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Recycling potential of separately collected post-consumer textile waste

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Executive summary

Background and objectives

As part of the Danish Textile Waste Partnership established by the Ministry of Environment, this project was commissioned by the Danish EPA and carried out by the Department of Environmental and Resource Engineering at the Technical University of Denmark (DTU Sustain) between September 2023 and February 2024.
The project investigates opportunities and barriers of recycling separately collected post-consumer textiles, distinguishing between two separate collection streams. The aim is to evaluate the mass flows of discarded clothes that could be separately collected through a non-reusable 2nd stream that could potentially be available for material recycling, as well as exploring different options in terms of applicable textile-to-textile recycling technologies, with associated advantages and disadvantages.

Methodology

We use import and export flows to calculate the total supply of clothing to Danish households in 2022, divided into the 10 most common clothing categories. By means of material flow analysis (MFA), and by applying pre-determined sorting criteria, we identify the main recycling routes that an item could be eligible for. The MFA is done for each of the 10 categories, as well as the total across these categories. Finally, through available literature and expert judgements, the study examines the potential substitution rates of the recycled material.

Potentially recyclable textiles from private households

Overall consumption of clothing by Danish households in 2022 is estimated to be 98,935 tonnes, and if all discarded textiles were collected, it is expected they could be split almost evenly between 1st (~47%) and 2nd (~53%) collection stream (*home sorting*). Of garments potentially collected through the 2nd stream, about one third (~34%) are either dirty, wet, or contaminated, and sent to incineration (*manual sorting*). The remaining ~66% are both clean and dry, of which two thirds (22,937 tonnes) are found to be suitable for reuse, while the rest (~33%) are marked as non-reusable (*manual sorting*). This means that, of the ~52,000 tonnes of textile waste that are potentially separately collected through the dedicated 2nd stream, ~22% (11,478 tonnes) are estimated to be both clean, dry, and non-reusable, and as such potentially available for material recycling.

Fine-sorted fraction and applicable recycling pathways

After applying additional sorting criteria (*fine sorting*), the quantity of textiles across the different product categories that could potentially be recycled is lowered to 5,586 tonnes, while around 3,298 tonnes are estimated to be downcycled, and the remaining incinerated. However, differences are seen across product categories, with *trousers and shorts, dresses and skirts*, *shirts, blouses, and tops* and *t-shirts and vests* representing the categories with the highest textile-to-textile recycling potentials, while some of the most challenging categories with this regard are *overcoats and anoraks, suits and blazers,* and *sportswear and swimwear*.

Evaluating textile recycling technologies

With regards to textile-to-textile technologies for recycling post-consumer textile waste, it becomes apparent that there is currently no absolute best practice. A wide range of options are available to treat different types of garments of different fibre composition, and the evaluation of the associated pros and cons can be done following a various set of criteria.

A feedstock with a high substitution potential can be obtained via chemical recycling technologies, which on the other hand rely on an intense use of chemicals and need to repeat the textile value chain almost completely. Mechanical recycling is a mature-scale technology associated with low direct environmental impacts, but the harsh processes applied lead to output fibres of inferior quality and to a low substitution potential.

The efficiency of both mechanical and chemical methods highly depends on the purity of the input as well as on the desired output, and both are associated with a wide range of environmental impacts. When evaluating such impacts, it should be kept in mind that various categories can be affected, either directly or indirectly, by one technology or the other, and as such a too narrow focus on a single impact category can result in burden shifting.

The assessment should therefore be done in a case-by-case basis, in the absence of a one-size-fits-all type of solution, as all current recycling methods hold potential for further improvements, and trade-offs occur when focusing on one aspect or the other. Both recycling methods will likely be necessary in different combinations, requiring further improvements to process post-consumer waste more efficiently.

How to increase the amount of textile potentially available for recycling

The report concludes by giving an overview of some of the challenges associated with the potential recycling pathways of specific post-consumer textiles, resulting in possible recommendations for targeted textile collection and sorting. New collection methods, improvements in the communication between the different actors of the textile recycling value chain as well as clearer sorting guidelines for both the citizens and the collectors may be needed to increase separate collection and recycling rates of post-consumer textile waste.

Sammenfatning

Baggrund og målsætninger

Som en del af det nationale Tekstilaffaldspartnerskab nedsat af Miljøministeriet blev dette projekt bestilt af Miljøstyrelsen i Danmark og udført af Institut for Miljø- og Ressourceteknologi på Danmarks Tekniske Universitet (DTU Sustain) mellem september 2023 og februar 2024. Projektet udforsker muligheder og barrierer for genanvendelse af separat indsamlede tekstiler fra forbrugerne, med adskillelse i to separate indsamlingsspor. Målet er at evaluere massestrømmene af kasseret tøj, der potentielt kan indsamles separat gennem et ikke-genbrugeligt 2. spor, og herved være tilgængeligt for materialegenanvendelse. Desuden var det et delmål at undersøge recirkulerings-teknologier for tekstil-til-tekstil genanvendelse med tilhørende fordele og ulemper.

Metodologi

Vi anvendte import- og eksportstrømme til at beregne det samlede udbud af tøj til danske husholdninger i 2022, opdelt i de 10 mest almindelige tøj kategorier. Ved hjælp af materialestrømsanalyse (MFA) og ved anvendelse af forudbestemte sorteringskriterier identificerede vi de vigtigste genanvendelsesruter, som en genstand kan behandles ved. MFA'en udførtes for hver af de 10 kategorier samt det samlede antal på tværs af disse kategorier. Endeligt undersøgte studiet gennem tilgængelig litteratur og ekspertvurderinger de potentielle substitutionsrater for det genanvendte materiale.

Potentielt genanvendelige tekstiler fra private husholdninger

Det samlede forbrug af tøj fra danske husholdninger i 2022 estimeres til at være 98.935 ton, og hvis alle kasserede tekstiler blev indsamlet, forventes det, at de kunne opdeles næsten ligeligt mellem første (~47% til genbrug) og andet (~53% til genanvendelse) indsamlingsspor. Af beklædningsgenstande, der potentielt kunne indsamles gennem andet spor, estimeres de at omkring en tredjedel (34%) er beskidte, våde eller kontaminerede, og derfor frasorteres i manuel sortering og sendes til forbrænding. De resterende 66% er både rene og tørre, og sammensætningen lige nu viser at to tredjedele (22 937 ton) kan genbruges, mens den resterende tredjedel ikke kan genbruges og derfor kan sendes til genanvendelse. Det betyder at, cirka 52 000 ton tekstilaffald potentielt kan indsamlet separat i en dedikeret genanvendelses spor med udtag til genbrug, hvoraf ~22% (11.478 ton) findes at være både rene, tørre og ikke-genbrugelige og som sådan potentielt tilgængelige for materiel genanvendelse.

Endelig sorteret mængde og behandlingsmulighed

Efter anvendelse af yderligere sorteringskriterier, falder mængden af tekstiler på tværs af de forskellige produktkategorier der potentielt kan genanvendes, til 5.588 tons, mens cirka 3.302 tons estimeres at blive anvendt til andre formål, og resten forbrændt. Der ses dog forskelle på tværs af produktkategorierne, hvor bukser og shorts, kjoler og nederdele, skjorter, bluser og toppe samt t-shirts og veste repræsenterer kategorierne med det højeste genanvendelsespotentiale.

Evaluering af tekstilgenanvendelsesteknologier

Med hensyn til tekstil-til-tekstil genanvendelsesteknologier for post-forbruger tekstilaffald viste studiet, at der i øjeblikket ikke er en absolut bedste praksis. Der er et bredt udvalg af teknologier til rådighed til behandling af forskellige typer af beklædningsgenstande sammensat af forskellige fibre, og evalueringen af de tilknyttede fordele og ulemper kan gøres efter forskellige kriterier.

Et nyt råmateriale med et højt substitutionspotentiale kan opnås via kemiske recirkuleringsteknologier, som på den anden side er afhængige af en intens brug af kemikalier og behov for at starte næsten forfra i tekstilværdikæden. Mekanisk genanvendelse er en mere moden teknologi forbundet med lave direkte miljøpåvirkninger, men de hårde processer, der anvendes, fører til oparbejdede fibre af ringere kvalitet og til et lavt substitutionspotentiale.

Effektiviteten af både mekaniske og kemiske metoder afhænger i høj grad af renheden af input samt det ønskede output, og begge metoder er forbundet med et bredt spektrum af miljøpåvirkninger. Ved evaluering af miljøpåvirkningskategorierne, må man ikke fokusere ensidigt på en enkelt påvirkningskategori, da forskellige teknologier kan klare sig bedre/dårligere alt afhængigt af påvirkningskategori, og derfor kan et for snævert fokus på en enkelt påvirkningskategori resultere i en byrdeflytning.

I mangel af en one-size-fits-all-løsning i dag, bør vurderingen af forskellige teknologier bør derfor foretages på en case-by-case-basis, da både kemiske og mekaniske genanvendelses-metoder har potentiale for yderligere forbedringer, og der opstår afvejninger, når man fokuserer på det ene eller det andet aspekt. Begge genanvendelsesmetoder vil i fremtiden sandsynligvis være nødvendige i forskellige kombinationer og kræve yderligere forbedringer for at behandle post-forbruger tekstilaffald mere effektivt.

Hvordan øges mængden af tekstil potentielt tilgængelig for anvendelse

Til slut gives i rapporten et overblik over nogle af udfordringerne forbundet med de potentielle genanvendelsesveje for specifikke post-forbruger tekstiler, og der gives en række potentielle anbefalinger til målrettet tekstilindsamling og sortering. Disse omfatter, nye indsamlingsmetoder, forbedringer i kommunikationen mellem de forskellige aktører i tekstilgenanvendelses-værdikæden samt klarere sorteringsvejledninger både for borgerne og indsamlerne kan være nødvendige for at øge separat indsamling og genanvendelsesprocenter for post-forbruger tekstiler.

1. Introduction

EU Member States are required to establish systems for separate collection of discarded textiles by 2025 (OJ L150/109, 2018). In Denmark, such regulation came into force as of July 1st, 2023 (Miljøministeriet, 2021), and since then, Danish municipalities have begun to collect textiles discarded from households separately from other waste fractions.

Discarded textiles consist of two primary fractions: reusable textiles and textile waste. Reusable textiles refer to materials that can be used again for the same purpose for which they were conceived, either directly or with minor alternations or repairs (OJ L312/3, 2008). On the contrary, textile waste comprises worn-out textiles such as clothing, linens, and curtains that cannot be reused.

Prior to the new mandate, collection of discarded textiles in Denmark prioritized reusable textiles and was performed mainly by charity organizations and private actors, via bring-banks and over shop counters (Koligkioni et al., 2018; Watson et al., 2020). The remaining textiles, regarded as textile waste, were collected with e.g. bulky waste or residual waste, and sent to incineration (Nørup et al., 2019b; Watson et al., 2018).

The implementation of the new Danish regulation mainly targets textile waste previously discarded with general waste, which will be collected separately from the reusable textiles and from other waste fractions with the purpose of increasing the share available for recycling. This results in a two-stream system, where reusable textiles, representing the 1st stream, will still be collected as usual; non-reusable ones, comprising the 2nd stream, will be included as the 10th fraction in the Danish waste collection system, and as such, they will be sorted at home and at recycling stations by citizens and collected separately from any other waste. For instance, in the previous system a worn, non-reusable t-shirt would be disposed of together with e.g. residual waste and would thus be incinerated, whereas in the new set-up, it will be collected via the dedicated 2nd stream, and could potentially be recycled. This initial sorting is performed at the household level by the citizen and is referred to as home sorting.

Criteria and guidelines are already in place for the citizens to sort the textiles they want to discard through the 2nd stream and are presented in
Table 1.1. As shown in Table 1.1, reusable items should still be donated, while, for example, textiles that are wet or soiled, products of specific categories such as leather clothing or worn shoes, as well as accessories such as belts and bags should be disposed of together with the residual waste or delivered to a recycling centre[1].

The 2nd collection stream should only comprise of dry, non-contaminated, and non-reusable textiles. To ensure this, and correct sorting mistakes (missortings) deriving from the home sorting phase, after textiles have been collected, a second sorting is performed by trained staff to remove any wet, dirty, contaminated (1st step) as well as potentially reusable textiles (2nd step), redirecting these fractions to incineration or reuse, respectively. This is usually performed manually and is hence referred to as manual sorting.

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[1] Note that, in the present context, the term recycling centre (*genbrugsplads* in Danish), or recycling station, refers to a site where waste is further sorted with the purpose of subsequent reuse or recycling, and not to an actual textile recycling facility.

TABLE 1.1. Current sorting guidelines for home sorting of post-consumer textile waste (non-exhaustive list). Translated from Danish[2]

Yes	No	Destination
Dry textile waste in the form of used clothing and textiles; this means clothes and textiles that are holed, worn, stained or damaged and can no longer be used	Reusable clothing and textiles, including leather clothing, rain gear, shoes, boots, belts and bags	Reuse
	Clothes and textiles that are wet, mouldy, soiled, or with food residues	Residual waste
	Clothes and textiles that contain unwanted substances that can cause problems in recycling, e.g. chemical, oil or paint stains as well as certain impregnation agents	Recycling centre or residual waste
Examples	**Examples**	
Textile waste in the form of used clothing: Blouses, tops, t-shirts, shirts, and jumpers Trousers, shorts, jeans, and leggings Dresses and skirts Underwear, pyjamas Socks, stockings, and pantyhose Sportswear and swimwear Cloth diapers that are clean Hats, mittens, and scarves Parts and pieces of clothing	Leather clothing and rainwear that are worn or damaged	Recycling centre or residual waste
	PVC rainwear	Recycling centre
	Shoes and boots, worn or damaged and regardless of material	Recycling centre or residual waste
	PVC shoes and boots	Recycling centre
	Belts and bags that are worn or damaged	Recycling centre or residual waste
Textile waste in the form of end-of-life textiles: Towels and washcloths Tea towels and dishcloths Tablecloths and napkins Linens Curtains made of textile only Throws/carpets Pillow and cushion covers Fabric residues Rag rugs only made of textile Net/tote bag only made of textile	Thermal blankets, jackets, and similar items containing electronics	Recycling centre
	Carpets with rubber coating	Recycling centre
	Upholstery	Recycling centre
	Mattresses, box mattresses etc.	Recycling centre
	Wax cloth	Recycling centre
	Handkerchiefs, face masks and disposable diapers	Residual waste

In addition to the sorting performed at the household level and by specialized manual sorters, further steps are needed prior to recycling which can reduce the amount of material that is ultimately reprocessed into yarn (Logan et al., tbd; Rossi, 2023). For example, textiles need to be identified and sorted according to the different fibre blends, but the complexity of textile yarns

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[2] Source: https://www.retsinformation.dk/eli/retsinfo/2022/9793

poses a challenge to available automatic sorting technologies (Damayanti et al., 2021). Moreover, design elements such as zippers, buttons, and patches, also known as *findings*[3] of a garment, cannot be identified by these technologies but, if not removed, can impact textile recycling efficiencies both qualitatively and quantitatively (Rossi, 2023). Such steps are included in the *fine sorting* phase, which is performed by specialized personnel prior to recycling either directly at the recycling facility or at a separated sorting centre.

TABLE 1.2. Overview of the main types of sorting required prior to post-consumer textile recycling.

