in Appendix B.

8. Data sources

Table 20 provides an overview of the most important data sources used in the project, their geographical coverage and their validity period. As can be seen are many of the processes commented in one way or the other. The main reason for this is that the processes have been modified in order to reflect actual conditions more precisely than is possible using the original datasets.

It is noted that many of the datasets used in the calculations are only shown on the highest level (aggregated) in the figures depicting the scenarios – and also in Table 20. In practice, many datasets are constructed from dozens of underlying datasets, each of which has its own basic source of information. This is for example the case for the top-level process "Marginal electricity", the content of which is described in detail in 4.1.2. The reader is therefore referred to the general text in the report if more information is sought for.

Table 20: Data sources used in the study

Scenario	Process name	Geographical area	Data source	Validity period	Comment
1A	Polyethylene terephthalate (PET) (in municipal waste incinerator)	EU-27	GaBi, 2015	2013–2016	PET in waste-to-energy plant with dry flue gas treatment, without collection, transport and pre-treatment. See also 5.2.1
2A	Cotton in municipal waste incinerator	EU-27	GaBi, 2015	2013–2016	Modified from a generic dataset for "textiles" in municipal waste incinerator, see 5.2.2
3A	Wool in municipal waste incinerator	EU-27	GaBi, 2015	2013–2016	Modified from a generic dataset for "textiles" in municipal waste incinerator, see 5.2.2
Multiple	Marginal electricity	Denmark, Finland, Norway, Sweden, average Nordic	GaBi, 2015	2011–2016	National scenarios established by FORCE Technology, using GaBi-data for specific technologies, See 4.1.2
Multiple	Marginal thermal energy	Denmark, Finland, Norway, Sweden, average Nordic	GaBi, 2015	2011–2016	National scenarios established by FORCE Technology, using GaBi-data for specific technologies, See 4.1.2
Multiple	Electricity mix (energy carriers, generic)	Country specific or EU-27 average as appropriate	GaBi, 2015	2011–2016	Electricity production mix are used to reflect the consumption in selected countries. See individual scenarios for details
1B,1C, 3D	Polyester (PET) fabric	EU-27	GaBi, 2015	2013–2016	Assumed to be representative also for production outside of EU
2B, 2C	Cotton fabric	China, India, USA	GaBi, 2015	2013-2016	Basic source is Cotton Incorporated, USA
3B, 3C	Wool fabric	Produced in USA, scoured in New Zealand, spun, knitted and finished in EU-27	Ecoinvent 2.2 (wool), GaBi 2015 (scouring), BREF (spinning, knitting, finishing)	Ecoinvent: 2001–2006 GaBi: 2002-2012 BREF: 2004–?	An array of processes combined by FORCE Technology from different sources
4 B, 4C	Flax fleece	Germany	GaBi, 2015	2013–2016	
Multiple	Cutting and sewing	World	Beton, 2014	Not available	Assumes 15% cut-off being landfilled
2B, 2C, 2D, 4C	Landfill of biodegradable waste	EU-27	GaBi, 2015	2013–2016	Includes collection of landfill gas, but its utilisation is not included
1B, 1C, 1D	Landfill of plastic waste	EU-27	GaBi, 2015	2013–2016	Includes collection of landfill gas, but its utilisation is not included
Multiple	Transport (several processes in different trucks as well as container ship)	World	GaBi, 2015	2012–2016	Considers utilisation rates as described in relevant scenarios
Multiple	Collection and sorting of textiles for Nordic reuse	Nordic countries	Fretex, Norway	Not applicable	Distances established by project group

Scenario	Process name	Geographical area	Data source	Validity period	Comment
2E	Cotton fibre (bales after gin-ning)	China, India, USA	GaBi, 2015	2009–2015	Based on Cotton Incorporated, 2013
Multiple	Shredding of textiles	World	FORCE Technology	Current average	Based on information from provider of machinery
2E, 2F	Carding of textiles	World	Jewell, 2013	Current average	From Cotton Incorporated report, 2013
2D	sulfate pulp production, un-bleached	Europe (RER)	Ecoinvent, 2015	Reference year 2015	

9. Data quality assessment

9.1 The Pedigree approach

A pedigree (hybrid) approach, modified from Weidema and Wesnæs (1996) was used to assess the data quality. For each unit process the data quality is scored on a scale from 1–4 with respect to Technology, Time, Geography, Completeness and Reliability. The scores from 1 to 4 reflect whether the data are "poor", "fair", "good" or "very good". In this way an operational overview is established, but it must be acknowledged that the scoring to a large extent is subjective and that the matrix is not equally well suited to address all types of processes. It is also noted that many of the unit processes scored in this way in fact reflects aggregated values established from a number of sub-processes. Finally, it is mentioned that some unit processes have not been scored with respect to data quality, because they are judged to be without importance in the overall results.

The matrix is shown in Table 21.

