European Commission

Study on the technical, regulatory, economic and environmental effectiveness of textile fibres recycling

Final Report

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Abstract

The findings of this study can be used as evidence base to improve the knowledge of the effectiveness of recycling capabilities of textile waste. This study wants to substantiate the understanding of the existing technologies industrially applied or at research stage, which relate to all the different types of recycling (e.g. mechanical recycling, chemical monomer recycling, chemical polymer recycling, etc.). It also provides an analysis of the economic and environmental effectiveness of those recycling technologies and a roadmap of the textile recycling technologies under development in order to support their industrial uptake. Finally, it also provides an analysis on relevant policy initiatives in order to tackle potential regulatory barriers and scale up textile waste recycling activities in the EU.

Executive summary

One of the main objectives of the Commission is to reinforce the competitiveness of EU textile and clothing industry, while advancing its green and digital transformation. The general objective of this initiative is to increase resource efficiency and help EU researchers and European textile and clothing industry, emerge as global leaders in the nascent circular business models and technologies related to recycling, by providing substantial knowledge about the state of play and state of art, opportunities and negative side effects of textile recycling. The **objectives** of this study are to (i) improve the knowledge about opportunities and challenges of textile waste recycling technologies, developed and applied at global and EU level with regard to their technical feasibility and maturity for market uptake and, economic and environmental effectiveness, (ii) identify promising areas for future research and innovation projects and necessary steps to support the industrial uptake of textile recycling technologies already under development and (iii) provide policy makers with an in-depth analysis of existing regulatory barriers and present alternative policy options to improve and scale up textile waste recycling activities in the EU.

Overview of textile fibres recycling technologies

Mechanical recycling is a process based on physical forces, which may be used in isolation for fabric or fibre recycling or as pre-processing for thermo-mechanical or chemical and biochemical recycling processes. The recycling technology is currently at Technology Readiness Level 9 (TRL 9) and is an established technology in the market with already decades of experience, for example, for wool in the Prato region in Italy or other natural fibres (cellulose-based such as cotton, jute, sisal, flax, etc.) and also synthetic fibres (polyester, polyamide, acryl, viscose, PP, etc.) in various European regions (Belgium, France, Germany, Sweden, etc.). The survey conducted among technology holders revealed a wide range in production capacities, going from 5 000 to 10 000 tonnes/year to as much as 36 000 tonnes per year. New developments, starting from TRL 7, are mainly focusing on increasing the amount of spinnable fibres and improving the quality of the fibres that are recycled. These developments mainly focus on adjustments to the machinery or recycling line set-up, additional (chemical) treatments and better sorting of the input material. The main advantages of mechanical recycling is that it can process practically any textile waste stream (material and structure), it can handle relatively small quantities of waste material, requires a relatively low level of investment and space and less highly skilled personnel than chemical recycling technologies. The process uses a relatively low number of resources. In a mechanical recycling process, the original properties of the fibre remain although this might be altered depending on the state of the fibre. (Hazardous) chemicals such as additives, dyes, finishes, etc. present in textile products (both through production and product use) can not be removed in a mechanical recycling process and stay in the output. The remaining of colorants in the output fraction might be experienced as a disadvantage. Next to this it is difficult to claim conformity to certain legislation like REACH and on textile fibre names and related labelling and marking of the fibre composition of textile products. The outputs of the mechanical recycling process are spinnable fibres, fluff, filling materials and dust. The fraction of spinnable fibres, which are fibres long enough to be respun in to yarn, is 5-20% of the textile material input in case of natural fibres (e.g. cotton) and 25 – 55% of textile material input in case of polycotton or polyester. Polyamide is practially not recycled via mechanical recycling. The quality of these fibres depends on the input product's quality, but is lower than the quality of virgin fibres. Mechanically recycled fibres can replace virgin cotton fibres, but need to be blended with virgin material to reach a yarn of an acceptable quality. The remaining output fraction (fluff, filling materials and dust) has a lower quality than the spinnable fibre fraction and can be used in the non-woven industry, as a filling material or as reinforcement in composites of artificial material or burned with energy recovery.

Thermal recycling is a process based on heating with the aim to recover either polymers or low molecular weight building blocks. A distinction is being made between thermo-mechanical recycling and thermo-chemical recycling.

Thermo-mechanical recycling is a process used in a recycling system that melts a polymer, typically employed to permit polymer recycling. These are technologies for recycling thermoplastic textiles, e.g. polyester, polyamide, polypropylene, etc. by melt processing them into a regranulate and/or new fibres. The process is similar to melt processing of virgin material (with the exception of shredding, cleaning, feeding and degassing steps), even more similar to the more established mechanical recycling of solid plastic waste. It is also a cost-effective, efficient and well-known process which means it can be easily implemented. This recycling process is particularly interesting for the recycling of production waste and some specific consumer waste that has been collected in specialized centres. One of the consulted technology holders, with a current production capacity of 5000 tonnes/year expects to reach TRL 7 soon for post-industrial textile waste. However, the addition of virgin material is required and only a limited amount of recycled material will be present in the final fibre. One of the technology holders blends 20% of recycled polyester with virgin material. Further research will be done in an attempt to use chemicals to increase the quality of the polymer. TRL 9 is expected to be reached by 2022/2023, with still a limited percentage of recycled content and the same input material limitations. The recycling of blends of thermoplastic materials into hybrid yarn is being investigated, although currently at low TRL (2-3). Fibre spinning is a very delicate process and the presence of even a small amount of an incompatible polymer can cause problems in processing and reduce output properties. The practice of using compatibilizers is being studied for thermo-mechanical recycling of textiles to mitigate the immiscibility of polymer blends. Other contaminants such as pigments, prints, wash residues, flame retardants, coatings, etc. that are present in or on the fibre or textile, can also hinder the spinning process and/or result in severely reduced output quality. Pigments, dyes and other chemicals remain in the material, making the output colour dependent on the colours of the input materials. Hence, to avoid irregular and unwanted colours either the input textile should be colour sorted or a dark dye or pigment should be added. Moreover, some remaining contaminants may be in violation with the REACH regulation. The output are fibres can be used in various textile applications, depending on the quality. However, the polymer/fibre properties deteriorate after each cycle. There is no LCI data available for thermo-mechanical recycling.