Type of sorting	Performed by	Main sorting criteria
Home sorting	Citizen, at the household level	- Reusable/non reusable - Clean & dry/dirty, wet, contaminated
Manual sorting	Professionals, at dedicated facility	- Reusable/non reusable - Clean & dry/dirty, wet, contaminated
Fine sorting	Professionals and automated machinery, at dedicated facility	- Automatic sorting - Recyclable/non-recyclable

A range of fibre-to-fibre recycling methods and technologies is present on the market, at pilot and at industrial scale (Damayanti et al., 2021; Loo et al., 2023; Piribauer & Bartl, 2019; Sandin & Peters, 2018). Each recycling route has specific criteria with regard to the input material, in terms of fibre type, purity, and composition (Harmsen et al., 2021; Ipsmiller & Bartl, 2022). This means that an item can be recycled only via certain pathways depending on these characteristics, if it can be recycled at all (Harmsen et al., 2021; Logan & Damgaard, 2022). Different technologies also lead to products of different quality (Eppinger, 2022; Harmsen et al., 2021; Loo et al., 2023), which can ultimately replace yarns made of virgin material only to a limited, variable extent (Trzepacz et al., 2023). The specific material that can be replaced also differs depending on the recycling method adopted, thus also influencing the potential to replace the use of new fibres (Rossi, 2023).

The development of a more effective system for the fibre-to-fibre recycling of post-consumer textiles hence depends, among other factors, on a thorough understanding of the specific sorting criteria needs at different steps of the post-consumer textile recycling value chain.

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[3] A finding, or recycling disruptor, is an item added to the garment during the design/production phase, which was not part of the textile fabric in the first place. Other examples include rivets, fasteners, eyelets.

2. Project objectives and outputs

The introduction of textile waste as the 10th fraction in the Danish waste collection system aims at increasing the share of recycled textiles while decreasing the amount going to incineration. This report seeks to evaluate the mass flows of post-consumer clothes that could be collected through the 2nd stream and that could potentially be available for material recycling, after applying a series of pre-determined sorting steps necessary to filter out non-recyclable items. Another purpose of this report is to increase knowledge about opportunities and challenges associated with the current waste management system and with selected technologies for recycling of post-consumer textiles collected in Denmark.
Finally, this report concludes by listing its main assumptions and limitations and, in this context, suggests potential recommendations for targeted textile collection and sorting.

Consequently, in this report we provide:

- An estimation of the annual Danish supply of selected categories of textiles, as well as an estimation of the flows of potentially recyclable material.
- An estimation of how much and what type of products could be eligible for recycling through selected recycling pathways, as well as how much and what virgin material can potentially be substituted by recycled textiles depending on the specific technology adopted.
- An initial overview of main challenges and opportunities of post-consumer textile recycling, with regards to both technical and environmental aspects, in support of the development of guidelines for increasing the recycling rates of textiles in Denmark.

3. Method for data collection and analysis

This section gives an overview of the project scoping and the scenarios investigated, as well as the core data sources employed (3.1), followed by the main steps used to quantify the 2nd collection stream (3.2) and the recycling eligibility criteria adopted (3.3). Main assumptions and sources of data uncertainties are presented in 3.4.

3.1 General principles

3.1.1 Scope – product types and categories

We use import and export flows to calculate the total supply of new textiles to Denmark. We focus on clothing for use in the private sector in Denmark. More specifically, for new textiles we consider a selection of products that have Combined Nomenclature[4] CN 2-digit codes 61 and 62. This comprises a total of 311 different product groups under the CN 8-digit categorisation and 35 different product groups at the more aggregated CN 4-digit level. For the methodology and details on this study please refer to the retail survey by Logan et al. (2023).

For accurate calculations of the consumption of new textiles we use the 8-digit CN product groups. For presentation purposes, however, we adopt a more simplified aggregation of 10 groups of products. An overview of these groups and their relationship to CN codes can be found in Appendix A.1.

3.1.2 Data year and units

Four main types of data are used in this report to build the material flow analysis (MFA), and derive from different sources:

- Import and export flows of selected categories of clothing in 2022 are retrieved from Statistikbanken[5].
- The share of clothes consumed by households, as well as the split between 1st and 2nd stream, are estimated from Watson et al. (2018). The absolute values in Watson et al. (2018) refer to 2016 consumption, thus only the relative shares are considered for this study and are applied to total supply data for 2022.
- Preliminary collection efficiencies from the May 2023 Collection Pilot Program in Denmark (UFF-Humana, 2023). Relevant information of clothes collected via the new 2nd stream in 2023 is retrieved from industry expert interviews with the Environmental and Reuse advisor at UFF-Humana.
- Specific data on garments at the product-type level, as well as the core selection of products categories to include in the study, are based on Logan et al. (2023).

All flows are presented in physical units (weight in tonnes).

3.1.3 Definition of scenarios

As mentioned, from 1st July 2023 discarded post-consumer textiles have been collected separately from any other waste fraction. In the new two-stream system, reusable textiles represent the 1st stream, while non-reusable ones comprise the 2nd stream.

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[4] For a description see https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:01987R2658-20230617

[5] https://www.statbank.dk/statbank5a/SelectVarVal/Define.asp?Maintable=KN8MEST&PLanguage=1

Two scenarios are evaluated in the present report: a baseline scenario, where textile waste collected through the 2nd stream is incinerated; an alternative scenario, which evaluates the maximum potential for recycling of textile waste collected through the 2nd stream, focusing on the textile recycling value chain and on textile recycling practices. In both scenarios, post-consumer clothes comprising the 1st stream are collected with the purpose of reusing them. Figure 3-1 illustrates the supply chain up until the collection of post-consumer textiles and the two different scenarios considered in the report.

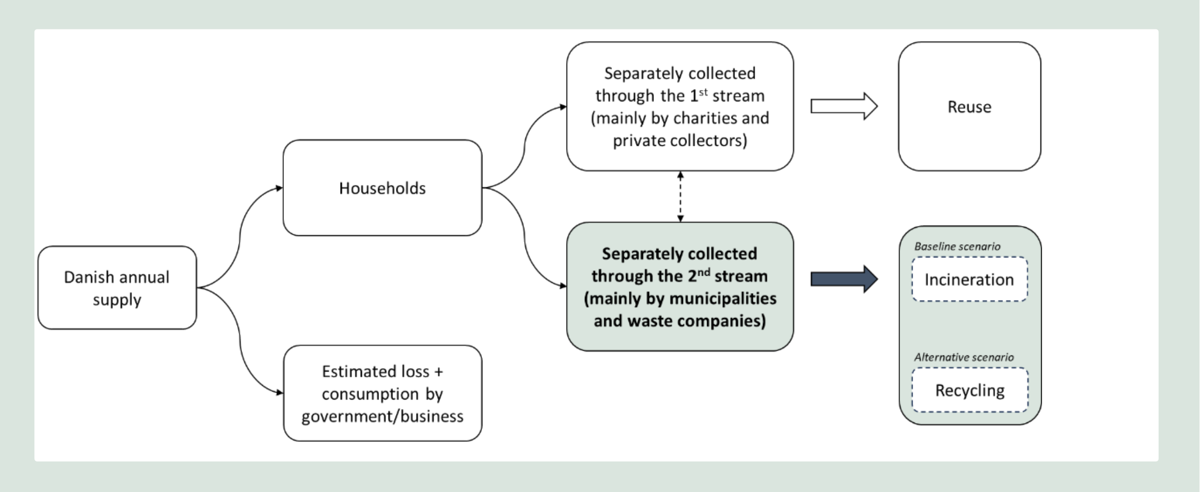

FIGURE 3-1. Visual representation of the two different scenarios evaluated in the report. The scope of the project concerns the non-reusable textile fraction collected from the private sector (highlighted in green)

As mentioned, the baseline scenario assumes that anything that is not collected through the 1st stream is incinerated, without requiring further treatment. The alternative scenario is described more in detail in later sections.

3.2 Calculations of flows of potentially separately collected post-consumer textiles in Denmark

The mass flows of textiles in Denmark potentially available for the 2nd stream are obtained through the calculation steps presented below, and a representation is given in Figure 3-2.

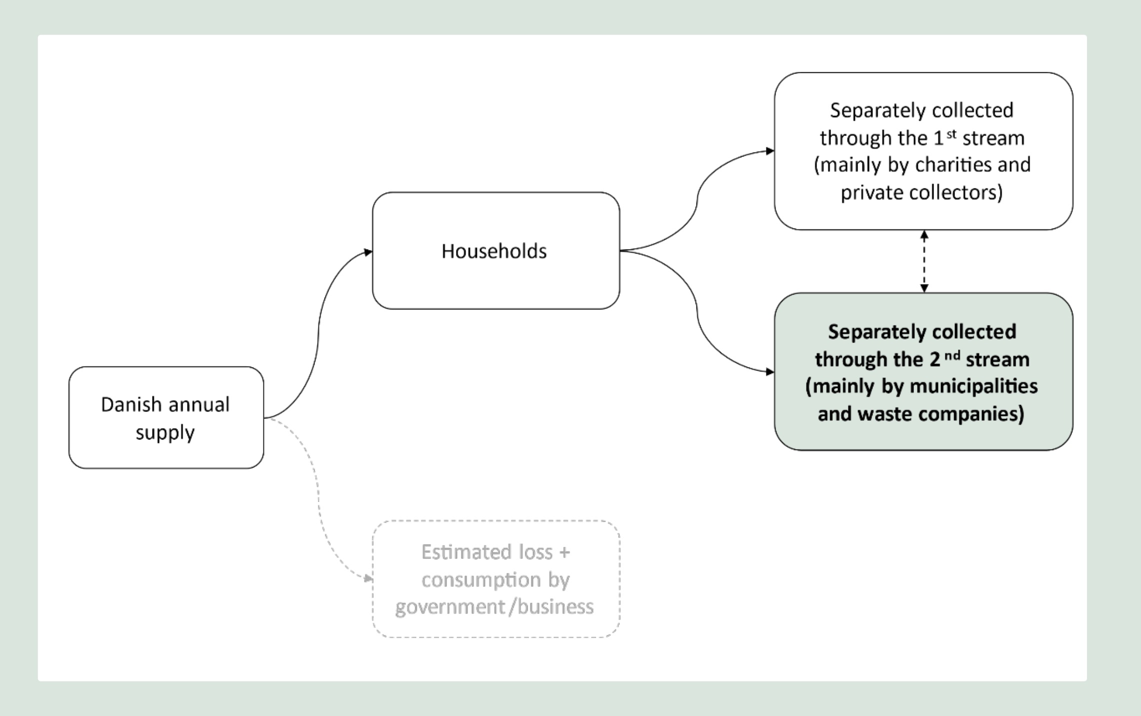

FIGURE 3-2. Textile supply and generic overview of separate collection streams

Starting from the annual supply of clothes in Denmark, we focus on the fraction consumed by households, as explained below. Then, we evaluate the split between the two different streams for separate collection.

3.2.1 Total supply of textiles to households in Denmark

The overall consumption (t) of clothing in Denmark is assumed to be equivalent to the national supply, as suggested by Watson et al. (2018). In this report, it is assumed that domestic production of clothes in Denmark is negligible (Logan & Damgaard, 2022), and that supply is guided by the equation modified from Watson et al. (2018):

$$Supply = Import - Export \qquad (1)$$

Annual supply can be calculated for any product for which there is compatible import and export data[6]. Import and export data is available in kg, which is then converted to tonnes. In this study, we focus on adult garments imported/exported from/to all countries in 2022. Childrens clothing (~1%) is excluded from the assessment, to align with the data available in the retail survey and due to differences in children's textile regulations[7].

In this model, the yearly supply of clothing to Denmark is assumed to be entirely consumed by households. For 2016, it was estimated that less than 9% of the clothing supplied to Denmark was destined to the public sector (Watson et al., 2018). Data on the industrial and government consumption of garments often encompasses high uncertainty (Watson et al., 2018), as such no distinction between sectors is made in the present report. “Estimated loss” (Figure 3-2) comprises unsold/returned items as well as lint loss during use, which are also not taken into

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[6] Dataset KN8Y found in Statistics Denmark’s statistics bank: https://www.statistikbanken.dk/KN8Y

[7] For example, REACH regulation and EN standards such as EN 14682 Safety of children’s clothing — Cords and drawstrings on children’s clothing; EN 17394 Safety of children’s clothing – Security of attachment of buttons – Test method; EN 14878 Textiles – Burning behavior of children’s nightwear – Specification.

account in this study as they are estimated to represent less than 1% of the total supply (Watson et al., 2018).

3.2.2 Collection of household post-consumer textiles

The relative share (%) of annual clothing separately collected from households for reuse is retrieved from Watson et al. (2018), which refers to supply data from 2016. This share is assumed to be constant and is applied to consumption data for 2022. Since these values are based on a study conducted when the two-stream system was not yet in place, some adaptations are necessary. Specifically, the flow identified as *separate collection* by Watson et al. (2018) is assumed to represent the current 1st collection stream. The remaining textiles, collected according to Watson et al. (2018) together with either *bulky waste, small combustibles*, or *household mixed waste*, are assumed to comprise the current 2nd collection stream. Figure 3-3 provides an illustration of such adaptation.

For both scenarios, a dedicated stream is assigned to clothes collected for reuse that matches the *separate collection* flow percentage calculated by Watson et al. (2018) (Figure 3-3) and corresponds in this report to the 1st stream. Household textiles that are not collected for reuse fall in the 2nd stream and are assumed to be either sent to incineration or recycling, depending on the scenario.

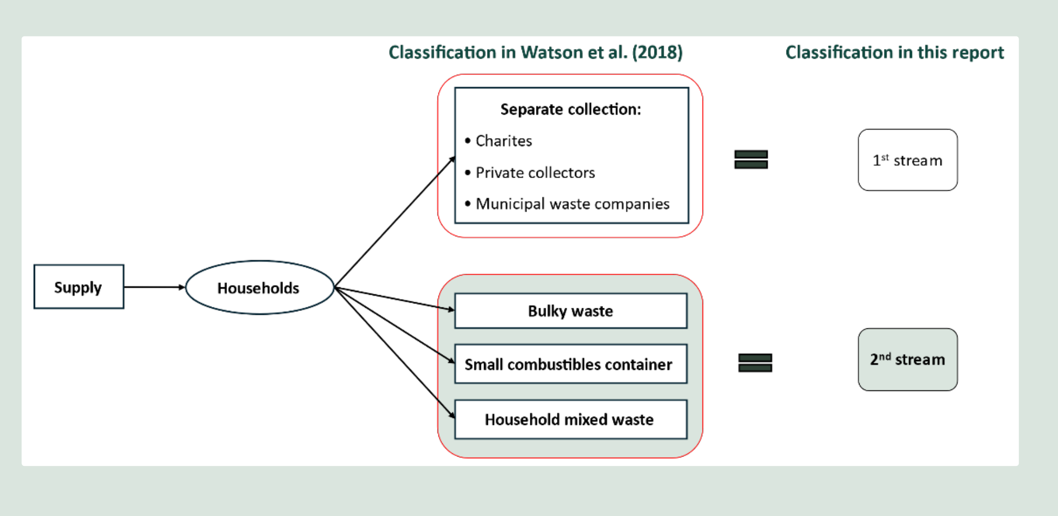

FIGURE 3-3. Qualitative overview of flows of textiles to and from households, adapted from Watson et al. (2018). Red boxes indicate the collection flows prior to the implementation of the new two-stream system.

3.2.3 Additional sorting steps

The household textiles collected with the 2nd stream are sorted between *clean and dry* and *dirty/contaminated/wet* according to data from UFF-Humana Denmark. These data are based on manual pre-sorting of ~18 tons of textile waste collected in three different Danish municipalities during 2023 (UFF-Humana, 2023). The relative shares are adapted to exclude the types of products that are out of scope for the present report, so to be compatible with data from Logan et al. (2023), namely *shoes & bags*; *other waste, feathers & down*; and *plastic bags*. This lowers the sample to ~16 tons of textile waste. The original data can be found in Appendix A.2, together with an explanation of the product groups.

The share of clean and dry textiles is then sorted between *reusable* and *non-reusable* garments, based on the same source (Appendix A.2). Further sorting steps are then applied to estimate the potentially recyclable share of the non-reusable fraction and are based on the sorting hierarchy proposed by Logan et al. (tbd).