Table 21: Data quality matrix

Score	Technology	Time	Geography	Completeness	Reliability
Very good Score 4	Data generated using the same technology	Data with less than 3 years of difference	Data from the same area	Data from all relevant process sites over an adequate time period to even out normal fluctuation	Verified data based on measurements
Good Score 3	Data generated using similar but different technology	Data with less than 6 years of difference	Data from similar area	Data from more than 50% of sites for an adequate time period	Verified data partly based on assumptions or non-verified data based on measurements
Fair Score 2	Data generated using a different technology	Data with less than 10 years of difference	Data from different area	Data from less than 50% of sites for an adequate time period to even out normal fluctuations or more than 50% of sites but for a shorter time period	Non-verified data partly based on assumptions or a qualified estimate (e.g. by sector expert)
Poor Score 1	Data where technology is unknown	Data with more than 10 years of difference	Data from an area that is unknown	Data from less than 50% of sites for a shorter time period or representativeness is unknown	Non-qualified estimate

Source: Derived from Weidema and Wesnæs (1996).

9.2 Scoring of data quality

The scoring of the data quality for the most important unit processes included in the calculations is shown in Table 22. It appears from the table that most processes in general gets a score of 3 ("good") or 4 ("very good") in the five elements of the pedigree matrix.

Processes, where one or more of the scores is 2 or 2–3, must be regarded as having a relatively poor data quality, although the general term for data quality "2" is "fair". In practice, a score of 2 means that the element is associated with some uncertainty and results from the process must therefore be handled with caution.

An example of this is the score 2 given for the geography element in production of polyester. The low score is given because the project group assumes that most polyester production takes place in China and Asia, whereas the inventory reflects polyester production in Europe. There may be differences between the efficiency in the process in the two regions, and there are most certainly differences with respect to the energy that is used in the production steps. There are, however, not better data available in GaBi for the calculations, and the interpretation of the results must therefore reflect the uncertainty. In the case of polyester production it can be speculated that Asian production probably is less efficient than European production, and it is known the electricity used in e.g. China is more polluting than European electricity, at least on the general level. The benefits from reuse of polyester will therefore, be even larger than those calculated and reported here. It is, however, not possible to give a fair estimate of how much larger the benefits may be.

Table 22: Scoring of data quality

Process	Technology	Time	Geography	Completeness	Reliability
Marginal production of electricity	4	3	4	3	3
Marginal production of thermal energy	3	3	3	3	3
Cotton in municipal waste incinerator	3	4	3	3	3
Polyester in municipal waste incineration	3	4	3	3	3
Wool in municipal waste incinerator	3	4	3	3	3
Flax in municipal waste incinerator	3	4	3	3	3
Production of polyester fabric (avoided)	4	4	2	4	4
Chemical recycling of PET (induced)	4	3	4	2–3	2–3
Production of DMT and EG (avoided)	3	4	3	2–3	2–3
Production of cotton fabric (avoided)	4	4	3	4	4
Chemical recycling of cotton (induced)	4	4	3	2	2–3
Production of wool fabric (avoided)	3	2	2–3	3	3
Cutting and sewing of fabric (avoided)	4	3	3	4	4
Production of flax (avoided)	3	3	3	3	3
Transport of new textiles	4	4	3	3	3
Landfill of biodegradable waste	3	3	3	3	3
Landfill of plastic waste	3	3	3	3	3
Sulfate pulp production (avoided)	3	3	4	3	3
Shredding and carding of textiles	4	4	4	3	3

It is noted that the chemical recycling processes also have a relatively low score. For chemical recycling of PET the reason is that it is very difficult to assess the completeness and the reliability of the information coming from Teijin, the company managing the recycling technology. Much is known about the process, but it has not been possible to verify core information about the yield from the process. Accordingly, the reliability of the dataset is regarded as "fair" to "good".

For chemical recycling of cotton the uncertainty is also mainly related to the (in)completeness of the dataset. The process is still in development, and the technical LCA-relevant information coming out from the development process is only regarded as "fair". It is noted in this context that the role of the recycling process in a broader context is somewhat uncertain. The full effect of the process will first emerge when it is known what the dissolved pulp will substitute in practice (is sulfate pulp a relevant substitute?) and whether (and how) other types of textiles (e.g. cotton/polyester blends) can be recycled in the process.

It is judged that the conclusions made in this study reflects the data quality in an appropriate way. It is obvious from the above discussion that the available knowledge cannot provide sufficient data quality for clear-cut and detailed answers, but the results nevertheless give a clear indication of where the main benefits are and where more knowledge should be established before making conclusions.

10. Interpretation

The study does not aim to present a unified picture of the environmental consequences of applying different reuse and recycling technologies to textiles currently being collected for incineration in the Nordic countries.

Instead, the focus is to give an indication of the impacts and benefits associated with selected end of life treatment routes as they emerge from scientific and grey/yellow literature as well as dialogue with the companies using or planning to use the technologies.

In total, 18 different combinations of fibre material and end of life treatment have been examined for each of the four countries. The results are presented in the report as normalised results, allowing non-experts in LCA-methodologies an insight into the relative importance of the environmental impact types currently included in the ILCD methodology. The results are also presented as characterised results in spreadsheet files that can be downloaded from the same website as the report. The characterised results allow LCA-practitioners to assess their own scenarios, e.g. defining and combining several fibre types and end of life treatment routes in a single scenario. The review process has shown the need for this, and the project group believes that it is feasible using the spreadsheet files remembering the limitations that are addressed throughout the report and summarised in the following.