Thermo-chemical recycling is a process using partial oxidation reaction of polymers to produce low molar mass components or heat to degrade polymers to monomers that can be used as feedstock for the chemical industry, with the exclusion of fuels used for energy production or other combustion or energy recovery processes. It is considered a mature technology, although developments to allow the production of raw materials for the chemical industry (as opposed to energy recovery or fuel production) are very recent. Up to now, not many waste gasification processes have been piloted and tested but there are a few that have already been implemented as industrial plants (TRL 9) processing actual waste. One of the interviewed technology holders is able to process 22 million tonnes of plastic waste, including polyester textiles and carpets. Moreover, a Canadian company has commercialized a gasification process for municipal solid waste in which the produced syngas is used for methanol production. Their first commercial-scale facility in Edmonton has a capacity of 100 000 tonnes/year. There are also plans for a facility in Rotterdam with a capacity for processing up to 360 000 tonnes of waste per year. The process is especially interesting for textile waste that is untreatable by mechanical, thermo-mechanical or (bio)chemical recycling and for textile fractions that are too little in quantity. The technology leads to pure, uncontaminated, virgin-like feedstocks, making it ideal for textiles containing non-REACH compliant chemicals that cannot be removed via other recycling technologies. Moreover, the main output, syngas, has many application possibilities in chemical synthesis reactions leading to a whole range of desirable products. There is a risk for greenwashing when gasification is claimed for recycling because a major part of the input material can go to fuel production instead of feedstock for the chemical industry. This is technology dependent so clarification is required to ensure credibility of claims. The energy requirements for thermo-chemical recycling are very high due to the high temperatures needed. Together with the required separation and purification steps, the enviromental impact is expected to be higher compared to mechanical and thermo-mechanical recycling of thermoplastic polymers. No LCI data on thermo-chemical recycling could be shared by technology holders. According to literature, the impact on climate change of syngas production by thermo-chemical recycling was calculated to be 22% lower than for traditional syngas production (i.e. by coal gasification). In the optimal scenario, a carbon footprint reduction of 50% would be obtained.

Chemical recycling is a process using chemical dissolution or chemical reactions which is employed in polymer recycling (system for disassembling used fibres, extracting polymers and re-spinning them for new uses) or monomer recycling (system for breaking down polymeric textile materials into their constituent monomers and rebuilding polymeric fibres for new uses). There are several possibilities within this recycling technology and three major technologies can be identified in this respect.

<u>Polymer recycling of cotton via a pulping process</u> is a process that generates cellulosic pulp which can be obtained via different types of pulping processes: sulphate, sulphite and sulphur-free. This process can recycle cellulose from different sources (e.g., wood, cotton, viscose, cardboard) but as these differ in chemical structure and viscosity, most technology holders indicated that changing the source would require adaptations to the pulping process or pre-treatment. Technology holders prefer textile waste with a cotton content of at least 50%, preferably as high as possible. Most processes could technically handle lower cotton levels, however this would not be economically feasible. The higher the cotton content in the input stream, the lower the amount of chemicals required for the pulping process. Some technologies can separate PET from cotton, but this is currently less appealing economically due to the additional separation and purification steps that need to be implemented/developed. The application of sorted textile waste is very important as the efficiency of the recycling process depends highly on the purity of the input material. The tolerance to dyed textiles depends on the process, but most technologies include a decolouring and/or bleaching step, although with varying efficiencies. Knowledge of the applied dyes and additives would allow a more efficient removal. At present, most technologies have already reached a high TRL of 7 to 9, at least for pure cotton textiles as input material. The TRL 7-8 technologies are expected to reach TRL 9 by 2025 at the latest. Process capacities range from 10 kg/day to thousands of tonnes/year. The main requirements for further upscaling are more production time and customer feedback for optimization of the process and continuous deliveries of suitable textile waste (in terms of purity and composition) as feedstock. The output of the pulping process (cellulose pulp) can be used as input in a viscose or lyocell process and can be blended with wood pulp before it can be processed in a traditional spinning process for man-made cellulosic fibres. A technology holder reports that up to 40-50% wood based pulp can be replaced. Some technologies process 100% waste but mix with virgin wood pulp for better fibre properties, to avoid process modifications or simply because the production capacity of recycled cellulose pulp is low. Although life cycle inventory data used are of low quality leading to a high uncertainty on the results, the impact on climate change of the recycling process is higher than the avoided impact due to the avoided primary production of the recycled product.

<u>Monomer recycling of PA6 and PET</u> is a depolymerization process where the polymer chains are broken down into monomers. The PA6 or PET materials are depolymerized, some after first dissolving the polymer, via different technologies and various reaction conditions (temperatures / pressures / time / catalysts). The applied solvents are typically water (i.e., hydrolysis), alcohols (i.e., methanolysis) or glycols. In practice PA6 is generally depolymerized via hydrolysis. For PET all three of the reaction mechanisms are used for depolymerization, although glycolysis is the most common. In addition to the three

solvolysis methods, recently a fourth method has become available, namely an enzymatic depolymerization reaction. This technology can be considered a biochemical recycling process since the chemical reaction is mediated by a biological catalyst, the enzyme. It allows the recycling of all forms of PET plastics and fibres, even in mixtures as the enzyme is selective for PET. Although the final output depends on the reagent, PTA and MEG are the traditional monomers obtained from PET which can be repolymerized to obtain high-purity, virgin grade PET, while for PA6 the output is caprolactam which can be repolymerized to virgin grade PA6. The efficiency of the chemical recycling of synthetic fibres depends highly on the purity of the input material. For economic reasons, the PET or PA content of the input should be around 80-90%. Current practices proceed from packaging waste PET and industrial waste PET. For PA6, one technology holder, treating an input stream consisting of carpets, fishing nets and textile and plastic scraps (which consists of other components than PA6, such as PP, backing, coating etc.), recovers an average of 65% of the input stream. With regards to the output quality, it is beneficial that the impurities in the input material are known since (depending on the chemicals involved) they might negatively impact the depolymerization reaction. Chemical monomer recycling is energy demanding due to the required conditions for the depolymerization reaction as it is carried out at high temperatures and pressures. The climate impact of monomer recycling of PET could not be quantified. The reported climate change impact for the production of Bulk Continous Filament (BCF) yarns (for textile flooring applications) made from the recovered PA6 is well below the impact on climate change of the avoided virgin fibre. Chemical recycling of PA6 textiles via depolymerization is already an established technology, being at TRL 9 for a decade. For PET textiles the TRL-levels vary from 4 up to 7, with 500 tonnes/year being the largest available production capacity to date. The first technologies are expected to reach TRL 9 by 2023 as currently an industrial production line is being built. For the lower TRL technologies, funding and more R&D at the pilot level are mainly needed to make further progress.