3.3 Recycling eligibility criteria, recycling route, and substitution potential

The feedstock eligibility criteria, i.e., which recycling pathways are suitable for a specific item, are based on Logan et al. (tbd). An abbreviated version is given in Table 3.1 below. It should be reminded that these choices are made to have a selection of the wide range of recycling methods currently available, but there might be some technologies that are able to process input of lower qualities (Björquist, 2017; Girn et al., 2019; Palme, 2017).

TABLE 3.1. Recycling eligibility criteria. *In the case of mechanical recycling of wool-based materials, the wool content should be >80%.

Textile waste composition	Recycling technology	Input composition
Cellulose-based fibre blends	Chemical recycling (oligomer recycling)	Cellulose > 80%
Polyester-based fibre blends	Chemical recycling (monomer recycling)	Polyester > 80%
Synthetic fibre blends, polyester-based	Chemical recycling (polymer recycling)	Polyester > 60% Rest: synthetic fibres
Other blends	Mechanical recycling	Leading fibre > 60%*
Any	Downcycling	-

In this report, mechanical recycling refers to fibre recycling, meaning that the fabric is disassembled, but the original fibres are maintained (Sandin & Peters, 2018). The leading fibre in the input textile should represent at least 60% of the garment, with a required share of 80% in case of wool recycling (Table 3.1). Chemical recycling is here distinguished between oligomer/polymer recycling and monomer recycling (Table 3.1). In the first case, fibres are disassembled, while oligomers or polymers are conserved. A content of at least 80% cellulose is required for oligomer recycling, while only textiles entirely composed of synthetic materials and with minimum 60% polyester are assumed eligible for polymer recycling. In the second case, oligomer/polymers are disassembled, but the monomers are preserved (Sandin & Peters, 2018). In this study, a garment is assumed to be eligible for monomer recycling if it is composed of at least 80% polyester. Finally, downcycling refers to recycling pathways that reprocess the original item into a recycled material of lower quality (Sandin & Peters, 2018), and no specific restriction in terms of input composition is required.

For what concerns the selection of the specific technology allocated to a garment, there is currently no absolute best[8] (Boschmeier, Ipsmiller, et al., 2023). While the flows calculated in this study represent possible recycling routes, textiles may be sorted and used in any pathway in which they are eligible. The assignment of these pathways will in reality depend on the market dynamics and demand of the local textile sorting and recycling system. In any case, this is a simplification of the actual recycling scenarios, where a combination of two or more different processes are often required (Loo et al., 2023; Sandin & Peters, 2018).

In this report, recycling technologies are ranked based on the substitution potential of the final monomer, oligomer/polymer, or fibre substituted. If an item is eligible for more than one recycling method, the one with the highest substitution potential is assigned to it.

The substitution potential of fibres obtained from post-consumer textile material depends, among other factors, on the technology used for the recycling process. Table 3.2 gives an overview of the substitution potentials relative to each of the recycling technologies considered in this study, retrieved from Logan et al. (tbd). It is important to note that, even though certain

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[8] For a more details, please refer to section 4.5 in this report.

ranges are adopted in this report, substitution potentials vary depending on the specific technology. The values utilized for this study are based on estimations and literature review, but there may be companies that are able to reach higher substitution potentials. For example, the Italian company Rifò[9] claims to be able to produce garments 100% based on recycled wool.

TABLE 3.2. Assumed substitution potential of different recycling technologies and type of material that could be replaced. *In case of chemical recycling processes, the substitution potential refers to the monomer, oligomer, or polymer substituted, not the fibre.

Recycling technology	Substitution potential	Substituted feedstock
Chemical recycling (monomer recycling)	~100%*	Monomer to reprocess into same or other fibre
Chemical recycling (oligomer or polymer recycling)	<100%*	Oligomer/polymer to reprocess into same or other fibre (e.g., chemical recycling of cotton leads to manmade fibres such as viscose or lyocell)
Mechanical recycling (wool)	<80%	Same fibre
Mechanical recycling (other than wool)	10-35%	Same fibre
Downcycling	-	Other (e.g., insulation material, material used for industrial wipes)

As can be seen from Table 3.2, chemical recycling methods lead to the highest substitution potentials. Through monomer recycling technologies, virgin quality fibres could be achieved (Harmsen et al., 2021; Loo et al., 2023; Piribauer & Bartl, 2019), since the process would restart at the monomer level. For what concerns oligomer and polymer recycling, few information is available that would help determine the substitution potential. However, differently from monomer recycling, virgin resources would need to be mixed with the recycled fibre to overcome the loss of quality (Loo et al., 2023; Ribul et al., 2021). In addition, chemical recycling of cellulose does not always lead to the same fibre type. For example, chemical recycling of cotton does not lead directly to the substitution of virgin cotton, because the material is recycled into man-made cellulosic fibres (MMCF) such as viscose or lyocell (Duhoux et al., 2021; Harmsen et al., 2021; Loo et al., 2023; Wedin et al., 2019).

Mechanical recycling can be applied to a wider range of product compared to chemical technologies, although the final product presents a significantly lower potential for substitution of virgin fibres. This is mainly due to the harsh treatment textiles are subjected to, which deteriorate fibre properties (Eppinger, 2022; ETC/WMGE, 2019; van Duijn et al., 2022). Mechanical recycling of post-consumer wool can lead to more promising results, with examples of substitution potential up to 80% (Russell et al., 2016).

Downcycling is listed here among the other technologies due to its being a widespread treatment method. Nonetheless, it should be kept in mind that downcycling practices are mostly identified as *open-loop recycling*, and not as *closed-loop recycling* as the processes mentioned above, which result in the production of new apparel material (Dissanayake & Weerasinghe, 2021; Eppinger, 2022; Sandin & Peters, 2018). In this instance, it is not possible to suggest a value for the substitution potential, since the term *downcycling* can refer to a variety of processes, leading to different types of products, such as industrial rags, low-grade blankets, and insulation materials (Eppinger, 2022; Roos et al., 2019; Sandin & Peters, 2018). In any case, the material replaced by downcycled garments would not replace new fibre to any extent, hence why the classification as *open-loop recycling*.

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[9] https://rifo-lab.com/en/pages/recycled-textile-materials

3.4 Main assumptions and uncertainties

The data sources used present different aggregation levels

The data used in this report are retrieved from multiple sources, and present different levels of aggregation. This means that the fractions applied throughout the MFA to estimate the various material flows are based on information compiled and summarised at different levels of detail. These can be divided, from the most generic to the most detailed, into *material type*; *application*; *product category*; *fibre family and composition ranges*; and *fibre type and composition ranges* (Figure 3-4). The last two are based on the single item. The physical condition of the product is independent from the other subgroups, although here it is considered a more detailed information than the material type, but more aggregated than the application.

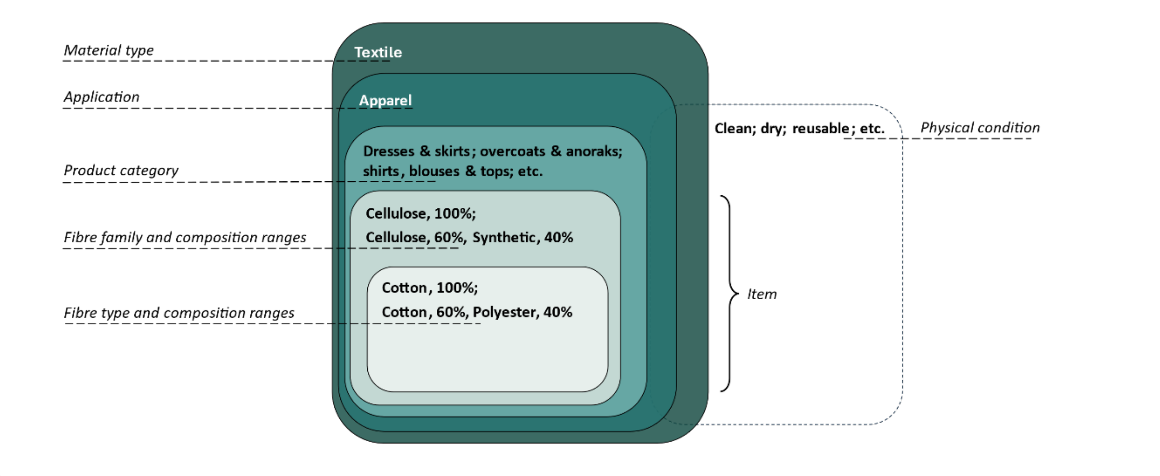

FIGURE 3-4. Different levels of classification of textile material adopted in this report. The colours of the boxes go from the most generic (dark) to the most detailed (light) level. The physical condition is assumed independent from other subgroups.

To further illustrate the example in Figure 3-4, a t-shirt (product category) would be an apparel (application) textile (material type) which could be made of 60% cotton and 40% polyester (fibre type and composition), that in turn would mean it is made of 60% cellulosic and 40% synthetic fibres (fibre family and composition).

Data aggregation is useful for presentation purposes, and it is in some cases dictated by the availability of data from the different sources. The data used for a certain process in the model might be more detailed than data relative to a process happening downstream, which means that there is not a linear progression from more to less aggregated data along the value chain. This is shown in Figure 3-5, which illustrates how the various processes are modelled with data from multiple data sources presenting different levels of details.

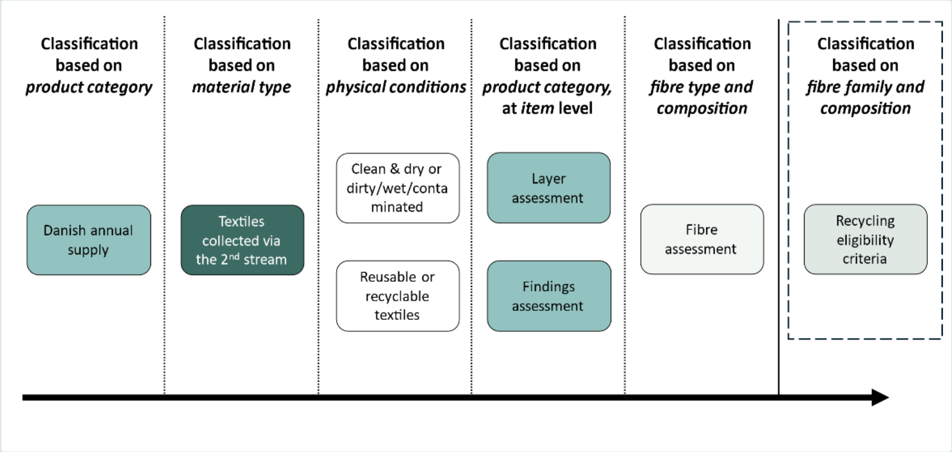

FIGURE 3-1. Schematization of the flows of value chain considered in this report, and relative level of detail of the data used for each process. The arrow indicates the order of the flows. The recycling eligibility criteria represent a qualitative rather than a quantitative evaluation, outside of the specific value chain. The different colours are meant to highlight the different level of detail the process steps, as assigned in Figure 3-4 where a darker colour indicates a more generic level of detail (e.g., *material type)* compared to a lighter colour (e.g., *fibre family and composition*).

This means that, even if processes relative to layer, findings, and fibre assessment are based on recent primary data, upstream processes are modelled through more aggregated data. These upstream data carry a higher underlying uncertainty, which propagates to downstream processes and increase the overall uncertainty of the model.

Discrepancies between CN 8-digit codes

In Logan et al. (2023) the CN codes are solely used to define sampling guidelines, the focus of the survey being to obtain a representative sample of the market composition across common categories. The same codes are used to retrieve the import/export flows of textile apparel, with an interest on the exact accounting of the market. However, a few exceptions apply, as it is not possible to ensure that every single one of the garments sampled belongs to a specific category as import codes are often not included on the retail tagging for the garments. Additionally, CN codes and relative classifications have changed throughout the years, but these changes are not reflected in the legislation for CN codes. This is specifically the case for *overcoats and anoraks* and *sportswear and swimwear* product types. In the first case the CN 8-digit codes vary for 2022 compared to previous years, leading to different groupings. For *sportswear and swimwear*, we include in the calculation of the national supply additional codes on top of those listed in Logan et al. (2023), as some of the garments sampled might ultimately belong to these categories.

Exclusion of clothing production in Denmark

Watson et al. (2018) include domestic production in their calculations of the Danish national supply, while here it is assumed to be negligible, and therefore excluded. This is not deemed to have an impact on the overall results, but it might lead to small differences at the product category level. Local production in high income service economies often belong to the luxury and designer markets or workwear rather than the fast fashion mass retail market, as such they were excluded from the market sample in Logan et al. (2023) and are not represented in this study.

The data available from the retail survey represent a specific season

The dataset represents the composition of the Danish retail market in the 2022 spring/summer retail seasons. Seasonality influences the characteristics of the garments assessed, such as fibre type, finding presence, and number of layers, therefore the material flows of the different recycling technologies may be affected in other retail seasons, i.e., autumn/winter.

Annual clothing consumption by households may be overestimated

The yearly supply of clothing to Danish households retrieved for 2022 is likely to include small quantities of workwear consumed by the government and businesses. Therefore, recyclable quantities might be overestimated, since textiles consumed by the public sector are seldom collected for recycling (Watson et al., 2018). Nonetheless, this would only affect the absolute results, while the relative share could still be applied to the amount of post-consumer textiles separately collected from households. Alternatively, within each product category, it would be possible to retrieve the share of garments destined to the public sector. However, it is argued that it would not result in any added value, since such split is found to be highly uncertain (Watson et al., 2018).

The 1st collection stream may contain a fraction of recyclable garments

The amount of post-consumer textiles collected via the 1st stream is based directly on values from Watson et al. (2018). These are relative to 2016, when the two-streams system was not yet in place, meaning that all textiles separately collected for reuse from households are accounted for in the 1st stream. This includes a small fraction of textiles collected from municipal waste companies. While the focus of this report is on the 2nd stream, it is more specifically on the fraction of recyclable post-consumer textiles collected from households. This fraction would be higher than the one estimated if the fraction collected by municipalities was to be included among the 2nd stream in the new system. More specifically, Watson et al. (2018) estimated that around 13% of the textiles collected with what we assumed would be the 1st stream would be sent to recycling, mostly outside of Denmark. This is in agreement with the study conducted by (Nørup et al., 2019a), where an MFA of textile flows in a European textile sorting centre showed that around 15% of the textiles collected for reuse were in fact non-reusable, and sent to recycling instead.

The collection efficiencies applied are based on data collected prior to the implementation of mandatory separate collection of textile waste in Denmark

The data used to estimate the share of reusable/non-reusable post-consumer textiles collected via the 2nd stream are retrieved from a pilot project carried out by UFF-Humana Denmark. The pilot program involved three different municipalities in Denmark whose textile waste was collected and delivered to UFF-Humana Denmark (UFF-Humana, 2023), and it dates back to early 2023, before the separate collection of textile waste was mandatory. In this report, it is assumed that the information gathered is representative for the current system as well. Collection efficiencies will however hopefully improve as a consequence of new guidelines and as the two-stream system gradually gets more established, which would in turn imply a lower share of reusable items collected together with the 2nd stream and a higher share of non-reusable textiles. Similarly, the fraction of missorted, non-reusable garments collected through the 1st stream is expected to be decreasing as well.

On the other hand, this underscores the importance of clear guidelines, as the option of household collection of textile waste could also be seen by the consumer as an easier way to dispose of their clothes compared to taking them to bring banks or charity organizations. This could result in a higher share of reusable clothes collected via the 2nd stream, which could thus diminish their reuse potential.