Firstly, it must be remembered that the level of detail reflects a simplified LCA approach. We are not aware that significant sources of environmental impacts are missing and we therefore consider the system boundaries to be sufficiently complete to provide the intended knowledge base for future decision-making. Traditionally, use of electricity and transportation are mentioned as potentially important sources or errors, and we have therefore made focused sensitivity analysis of these two issues. The results of this indicate that the issues are of relatively low importance and they are therefore not investigated further. It is, however, underlined that any practitioner can add an additional transport scenario or use of electricity, if a need for this is identified.

Secondly, it must be remembered that consequential foreground data are combined with allocated background data from the internationally well-reputed GaBi database from thinkstep[ts]. This is an approach often applied in all types of LCA, but it obviously is a drawback if a dataset for production of textile fibres in Europe must be used as a surrogate for a dataset reflecting the average production in the World or – even better – the actual supplier affected by a change in Nordic waste management practices. Neither of these possiblities have for practical reasons been investigated in the project, and the results (both the basic results in this report and the results of future calculations) shall therefore be interpreted with great care.

Thirdly, the general shortcomings of LCA must as always be kept in mind. As described in section 3.5, some of the impact categories in the ILCD methodology are associated with large uncertainties, and the project group therefore strongly recommends also to combine scientific knowledge with common sense when the results are used in decision-making.

Finally, we would like to point to the substitution factor as being the most sensitive factor in determining impacts and benefits from recycling and – especially – reuse. If reuse of a garment does not offset the purchase of a similar new garment, then the environmental benefits disappear – and they may even increase. Likewise, if recycled fibres are used for purposes that would not otherwise have been addressed, then the reduction in impacts is very limited or maybe even absent. It is, however, not possible to investigate all potential scenarios in detail in the report. This is for future investigations.

The limitations described here and throughout the study shows that addressing and assessing textile reuse and recycling is a complex process. Lack of good data, especially on emerging recycling technologies, underlines the need for a cautious interpretation. Hopefully, readers of the report and users of the results will acknowledge this.

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12. Sammenfatning

Det primære mål for projektet har været at etablere et overblik over de miljømæssige fordele og ulemper, der er forbundet med forskellige alternativer til at behandle kasserede tekstiler i fire nordiske lande. Hensigten med dette overblik er at skabe en solid, kvantitativ basis for fremtidige politiske beslutninger.

Til formålet er anvendt en livscyklusbaseret tilgang til at etablere og sammenligne forskellige scenarier for behandling af et ton kasserede tekstiler. Selv om det overordnet set er hensigten, at resultaterne skal anvendes i fremtidige analyser, tegner der sig en række fund, der med den nuværende viden kan bruges til at formulere strategier for behandling af kasserede tekstiler:

- 365,000 ton beklædningsgenstande og hjemmetekstiler bringes på markedet i de nordiske lande hvert år. Når de er udtjent, indsamles en tredjedel i separate ordninger med henblik på genbrug og genanvendelse, mens de resterende to tredjedele indsamles sammen med andet husholdningsaffald og generelt sendes til forbrænding. Meget af dette affald er egnet til genbrug og genanvendelse.
- Genbrug, uanset om det finder sted i Norden eller i andre egne af verden, giver klart de største miljømæssige fordele sammenlignet med genanvendelse og forbrænding.
- Vi har i vores beregninger antaget, at en genbrugt beklædningsgenstand fuldt ud erstatter et nyt stykke tøj af samme type. Dette er sikkert optimistisk, men selv hvis der skal 4 stykker genbrugstøj til at erstatte et nyt stykke tøj, er det fordelagtigt for miljøet.
- Dagens genanvendelsesteknologier er hovedsageligt mekaniske og kan populært karakteriseres som *downcycling* til produkter af en lavere kvalitet. Kemiske processer, hvor fibre genanvendes til fibre, er under udvikling og kan give større fordele i form af en bedre kvalitet fibre. Datakvaliteten for disse processer er imidlertid ikke god, så resultaterne er ikke robuste.
- For alle kombinationer af fibertype og genanvendelsesteknologi tegner genanvendelse sig som mere fordelagtig end forbrænding.

- Uld er den fibertype, hvor man kan få den største miljømæssige fordel per ton ved genbrug og genanvendelse. Datakvaliteten for uld-relaterede processer er dårlig, men det miljømæssige udbytte er så højt, at uld fortjener et specielt fokus i fremtidige aktiviteter. Uld udgør omkring 4% af fibermængden på det nordiske marked.
- Det miljømæssige udbytte ved genanvendelse og især genbrug af bomuld er også højt. Samtidig er bomuld er den dominerende fibertype i norden med 57% af den samlede mængde (i vægt). Mekanisk genanvendelse af bomuld kan på nuværende tidspunkt kun gennemføres for brugte tekstiler af 100% bomuld og er dermed ikke anvendeligt de mange produkter på markedet, hvor bomuld er blandet med andre fibre.
- Polyesterfibre er hovedsagelig fremstillet af fossile brændsler. Derfor giver det specielt for bidraget til klimaforandringer store fordele at genbruge og genanvende polyester fremfor at forbrænde det. Fordelen med hensyn til andre typer af miljøbelastninger er relativt beskeden sammenlignet med uld og bomuld, men da polyesterfibre udgør en stor del affaldet skal man ikke negligere de fordele, der kan opnås især ved genbrug.
- Energiforbruget og de dermed forbundne miljøbelastninger ved indsamling, sortering og transport af tekstiler til genbrug og genanvendelse er relativt beskedent i det samlede billede.
- Kasserede tekstiler kan enten genbruges i de nordiske lande eller eksporteres til genbrug i et andet land i verden. Fordelene ved genbrug er meget ens i begge tilfælde, på trods af store forskelle i transportafstande.
- Forskellige marginaler for energiproduktion i de nordiske lande afspejler sig i forskelle i fordele og ulemper ved forbrænding. Forskellene ændrer dog ikke signifikant ved de overordnede resultater, når der skal etableres strategier for indsamling, genbrug og genanvendelse i de nordiske lande. Når nye initiativer skal vurderes, anbefales det dog at bruge nationale energiscenarier til benchmarking.
- Fordelene ved forbrænding vil blive mindre over tid, fordi andelen af fornybare energikilder, der erstattes ved forbrænding, bliver større.
- Nogle af de farlige stoffer, der findes i nye tekstiler, forbliver i produktet indtil det kasseres, også selvom det har været vasket adskillige gange.
- Ved mekanisk genanvendelse forbliver alle kemikalier i materialet og vil derfor blive bragt videre i det nye, genanvendte produkt. Ved