<u>Recycling of polycotton blends</u> can be done via different methods as several technologies (can) focus on recycling of both cotton and PET from polycotton blends. A first method applies solvent-based dissolution and filtration processes to separate different materials and extract the desired components (polymer recycling). The recovered cellulose can be applied in a typical pulping and wet spinning process, while the PET polymers remain largely intact. According to a technology holder, the quality of the output dissolving pulp is of 100% purity. PET resins can be respun to filaments, but, in today's practice, they are incinerated for energy recovery. The solvent-based dissolution and filtration technology is currently at TRL 5 and is expected to reach TRL 6 in 2022 and TRL 9 in 2024/2025. A demonstration facility is currently being designed and will be built in 2022. A second type of technology consist of a hydrothermal approach to (partially) degrade either cotton or PET or both. These processes rely on water, pressure, temperature and green chemistry where the final output depends on the specific process applied. The different hydrothermal technologies are approximately at TRL 6 to 7. They are expected to reach TRL 9 in 2023/2024. A third approach focuses on (partial) degradation of cotton from polycotton blends via an enzymatic route (i.e., biochemical recycling) resulting in glucose, cellulose powder and PET fibres. The glucose syrup can be used in other industrial applications; for instance it can be converted into plastics, surfactants and chemicals. In order to obtain PET fibres (through a melt-spinning process) which are suitable for textile applications, PET bottle chips have to be added to the recovered polyester fibres in a 80-20 ratio. This leads to the conclusion that the quality of the recovered polyester pellets is rather low. The enzymatic recycling process is at TRL 5, expected to reach the next TRL in 2021 Q3 and TRL 9 in 2023. Most technologies can deal with a certain percentage of contamination with other materials (nylon, acrylic, wool, elastane…), however hard/metallic accessories such as zippers and buttons and generally also coatings must be removed. Sorting of textiles waste is required as knowledge of the composition is required for a good process efficiency. Current process capacities range from 15 to 2800 tonnes/year.

Potential supporting initiatives to scale textile recycling technologies

Practically all textile recycling technologies depend on having a well-defined input. The purity of the input also determines the efficiency and economic viability of the recycling process. However, at the moment most textile products on the market are not designed to be optimally recycled. Therefore, priority should be given to initiatives that within the existing context contribute to lowering overall process cost and improving the accuracy of the input. **Further development of advanced sorting techniques** has the potential to deliver sufficient, well-defined and low-cost input to recycling processes, however, to date, this potential is not yet fulfilled. The **development of sorting and recycling hubs** can also further optimize the recycling process by lowering the cost of logistics and align collection, sorting and recycling processes. Concurrently, the current lack of coordination and exchange of information in the textiles value chain is a major barrier for the uptake of textile fibres recycling. There is a clear need for a joint strategic approach that aligns interests and fosters **cooperation along the value chain** from brand and retailers to garment makers to yarn and fabric suppliers, from collectors to recyclers. Increasing the knowledge about the possibilities and limitations of recycled fibres, the alignment of needs and matchmaking mechanisms, combined with multi-year purchasing commitments could **create a market pull** and at the same time would **support investment** from recyclers to further develop its activities. Currently, a lack of funding exists as there are hardly any financial resources available for technologies that reached a higher TRL than a demonstrated proof of concept. Finally, the wider effect of (hazardous) chemicals such as dyes, anti-wrinkle agents, water repellents, but also fibre tracers on circularity needs to be further investigated. Novel technological solutions and further research over the coming years is needed on **removing, purifying and recovering additives and dyes** from the recycled textile fibres and its by-products.

At the same time, initiatives need to be taken to improve the recyclability of disposed textile products over time by making sure new products entering the market are better recyclable. Further implementation of eco-design principles and **development of desintegration techniques** could support this. Also the **development of an alternative for elastane** would improve the efficiency**,** as elastane acts as a contaminant in nearly all textile recycling technologies. Finally, **implementing fibre- or product traceability** could enable high-quality recyclability as it could provide information to the sorting facility and recycler about used fibres, additives and (hazardous) chemicals in the product in order to ensure a well-defined input.

Policy options to advance textile-to-textile recycling

For the identification and analysis of policy options, stakeholder feedback – including from recycling technology holders, fibre and textile producers and lables, as well as national and EU administrations, civil society organisations and academia – was used to reflect on their perspectives and needs. This study focused on policy options that address existing bottlenecks and gaps, which currently pose an obstacle to textile-to-textile recycling. In particular, this entails to (i) improve information and traceability on what has been used to produce textiles, (ii) continue technical standardisation processes in the area of textile recycling, (iii) set incentives for designing textiles for recyclability, and (iv) set market incentives to use recycled fibres in textile products, as well as to (v) foster the development of recycling capacity and attract necessary investments.

The table below summarises key policy options to enhance textile-to-textile recycling identified, links them to policy support needs from the stakeholder perspective and points out their likely effects on textile recycling activities. This set of options presents a policy mix with interlocking elements that are likely to work best in combination to foster preparation for re-use and textile-to-textile recycling.

Policy needs to enhance textile-to-textile recycling from stakeholder perspective	Key policy elements that could be considered to enhance textile-to-textile recycling	Expected contributions of policy elements to a circular textile economy
Enhance traceability of materials and chemicals used in textiles	Considering mandatory information declaration Considering the introduction of machine-readable data carriers and a digital product passport for textiles	Stimulate new, circular business models, increase sorting efficiency, improve availability of pure(r) feedstocks for recycling, ease monitoring and enforcement of EU Chemicals legislation and due dilligence along the textile supply chain
Promote design for recyclability	Considering minimum design requirements	Achieve more circular design of textile products, enable and increase adequate and more regular feedstock volumes for recycling, ease disassembly of textile products, provide planning security for economic actors
Ease access to feedstocks for textile fibre recycling	Easing shipment of sorted textile waste destined for preparation for re-use and for recycling Investigating the need for further clarifying end-of-waste criteria	Establish legal clarity, reduce disagreements between textile waste and non-waste classifications across Member States, ease the sourcing of specified feedstocks and improve availability of feedstock volumes for recycling
Stimulate the demand for recycled fibres	Considering mandatory recycled content for specific textile products Adressing greenwashing claims on recycled content in textile products	Create a market for recycled fibres, provide planning security for economic actors, incentivise investments into recycling technologies, capacities and circular business models, level the playing field for recycled fibres on the market
Set a frame with clear long-term direction	Discussing binding targets for separate collection, recycling and preparation of reuse of textile waste Considering Extended Producer Responsibility Schemes for textiles	Provide planning security for economic actors, secure funding for uptake of technologies and infrastructures, improve feedstack availability for recycling, incentivise circular design of textile products

Regarding the timeline of such a policy mix, it appears reasonable to first clarify and set the frame and long-term goals and to secure funding (e.g. through considering an EPR scheme for textiles and use of EU funding). Based on this, provision of and access to feedstock for recycling could be simplified. Initiating and further supporting standardisation efforts, e.g. in the area of sorting, appears as a key measure, and could result in taking up harmonised standards in EU legislation. A further important step could be to enhance the traceability of materials and chemicals used in textiles. Enabling automatic sorting of textile waste could induce a leap forward in the uptake of textile recycling technologies, making it economically more attractive. Once a starting position of textile-to-textile recycling is prepared, as a second step, design for recyclability could be facilitated and, at the same time, the market for recycled fibres be stimulated. The findings of this study indicate that jeans and T-shirts could be suitable product groups to pioneer mandatory design requirements as well as mandatory recycled content. Design requirements could ensure that when producing these products, recyclability is taken into account. Over time, this could enable a gradual increase of recycled content.