Home sorting efficiency of textile waste will most likely be lower than 100%

The recycling scenario modelled in this study assumed that all textiles that are not collected through the 1st stream will be sorted out into the 2nd stream. However, experience from other material fractions (Kromann et al., 2019) shows that this is not to be expected, and some potentially reusable or recyclable textiles will still be discarded together with general waste. Furthermore, it should be noted that the presence of dirty/contaminated textiles in the sampling carried out by UFF-Humana should be considered *missorting* by the consumer according to the new guidelines. Thus, the actual amount of non-recyclable textiles in households will be higher, since it must be expected that most dirty/contaminated textiles is already sorted into residual waste. As such, the MFA reflects an “optimal” situation, as in reality an additional fraction of textiles will be lost to incineration.

Recycling eligibility criteria adopted and prioritization made

In order to apply material flow analysis and evaluate the recycling route a specific garment could be treated with, certain eligibility criteria are adopted. However, such criteria are not univocal nor are they independent from the specific recycling technology, as for different processes requirements change in terms of composition of the input textiles. We acknowledge that there might already be companies that are able to handle a wider range of materials, and that, for instance, might be able to mechanically recycle products where the leading fibre is lower than 60%, or chemically recycle back to monomers items where polyester represents less than 80% of the fibre composition. Similarly, in the present study only one recycling pathway is assigned to each item, although, in most cases, multiple methods can be used to recycle it. This represents a simplification of the model, and it should be kept in mind that the prioritization made for this study, i.e., based only on the assumed substitution potential, does not necessarily represent the reality, and that multiple factors influence which recycling pathway textiles undergo. On this note, it is also important to remember that the substitution potentials refer to different recycled materials, namely fibre, monomer, or oligomer/polymer. This means that only in the case of fibre-to-fibre, therefore mechanical recycling the substitution potential represents the amount of textile fibres that could be replaced, whereas chemically recycled textiles would substitute monomers or oligomers/polymers, which would then need to be reprocessed into new fibres, although in this report the efficiencies of these processes are not evaluated.

4. Results

The following results provide a snapshot of the potential pathways for the Danish 2022 fast fashion market and highlight the importance of considering garment composition instead of only fibre type in planning for textile circularity. The consumption of garments in Denmark during 2022 and the estimation of the related flows of potentially recyclable textiles are presented in 4.1 and 4.2, respectively. The two different scenarios evaluated are then illustrated in section 4.3 (baseline scenario) and 4.4 (alternative scenario). Lastly, focus on aspects related to the different recycling technologies considered in this report is provided in section 0.

4.1 Annual supply of clothing in Denmark

The supply of clothing to Denmark in 2022 is presented in Table 4.1, grouped according to product categories. The same data are also illustrated for 2016, which is the reference year for Watson et al. (2018) and are shown here for comparative purposes. These values are categorized based on Logan et al. (2023), i.e., they only include apparel textiles, thus do not match the values estimated by Watson et al. (2018). Nonetheless, adopting the same categorization allows to compare data across years.

TABLE 4.1 Supply of textile clothing to Denmark in 2016 and 2022, presented in absolute and relative values.

Product category	2016		2022	
	Supply (t)	Relative share	Supply (t)	Relative share
Overcoats and anoraks	4793	8%	10239	10%
Suits and blazers	3198	5%	5112	5%
Trousers and shorts	13919	24%	24644	25%
Dresses and skirts	2707	5%	5299	5%
Shirts, blouses, tops	5750	10%	4157	4%
Underwear, socks, and night clothes	7136	12%	6889	7%
T-Shirts and vests	9048	15%	10889	11%
Sweaters and cardigans	9130	15%	14703	15%
Sportswear and swimwear	1343	2%	14400	15%
Handkerchiefs, ties, scarves, gloves, and other	2367	4%	2603	3%
Total	**59392**		**98935**	

Approximately 98,935 tonnes of clothing were consumed in Denmark in 2022, a 67% increase from 2016[10]. The increase is likely partly due to increased consumption, but it is expected to be also due to stock changes due to COVID-19 as the increase from 2020 and 2021 to 2022 is quite high for some CN's. An increment can be observed in the absolute consumption of all categories, except for *shirts, blouses, tops* and *underwear, socks, and night clothes*, which registered a decrease in the amount supplied annually. The supply of products falling into the categories *overcoats and anoraks*, *suits and blazers*, *trousers and shorts* and *dresses and*

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[10] Source: https://www.statbank.dk/statbank5a/SelectVarVal/Define.asp?Maintable=KN8MEST&PLanguage=1

skirts nearly or slightly more than doubled in absolute terms from 2016 to 2022, while the consumption of *sportswear and swimwear* shows almost a ten-fold increase. *T-shirts and vests*, *sweaters and cardigans*, and *handkerchiefs, ties, scarves, gloves, and other* also present an increase in the annual consumption across the years, but to a lower extent.

The relative shares are similar across the years for most product categories, with a notable increase of the fraction of *sportswear and swimwear* (from 2% in 2016 to 15% in 2022). This is due, in part, to the growth of Athleisure as its own market segment, and the increasing development of sportswear and functional textiles to enhance performance (Watts & Chi, 2019).

4.2 Flows of recyclable textiles in Denmark

4.2.1 Estimation of separately collected textiles

The share of textiles that are separately collected from households are estimated based on the work by Watson et al. (2018), as shown in Table 4.2. Note that the total value of 75,930 tonnes in Table 4.2 differs from the total supply of 59,392 tonnes shown in Table 4.1 because it includes also items other than apparel textiles (see 3.2.1).

TABLE 4.2 Estimation of collection streams. Adapted from Watson et al. (2018).

Textiles consumed by households in Denmark (2016)	**Amount collected (t)**	**Relative share**	**Collection stream**
Separate collection	36000	47%	1st stream
Bulky waste	5600	7%	2nd stream
Small combustibles container	14300	19%	2nd stream
Household mixed waste	20000	26%	2nd stream
Lint loss during use	30	~0%	Lost to the environment
Total	75930		
	36000	**47%**	1st stream
	39900	**53%**	2nd stream

The flow *separate collection* with regards to 2016 is assumed to represent the 1st collection stream and covers 47% of textiles consumed by households. The textiles collected with *bulky waste*, *small combustibles container* and *household mixed waste* in the traditional waste management system are assumed to compose the 2nd stream in the new waste management system. These represent the remaining 53% of post-consumer textiles collected from households.

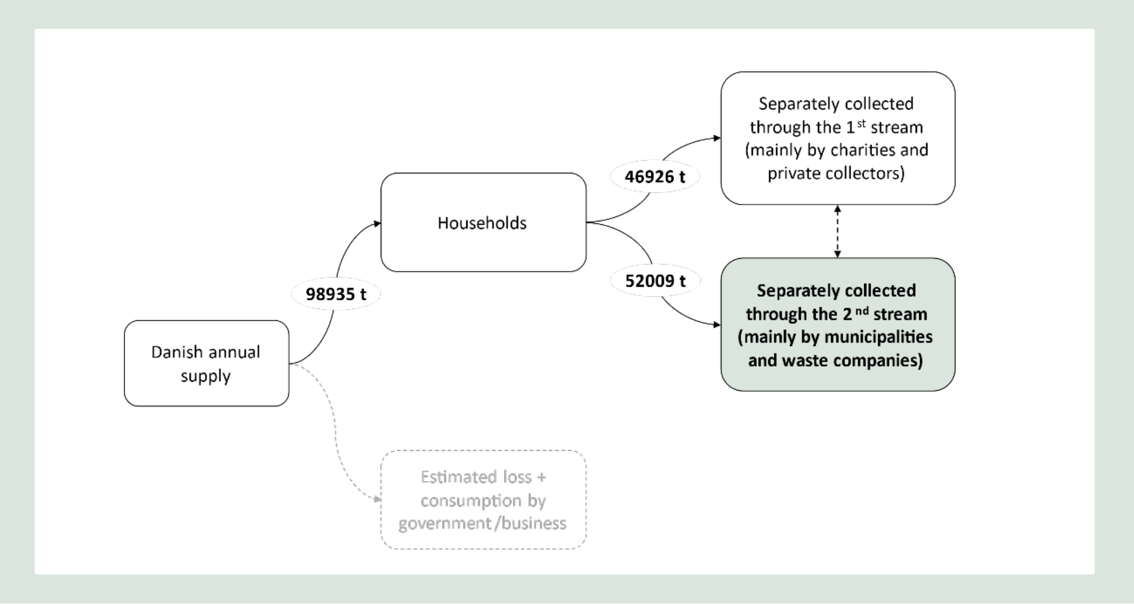


FIGURE 2-1. Garments that could potentially be collected through the 1st and 2nd streams in the new system.

Applying these fractions to the total supply of clothing in Denmark in 2022 (98,935 tonnes), the quantity of garments collected through the 1st and the 2nd stream are presented in Figure 4-1. Approximately 52,009 tonnes of clothing are estimated to be collected from households via the 2nd stream, i.e., are sorted as non-reusable by the consumer. The remaining 47% (46,926 tonnes) is assumed to be managed mainly at charity organizations and by private collectors.

It should be kept in mind that these values are highly uncertain, due to the lack of primary data and the assumptions made (see 3.4). Since this is the starting point of the MFA, these uncertainties will propagate throughout the model, affecting downstream processes despite them being modelled according to more accurate data.

4.3 Incineration scenario

In the baseline scenario, post-consumer textiles that are collected through the 2nd stream are directly sent to incineration which is the dominant treatment method for residual waste. Figure 4-2 gives a simple representation of the incineration scenario.

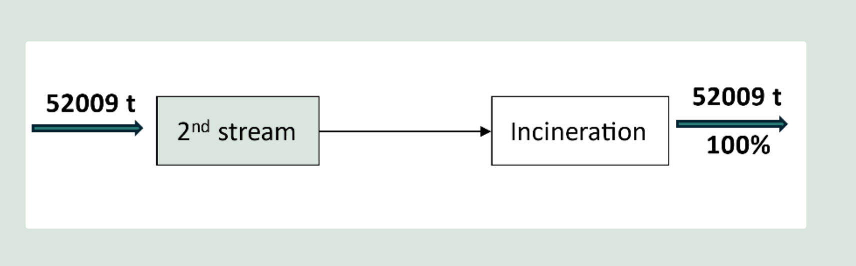


FIGURE 3-2. Visual representation of the baseline scenario, where everything that is not collected for reuse is sent to incineration.

No additional sorting steps are assumed to be required prior to incineration, thus the MFA can be directly set up as shown in Figure 4-2. The estimated value of 52,009 tonnes only refers to the clothes assumed collected via the 2nd stream, although it should be reminded that also a fraction of textiles collected through the 1st stream would potentially be incinerated. Nonetheless, this additional fraction would be the same regardless of the scenario considered, thus it will not be discussed further.

4.4 Recycling scenario

Clothes collected via the 2nd stream with the purpose of recycling require a series of additional sorting steps (Logan et al., tbd), which are briefly described in the following sections.

4.4.1 Recyclable textiles after 1st and 2nd sorting steps (manual sorting)

The fractions of valuable textiles and textile waste obtained after the 1st sorting, as well as the share of reusable and non-reusable materials sorted out in the 2nd sorting are presented in Figure 4-3. These are based on data from UFF-Humana Denmark (UFF-Humana, 2023).

The total value of ~16 tonnes is derived from the adaptation of the data provided, and it is obtained grouping the categories related to textile material only (see Appendix A.2). It should be noted that this value may include textiles other than clothing, since the aggregation is made based on the *physical condition* of the item rather than on the product *application* (see 3.4).

Among the total of textiles collected via the 2nd stream, 34% are either dirty, wet, or contaminated, and is sent to incineration. The remaining 66% are both clean and dry, 67% of which are found to be suitable for reuse, while 33% are marked as *non-reusable*. This fraction is either incinerated (baseline scenario) or pre-treated for recycling (alternative scenario).

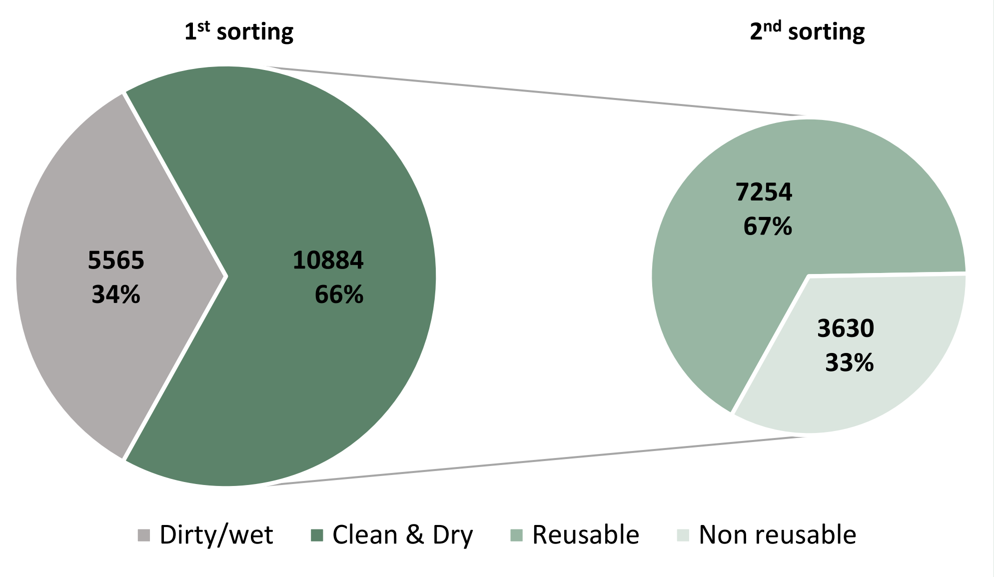


FIGURE 4-3. Split of collected post-consumer textile waste after the 1st and 2nd sorting steps based on data adapted from UFF- Humana Denmark (UFF-Humana, 2023). Values are in kilograms (kg).

These shares are applied to the clothes assumed collected via the 2nd stream in Denmark in 2022 to obtain the mass flows relative to the 1st and 2nd sorting steps, represented in Figure 4-4.

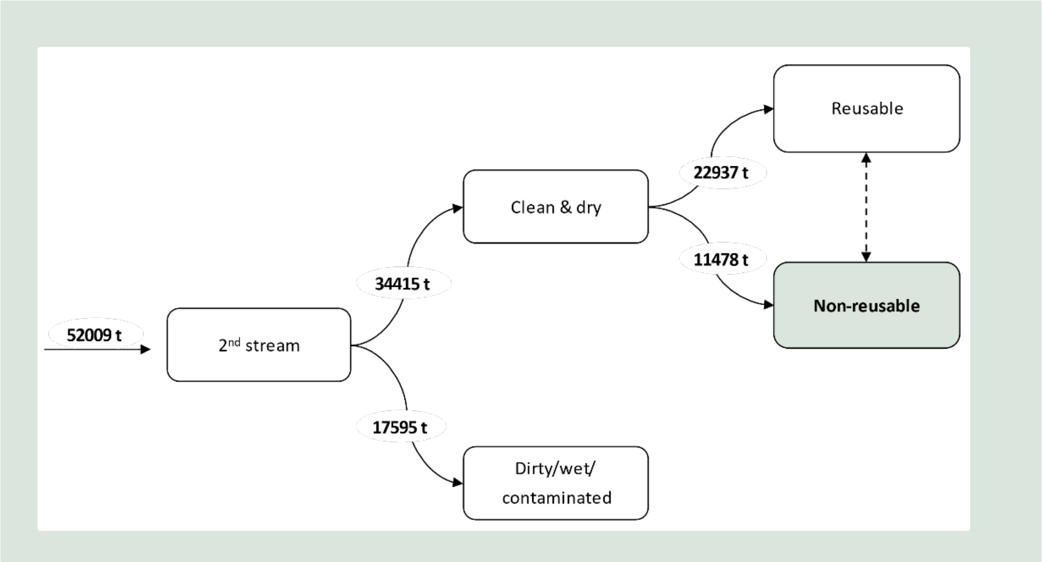


FIGURE 4-4. Estimation of material flows of clothing assumed collected via the 2nd stream in Den-mark in 2022 and split into clean & dry or dirty/wet/contaminated and re-usable and non-reusable after the 1st and the 2nd sorting, respectively. Cases of values not adding up are due to rounding.