kemisk genanvendelse kan nogle stoffer forblive i materialet, og både farlige og ikke-farlige stoffer kan give tekniske problemer i processen.

- Strategier for håndtering af kasserede tekstiler skal tage hensyn til den potentielle eksponering af mennesker og miljø for farlige stoffer i genbrugte og genanvendte materialer.
- Det skal bemærkes her, at der er betydelige usikkerheder i de resultater, der er præsenteret. Dette kan ikke undgås i LCA’er af denne type, men projektgruppen vurderer samlet set, at resultaterne er tilstrækkelig robuste til at blive anvendt i fremtidige vurderinger.

Appendix A – Fibre mixes

One of the groups of comparison scenarios in this study is for one tonne of average textiles collected in Nordic countries assuming no sorting into various fibre types.

To carry out LCA-modelling for this mix an overview of its content in terms of share of different fibres is needed. We assume that the collected textiles have the same average fibre content as textiles put on the market. The method used to calculate the fibre mix put on the market can be summarised as follows:

- Identify all individual textile product types that comprise clothing and home textiles, at a disaggregation level which identifies fibre type.
- Gather data on the import, export and domestic production of each of these products.
- Calculate the total quantities of each of these products put on the market using the data gathered above.
- Add up these quantities for all products of the same main fibre type.
- Calculating shares of fibres in total weight.

Stage 1 – Identifying product types

The Common Nomenclature system for products distinguishes (partially) between fibre types at the 8-digit level: otherwise known as CN8. Clothing and household textiles products are included in CN 2 digit groups 61, 62 and 63. There are nearly 450 different product types of clothing and home textiles distinguished in these groups at the 8 digit level.

A typical example of a group of related CN8 product categories is:

- 61033100 Men's or boys jackets and blazers of *wool or fine animal hair*, knitted or crocheted (excl. wind-jackets and similar articles).
- 61033200 Men's or boys jackets and blazers of *cotton*, knitted or crocheted (excl. wind-jackets and similar articles).

- 61033300 Men's or boys jackets and blazers of *synthetic fibres*, knitted or crocheted (excl. wind-jackets and similar articles).
- 61033900 Men's or boys jackets and blazers of textile materials *(excl. of wool, fine animal hair, cotton or synthetic fibres, wind-jackets and similar articles).*

As can be seen, product definitions under the CN8 categorisation system tend to distinguish between cotton products, wool (and animal hair) products, products from man-made/synthetic fibres and then some products that are made from none of these. These latter can comprise silk, flax, hemp and other natural fibres. We have named this group "other fibres". Finally, in some cases no fibre type is given at all. These have been grouped under a fourth category we have called "unspecified".

A significant share of textile products put on the market has a blend of fibres. In these cases it is understood that products are allocated to the group according to the dominant fibre in the mix i.e. a men's jacket made from 70% cotton and 30% polyester will be allocated in import/export and production data to group 61033200 Men's or boys jackets and blazers of *cotton* etc.

In the absence of other data we assumed that all textiles in each CN8 product code are 100% comprised of the stated dominant fibre (i.e. cotton in the example above).

This approach obviously introduces an uncertainty and therefore a potential error. This was the only approach available to us and the errors ought to balance themselves out to a certain extent between product groups.

Stage 2 – Gathering import, export and domestic production data

All Nordic countries were found to maintain regularly updated import and export export data according to CN8 product categories. This data provides total imports and total exports of each of the 450 CN8 product types that we had identified as relevant. The imports and exports are provided by weight (tonnes or kgs) and by value in the national currency.

However, domestic production data as less readily available in the required format i.e. at CN8 level:

- *Denmark* **–** domestic production data was available at the CN8 product level. However, the data was only provided in monetary values (and sometimes as pieces) but not by weight. We solved this problem by converting production data into weights by using weight/kroner ratios for each CN8 product as derived from the export data.
- *Finland* **–** domestic production data was only available in so-called in Prodcom format. While Prodcom to CN code conversion tables are available these do not allow one to distinguish between products down to the CN8 level but rather the CN6 level, which doesn't distinguish between fibre types.
- *Norway* – was also on available in Prodcom format and not possible to transfer to CN8 format. Moreover, production data is mostly not made publicly available for textiles products for confidentiality reasons. This is presumably because where there is any production of a product this is by a single company.
- *Sweden* – production data is available in CN8 codes. However, most of the data is set at zero. We know that there is production of textiles in Sweden but there is no production data available at the CN8 product code level – i.e. which gives information on fibre type.