Résumé

L'un des principaux objectifs de la Commission est de renforcer la compétitivité de l'industrie européenne du textile et de l'habillement, tout en faisant progresser sa transformation verte et numérique. L'objectif général de cette initiative est d'augmenter l'efficience des ressources et d'aider les chercheurs de l'UE et l'industrie européenne du textile et de l'habillement, à émerger en tant que leaders mondiaux dans les modèles économiques circulaires naissants et les technologies liées au recyclage, en fournissant des connaissances considérables sur l'état des lieux et l'état de l'art, les opportunités et les effets secondaires négatifs du recyclage des textiles. Les **objectifs** de cette étude sont (i) d'améliorer les connaissances sur les opportunités et les défis des technologies de recyclage des déchets textiles, développées et appliquées aux niveaux mondial et européen en ce qui concerne leur faisabilité technique et leur maturité pour l'adoption par le marché et, l'efficacité économique et environnementale, (ii) d'identifier les domaines prometteurs pour les futurs projets de recherche et d'innovation et les mesures nécessaires pour soutenir l'adoption industrielle des technologies de recyclage des textiles déjà en cours de développement et (iii) de fournir aux décideurs politiques une analyse approfondie des obstacles réglementaires existants et de présenter des options politiques alternatives pour améliorer et augmenter les activités de recyclage des déchets textiles dans l'UE.

Aperçu des technologies de recyclage des fibres textiles

Le **recyclage mécanique** est un processus basé sur des forces physiques, qui peut être utilisé isolément pour le recyclage des tissus ou des fibres ou comme prétraitement pour les processus de recyclage thermomécaniques ou chimiques et biochimiques. La technologie de recyclage est actuellement au niveau de préparation technologique 9 (TRL 9) et est une technologie établie sur le marché avec déjà des décennies d'expérience, par exemple, pour la laine dans la région de Prato en Italie ou d'autres fibres naturelles (à base de cellulose comme le coton, le jute, le sisal, le lin, etc.) et également des fibres synthétiques (polyester, polyamide, acryl, viscose, PP, etc.) dans diverses régions européennes (Belgique, France, Allemagne, Suède, etc.). L'enquête menée auprès des détenteurs de technologies a révélé un large éventail de capacités de production, allant de 5 000 à 10 000 tonnes/an à 36 000 tonnes/an. Les nouveaux développements, à partir de TRL 7, se concentrent principalement sur l'augmentation de la quantité de fibres filables et l'amélioration de la qualité des fibres recyclées. Ces développements se concentrent principalement sur des ajustements des machines ou de la configuration de la ligne de recyclage, sur des traitements (chimiques) supplémentaires et sur un meilleur tri du matériau d'entrée. Les principaux avantages du recyclage mécanique sont qu'il peut traiter pratiquement n'importe quel flux de déchets textiles (matériau et structure), qu'il peut traiter des quantités relativement faibles de déchets, qu'il nécessite un niveau d'investissement et d'espace relativement faible et un personnel moins qualifié que les technologies de recyclage chimique. Le processus utilise un nombre relativement faible de ressources. Dans un processus de recyclage mécanique, les propriétés originales de la fibre sont conservées, même si elles peuvent être modifiées en fonction de l'état de la fibre. Les produits chimiques (dangereux) tels que les additifs, les colorants, les finitions, etc. présents dans les produits textiles (à la fois lors de la production et de l'utilisation du produit) ne peuvent pas être éliminés dans un processus de recyclage mécanique et restent dans le produit final. Le fait que des colorants restent dans la fraction de sortie peut être considéré comme un inconvénient. En outre, il est difficile de revendiquer la conformité à certaines législations comme REACH et sur les noms des fibres textiles et l'étiquetage et le marquage de la composition des fibres des produits textiles. Les résultats du processus de recyclage mécanique sont des fibres filables, des peluches, des matériaux de remplissage et de la poussière. La fraction de fibres filables, qui sont des fibres suffisamment longues pour être filées, représente 5 à 20 % de la matière textile utilisée dans le cas des fibres naturelles (par exemple le coton) et 25 à 55 % de la matière textile utilisée dans le cas du poly-coton

ou du polyester. Le polyamide n'est pratiquement pas recyclé par recyclage mécanique. La qualité de ces fibres dépend de la qualité du produit d'entrée, mais elle est inférieure à celle des fibres vierges. Les fibres recyclées mécaniquement peuvent remplacer les fibres de coton vierges, mais doivent être mélangées à des matériaux vierges pour obtenir un fil de qualité acceptable. La fraction de sortie restante (peluches, matériaux de remplissage et poussières) est de qualité inférieure à la fraction de fibres filables et peut être utilisée dans l'industrie des non-tissés, comme matériau de remplissage ou comme renfort dans les composites de matériaux artificiels ou incinérée avec récupération d'énergie.

Le **recyclage thermique** est un processus basé sur le chauffage dans le but de récupérer soit des polymères, soit des blocs de construction de faible poids moléculaire. Une distinction est faite entre le recyclage thermo-mécanique et le recyclage thermochimique.