Out of the 52,009 tonnes of apparel textiles assumed to be collected, 17,595 tonnes are sent to incineration, mainly due to items being either dirty, wet, or contaminated. The other 34,415 tonnes are estimated to be suitable for further sorting. Of these, 22,937 are deemed reusable, while the rest (11,478 tonnes) are found to be suitable for recycling.

4.4.2 Recyclable textiles after additional sorting steps (fine sorting)

Additional sorting steps (fine sorting) must be applied to the non-reusable fraction of textiles, which are briefly described in the present section. For a detailed overview, we refer to Logan et al. (tbd).

Due to current limitations in separation and automated sorting technologies, only mono-layered garments are suitable for fibre-to-fibre recycling, while the rest are downcycled (Logan et al., tbd; van Duijn et al., 2022).

Metal findings need to be removed from the garment prior to recycling, while plastic findings can be shredded without damaging the machinery (Damayanti et al., 2021; Logan et al., tbd). Items heavily contaminated with findings cannot be treated and are directed to incineration (Logan et al., tbd; van Duijn et al., 2022).

Lastly, textiles are analysed at the fibre blend level. At this stage, it is assessed if the garment is suitable for fibre-to-fibre recycling (either mechanical or chemical), if it can only be downcycled, or if it should be incinerated (Logan et al., tbd; van Duijn et al., 2022).

These additional sorting steps all contribute to reduce the amount of textile material available for fibre-to-fibre recycling, diverting part of it either to downcycling practices or to incineration. In addition, garments need to be shredded prior to the recycling step, which results in further loss of textiles to incineration. This fraction, however, is not taken into account in this study.

Figure 4-5 provides an overview of the mass flow analysis of textiles collected via the 2nd stream in the recycling scenario, where a distinction is kept between *closed-loop recycling* (recycle) and *open-loop recycling* (downcycle). The values presented refer to the total flow of textile material, obtained by aggregating the 10 different product categories. Grey boxes indicate processes that are common to all product categories, whereas white boxes are associated with flows that depend on the specific product category.

As can be seen in Figure 4-5, out of the total clothes collected through the 2nd stream, 44% could be reused, 6% would be downcycled, up to 39% would need to be incinerated, and 11% could potentially be recycled into new fibres.

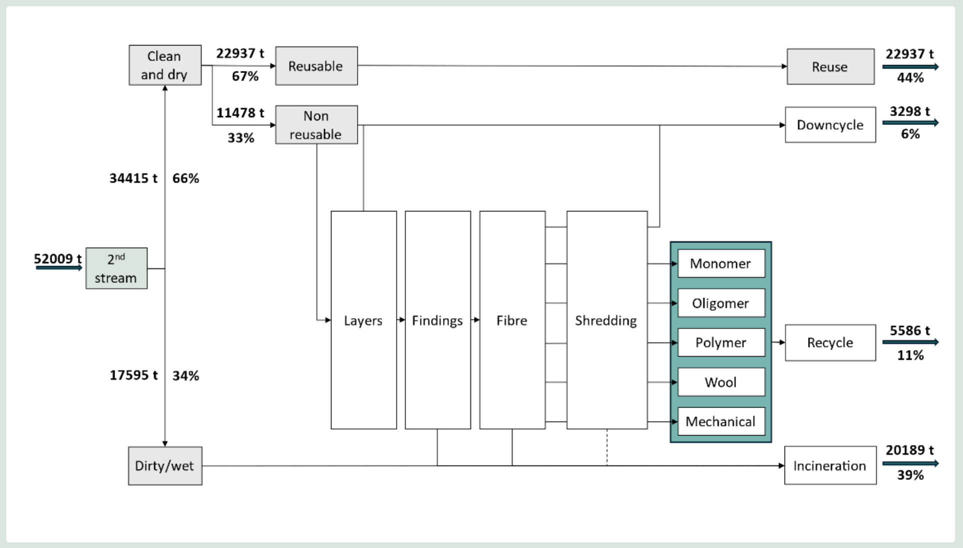


FIGURE 4-5. Material Flow Analysis (MFA) of separately collected clothing to the Danish 2nd stream, and steps associated with the textile recycling supply chain (alternative scenario). Dis-tinction is here made between open-loop recycling, identified by the box “downcycle”, and closed-loop recycling, identified by the box “recycle”

Similarly, Figure 4-6 provides an overview of the mass flow analysis of textiles collected via the 2nd stream in the recycling scenario, where no distinction is made between *closed-loop recycling* and *open-loop recycling*.
In the case illustrated in Figure 4-6, out of the total clothes collected through the 2nd stream, the shares of what could be reused and what would need to be incinerated do not change, whereas the fraction of what could potentially be recycled increases to 17%.

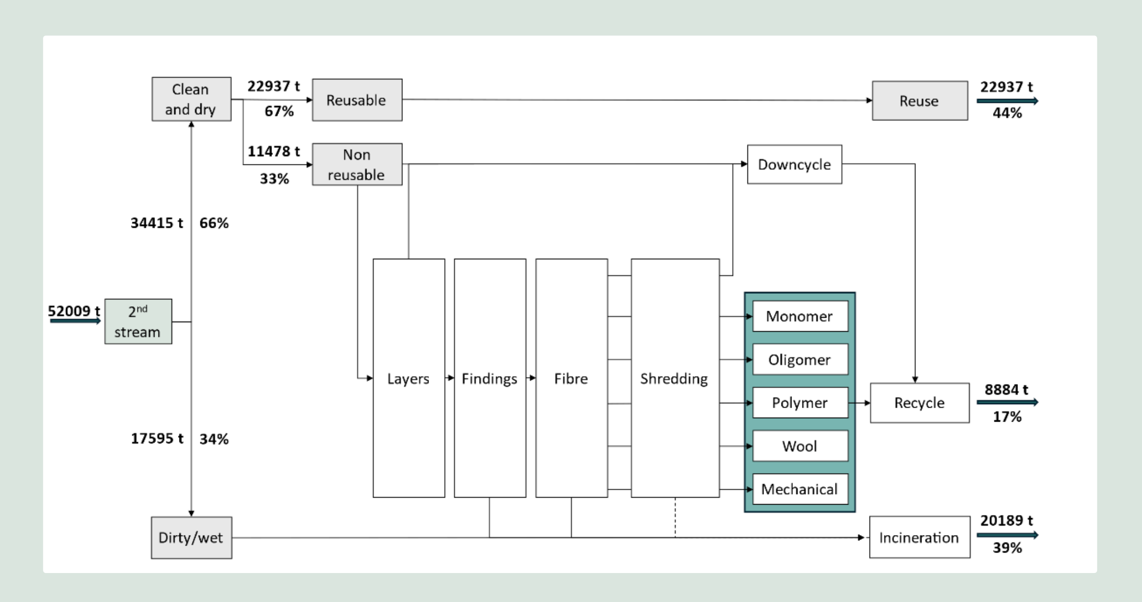


FIGURE 4-6. Material Flow Analysis (MFA) of separately collected clothing to the Danish 2nd stream, and steps associated with the textile recycling supply chain (alternative scenario). No distinction is made here between open-loop recycling and closed-loop recycling, as both fall into the box "recycle"

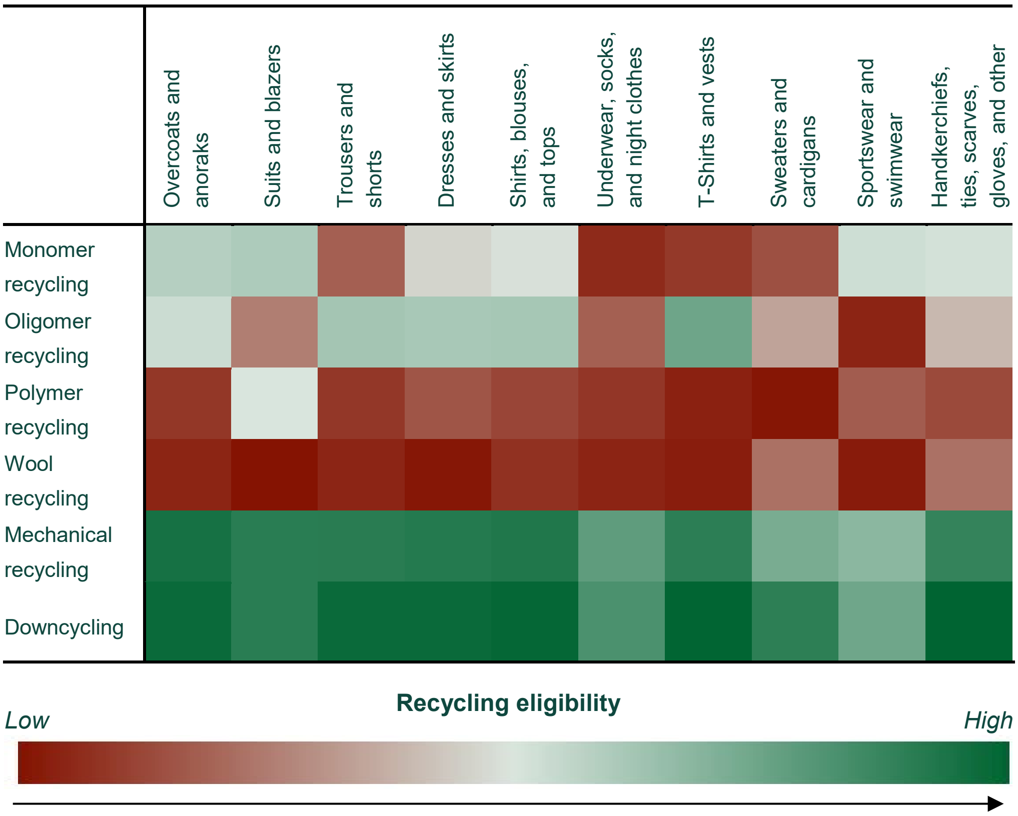
It should be kept in mind that the Danish clothing supply is assumed here to be entirely destined to households, although this includes the relatively small share consumed by government and business (see 3.2.1). Since the most likely option for treating textiles consumed by the public sector is incineration (Watson et al., 2018), the textiles flows available for reusing and recycling might be overestimated, while those going to incineration might be underestimated. Additional recyclable textiles as well as textiles sent to incineration could also derive from the 1st collection stream, as also mentioned before.

Textile recycling does not comprise of a single route, as it can be done through different technologies (Piribauer & Bartl, 2019; Sandin & Peters, 2018). The specific recycling pathway mainly depends on the fibre composition of the garment and the sorting steps employed prior to recycling (see 3.3). As shown in Table 4.3, for this project we consider both chemical recycling, in the form of monomer, oligomer, or polymer recycling, and mechanical recycling of either wool or other types of fibre. As said, we apply specific criteria to establish which recycling technology a certain item is treated with, although in most cases multiple pathways are applicable. It is important to consider that textile may be eligible for different recycling routes, as the efficiencies and environmental savings of different recycling pathways vary (Sandin & Peters, 2018).

While in the MFA we explore the best-case scenario for recycling, it is important to note that other pathways may also be applicable to a given garment. Table 4.3 highlights the applicability of the different recycling routes examined to each product category analysed in this study. Note that these qualitative assumptions are based on the share of garments per product category that are found to be eligible for recycling after passing the sorting steps required prior to fibre assessment (Logan et al., tbd). Thus, only mono-layered garments with no or treatable findings are expected to enter these recycling pathways. This means that distinctions across product categories are due only to differences in the average fibre types.
For example, across all product categories, mono-layer garments can generally be recycled via downcycling and mechanical recycling (Table 4.3). Monomer recycling is most applicable to more complex products which have high synthetic compositions, such as *suits and blazers*,

sportswear and swimwear and *handkerchiefs, ties, scarves, gloves, and other*. On the contrary, oligomer recycling is generally an accessible pathway for *trousers and shorts*, *dresses and skirts* and *t-shirts and vests*, which tend to have higher protein- and plant-based fibre contents. Wool recycling is most likely underrepresented partially due to the fact that the retail survey data are sampled on the spring/summer collection.

TABLE 4.3. Recycling technologies for which textiles from different product categories are eligible. Applicability is expressed through from lowest (dark red) to highest (dark green), as shown in the graded colour scale below the table.



In terms of product categories, when evaluating the recycling eligibility based solely on the fibre composition of the garments, *overcoats and anoraks*, *dresses and skirts* and *shirts, blouses and tops* appear to be suitable for a wider range of options compared to other types of textiles (Table 4.3). However, as mentioned, in order to set up the material flow analysis, recycling technologies are ranked in this report based on their substitution potential (see 3.3). Therefore, each garment is associated with a single recycling pathway which corresponds to the one leading to the highest substitution potential for that specific garment. Nonetheless, multiple alternatives exist to recycle an item, as different products consisting of different fibre compositions can be handled in various ways. Assigning a single recycling route to a garment by applying specific criteria is necessary for modelling purposes, but it does not reflect the actual market, which is in fact both highly versatile and resilient. This means that even if, for example, the *preferred* technology - as defined here - is not a viable pathway in Denmark for a specific item, other options would still be available to recycle it.

Table 4.4 presents an overview of the flows split according to the 10 different categories in case the recycling technologies are applied according to the ranking system adopted in this report. Apart from reuse, for which data are not available at the *product type* level, differences can be appreciated among the 10 groups in all other treatment options. These are related to the characteristics of the garment, which present similarities within the same product category and might vary across different product categories. For detailed analysis, we refer to Logan et al. (tbd). Please note that numbers shown in Table 4.4 should not be read as how many garments are recyclable, in absolute or relative terms, according to the single technology, because they display a scenario where a specific ranking system is applied.

Table 4.4. Potential recycling per category. Values are expressed in tonnes (t). Relative shares are calculated within the product category. Note that values are rounded and might not add up to the total. *Mech. Recycling = mechanical recycling.

	Overcoats and anoraks	Suits and blazers	Trousers and shorts	Dresses and skirts	Shirts, blouses, and tops	Underwear, socks, and night clothes	T-Shirts and vests	Sweaters and cardigans	Sportswear and swimwear	Handkerchiefs, ties, scarves, gloves, and other	**Total**
Reuse	2374	1185	5713	1229	964	1597	2525	3409	3339	603	**22937**
	44%	44%	44%	44%	44%	44%	44%	44%	44%	44%	**44%**
Monomer recycling	108	19	222	134	116	7	61	124	304	17	**1113**
	2%	1%	2%	5%	5%	0%	1%	2%	4%	1%	**2%**
Oligomer recycling	89	6	993	231	191	22	764	292	22	13	**2623**
	2%	0%	8%	8%	9%	1%	13%	4%	0%	1%	**5%**
Polymer recycling	0	0	5	4	1	3	0	0	5	0	**19**
	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	**~0%**
Wool recycling	6	0	53	3	17	5	18	190	11	7	**310**
	0%	0%	0%	0%	1%	0%	0%	2%	0%	0%	**1%**
Mech. recycling*	22	12	579	87	52	105	208	307	141	10	**1521**
	0%	0%	5%	3%	2%	3%	4%	4%	2%	1%	**3%**
Downcycling	516	549	728	85	55	95	171	394	645	58	**3298**
	10%	20%	6%	3%	3%	3%	3%	5%	9%	4%	**6%**
Incineration	2268	915	4662	1013	789	1788	1978	3013	3103	660	**20189**
	42%	34%	36%	36%	36%	49%	35%	39%	41%	48%	**39%**
Total	**5382**	**2687**	**12955**	**2786**	**2185**	**3622**	**5724**	**7729**	**7570**	**1368**	**52009**

Oligomer and monomer recycling are mainly suitable for garments containing high content (>80%) of cellulose and polyester, respectively. Potentially 5% of the overall clean and dry clothes collected from household could be recycled through oligomer recycling, while 2% could potentially be suitable for monomer recycling. These shares differ a lot across product types. Among the categories presenting higher shares of products eligible for oligomer recycling, we find mainly *t-shirts and vests, trousers and shorts*, *shirts, blouses and tops* and *dresses and skirts*. The last two show also greater amounts of clothes potentially recyclable through monomer recycling compared to the overall average, together with sportswear and swimwear.