Stage 3 – Calculation of total quantities of each textile put on the market

The calculation of products put on the market uses a simple mass balance equation:

> Quantity of Product put on market = domestic production of Product + import of Product – export of Product

Where all quantities are in tonnes.

However of the four countries, only Denmark has all the data necessary to carry out a full calculation of textiles put on the market. The other countries are missing domestic production data. In general, however, imported goods dominate textiles put on the market in Nordic countries and local production is relatively insignificant. Therefore we made the assumption that calculation of the average fibre mix for a country will be similar whether or not we include domestic production data. One fibre that may be underestimated, however, is wool due to production in Norway.

Stage 4 – Aggregating into totals of each fibre type put on the market

For each country we then added up all quantities for all products put on the market of a particular fibre type i.e. cotton, synthetics, wool etc. as defined by the product code. The results of the calculations for 2013 and 2014 are provided in Table A1. As can be seen, fibre mix calculation results for Denmark were found to be very similar to those of the other three countries even though they had no available CN8 production data.

Table 1: Quantities of clothing and home textiles *for which fibre information is available* put on the market in Nordic countries by fibre type

2013	Total	Wool	Cotton	Synthetics	Other	Unspecified
Denmark	79,597	3,748	39,295	25,687	4,158	6,679
Sweden*	109,310	3,366	64,406	30,025	3,801	7,620
Finland*	50,818	1,778	29,498	13,023	1,755	4,733
Norway*	74,758	1,831	35,404	21,682	4,130	11,711
Total Nordic**	314,483	10,722	168,603	90,418	13,844	30,743
Average distribution		3.4%	53.6%	28.8%	4.4%	9.8%
2014						
Denmark	83,626	3,778	40,379	27,790	4,701	6,962
Sweden*	116,488	4,271	65,323	35,420	3,822	7,588
Finland*	48,278	1,709	27,308	12,984	1,706	4,553
Norway*	75,970	1,904	34,055	22,719	5,011	12,282
Total Nordic**	324,363	11,661	167,065	98,912	15,241	31,385
Average distribution		3.6%	51.5%	30.5%	4.7%	9.7%

Note: *all quantities for this country exclude domestic production.
** excludes domestic production data in Norway, Sweden and Finland.

Stage 5 – Calculating shares of fibres in total weight

We still need to make some further assumptions for some of the more vaguely defined fibre groupings to allow us to model them in the LCA model, as follows:

- Synthetics are modelled using polyester as a proxy.
- We assume that the category “other” can be modelled using flax as a proxy, since we in any case need to model the lifecycle of this fibre for one of the scenarios.
- We assume that the fibre mix of the textiles of “unspecified” fibre type reflect the average mix of textiles put on the market. i.e. we remove these textiles from the calculations.

The calculations and assumptions give the following rough estimates for average distribution between fibre types in textiles put on the market in Nordic countries, for use when modelling the fourth group of scenarios – the Nordic Average Fibre Mix (see Table 1 in the main report):

- Cotton: 57%.
- Polyester: 34%.
- Wool: 4%.
- Flax: 5%.

Appendix B – links to results

Appendix B contains links to excel files in.csv-format with the characterised results for all 18 scenarios in the five geographical settings. The intention is that interested person shall be able to use the basic results for further calculations using volumes and EOL treament routes defined outside the frames of the current study.

The five files are:

- Nordic.csv.
- Denmark.csv.
- Finland.csv.
- Norway.csv.
- Sweden.csv.

Users of the results file shall observe that substitution factor 1 is used for all reuse scenarios. The sequence of the scenarios reflects their development. The user may also choose to transform the characterised data into normalised results. This is done by using the normalisation references described in 3.4 – or other applicable approaches.

Appendix C – Critical review

Life Cycle Assessment (LCA) of different treatments for discarded textiles

Draft final report: Critical Review

Massimo Pizzol[36] and Jannick H Schmidt[37]

Date: 26–05–16

Figure 1: Aalborg University logo

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Critical review methodology

Reviewer

The reviewers are Massimo Pizzol (Danish Centre for Environmental Assessment, Aalborg University) and Jannick H Schmidt (2.–0 LCA consultants).

Reviewed study

The current critical review report summarizes the critical review of the following LCA report: "Life Cycle Assessment (LCA) of different treatments for discarded textiles – Final draft report" by Anders Schmidt, David Watson, Sandra Roos, Cecilia Askham & Pia Brunn Poulsen, dated December 2015.

ISO 14040/44 on critical review of LCA

This critical review is carried out in accordance with ISO 14040/44.

The current LCA have the following characteristics which mean that ISO 14044 defines some additional requirements to the study as well as the critical review: The study is a third party report (ISO 14044, section 5.2).