<u>Le recyclage thermo-mécanique</u> est un procédé utilisé dans un système de recyclage qui fait fondre un polymère, généralement employé pour permettre le recyclage des polymères. Il s'agit de technologies permettant de recycler les textiles thermoplastiques, par exemple le polyester, le polyamide, le polypropylène, etc. en les transformant par fusion en granulés et/ou en nouvelles fibres. Le processus est similaire au traitement par fusion de matériaux vierges (à l'exception des étapes de déchiquetage, de nettoyage, d'alimentation et de dégazage), et encore plus similaire au recyclage mécanique des déchets plastiques solides. Il s'agit également d'un procédé rentable, efficace et bien connu, ce qui signifie qu'il peut être facilement mis en œuvre. Ce procédé de recyclage est particulièrement intéressant pour le recyclage des déchets de production et de certains déchets de consommation spécifiques qui ont été collectés dans des centres spécialisés. L'un des détenteurs de technologie consultés, dont la capacité de production actuelle est de 5 000 tonnes/an, prévoit d'atteindre prochainement le TRL 7 pour les déchets textiles postindustriels. Cependant, l'ajout de matériau vierge est nécessaire et seule une quantité limitée de matériau recyclé sera présente dans la fibre finale. L'un des détenteurs de la technologie mélange 20% de polyester recyclé avec du matériau vierge. Des recherches supplémentaires seront menées pour tenter d'utiliser des produits chimiques afin d'augmenter la qualité du polymère. Le TRL 9 devrait être atteint d'ici 2022 - 2023, avec toujours un pourcentage limité de contenu recyclé et les mêmes limitations concernant les matières premières. Le recyclage des mélanges de matériaux thermoplastiques en fils hybrides est à l'étude, bien qu'il soit actuellement à un faible TRL (2-3). Le filage des fibres est un processus très délicat et la présence d'une quantité même minime d'un polymère incompatible peut causer des problèmes de traitement et réduire les propriétés du produit. L'utilisation d'agents compatibilisants est étudiée pour le recyclage thermomécanique des textiles afin d'atténuer l'immiscibilité des mélanges de polymères. D'autres contaminants tels que les pigments, les impressions, les résidus de lavage, les retardateurs de flamme, les revêtements, etc. présents dans ou sur la fibre ou le textile, peuvent également entraver le processus de filage et/ou entraîner une réduction importante de la qualité du produit final. Les pigments, les teintures et autres produits chimiques restent dans le matériau, ce qui rend la couleur de sortie dépendante des couleurs des matériaux d'entrée. Par conséquent, pour éviter les couleurs irrégulières et indésirables, il faut soit trier les couleurs du textile d'entrée, soit ajouter un colorant ou un pigment foncé. En outre, certains contaminants restants peuvent être en infraction avec la réglementation REACH. Les fibres obtenues peuvent être utilisées dans diverses applications textiles, en fonction de leur qualité. Cependant, les propriétés des polymères/fibres se détériorent après chaque cycle. Il n'y a pas de données ICV disponibles pour le recyclage thermomécanique.

<u>Le recyclage thermochimique</u> est un procédé utilisant une réaction d'oxydation partielle des polymères pour produire des composants de faible masse molaire ou la chaleur pour dégrader les polymères en monomères qui peuvent être utilisés comme matière première pour l'industrie chimique, à l'exclusion des combustibles utilisés pour la production d'énergie ou d'autres procédés de combustion ou de récupération d'énergie. Elle est considérée comme une technologie mature, bien que les développements permettant la production de

matières premières pour l'industrie chimique (par opposition à la récupération d'énergie ou à la production de carburant) soient très récents. Jusqu'à présent, peu de procédés de gazéification des déchets ont été pilotés et testés, mais quelques-uns ont déjà été mis en œuvre en tant qu'installations industrielles (TRL 9) traitant des déchets réels. L'un des détenteurs de technologie interrogés est capable de traiter 22 kMT de déchets plastiques, y compris des textiles et des tapis en polyester. En outre, une entreprise canadienne a commercialisé un procédé de gazéification des déchets solides municipaux dans lequel le gaz de synthèse produit est utilisé pour la production de méthanol. Leur première installation à l'échelle commerciale à Edmonton a une capacité de 100 000 tonnes/an. Il est également prévu de construire une installation à Rotterdam, qui pourra traiter jusqu'à 360 000 tonnes de déchets par an. Le procédé est particulièrement intéressant pour les déchets textiles qui ne peuvent être traités par un recyclage mécanique, thermomécanique ou (bio)chimique, ainsi que pour les fractions textiles en quantité trop faible. La technologie permet d'obtenir des matières premières pures, non contaminées et vierges, ce qui la rend idéale pour les textiles contenant des produits chimiques non conformes à la directive REACH qui ne peuvent être éliminés par d'autres technologies de recyclage. En outre, le principal produit, le gaz de synthèse, offre de nombreuses possibilités d'application dans des réactions de synthèse chimique conduisant à toute une gamme de produits intéressants. Il y a un risque de greenwashing lorsque la gazéification est revendiquée pour le recyclage, car une grande partie des matières premières peut être utilisée pour la production de carburant au lieu de matières premières pour l'industrie chimique. Cela dépend de la technologie et une clarification est donc nécessaire pour garantir la crédibilité des déclarations. Les besoins énergétiques du recyclage thermochimique sont très élevés en raison des hautes températures nécessaires. Avec les étapes de séparation et de purification nécessaires, l'impact environnemental devrait être plus élevé que celui du recyclage mécanique et thermomécanique des polymères thermoplastiques. Les détenteurs de technologie n'ont pas communiqué de données d'ICV sur le recyclage thermochimique. Selon la littérature, l'impact sur le changement climatique de la production de gaz de synthèse par recyclage thermochimique a été calculé comme étant 22% inférieur à celui de la production traditionnelle de gaz de synthèse (c'est-à-dire par gazéification du charbon). Dans le scénario optimal, une réduction de l'empreinte carbone de 50 % serait obtenue.

Le **recyclage chimique** est un processus utilisant la dissolution chimique ou des réactions chimiques qui est employé dans le recyclage des polymères (système permettant de désassembler les fibres usagées, d'extraire les polymères et de les filer à nouveau pour de nouvelles utilisations) ou le recyclage des monomères (système permettant de décomposer les matériaux textiles polymères en leurs monomères constitutifs et de reconstruire les fibres polymères pour de nouvelles utilisations). Il existe plusieurs possibilités au sein de cette technologie de recyclage et trois technologies majeures peuvent être identifiées à cet égard.

<u>Le recyclage des polymères du coton par le biais d'un processus de réduction en pâte</u> est un processus qui génère de la pâte cellulosique qui peut être obtenue par différents types de processus: au sulfate, au sulfite et sans sulfure. Ce procédé peut recycler la cellulose provenant de différentes sources (bois, coton, viscose, carton, etc.), mais comme ces sources diffèrent en termes de structure chimique et de viscosité, la plupart des détenteurs de technologie ont indiqué que le changement de source nécessiterait des adaptations du procédé de réduction en pâte ou du prétraitement. Les détenteurs de technologie préfèrent les déchets textiles dont la teneur en coton est d'au moins 50 %, et de préférence aussi élevée que possible. La plupart des procédés pourraient techniquement traiter des niveaux de coton inférieurs, mais cela ne serait pas économiquement viable. Plus la teneur en coton du flux d'entrée est élevée, plus la quantité de produits chimiques nécessaires au processus de réduction en pâte est faible. Certaines technologies permettent de séparer le PET du coton, mais cette solution est actuellement moins intéressante d'un point de vue économique en raison des étapes supplémentaires de séparation et de purification qui