Wool recycling could potentially be applicable for about 1% of the sorted textiles, mostly *sweaters and cardigans*. In any case, as mentioned above, woollen garments are most likely underrepresented due to the seasonality of the retail survey.

All textiles with a leading fibre content higher than 60% are considered eligible for mechanical recycling (Logan et al., tbd). Thus, the relative low share (3%) of potentially mechanically recycled garments is linked to the prioritization made.

In terms of downcycling, the category *suits and blazers* presents a much higher share of products (20%) compared to that estimated at the total clothing level (6%). This is mainly due to

the big portion of multi-layer garments in this group. A similar consideration is true for *overcoats and anoraks* and *sportswear and swimwear*, although to a lower extent. On the contrary, within categories *dresses and skirts*, *shirts, blouses, tops*, *underwear, socks, and night clothes* and *t-shirts and vests* the share of products sent to downcycling is about half (2-3%) compared to the overall average (6%).
Finally, incineration is required for about 39% of the garments collected via the 2nd stream and sorted according to the criteria mentioned, mostly because of the dirty/wet/contaminated fraction. It is worth observing that categories *underwear, socks, and night clothes* and *handkerchiefs, ties, scarves, gloves, and other* show a notably higher fraction of items sent to incineration, mainly due to the presence of complex findings.

4.4.3 Substitution potential

The substitution potentials can be used in combination with the results of the MFA to estimate the amount of virgin material that could potentially be substituted by the recycled post-consumer textiles collected via the 2nd stream in Denmark. Table 4.5 below gives an overview of such substitution potential, and it is essential to keep in mind that the feedstock that could be replaced refers to *fibres*, and not to *textiles*.

TABLE 4.5. Combined results with MFA of materials to recycling, and the substitution potential at the aggregated level. Values are presented in tonnes (t). *The substituted fibre may differ from the fibre that constitutes the correspondent recycled textile material.

Recycling method	Textiles to recycling	Feedstock substitution potential
Monomer recycling	1113	~100%
Oligomer recycling	2623	<100%*
Polymer recycling	19	<100%
Wool recycling	310	<80%
Mechanical recycling	1521	10-35%

The clothes estimated to be reprocessed via monomer recycling (1,113 tonnes) could potentially substitute a similar amount of the same type of virgin fibre they are made of once the recycled monomers are polymerised and the fibres are formed. In the present setup, most garments (2,623 tonnes) would go through oligomer recycling, which is associated with a hard-to-estimate feedstock substitution potential. A similar case is presented by polymer recycling, although with the chosen prioritization of recycling technologies only a limited amount of textile is assumed to be treated this way. Recycling of wool also covers a minor share of items, but the relatively high substitution potential associated with it could replace up to 248 tonnes of virgin woollen fibres. Lastly, roughly 27% of the textiles sent to recycling are treated mechanically. However, given the limited substitution potential, these could replace only between 152 and 532 tonnes of virgin fibres of similar type.

Overall, it is estimated that between 4,155 and 4,535 tonnes of virgin fibres of different types could be replaced by recycled post-consumer clothing, assuming the peak substitution potential of 100% for chemical recycling methods. This represents between 74 and 81% of the weight of the theoretically recyclable garments, meaning that pre-treatment steps required prior recycling are responsible for an additional 19-24% of mass loss of the clean and dry, non-reusable items collected via the 2nd stream. However, these values need to be interpreted keeping in mind the assumptions made (3.4), and the fact that they reflect an “optimal” scenario, and as such should not be read as a snapshot of reality.

4.5 Textile recycling technologies

This section provides further insights on textile recycling technologies as considered in this report, presenting technical barriers and opportunities of chemical and mechanical methods (4.5.1), some considerations on the associated potential environmental impacts (4.5.2), and an initial overview of trade-offs between the two (4.5.3).

4.5.1 Barriers and opportunities of textile recycling technologies

The various technologies available for recycling textile differ in the feedstock substitution potential of their recycled products, scale, economic viability, and flexibility in input feedstock requirements, to cite a few. Table 4.6 provides an overview of main advantages and disadvantages that are specific to the technologies evaluated for this report (non-exhaustive list), which are available in literature.

TABLE 4.6 Overview of main advantages and disadvantages of recycling technologies assessed in this report (non-exhaustive list). Reference sources can be found at the bottom of the table.

Recycling technology	Advantages	Disadvantages
Chemical recycling (monomer)	High substitution potential[1,2,3,4,8] Can handle certain fibre blends[2,5,6] Easier removal of contaminants[12] Allows the recycling of low-quality fibres[2,5]	Long processing chain[2,3] Long residual value chain[3] Few industry-scale processes[1,6,8] Expensive process[1,2] Efficiency of the process depends on purity of input material[2,5] Currently only for synthetic fibres[8] Specific feedstock requirements[1,2,5] High consumption of chemicals, water, and energy[2,5] Generation of chemical waste[2] Less suitable for post-consumer textiles[1,7]
Chemical recycling (oligomer or polymer)	Potentially high substitution potential[1,2,3] Can handle certain fibre blends[2,5,6] Applicable to cellulosic, synthetic, and mixed fibres[8] Easier removal of contaminants[12] Allows the recycling of low-quality fibres[2,5]	Long processing chain[2,3] Long residual value chain[3] Few industry-scale processes[1,6,8] Expensive process[1,2] Efficiency of the process depends on purity of input material[2,5] Specific feedstock requirements[1,2,5] High consumption of chemicals, water, and energy[2,5] Generation of chemical waste[2] Less suitable for post-consumer textiles[1,7] Additional input of virgin feedstock[2,8]

Mechanical recycling	Well-established technology[1,6,8,11] Applicable to a large selection of fibres[1,2,5,8] Scalable process[2,8] Short processing chain[2] Economically viable [2,5,6,8,11] No or little use of chemicals[2] Low energy consumption [2,5,7]	Low substitution potential[1,2,5] Quality of recycled fibres depends on quality of input material[1,2,5] Deteriorates fibre properties[1,2,5,6,9] Often results in downcycling[1,2] Can hardly handle fibre blends[2,5,9,11] Challenged by presence of contaminants and findings[2,5,7,8,9,12]

[1] Eppinger, 2022; [2] Loo et al., 2023; [3] Piribauer & Bartl, 2019; [4] Harmsen et al., 2021; [5] Duhoux et al., 2021; [6] van Duijn et al., 2022; [7] Aronsson & Persson, 2020; [8] Ribul et al., 2021; [9] ETC/WMGE, 2019; [10] Roos et al., 2019; [11] Damayanti et al., 2021; [12] Le, 2018

These observations are made on a generic basis, e.g., chemical monomer recycling, without going into detail with the specific process applied, such as hydrolysis, glycolysis, enzymatic hydrolysis (Damayanti et al., 2021; Loo et al., 2023; Piribauer & Bartl, 2019).

Chemical recycling

Chemical recycling methods reduce textiles to their base components, i.e., monomers, oligomers, or polymers, which can then be used to make new fibres (Eppinger, 2022; Harmsen et al., 2021; Köhler et al., 2021; Loo et al., 2023). The potential to substitute virgin monomers/oligomers/polymers can be very high, achieving rates up to 100% in case of monomer recycling, which however is currently only applied to synthetic fibres (Duhoux et al., 2021; Harmsen et al., 2021; Ribul et al., 2021). Oligomers/polymers reach lower substitution potentials that are hard to define, as they need to be mixed, to a certain extent, with virgin resources (Girn et al., 2019; Harmsen et al., 2021; Loo et al., 2023), since the process often degrades the polymer chain (Damayanti et al., 2021; Ribul et al., 2021). For example, with regards to cellulosic fibres, while some technologies process 100% waste, most of them add significant portions of virgin wood pulp to achieve better fibre properties (Damayanti et al., 2021; Duhoux et al., 2021), thus it is not sure how much textile waste is necessary to produce a certain amount of recycled material, nor the share of virgin sources saved. In addition, also in case of monomer recycling some material is lost during the process, so despite the quality of the recycled product matches the quality of its virgin counterpart, a 1:1 substitution is most likely not achievable (Ribul et al., 2021).

In any case, going back to restoring the original monomer/oligomer/polymer means that the textile processing chain has to be redone almost completely, and a significant amount of resource is used to do so (Bartl, 2020; Boschmeier, Ipsmiller, et al., 2023; Harmsen et al., 2021; Hermary, 2023; Piribauer & Bartl, 2019). Repeating the early steps of the value chain, i.e., prior to the production of the fibre, also implies additional material losses throughout the processes that are required to create the final product. On the other hand, the final recycled fibre approaches virgin qualities (Damayanti et al., 2021; Harmsen et al., 2021).

Chemical recycling technologies entail relatively long processing chains, usually involving several steps, and often result in expensive processes and a high consumption of chemicals, energy, and water (Duhoux et al., 2021; Eppinger, 2022; Loo et al., 2023; Piribauer & Bartl, 2019). Nonetheless, chemical treatment might be the only option to recycle degraded or contaminated polymers and heavily damaged fibres that cannot be handled by other technologies, as even if the fibre structure is compromised, it still might be possible to go back to the polymer/monomer level and recover the base components (Duhoux et al., 2021; Karell & Niinimäki, 2019; Pensupa, 2020). Since the presence of contaminants (e.g., dyes and fabric finishes) in the input material can affect the efficiencies of the process, textiles must be cleaned and pre-treated prior to the actual chemical reactions (Damayanti et al., 2021; Harmsen et al., 2021; Le, 2018; Loo et al., 2023; Ribul et al., 2021). These steps might be crucial because they can affect the final yield (Damayanti et al., 2021) and already require the use of chemicals, which are then intensively applied during the recycling process itself.

The use of chemicals and the need for additional pre-treatment steps can be reduced if the purity of the input material is high (Loo et al., 2023; Wedin et al., 2019). This means that chemical recycling methods are especially indicated in case of homogenous fibre inputs, and as such, are better suited for industrial waste. Industrial waste can be relatively well-defined and homogeneous, since it can be collected as fibres, yarns, or fabrics, thus well before the garment is produced, and its fibre composition, processing chemicals, dyes, and finishes are usually known (Eppinger, 2022; Harmsen et al., 2021; Le, 2018), which allows for a more targeted, efficient removal of contaminants (Duhoux et al., 2021). For instance, many current methods of chemically recycled fibres are made from sources other than post-consumer garments, such as PET bottles or fishing nets (Bartl, 2020; Harmsen et al., 2021; Hemkhaus et al., 2019; Le, 2018), or use a certain percentage of industrial waste as feedstock (Palme, 2017).

With regards to fibre blends, chemical processes can potentially handle a wider range compared to mechanical methods, as technologies are being upscaled that enable the chemical separation of these materials for polymer and monomer recycling (Ribul et al., 2021). More specifically, some methods are currently available to recover fibres from polycotton blends (Duhoux et al., 2021; Palme et al., 2017; Ribul et al., 2021). This could help to increase notably the amount of textiles that are recycled, reducing the share destined to incineration or landfill, since a significant portion of textiles available in the market are composed of cotton and polyester (Loo et al., 2023). At the same time, separation often requires additional use of solvents, and the excessive use of non-recoverable chemicals, high temperatures and unwanted side reactions with the secondary fibre material can make these processes potentially not ecological or even impossible to operate (Piribauer & Bartl, 2019).
Another fibre that is commonly present in blended textiles but poses problems to recycling processes is elastane (Boschmeier, Archodoulaki, et al., 2023; van Duijn et al., 2022). Nonetheless, some recyclers claim to be able to overcome such issue (Duhoux et al., 2021) and processes are being developed that allow the chemical separation of elastane from other fibres (Boschmeier, Archodoulaki, et al., 2023).

Overall, available pathways for the chemical recycling of textile are promising on multiple levels, although in many cases the associated benefits are currently linked to considerable downsides. Technologies for chemical recycling of textiles are still in the development stage and scaling to achieve the technology (TRL) or manufacturing readiness level (MRL) necessary to handle the projected volumes of low-value, blended, post-consumer textiles that will be collected (Eppinger, 2022; Köhler et al., 2021; Loo et al., 2023; van Duijn et al., 2022). This is due, in part, to the associated high skill requirements as well as the great investment and processing costs (Eppinger, 2022). In recent years, innovative technologies have broken through to industrial scale (Duhoux et al., 2021; Eppinger, 2022), however, these alone are not enough, and while more are expected to expand capacity over the next few years (Girn et al., 2019; Köhler et al., 2021), significant investment and time will be required, which is a challenge towards meeting the needs of the impending 2025 collection deadlines.

Mechanical recycling
Mechanical recycling involves processes such as cutting, shredding, and opening of textiles into loose fibres, that can be used for both open- and close-loop recycling (Loo et al., 2023; van Duijn et al., 2022). Technologies for the mechanical recycling of textiles are well-established in the industry (Eppinger, 2022; Loo et al., 2023; Roos et al., 2019), and traditionally, textile waste has served as material input for this type of fibre recycling (Karell & Niinimäki, 2019). The mechanical process is relatively both energy- and cost-efficient (Damayanti et al.,

2021; van Duijn et al., 2022), as well as relatively easy to scale up (Loo et al., 2023; Ribul et al., 2021).

The technology generally consists of quite short processing chain and involve no or little use of chemicals, as the system is mainly based on physical forces (Duhoux et al., 2021; Loo et al., 2023). This also means that it is less suitable to handle chemically contaminated textiles, since hazardous substances would usually not be removed and would thus remain in the recycled material (Duhoux et al., 2021; ETC/WMGE, 2019; Le, 2018; Loo et al., 2023). Mechanical recyclers might therefore favour highly homogenous input textiles in both fibre type and colour, because the mechanical process does not include any intrinsic decolouration (Duhoux et al., 2021; Girn et al., 2019; Loo et al., 2023). Having multi-coloured textiles as input would eventually create multi-coloured fibres as an output, which would not be easy to market under current requirements as it would create low-quality yarn (Loo et al., 2023; van Duijn et al., 2022).

For some natural fibres, mechanical methods might be the only way to preserve the fibre type, as for example chemically recycled cotton would result in regenerated man-made cellulosic fibres (MMCF), e.g., viscose (Duhoux et al., 2021; Harmsen et al., 2021; Loo et al., 2023; Wedin et al., 2019), and not in recycled cotton fibres. In case of wool recycling, mechanical methods are currently the only available (Harmsen et al., 2021; Le, 2018).

While the chemical and most of the physical properties of the fibres are kept (Bartl, 2020; Loo et al., 2023), their length is highly compromised, since textiles need to undergo harsh treatment which results in shorter output fibres that might ultimately be impossible to re-spin into yarn (Damayanti et al., 2021; Eppinger, 2022; Lindström et al., 2020). Overall, mechanical recycling processes are thus associated with relatively low substitution potentials, as recycled fibres often need to be mixed with virgin ones to achieve a functional product that is comparable to one made from new materials (Celep et al., 2022; Girn et al., 2019; Karell & Niinimäki, 2019; Loo et al., 2023). Higher substitution potentials can in generally be achieved in case of mechanical recycling of wool compared to other fibres (Le, 2018; Russell et al., 2016).