As a consequence of the above mentioned characteristics of the study, the main additional requirements are:

- ISO 14044, section 5.2: Additional requirements and guidance for third party reports.
- ISO 14044, section 6.1: A panel of interested parties shall conduct the critical review.

It should be highlighted that the second requirement above is not fulfilled. Hence, the LCA study is not in compliance with the ISO standards with respect to the critical review.

Review procedure

- A draft goal and scope report was delivered for review on 8th May 2015.
- A phone meeting between Force Technology, NAG and the reviewers was held on 20th May 2015 to address the main concerns based on a draft review document.
- On 21st May 2015, the final review report was delivered.
- The final draft report was delivered for review on 9th December 2015.
- On 15th January 2016, a first full review report was delivered to NAG.
- On 26th April 2016, a revised – final – project report was received and the final review report was delivered to NAG on 26th May 2016.

The current review report includes the overall review statement as well as general comments to the study. The general comments are organised following the structure of chapters of the reviewed LCA report.

Final review statement

The LCA report has been reviewed with respect to compliance with the ISO 14040 and 14044 compliance. For most requirements in the ISO standards, the LCA study fulfils the requirements, but there are some elements that fail to comply. There are:

- The LCA is a comparative study intended disclosed to the public. For such studies, the ISO standards require a panel critical review. This has not been performed.
- ISO 14044 presents a hierarchy to model co-products, where the highest options include subdivision of multiple-product-output processes and substitution. Other, less preferable modelling options include allocation. With respect to allocation, the hierarchy has only been followed for the modelling of the foreground system. The background system, which is based on LCI databases, is based on various (non-described) allocation principles.
- The standard requires characterised results to be presented, while normalised results are optional. Even though characterised results are in appendix, the current report only presents the normalised results, which is not strictly in compliance with the standard.

- The ISO 14044 standard requires that an evaluation of sensitivity, consistency and completeness is included in the life cycle interpretation phase. This is not included.

General review comments

- According to ISO 14044, the life cycle interpretation shall include an evaluation of sensitivity, completeness and consistency. A section called "interpretation is included but the rest is missing.

Review comments to "2 Introduction and objectives"

- Goal of the project:) The stated goal is to "…generate a solid and well-founded knowledge base for comparing the life cycle environmental effects of various options for handling post-consumer textiles…". However, the actual investigated scenarios take 100% clean fractions for granted. This means that potentially significant collecting and sorting stages are assumed to be free of impacts which may distort results. The setup as illustrated in Table 1 shows that within each type of textile a number of treatment options are compared, e.g. incineration, re-use, and recycling of 100% cotton. There are two problems: 100% cotton probably does not exist as a waste fraction (at least only in extreme small quantities). The textile fractions will be mixed with other materials/contaminants – some fractions will be suitable for reuse, some for recycling and some only for incineration. Because of the different suitability referred to above, it would not make much sense to conclude that e.g. recycling is better than incineration if the recycling option is not a real-life option. Therefore, either the purpose or the scope of the study should be changed.

Review comments to "6 The general framework for LCA"

- It is stated that a consequential LCA approach is used. However, there is no description of what this is (and that it is opposed to attributional), what it implies for the life cycle inventory, and which guidelines have been used. Some of the most common guidelines for consequential LCA are:

- Definition of consequential and attributional LCA: Sonneman G W and Vigon B W (eds). (2011). Global guidance principles for life cycle assessment databases. UNEP SETAC Life Cycle Initiative.
- Ekvall T, Weidema B P (2004). System boundaries and input data in consequential life cycle inventory analysis. International Journal of LCA 9(3):161–171.
- Weidema B P. (2003). Market information in life cycle assessment. Environmental Project No 863. Danish Environmental Protection Agency, Copenhagen.
- Weidema B P, Ekvall T, and Heijungs R. (2009). Guidelines for application of deepened and broadened LCA. Guidelines for Applications of Deepened and Broadened LCA. Deliverable D18 of Work Package 5 of the CALCAS Project, (037075): 49.
- Section 6.1. Functional unit: since the waste composition is different in each scenario, in practice different functional units are used, this could be specified. It should be mentioned in the report that using this functional unit does not allow to assess prevention strategies (assumes that quantity of waste would be generated in anyway), and in that case something like the "treatment of textile waste generated in the Nordic Area in one year" should have been used).
- Section 6.2. System boundaries and scenarios. In our understanding, waste is generated in one or few fractions only: the default fraction would be the mixed average. This is then sorted and then the 100% pure fibre (e.g. 100% cotton) fractions may be obtained. Therefore:
- It is unclear how the collection and sorting would work for the 100% fractions scenarios (this seems unrealistic).
- Is it possible to achieve such a sorting level (100% pure fraction) or is this a virtual scenario to highlight the benefits of recycling, and push sorting towards this level of efficiency (this may be fine but must be specified)? It should also be considered/mentioned that such sorting might be associated to high costs and/or environmental impacts.
- The only realistic scenario remains the average mix scenario, which we think should be used as main scenario in the report. However, the data sources for this scenario have not properly described and references should be provided.