doivent être mises en œuvre/développées. La qualité du tri des déchets textiles est très importante car l'efficacité du processus de recyclage dépend fortement de la pureté du matériau d'entrée. La tolérance aux textiles teints dépend du procédé, mais la plupart des technologies incluent une étape de décoloration et/ou de blanchiment, bien qu'avec des efficacités variables. La connaissance des colorants et des additifs appliqués permettrait une élimination plus efficace. À l'heure actuelle, la plupart des technologies ont déjà atteint un TRL élevé de 7 à 9, du moins pour les textiles en coton pur comme matière première. Les technologies TRL 7-8 devraient atteindre le TRL 9 en 2025 au plus tard. Les capacités de traitement vont de 10 kg/jour à des milliers de tonnes/an. Les principales exigences pour le passage à l'échelle supérieure sont un temps de production plus long et un retour d'information de la part des clients pour l'optimisation du processus et des livraisons continues de déchets textiles appropriés (en termes de pureté et de composition) comme matière première. Le produit du processus de réduction en pâte de cellulose peut être utilisé comme matière première dans un processus de viscose ou de lyocell et peut être mélangé à de la pâte de bois avant d'être traité dans un processus de filage traditionnel pour les fibres cellulosiques artificielles. Selon un détenteur de technologie, il est possible de remplacer jusqu'à 40 à 50 % de la pâte à base de bois. Certaines technologies traitent 100 % des déchets mais les mélangent à de la pâte de bois vierge pour obtenir de meilleures propriétés de la fibre, pour éviter de modifier le processus ou simplement parce que la capacité de production de pâte de cellulose recyclée est faible. Bien que les données d'inventaire du cycle de vie utilisées soient peu précises, ce qui entraîne une grande incertitude sur les résultats, l'impact du processus de recyclage sur le changement climatique est plus élevé que l'impact évité en raison de la production primaire évitée du produit recyclé.

<u>Le recyclage des monomères du PA6 et du PET</u> est un processus de dépolymérisation dans lequel les chaînes de polymères sont décomposées en monomères. Les matériaux PA6 ou PET sont dépolymérisés, parfois après dissolution préalable du polymère, via différentes technologies et diverses conditions de réaction (températures/pressions/temps/catalyseurs). Les solvants utilisés sont généralement l'eau (par hydrolyse), les alcools (par méthanolyse) ou les glycols. Dans la pratique, le PA6 est généralement dépolymérisé par hydrolyse. Pour le PET, les trois mécanismes de réaction sont utilisés pour la dépolymérisation, bien que la glycolyse soit la plus courante. En plus des trois méthodes de solvolyse, une quatrième méthode est récemment devenue disponible, à savoir une réaction de dépolymérisation enzymatique. Cette technologie peut être considérée comme un processus de recyclage biochimique puisque la réaction chimique est induite par un catalyseur biologique, l'enzyme. Elle permet le recyclage de toutes les formes de plastiques et de fibres de PET, même dans les mélanges, car l'enzyme est sélective pour le PET. Bien que le résultat final dépende du réactif, le PTA et le MEG sont les monomères traditionnels obtenus à partir du PET qui peuvent être repolymérisés pour obtenir du PET vierge de haute pureté, tandis que pour le PA6, le résultat est le caprolactame qui peut être repolymérisé en PA6 vierge. L'efficacité du recyclage chimique des fibres synthétiques dépend fortement de la pureté du matériau d'entrée. Pour des raisons économiques, la teneur en PET ou en PA du matériau d'entrée doit être d'environ 80-90%. Les pratiques actuelles partent des déchets d'emballage en PET et des déchets industriels en PET. En ce qui concerne le PA6, un détenteur de technologie, traitant un flux d'entrée composé de tapis, de filets de pêche et de déchets textiles et plastiques (qui se composent d'autres éléments que le PA6, tels que le PP, le support, le revêtement, etc.), récupère en moyenne 65% du flux d'entrée. En ce qui concerne la qualité du produit final, il est utile de connaître les impuretés présentes dans le matériau d'entrée car (selon les produits chimiques concernés) elles peuvent avoir un impact négatif sur la réaction de dépolymérisation. Le recyclage chimique des monomères est gourmand en énergie en raison des conditions requises pour la réaction de dépolymérisation, qui s'effectue à des températures et des pressions élevées. L'impact environnemental du recyclage des monomères du PET n'a pas pu être quantifié. L'impact sur le changement climatique rapporté pour la production de fils à filaments continus texturés (BCF) (pour les applications de revêtement de sol textile) fabriqués à partir du PA6 récupéré est bien inférieur à l'impact

sur le changement climatique de la fibre vierge non reauise. Le recyclage chimique des textiles en PA6 par dépolymérisation est une technologie déjà bien établie, puisqu'elle est au niveau TRL 9 depuis une décennie. Pour les textiles en PET, les niveaux TRL varient de 4 à 7, 500 tonnes/an étant la plus grande capacité de production disponible à ce jour. Les premières technologies devraient atteindre le niveau TRL 9 d'ici 2023, une ligne de production industrielle étant actuellement en cours de construction. Pour les technologies de niveau de TRL inférieur, des financements et davantage de R&D au niveau de pilotes sont nécessaires pour progresser davantage.

Le **recyclage des mélanges de polycoton** peut se faire par différentes méthodes car plusieurs technologies peuvent se concentrer sur le recyclage du coton et du PET à partir des mélanges de polycoton. Une première méthode consiste à appliquer des processus de dissolution et de filtration à base de solvants pour séparer les différents matériaux et extraire les composants souhaités (recyclage des polymères). La cellulose récupérée peut être utilisée dans un processus typique de réduction en pulpe et de filage humide, tandis que les polymères PET restent en grande partie intacts. Selon un détenteur de technologie, la qualité de la pâte à dissoudre produite est d'une pureté de 100 %. Les résines de PET peuvent être refondues en filaments, mais, dans la pratique actuelle, elles sont incinérées pour la récupération d'énergie. La technologie de dissolution et de filtration à base de solvants est actuellement à TRL 5 et devrait atteindre TRL 6 en 2022 et TRL 9 en 2024/2025. Une installation de démonstration est en cours de conception et sera construite en 2022. Un deuxième type de technologie consiste en une approche hydrothermique pour dégrader (partiellement) soit le coton, soit le PET, soit les deux. Ces processus reposent sur l'eau, la pression, la température et la chimie verte, le résultat final dépendant du processus spécifique appliqué. Les différentes technologies hydrothermales sont à un niveau TRL 6 ou 7, approximativement. Elles devraient atteindre le niveau TRL9 en 2023/2024. Une troisième approche se concentre sur la dégradation (partielle) du coton des mélanges de polycoton par une voie enzymatique (c'est-à-dire le recyclage biochimique), ce qui donne du glucose, de la poudre de cellulose et des fibres de PET. Le sirop de glucose peut être utilisé dans d'autres applications industrielles ; il peut par exemple être converti en plastiques, en tensioactifs et en produits chimiques. Afin d'obtenir des fibres de PET (par un processus de filage à chaud) qui conviennent aux applications textiles, des copeaux de bouteilles de PET doivent être ajoutés aux fibres de polyester récupérées dans un rapport de 80-20. Cela permet de conclure que la qualité des granulés de polyester récupérés est plutôt faible. Le procédé de recyclage enzymatique est à TRL 5, devrait atteindre le TRL suivant en 2021 Q3 et le TRL9 en 2023. La plupart des technologies peuvent traiter un certain pourcentage de contamination par d'autres matériaux (nylon, acrylique, laine, élasthanne...), mais les accessoires durs/métalliques tels que les fermetures éclair et les boutons, et généralement aussi les enductions, doivent être retirés. Le tri des déchets textiles est nécessaire car la connaissance de la composition est indispensable pour une bonne efficacité du processus. Les capacités actuelles du processus vont de 15 à 2800 tonnes/an.