Moreover, most findings need to be removed prior mechanical treatments (Celep et al., 2022; Damayanti et al., 2021; Girn et al., 2019; Ribul et al., 2021), which might further reduce the textile material ultimately available for recycling as well as decrease the quality of the output products that can still be made (Rossi, 2023). Some chemical recycling technologies, instead, do not necessarily require such pre-treatment (van Duijn et al., 2022), which could be seen as an advantage over mechanical methods. Nonetheless, chemical processes are often preceded by mechanical ones (Damayanti et al., 2021; Eppinger, 2022; Girn et al., 2019; Köhler et al., 2021; Sandin & Peters, 2018), and a large part of chemical technologies also implies removal of findings (Celep et al., 2022; Duhoux et al., 2021; Ribul et al., 2021), so in most cases such advantage would be lost.

In case of multiple fibre blends, a mechanical separation is generally not possible (Boschmeier, Ipsmiller, et al., 2023; Loo et al., 2023; Piribauer & Bartl, 2019), and most fibre-to-fibre recycling technologies currently at scale only accept textiles consisting of pure materials (Celep et al., 2022; van Duijn et al., 2022). When processing multi-material textiles mechanically, the recycled output would result in a mixtures of different fibre types (Duhoux et al., 2021; Loo et al., 2023), which might be a problem especially in case of blends of natural and synthetic fibres, as the shredding process deteriorates the ones more than the others (Caro et al., 2023; Damayanti et al., 2021).

Lastly, although in principle mechanical recycling can handle any type of fibres (Eppinger, 2022), for most technologies the presence of more than 10% of elastane can be problematic (Duhoux et al., 2021), and for some the threshold is as low as 1% (Boschmeier, Ipsmiller, et al., 2023).

4.5.2 Potential environmental impacts of different recycling options

Chemical and mechanical textile recycling technologies lead to environmental impacts of different nature, i.e., both *direct* and *indirect*, which affect different categories (e.g., climate change, water use, land use, ecotoxicity), and one should not fall in the temptation of trying to establish which option is the most sustainable in absolute terms. Moreover, categorizing textile recycling methods as either “mechanical” or “chemical” undermines the complexity and diversity of both established and emerging technologies, since mechanical and chemical processes are often combined to yield a high-quality recycled fibre (Roos et al., 2019; Sandin & Peters, 2018).

Direct impacts are those that are explicitly caused by the individual technology, such as energy consumption, use of chemicals, water use, water contamination. Alternatively, *indirect* impacts are those that are associated with aspects other than the technology itself, for instance to what extent the recycled product can substitute an equivalent one made of virgin materials. The potential environmental benefits and disadvantages linked to the different recycling methods lie in these impacts. While this study does not conduct a full life cycle assessment (LCA), which would be necessary to offer any comparison of the environmental performance of different recycling routes, it offers an overview of the potential challenges each pathway may face with regards to direct or indirect impacts.

Direct impacts

Direct impacts such as water and chemical usage are vital in modelling chemical textile recycling, which involves an intensive use of these resources (Duhoux et al., 2021; Loo et al., 2023; Piribauer & Bartl, 2019; Ribul et al., 2021), as well as high energy consumption (Duhoux et al., 2021; Loo et al., 2023; Ribul et al., 2021). Chemical substances are needed both during the pretreatment phase, as is the case of dyes removal (Duhoux et al., 2021; ETC/WMGE, 2019; Ribul et al., 2021), and during the actual reaction, for example, during chemical dissolution with specific solvents (Duhoux et al., 2021; Harmsen et al., 2021; Loo et al., 2023; Ribul et al., 2021). As most of the chemicals employed are toxic for the environment, water is needed not only for pre-treatment and cleaning of the textile waste, but also for later washing of the reaction products and the reaction agents (Loo et al., 2023; Ribul et al., 2021), resulting in both high water consumption and water contamination. Mechanical processes, instead, are associated with a relative low consumption of both energy and water (Duhoux et al., 2021; Loo et al., 2023), and unless colour removal needs to be performed, no use of chemicals is involved.

The two methods also differ in terms of value chains, not only with regards to the actual recycling procedure, where mechanical technologies rely on relatively few steps in opposition to chemical treatments, but also in terms of downstream processes (Harmsen et al., 2021; Piribauer & Bartl, 2019). In fact, chemical recycling requires restarting the textile production chain at the monomer/oligomer/polymer level, so well before the manufacture of the fibre, and many phases need to be repeated (Hermary, 2023; Piribauer & Bartl, 2019). The output of mechanical fibre-to-fibre recycling, instead, is in fact a new fibre. This thus means that chemical technologies are more resource intensive not only during the actual recycling, but also throughout the subsequent steps necessary to reprocess the monomer/oligomer/polymer into a new fibre.

The maturity of the technology and its operation capacity are, in contrast, key aspects to both mechanical and chemical pathways (Loo et al., 2023; Ribul et al., 2021). While the first are already at the industrial scale and are able to process big quantities of textiles, the latter are still mostly in the scaling phase both in terms of TRL and MRL (Duhoux et al., 2021; Loo et al., 2023; van Duijn et al., 2022). As mentioned, the scaling up of chemical recycling technologies is mainly challenged by the high investment and processing costs (Eppinger, 2022), although concerns also arise with regards to the recycled fibre qualities, since properties that can be achieved at the small scale might be difficult to repeat at full commercial scale (Roos et al., 2019).

Indirect impacts

With regards to indirect environmental impacts, it is important to assess the substitution potentials of the recycled material. Greater energy and water consumption, as well as the intensive employment of chemicals, are often required to reach greater substitution potentials, as is the case of chemical recycling. The direct impacts associated with a more severe use of resources may therefore be counterbalanced if a final recycled feedstock of higher quality is obtained which can ultimately avoid the production of larger amounts of virgin material (Roos et al., 2019).

Mechanical methods are, on the one hand, low-resource intensive, but on the other they often lead to poor quality output fibres (Duhoux et al., 2021; Eppinger, 2022; van Duijn et al., 2022). Poor quality fibres are those which are either not long enough to be re-spun, and thus need to be downcycled (Eppinger, 2022; ETC/WMGE, 2019; Loo et al., 2023, 2023; van Duijn et al., 2022), or which need to be blended with a significant quantity of new fibres to obtain a recycled product that can be compared to one made with virgin feedstock (Damayanti et al., 2021; Eppinger, 2022; ETC/WMGE, 2019; Loo et al., 2023; van Duijn et al., 2022). In the former case, the substituted product is usually of inferior value than the original one, and the environmental savings associated with its avoided production are in most cases lowered. In the latter, the substitution potential can be quite narrow, as the final product is often made of no more than 35% recycled fibres (Celep et al., 2022; Duhoux et al., 2021; ETC/WMGE, 2019; Niinimäki, 2018), while the rest derive from virgin sources (Damayanti et al., 2021; Eppinger, 2022; Harmsen et al., 2021; Ribul et al., 2021).

Also in case of chemical polymer recycling, virgin feedstock need to be added to a certain extent due to challenges/losses during depolymerization (Damayanti et al., 2021; Harmsen et al., 2021), and even if in the context of monomer recycling virgin-quality monomers can be obtained, the overall efficiency of the process will most likely be less than 100% (Ribul et al., 2021), and as such, more than one unit of textile waste fibres will be necessary to obtain one unit of recycled feedstock. However, the substitution potential of chemically recycled fibres is higher compared to mechanical recycled ones, as once the monomer/oligomer/polymer is reprocessed into fibres, the resulting quality approaches virgin standards (Ribul et al., 2021).

The significant loss of quality of mechanically recycled fibres also implies that the process can only be applied a limited amount of times (Ribul et al., 2021) as it degrades the properties of the textiles, especially with regards to fibre length (Eppinger, 2022; ETC/WMGE, 2019; Loo et al., 2023). Similarly, chemical recycling does not prevent the material from ageing, as the intrinsic monomer and polymer degradation still happens and, in some cases, current processes also affect the polymer chain (Duhoux et al., 2021; Harmsen et al., 2021; Ribul et al., 2021). Either way, recycling cannot take place infinitely, and it can only add few extra life cycles before the feedstock needs to be incinerated or landfilled (Roos et al., 2019).

Another type of indirect impact might be associated with the purity and the fibre composition of the collected textile waste, as the more homogeneous, uncontaminated, undamaged, and defined the input, the more efficient the process for both chemical and mechanical pathways (Duhoux et al., 2021). More specifically, a pure input feedstock can help reduce the need for pre-treatment in case of mechanical, but especially chemical recycling, for example reducing the need for dye removal processes in case of colour-sorted material or skipping separation processes in case of mono-fibre textiles (Roos et al., 2019). In both cases, a more efficient recycling process would take place, leading both to higher quality outputs with associated greater substitution rates and to savings in terms of resource use. As for mechanical recycling, where the quality of the recycled fibres strictly depends on the quality of the input material, a pure input feedstock can improve the efficiency of the overall process, resulting again in a final product of greater quality that has the potential to substitute higher amounts of virgin resources (Duhoux et al., 2021; Eppinger, 2022; Loo et al., 2023; Roos et al., 2019).

Finally, for any kind of textile recycling to happen, an effective waste management system of collection, sorting, and transport needs to be in place. While all these processes are associated with direct environmental impacts especially with relation to fuel consumption, the collection and the sorting phases can play a major role in the overall efficiency of the recycling process (Roos et al., 2019; Rossi, 2023; Sandin & Peters, 2018). For example, it is crucial to keep clothes dry and to prevent contamination of the pure fraction during the collection phase, since, as seen in 4.4.1, only dry and clean textiles are eligible for reusing or recycling practices (Roos et al., 2019; UFF-Humana, 2023). The specific collection method can already play a role in this, as for instance, bring banks are usually associated with higher collection volumes and lower costs compared with door-to-door pick-up, although they present more risks of polluting the collected textiles with household waste (Rossi, 2023; UFF-Humana, 2023; van Duijn et al., 2022). The sorting phase, on its part, is crucial to ensure that the best combination of processes is applied to a specific type of feedstock, since information such as the fibre composition or the mono- or multi-layer nature of a garment can influence the eligibility to different recycling pathways (see 4.4.2).

4.5.3 Trade-offs between recycling routes

With both chemical and mechanical solutions presenting significant differences in technical performance as well as with regards to environmental impacts, there is lack of consent about which recycling technology is the most promising in absolute terms (Eppinger, 2022). A single route is probably not going to solve the need for efficient textile recycling, and in order to maximize the circular potential of textile waste, a range of technologies must be applied, mechanical as well as chemical (Eppinger, 2022; Roos et al., 2019). A combination of different technologies is needed, and several types of combinations as well.

It is important to take into account that how various machines and technologies are combined depends on the input textile material as well as on the intended output, and that process parameters such as speed of drum rotation in the case of mechanical recycling, or which solvents need to be used in case of a chemical method, can be adjusted accordingly to optimize productivity and quality of the recycled product (Duhoux et al., 2021). This means that not *all* technology holders are able to process *all* kinds of textiles, and choices must be made, which leads to specialisation in certain waste streams (Duhoux et al., 2021; Piribauer & Bartl, 2019).

In order to supply the different recycling processes with suitable feedstock, a sound collection system coupled with efficient and material-specific sorting of textiles is a prerequisite (Karell & Niinimäki, 2019; Roos et al., 2019). For example, this report estimates that up to one third of the separately collected post-consumer textiles could be directly sent to incineration, without reaching the 2nd sorting step, solely because they are dirty or wet (4.4.1), and that after subsequent sorting, about an additional 20% of the non-reusable garments would potentially not be suitable for material recycling (4.4.2). As also observed in 4.4.2, of the 17% estimated to be available for material recycling, 7% are assumed to be eligible for chemical recycling in the form of monomer (2%) or polymer (5%) recycling, while 10% are mechanically recycled, resulting either in downcycling (6%) or in reprocessed fibres (4%). However, as mentioned, these values are obtained by applying specific criteria, i.e., associating each recycling pathway with specific feedstock requirements and prioritizing the technology with the highest expected substitution potential, although textile fibres can usually be recycled via multiple methods, opening to a wide range of opportunities.

To navigate through the various combinations and scenarios possible, it is important to consider both direct and indirect impacts, keeping in mind that major trade-offs can occur between these and those. As seen above, the greater substitution potential of the final recycled product achievable by chemical recycling technologies carries a higher resource demand compared to mechanical processes.

While investigating innovation in textile recycling pathways, considering how water and chemicals are treated and disposed of is crucial to evaluate the direct impacts of chemical technologies. For those recycling routes where pretreatment is essential, the selection of one method or the other can help lower the negative environmental effects associated with it, as well as influencing the quality of the recycled material (Damayanti et al., 2021; Fei et al., 2020; Ribul et al., 2021). The development of novel technologies that can rely on less harmful as well as lower amounts of chemicals could help reduce the direct environmental impacts that characterize the current chemical recycling methods. Similarly, it is key to evaluate the impact of the intensive energy usage related with chemical recycling technologies, as depending on the energy source adopted, associated environmental impacts may be mitigated.

With regards to indirect impacts, as the main benefits of recycling typically arise when it prevents, to some extent, the production of a functionally equivalent material made from virgin resource and the associated impacts (Roos et al., 2019; Sandin & Peters, 2018), the environmental advantages of recycling largely depend not only on what material that is replaced, but also on how much of it is replaced (Roos et al., 2019; Rossi, 2023; Sandin & Peters, 2018; Trzepacz et al., 2023). In case of downcycling, for instance, it is important to estimate the environmental savings related to the avoided production of e.g. wiping rags or insulation material, and when assessing the advantages of fibre-to-fibre recycling, it should be taken into account not only how much, but also which specific feedstock is substituted, as it would result in savings of different entities and with respect to different impact categories, as, for example, chemical recycling of cotton results in man-made cellulosic fibres.

In any case, the fact that mechanical methods deteriorate the fibre quality and often result in downcycling does not necessarily mean that they are less preferable from a waste hierarchy perspective compared to chemical recycling, and in this perspective, a cascade approach could be adopted, in which the textile waste is first recycled mechanically, and once the fibre is so shortened that it cannot be re-spun, it is sent to polymer, oligomer or monomer recycling (Sandin & Peters, 2018).

Overall, novel approaches to recycling should consider the role of fibre length, colour, requirements in terms of virgin materials, and feedstock composition, which are critical in determining the environmental benefits of the overall process. While these aspects are especially important in determining the environmental performance of innovative methods, all recycling technologies are constrained by considerations related to the environmental burdens of collection, sorting, pre-treatment, and transport activities. With regards to transportation, it is important to consider both where the recycling process takes place as well as what the final destination of the recycled product is, in order to properly account for impacts in a life cycle perspective. At the European level, it is estimated that currently a significant part of the separately collected textiles[11] is exported to third countries, and that about 48% of the textiles sorted in Europe are subsequently exported outside the EU, mostly to Africa and Asia, where they are then either reused, recycled, incinerated, or sent to landfill (Huygens et al., 2023). Traceability of the item thus becomes essential to ensure that the impact of the overall recycling process, including collection, sorting, and transportation activities, is not larger than the benefits of avoided production of virgin material (Roos et al., 2019; Sandin & Peters, 2018).

Considerations should therefore not be done only on one aspect or the other, and a holistic view should rather be kept, focusing on specific typologies of textiles without attempting to find

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[11] Please note that these values include both reusable and non-reusable, recyclable textiles, as no distinction was made for the two streams for the reference study. Post-consumer textiles collected from municipalities, charities organizations, social enterprises, second-hand shops and retail companies (via take-back schemes) are included in the assessment (Huygens et al., 2023).

the same solution for the many kinds of materials present in the market. As such, there is currently no absolute best technology (Piribauer & Bartl, 2019), and both recycling methods will likely be necessary, requiring further improvements to process post-consumer waste more efficiently and the application of a set of different processes depending on the type and condition of the end-of-life textiles, in order to achieve the best possible environmental protection, benefit and the highest economic efficiency (Boschmeier, Ipsmiller, et al., 2023; Eppinger, 2022). In any case, when addressing the impact-reduction potential of textile recycling in relation to the overall environmental burden of the textile industry, it should be kept in mind that recycling is but one of many possible interventions, and although it is expected to play a key role towards making the overall practice more sustainable, it should not become a justification for maintaining unsustainable activities elsewhere in the value chain (Roos et al., 2019).