- Section 6.2. Table 1. It appears that EOL is included for by-products and for the associated substituted products. At least for some scenarios. It is a special case of standard substitution in life cycle inventory modelling, when including activities after the point of substitution; In most cases this is not needed because the induced use and EOF will cancel out the corresponding use and EOF of the substituted product. We agree that this is relevant for some of the scenarios in the current study, namely: When there are differences between a by-product's use and EOF stages and the corresponding use and EOF stages of the substituted product, then the differences need to be included. However, there is no description of this special case here, and it is not clear why EOF in included for some of the induced processes in table 1, while it is not mentioned for any of the avoided processes. The way this is described is very difficult to follow, and it does not allow us to assess if it has been correctly modelled – we have the same comment to chapter 8 (e.g. figures 25–28).
- Section 6.3 LCIA methods: It is stated that results are shown for GWP both with and without biogenic CO2, and that that interpretation is only carried out for GWP excluding biogenic CO2. We do not see the need for showing impact categories that are not interpreted. Further, it is stated that the CO2-uptake from the cultivation of bio-based textiles is "forgotten" when including biogenic CO2. This is in fact not true. Nothing is forgotten, the problem relates to the definition of the functional unit, which does not include the full life cycle of the textile products.
- Section 6.3 LCIA method: It is mentioned that an additional impact category "Total energy consumption" is added. Which methodology is this based on?
- Section 6.3 & 6.4 LCIA method: According to ISO 14044, characterised results are mandatory, while normalisation is just an optional element. Hence, the way the results are presented is not compliant with ISO 14044.
- Section 6.3, 6.4, 6.5 LCIA method: It has been chosen to use normalisation, which is one among other optional elements according to ISO 14044. What is the reason why weighting is not used?
- Section 6.5. Limitations – LCIA method. It is stated that: "The methods for LCA impact assessment have been continuously developed during the past 25 years. The scientific society has put a lot of effort into improving the precision and prediction power of each of the many methods that are in use. Most focus has been

applied to global warming and ozone depletion – because of the visibility of the impacts and their global scope – and today we can calculate the contribution to these impacts with a very high certainty". We do not agree in that. The used LCIA model for ozone depletion does not include the most significant contributor to ozone depletion; namely nitrous oxide, N2O (World Meteorological Organization Global Ozone Research and Monitoring Project—Report No. 55 http://www.esrl.noaa.gov/csd/assessments/ozone/2014/). Furthermore, the metric used for climate change (GWP100) is associated with many flaws, e.g. there is a lack of proportionality with effects on temperature changes (GTP is probably a better metric for that) and the standard version of GWP as in LCA software does not take into account temporal effects of GHG emissions.

Review comments to "7 Common elements in all or most scenarios"

- Section 7.1.1. In figure 5 it is not clear what is the content and units of the flows T0–4? It also seems like some flows are missing; a sorting plant will typically have some reject (not only non-textiles) that is sent to treatment (e.g. incineration or landfill).
- Section 7.1.1. Assumption on T0. Consumer transport in personal car with small amounts of textile waste for recycling can easily turn out to be significant. The assumed 0 km allocation to textile collection favours reuse maybe unrealistically. The validity of this assumption should be discussed and it should be tested in sensitivity analysis.
- Section 7.1.1. Table 2: It is not clear which energy is accounted for? Is it cumulative energy demand in the full life cycle of the transport operations (including capital goods and production of fuels) or is it only the calorific value of the directly used fuel? Which types of energy are included, only fossil or also non-fossil?
- Section 7.1.2. Marginal energy. It is described that it is only for substituted energy from waste incineration where energy has been modelled using a marginal approach. This means that electricity in all other processes in the background system is based on another approach. This way of modelling is inconsistent and will either favour incineration over reuse/recycling or the opposite. It should be assessed how this choice influences the results – at least in which direction.

- Section 7.1.2. Marginal thermal energy: There is no description of the methodological considerations behind the identification of marginal thermal energy. It should also be described how electricity by-products from heat have been modelled.

Review comments to “8 Modelling of scenarios for treatment for treatment of textile waste”

- Several processes from the GaBi databases have been used. Many of these processes are multiple-product-output processes, e.g. waste incineration (waste treatment+heat+elec), wool (wool+meat+milk), cotton (cotton+seed oil+seed meal). It is not described how these by-products have been modelled in the GaBi database and how that relates to the general approach to modelling in the current study: consequential modelling.
- Substituted materials: It is written (e.g. in section 8.3.1.) that it has been assumed that reused textiles substitute a product of the same fibre type. This is a major assumption since there is a large degree of substitutability between different fibres: sweaters, jeans, shirts etc. can be made out of different fibres. And typically a pair of jeans will be highly substitutable with another pair of jeans irrespectively that it is produced from other fibres. The assumption also implies, that reuse of some fibres will be favoured over others, irrespectively that the reuse process and substituted product may be the same for different reused fibres.
- Therefore, we do not find the identified substituted materials properly justified – and in many of the scenarios they are probably not representative for real-life substitutions. It does not seem realistic that the following is likely in all cases:
- Reusing average mix textile => substitute virgin average mix textile.
- Reusing polyester textile => substitute 100% virgin polyester textile.
- Reusing cotton textile => substitute 100% virgin cotton textile.
- Reusing wool textile => substitute 100% virgin wool textile.
- To identify the actually substituted materials, the marginal materials for second-hand clothes (maybe more than one market: low/cheap quality and/or vintage), rags, upholstery, stuffing, insulation should be identified. When reusing wool textiles, it could be that this will substitute knitted textiles of synthetic materials (cheaper quality).