Initiatives de soutien potentielles pour développer les technologies de recyclage des textiles

Pratiquement toutes les technologies de recyclage des textiles dépendent d'un intrant bien défini. La pureté de l'intrant détermine également l'efficience et la viabilité économique du processus de recyclage. Cependant, à l'heure actuelle, la plupart des produits textiles sur le marché ne sont pas conçus pour être recyclés de manière optimale. Il convient donc de donner la priorité aux initiatives qui, dans le contexte actuel, contribuent à réduire le coût global du processus et à améliorer la précision de l'intrant. La **poursuite du développement de techniques de tri avancées** a le potentiel de fournir des intrants suffisants, bien définis et peu coûteux aux processus de recyclage, mais à ce jour, ce potentiel n'est pas encore réalisé. Le **développement de centres de tri et de recyclage** peut également optimiser davantage le processus de recyclage en réduisant le coût de la logistique et en alignant les processus de collecte, de tri et de recyclage. Parallèlement, le manque actuel de coordination et d'échange d'informations dans la chaîne de valeur textile constitue un obstacle majeur à l'adoption du recyclage des fibres textiles. Il est clairement nécessaire d'adopter une approche stratégique commune qui aligne les intérêts et encourage la **coopération tout au long de la chaîne de valeur**, des marques et des détaillants aux fabricants de vêtements, en passant par les fournisseurs de fils et de tissus, les collecteurs et les recycleurs. Une meilleure connaissance des possibilités et des limites des fibres recyclées, combinée à un alignement des besoins et à des mécanismes de mise en relation, ainsi que des engagements d'achat pluriannuels pourraient créer un **appel du marché** et, dans le même temps, **soutenir les investissements** des recycleurs pour développer davantage leurs activités. Actuellement, il existe un manque de financement car il n'y a pratiquement pas de ressources financières disponibles pour les technologies qui ont atteint un TRL plus élevé qu'une preuve de concept démontrée. Enfin, l'effet plus large sur la circularité des produits chimiques (dangereux) tels que les colorants, les agents anti-froissement, les hydrofuges, mais aussi les traceurs de fibres doit être étudié plus avant. De nouvelles solutions technologiques et des recherches plus poussées sont nécessaires dans les années à venir pour **éliminer, purifier et récupérer les additifs et les colorants** des fibres textiles recyclées et de leurs sous-produits.

Parallèlement, des initiatives doivent être prises pour améliorer la recyclabilité des produits textiles éliminés au fil du temps en s'assurant que les nouveaux produits qui arrivent sur le marché soient recyclables. La poursuite de la mise en œuvre des principes d'éco-conception et le **développement de techniques de désintégration** pourraient y contribuer. Le **développement d'une alternative à l'élasthanne** améliorerait également l'efficacité, car l'élasthanne agit comme un contaminant dans presque toutes les technologies de recyclage des textiles. Enfin, **la mise en œuvre de la traçabilité des fibres ou des produits** pourrait permettre une recyclabilité de haute qualité, car elle pourrait fournir des informations au centre de tri et au recycleur sur les fibres utilisées, les additifs et les produits chimiques (dangereux) présents dans le produit, afin de garantir des intrants bien définis.

Options politiques pour faire progresser le recyclage des textiles en textiles

Pour l'identification et l'analyse des options politiques, le retour d'information des parties prenantes - notamment des détenteurs de technologies de recyclage, des producteurs et des labels de fibres et de textiles, ainsi que des administrations nationales et européennes, des organisations de la société civile et des universités - a été utilisé pour réfléchir à leurs perspectives et à leurs besoins. Cette étude s'est concentrée sur les options politiques qui s'attaquent aux obstacles et aux lacunes existants, qui constituent actuellement un frein au recyclage du textile au textile. Il s'agit en particulier (i) d'améliorer l'information et la traçabilité de ce qui a été utilisé pour produire des textiles, (ii) de poursuivre les processus de normalisation technique dans le domaine du recyclage des textiles, (iii) de mettre en place des incitations à concevoir des textiles en vue de leur recyclabilité, et (iv) de mettre en place des incitations commerciales à utiliser des fibres recyclées dans les produits textiles, ainsi que (v) de favoriser le développement de la capacité de recyclage et d'attirer les investissements nécessaires.

Le tableau ci-dessous résume les principales options politiques identifiées pour améliorer le recyclage des textiles en textiles, les relie aux besoins de soutien politique du point de vue des parties prenantes et souligne leurs effets probables sur les activités de recyclage des textiles. Cet ensemble d'options présente un mélange de politiques avec des éléments interdépendants qui sont susceptibles de fonctionner au mieux en combinaison pour favoriser la préparation à la réutilisation et le recyclage des textiles en textiles.