5. Conclusions and potential for improvement

This section provides an overview of main discussion points with relation to the primary assumptions made and limitations/applicability of the study (5.1) as well as a set of potential guidelines that could help increasing the recycling rate of post-consumer textile waste collected from households in Denmark (5.2).

5.1 Discussion points and limitations of the study

A certain amount of recyclable textile does not necessarily translate into the same amount of recycled material

The outcome of the MFA is based on specific, subsequent sorting criteria applied to the estimated annual clothing supply, leading to a projection of the flows of recyclable textiles. However, *recyclable* does not mean a garment will actually be recycled, or even accepted by recycling companies (Logan & Damgaard, 2022; Roos et al., 2019). For example, some textiles might be so worn that, despite meeting all the eligibility criteria considered for this study, the fibre is, in practice, not recovered. Furthermore, the flow of textiles collected through the 2nd stream is estimated assuming that all discarded textiles which are not collected for reuse (1st stream) are sorted out in the 2nd stream. Still, experience from other waste fractions show that this is not to be expected, as the sorting efficiency will most likely be lower than 100% (Kromann et al., 2019). Therefore, assuming sorting efficiencies equal recycling efficiencies is an overestimation, and rather represents an “optimal scenario” of the recycling potential. Future research should consider the substitution of the fibre based on the quality of the recycled materials, as the wear of the garment may impact the fibre length which in turn would decrease the spinnable fibre or weaken the final yarn (Sandin & Peters, 2018; Trzepacz et al., 2023).

Mechanical recycling and downcycling processes are in reality the most used

The prioritization of recycling pathways adopted in this report is based on the assumed feedstock substitution potential of the recycled material, thus favouring chemical methods over mechanical ones. In reality, most clothes are recycled mechanically and/or downcycled. When textiles are treated mechanically to obtain recycled fibres, the substitution potential of such fibres is low, due to, among other aspects, the harsh treatment they undergo (Aronsson & Persson, 2020; Eppinger, 2022; Köhler et al., 2021). For this reason, mechanical recycling is, in fact, often downcycling, in which case textiles are reprocessed into materials of lower quality, without replacing the production of new fibres (Köhler et al., 2021; Trzepacz et al., 2023; van Duijn et al., 2022). About 95% of the recovered fibres are in fact not re-spun into yarn, but are directly processed into nonwovens, because if the lengths of the fibres after the disintegration are too short, re-spinning into yarns is not possible (Eppinger, 2022; Piribauer & Bartl, 2019). This means that the environmental savings should be estimated in association with the avoided production of materials other than textile fibres, yarns, or garments. Since the main benefits of textile recycling are seen to be arising typically when it prevents the production of a functionally equivalent material made from virgin resources (Roos et al., 2019; Sandin & Peters, 2018), it is key to understand what is actually replaced by the recycled post-consumer garments.

Limited primary data available on the first two sorting steps (manual sorting)
Data relative to the 1st (*clean & dry* or *dirty/wet/contaminated*) and 2nd (*reusable* or *non-reusable*) sorting steps are retrieved from a pilot study conducted across three collectors (UFF-Humana, 2023). This is a limited sample set which is not to be deemed representative of Denmark, as differences may arise depending on the specific collection method and in association with different waste management systems, for example in the share of wet textiles (Rossi, 2023; UFF-Humana, 2023; van Duijn et al., 2022). In addition, marketing approaches vary across sorting centres, which influences whether items will be reused, recycled, or regarded as waste (Nørup et al., 2018).

There is a need to expand survey studies to increase knowledge and availability of primary data
The material flows and the final values calculated in this study, which represent *how much* of *what type* of garment could potentially be recycled *through which* specific technology, should not be seen as a “snapshot” of reality. For example, the set of data used to build the MFA is only representative of the Danish retail fast fashion market for the spring/summer season in 2022. While the year might affect the product categories sampled to a limited extent, seasonality is likely having an impact on the types of garments available, as well as on their fibre composition. This is a limitation of the study, although it is what could be achieved with the current knowledge, and it underlines the need for studies to expand such knowledge as well as for extensive retail surveys to increase the primary data available.

Economic and social aspects are not taken into account
This report focuses on the technical and environmental aspects related to recycling of post-consumer textiles, while economic and social matters are not discussed in detail. In any case, until demand for post-consumer recycled textiles increases, recycled yarns and fabrics could ultimately be more expensive than their virgin counterparts (Eppinger, 2022; Roos et al., 2019). Considering that the price of virgin fibre is relatively low, recycling costs need to be contained to make the industry economically attractive (Huygens et al., 2023; Pensupa, 2020). In addition, social aspects such as consumer purchasing habits should also be considered when evaluating the environmental savings of textile reuse and recycling (Piot, 2022). As mentioned, to what extent such practices can benefit the environment highly depend on how much of the virgin production is displaced, and the presence in the market of a recycled product does not necessarily imply that the acquisition of the one will replace the purchase of the other (Nørup et al., 2019c; Roos et al., 2019).

5.2 Guidelines and potential for improvement

The textile recycling value chain consists of many different processes and involves various types of actors, from the citizen disposing of used clothing at their household to the new fibre reprocessed at the recycling facility. Based on our research, we propose the following potential improvements guidelines, structured according to the specific process and the associated relevant actors. Although the present report focuses on the recycling potential of discarded post-consumer textile, earlier life cycle stages play a key role both in terms of waste prevention, which is at the top of the waste hierarchy, and with regards to their influence in downstream recycling processes. Therefore, aspects that are related to the design, manufacture, and use of textiles are also included here, and addressed in 5.2.1, while a focus on the recycling value chain is offered in 5.2.2.

5.2.1 Prevention, production, consumption

Process: Design, manufacturing, and retail
Relevant actors: Designers/manufacturers
Potential for improvement:

- Minimise the utilisation of fibre blends to the extent possible, prioritising mono-fibre yarns if keeping a similar quality is feasible.

- Minimise the utilisation of multi-layers to the extent possible, prioritising mono-layer garments if keeping a similar quality is feasible.
- Minimise the utilisation of findings to the extent possible, prioritising the application of removable or repairable ones.

Process: Clothing purchasing, use, and disposal
Relevant actors: Citizen/consumer
Potential for improvement:

- Practice mindfulness in purchasing new clothing, reducing the consumption, and prioritizing the acquisition of second-hand textiles. When purchasing new garments, look for items with three or fewer fibre types on the care label.
- Purchase garments with fewer or repairable findings (e.g., buttons instead of zippers), and seek repair before disposal.
-

5.2.2 Recycling value chain

Process: Home sorting and collection
Relevant actors: Municipalities; charities and private organizations
Potential for improvement:

- Collaborate to provide clear and easy guidelines for consumers regarding which textiles are accepted, criteria for clean and dry collections, and when to sort for reuse versus waste.
- Municipalities to implement home sorting criteria so that the citizen, when in doubt, sorts used textiles together with the 1st stream, leaving the judgement to trained personnel. If the item is not deemed reusable, it will anyway be sorted for recycling. This could lower the overall quality of the 1st stream but could help minimizing recycling garments that could have been reused.
- Municipalities to implement home sorting criteria to focus on reducing the share of wet/dirty/contaminated textiles collected from households via both the 1st and 2nd collection streams, and to ensure that the collected material remains both dry and clean throughout collection. This could reduce the amount of clothing sent to incineration due to contact with wet and/or contaminated textiles.
- Municipalities to implement home sorting criteria to guide the citizen through clear communication of accepted fibre content ranges, using the labels on textiles during source separation in order to harmonise the material composition of textiles collected for recycling as well as discouraging them from removing the tags.
- Municipalities to implement home sorting criteria to encourage the citizen to donate their re-wearable garments to charities and private organizations, at bring banks or over shop counters. With the introduction of a two-stream system, containers dedicated to textile waste may become easier to reach, which could risk diverting to recycling also textiles that would be suitable for reusing.
- Municipalities could play a role in understanding the feedstock available at the Danish household level, for example by setting up retail surveys and wardrobe research initiatives to investigate the average composition of a Danish wardrobe.

Process: Manual sorting
Relevant actors: Municipal waste companies; charities and private organizations
Potential for improvement:

- Collaborate to provide clear and easy guidelines for manual sorters regarding which textiles should be reused, recycled, or regarded as waste, in order to harmonize marketing approaches.
- Manual pre-sorting to prioritize reuse, and to ensure that textiles which are highly contaminated with findings as well as textiles with complex fibres are directly sent to incineration, avoiding diverting them to recycling practices.

- Elastane is problematic in most cases and should be diverted away from recycling already in the pre-sorting phase, as it cannot be easily detected by currently available automatic sorting facilities.

Process: Fine sorting for recycling
Relevant actors: Sorters; yarn recyclers; municipal waste companies
Potential for improvement:

- Align and develop clear communications on sorting criteria based on technologies currently available and not on potential future efficiencies.
- Clear communication about accepted fibre type as well as ranges of acceptable contamination based on the specific recycling technology.
- Clear communication about recycled output material and about what virgin feedstock as well as how much of it can potentially be replaced.
- Transparency about intermediate as well as final destination of the textile waste and of the recycled material.
- Transparency about energy requirements as well as source of energy adopted to run the operations needed.
- Since findings pose a problem to both technologies and need to be removed, prioritize sorting/recycling technologies that can handle them.
- In line with the work done by van Duijn et al. (2022):
    - Strive to provide open access to data that have the potential to support and direct investment into necessary infrastructure.
    - Update and utilise the Recycler's Database[12], an overview of currently one hundred recyclers across the world aiming to provide insights into current and potential end market for sorted post-consumer textile waste which can help to build knowledge about mechanical and chemical recycling options.
    - Increase communication with relevant stakeholders to design products for recyclability without deprioritizing design for durability and longevity.
    - Replicate analysis of textiles in focus countries and beyond to create even more reliable insights into the characteristics of post-consumer textiles and their suitability for recycling.

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[12] https://airtable.com/shr4HXLP5MoJLQ8Bf

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Appendix A

Appendix A.1 Clothing product groups for calculations and presentation

The Combined Nomenclature (CN) is a tool for classifying goods set up to meet the requirements of both the Common Customs Tariff and the EU's external trade statistics[13]. The system has various levels of aggregation of product types. The detailed 8-digit level comprises many thousands of different product groups while at the 2-digit level contains roughly 100. The textiles we are interested in for this project, clothing used in the private sector, are covered by 2 different 2-digit codes; 61 and 62. At the detailed 8-digit CN product disaggregation level, products are divided not only by type and function but also by fibre type. We have used this level of detail for calculations of textile supply, and we selected products mostly based on Logan et al. (2023). However, it should be noted that these codes are only used to set definitions for sampling guidelines, and not to gain an exact accounting of the market. This might result in some discrepancies between such codes and the codes available in Denmark statistics. These are noted in the table below.

The categories selected for this report at the detailed 8-digit CN product disaggregation level amount to 311. For presentation of results in Table A.1 we group some of these together in 10 different product groups. For example, there is no need to distinguish between men's/boys' coats and women's/girls' coats or between crocheted and non-crocheted coats. This is in line with Watson et al. (2018).

TABLE A.1 Overview of selected product groups presented at the 4-digit CN product disaggregation level. *Sub-codes changed over the years.

Product group	4-digit CN Codes
Overcoats and anoraks	6101, 6102, 6201*, 6202*
Suits and blazers	6103-1 to 3, 6104-1 to 3, 6203-1 to 3, 6204-1 to 3
Trousers and shorts	6103-4, 6104-6, 6203-4, 6204-6
Dresses and skirts	6104-4 to 5, 6204-4 to 5
Shirts, blouses, tops	6105, 6106, 6205, 6206
Underwear, socks, night clothes	6107, 6108, 6115, 6212, 6215
T-shirts, singlets and vests, hoodies, and crewnecks	6109
Sweaters and cardigans	6110
Sportswear and swimwear	6112, 6114[14], 6211[15]
Handkerchiefs, ties, scarves, gloves, and other	6116, 6117, 6213, 6214, 6216, 6217

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[13] https://taxation-customs.ec.europa.eu/customs-4/calculation-customs-duties/customs-tariff/combined-nomenclature_en

[14] Not included in Logan et al. (2023)

[15] Only a selection included in Logan et al. (2023)

Appendix A.2 Clean & dry, dirty/contaminated/wet, reusable, non-reusable textiles

Data regarding the fraction of clean & dry and dirty/wet/contaminated, as well as reusable and non-reusable garments collected through the 2nd stream are based on a pilot project carried out by UFF-Humana Denmark. Table A.2 presents the data as retrieved from UFF-Humana (UFF-Humana, 2023). The data have been adjusted to exclude non-apparel textiles, namely shoes & bags, other waste, feathers & down and plastic bags, this does not entail that the materials are not sent for recycling, just that they are exempt from this study. Reuse and recycling refer to textiles that are found to be both clean and dry, while textile waste and wet textiles are suitable for incineration, as described below.

TABLE A.2 Overview of textile waste sorted by UFF-Humana Denmark (manual sorting). Light grey values indicate products excluded from this report.

Classification	Textiles (kg)	Relative share
Reuse	7,254	39.1%
Recycling	3,630	19.6%
Shoes & bags	1,560	8.4%
Non-recyclable textile waste	3,568	19.2%
Other waste	170	0.9%
Feathers & down	196	1.1%
Plastic bags	167	0.9%
Wet textiles	1,997	10.8%
Total (kg)	18,542	

Reuse: all functionally reusable textile items as well as recyclable textile items that do not meet sorting instructions provided by SIPTex[16] (IVL Swedish Environmental Research Institute, 2022).
Recycling: recyclable textiles according to criteria by SIPTex.
Non-recyclable textile waste: dry textile waste that cannot be recycled. For incineration.
Other waste: flea market items, any waste belonging to the other 9 standard waste categories.
Feathers & down: dry duvets & pillows in a proper condition. For reuse/recycling.
Plastic bags: packing material (e.g., the special red bags for textile waste). For recycling.
Wet textiles: humid/wet textiles, regardless of cleanliness. For incineration.

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[16] Swedish innovation platform for textile sorting. See recycling criteria at https://www.sysav.se/foretag/sorteringsguiden-for-foretag/fraktion/textil/textil

Recycling potential of separately collected post-consumer textile waste

This project evaluates potential material available for recycling from post-consumer garments, separately collected in Denmark. By analysing import and export flows of textiles, the total clothing supply to Danish households in 2022 is calculated. The eligibility of garments for recycling is then mapped using material flow analysis (MFA), which is supported by the application of pre-determined sorting criteria. This report finds that ~11% (5586 tonnes) of garments in Denmark are eligible for textile-to-textile recycling. In addition, findings indicate that ~34% of garments collected through the second stream end up incinerated due to contamination, while 44% are reusable.

A wide range of options are available to treat different types of garments of different fibre composition, and the evaluation of the associated pros and cons can be done following a various set of criteria. Both mechanical and chemical recycling methods will likely be necessary in different combinations, requiring further improvements to process post-consumer waste more efficiently. This report concludes that although various treatment options exist, there is no absolute best practice for textile recycling due to the composition and sorting capacities available to Denmark today. However, improving communication among stakeholders and providing clearer sorting guidelines could be essential steps for increasing recycling rates of post-consumer textile waste.

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