Similarly, reused cotton may also substitute cheaper synthetic textiles.

- Marginal suppliers: It seems inconsistent to identify marginal electricity suppliers and not marginal material suppliers (e.g. for the substituted materials/products). The authors claim this effort was outside the scope of the study but we argue it is necessary to keep the study consistent and representative. E.g., modelling all suppliers as located in Europe is not representative. Some information about the location of textile suppliers is provided by the authors (though not referenced). That could be used to improve the assessment of the marginal suppliers. Information on the location of suppliers of textile products can be found in: Høst-Madsen N K, Damgaaard C K, Jørgensen R, Bartlett C, Bullock S, Richens J, de Saxcé M, Schmidt J H (2014). Danish apparel sector natural capital account. Danish Environmental Protection Agency, October 2014 http://lca-net.com/p/1746. Detailed information on suppliers of all products for all countries in the world is available in trade statistics. This is e.g. provided in the Exiobase input-output database (http://www.exiobase.eu/).
- Section 8.3.1. LCI data from both GaBi and ecoinvent are used. These databases are based on different data (temporal, geographical and technological scope) and have different cut-off criteria. Which implications does this have for the results?
- Section 8.3.4. Below figure 14, it is written: "In both the avoided process and in the induced reuse process the textile is incinerated at EOL…" It is a special case when including activities after the point of substitution. We agree that this is relevant for some of the scenarios in the current study, namely: When there are differences between a by-product's use and EOF stages and the corresponding use and EOF stages of the substituted product, then the differences need to be included. However, the way it is described is very difficult to follow, and it does not allow us to assess if it has been correctly modelled.
- Section 8.3.5. Cotton is modelled using data from the GaBi database. How are by-products from cotton modelled? In case the GaBi data are allocated, it is not consistent with the applied consequential modelling approach.
- Section 8.3.6. Wool is modelled using an allocated (attributional) sheep process from a previous version of ecoinvent. This is not consistent with the applied consequential modelling approach.

- Section 8.6. Generally, the used data for the modelling of recycling are based on specific examples on how recycling can be done and on many estimates. The uncertainties seem to be significant – and the level of the use of rough estimates seems to be higher than for the other scenarios.
- Reuse and recycling outside EU (section 8.4):
- What is the difference in the marginal energy supplier and technology for re-processing in the Nordic countries versus Eastern Europe/Africa?
- Are different products substituted in the different regions, and which ones?
- In cases where the substitution effect is low, the environmental benefit of reusing is small, but the social impact (in the good way) may be large (e.g. in cases of charity, red cross aid etc.), can add some considerations about this in the discussion?

Review comments to "9 Results"

- The agreement with NAG is not a valid reason for not presenting characterized results in the report. Normalization is an optional and very arbitrary step in LCA, so if the study has to be ISO compliant, characterized results should be included in the main document and not as appendices.
- Contribution analysis is missing, please include and discuss it (what are the processes and substances mainly responsible for the different impacts)?
- An overview of significant assumptions and how they have been addressed in sensitivity analyses is missing. It is hard to obtain such an overview, when the sensitivity analyses are spread out over many pages. Similarly, it is difficult to identify which assumptions are the most crucial for the conclusions.
- Table 11, Table 14, Table 17: Is there a mistake in these tables? Finland equals the Nordic average.

Review comments to “10 Data sources”

- Reporting of LCI could be done more transparently. Good with a list of database processes reported in the appendix. But in general, an LCA practitioner would have a hard time reproducing the results – this is mainly because the inventory flow charts are difficult to read (see comments to figure 6–30 under Review comments to “6 Common elements on all or most scenarios”). The LCI information should be provided in a complete and organized way in the appendix, so that the LCI can be understood and eventually reproduced with reasonable effort.

Review comments to “11. Data quality assessment”

- The data quality assessment is performed on a highly aggregated level. Since each one of the assessed “processes” in table 22 are a result of probably thousands linked upstream processes, it is doubtful how the scores have been assigned to them. A better approach would have been to perform a Monte Carlo analysis based on the uncertainty information available in the used LCI databases combined with estimates of the uncertainty of each data point in the foreground system.

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Gaining benefits from discarded textiles

Nordic consumers purchase 365 000 tonnes of new clothing and home textiles each year. After food, housing and mobility, textiles is our consumption area that causes most environmental impacts. Reusing and recycling used textiles can offset some of these impacts but with an increasing number of options available, government and business need more information to make decisions on which pathways to choose.

The Nordic Council of Ministers commissioned a consortium to carry out an LCA study to compare the environmental benefits of treatment options. Reuse was found to give by far the greatest benefits, regardless of whether the textiles are reused in the Nordic region or exported for reuse elsewhere. Further down the waste hierarchy, recycling is a better environmental option than incineration, although the benefits are moderate compared to the benefits of reuse.

The primary aim of the project was to provide a database that can assist policymakers and businesses to estimate the environmental benefits of strategies for gathering and treating discarded textiles. As such this report presents only a fraction of the results of the LCA modelling. Hundreds of additional results can be found in a number of spreadsheets that can also be downloaded on the Nordic Council of Minister's website: http://dx.doi.org/10.6027/TN2016-537.

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