Besoins politiques pour améliorer le recyclage textile-textile du point de vue des parties prenantes	Principaux éléments de politique qui pourraient être envisagés pour améliorer le recyclage des textiles en textiles	Contributions attendues des éléments de politique à une économie textile circulaire
Améliorer la traçabilité des matériaux et des produits chimiques utilisés dans les textiles	Envisager une déclaration d'information obligatoire Considérant l'introduction de supports de données lisibles par machine et d'un passeport numérique pour les produits textiles	Stimuler de nouveaux modèles économiques circulaires, accroître l'efficacité du tri, améliorer la disponibilité de matières premières pures pour le recyclage, faciliter le contrôle et l'application de la législation européenne sur les produits chimiques et la diligence raisonnable tout au long de la chaîne d'approvisionnement textile.
Promouvoir la conception pour la recyclabilité	Prise en compte des exigences minimales de conception	Réaliser une conception plus circulaire des produits textiles, permettre et augmenter des volumes adéquats et plus réguliers de matières premières pour le recyclage, faciliter le désassemblage des produits textiles, fournir une sécurité de planification aux acteurs économiques.
Faciliter l'accès aux matières premières pour le recyclage des fibres textiles	Faciliter le transfert des déchets textiles triés destinés à être préparés en vue de leur réutilisation et de leur recyclage. Examiner la nécessité de clarifier davantage les critères de fin de vie des déchets	Établir la clarté juridique, réduire les désaccords entre les classifications des déchets et des non-déchets textiles dans les États membres, faciliter l'approvisionnement en matières premières spécifiées et améliorer la disponibilité des volumes de matières premières pour le recyclage.
Stimuler la demande de fibres recyclées	envisager un contenu recyclé obligatoire pour certains produits textiles Lutter contre les allégations de blanchiment écologique concernant le contenu recyclé des produits textiles	Créer un marché pour les fibres recyclées, offrir une sécurité de planification aux acteurs économiques, encourager les investissements dans les technologies de recyclage, les capacités et les modèles économiques circulaires, uniformiser les conditions de concurrence pour les fibres recyclées sur le marché.
Fixer un cadre avec une orientation claire à long terme	Discussion d'objectifs contraignants pour la collecte sélective, le recyclage et la préparation à la réutilisation des déchets textiles Envisager des systèmes de responsabilité élargie des producteurs pour les textiles	Assurer la sécurité de la planification pour les acteurs économiques, garantir le financement de l'adoption des technologies et des infrastructures, améliorer la disponibilité des matières premières pour le recyclage, encourager la conception circulaire des produits textiles.

En ce qui concerne le calendrier d'une telle combinaison de politiques, il semble raisonnable de commencer par clarifier et fixer le cadre et les objectifs à long terme et d'assurer le financement (par exemple en envisageant un système de REP pour les textiles et en utilisant le financement de l'UE). Sur cette base, la fourniture et l'accès aux matières premières pour le recyclage pourraient être simplifiés. Lancer et soutenir davantage les efforts de normalisation, par exemple dans le domaine du tri, apparaît comme une mesure clé, et pourrait aboutir à l'adoption de normes harmonisées dans la législation européenne. Une autre mesure importante pourrait consister à améliorer la traçabilité des matériaux et des produits chimiques utilisés dans les textiles. Le fait de permettre le tri automatique des déchets textiles pourrait entraîner un bond en avant dans l'adoption des technologies de recyclage des textiles, ce qui les rendrait économiquement beaucoup plus attrayantes. Une fois la position de départ du recyclage de textile à textile préparée, dans un deuxième temps, la conception visant la recyclabilité pourrait être facilitée et, en même temps, le marché des fibres recyclées serait stimulé. Les résultats de cette étude indiquent que les jeans et les T-shirts pourraient être des groupes de produits appropriés pour être à l'avant-garde des exigences de conception obligatoires ainsi que du contenu recyclé obligatoire. Les exigences de conception pourraient garantir que la recyclabilité est prise en compte lors de la fabrication de ces produits. Au fil du temps, cela pourrait permettre une augmentation progressive du contenu recyclé.

1. Background

With a strong capacity of generating growth and employment in the EU while contributing to development and economic integration, the textile and clothing industry plays an important role in the EU economy. In 2019, EU textile and clothing industry reached a turnover of 162 billion EUR, employing over 1.5 million people across 160 000 companies (Euratex, 2020a). The Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on the implementation of the Circular Economy Action Plan (CEAP) adopted in 2019, highlighted textiles as an industrial sector with a potential for circularity (COM, 2019). The related Commission Staff Working Document on "Sustainable Products in a Circular Economy - Towards an EU Product Policy Framework contributing to the Circular Economy" highlighted how sustainability aspects of textiles are wide (SWD, 2019) The production of bio-based materials such as cotton, wool or man-made cellulosic fibres, such as viscose, requires a considerable quantity of inputs (e.g. water and other agricultural inputs or energy), while synthetic fibres and yarns used for the production of textiles are mainly fossil based and have been considered as one of the potential main sources of micro-plastics release through washing of textiles products.

It is acknowledged that the textile and clothing industry, considered at global level, is a sector with an impact on the environment. The EU already provides a consistent regulatory framework for the production and free movement of textile goods with specific regard to health, safety and environment. Nevertheless, with the emergence of fast fashion (mainly, imported clothing), clothes became true fast moving consumer goods; they are easily accessible in great quantities, replaced frequently and ultimately end up piling up in landfills or incinerated for energy production across the EU. It is critical to highlight that textile products imported from third countries represent 60% of the consumption (by value) in the EU. Despite the limited availability of data, it is estimated that only less than 1% of material used to produce clothing is recycled into new clothing globally. Currently, in the EU collection rates of textile waste are estimated to be at 25%, though large differences between Member States exist.

The revised Waste Framework Directive ((EU) 2018/851) obliges Member States to set up separate collection schemes for textiles waste by 1 January 2025. The Directive (article 11(6)) also mandates the Commission to, by December 2024, consider setting up targets for re-use and recycling of textile waste. Ensuring ambitious textile re-use and recycling targets and enabling effective recycling at an industrial scale requires preparation of the companies (across the entire value chain, from fibre production to mechanical or chemical recycling of textiles) and, in particular, support in addressing existing bottlenecks.

Recycling in textile and clothing can take place through different methodologies (e.g. mechanical or chemical recycling), which apply different technologies, and from different sources (e.g. PET bottles, production waste PET, waste from fishing nets, carpets waste and textile-to-textile).

Currently, using secondary raw materials as an input for new clothes is an already developed way to increase the recycling content of garments. However, the economics and output quality of existing recycling technologies for common materials need to be drastically improved to capture the full value of materials in recovered clothing.

The most developed process for recycling is related to synthetic fibres (with polyester being the most commonly used) through mechanical recycling. Most of those recycled fibres are not made from post-consumer garments but from other sources (e.g. used plastics).

Natural fibres, like cotton, are also mainly recovered via mechanical recycling. Clothes are sorted by colour as well as material and fibres, and are shredded, including through processes of unravelling, grinding, defibrating and cutting. As the fibres are shortened, weakened and damaged during the recycling process, their properties, functionality as well as quality deteriorate, making the supplement of new and high quality fibres necessary.

Closed-loop textile-to-textile recycling processes (especially, chemical recycling) are still under development and have not yet reached commercial stage or market penetration on a large scale. Taking place to a limited extent, recycling of textiles is often a matter of downcycling where the recycled material is of lower quality and functionality than the original material. Concerning mechanical recycling, most natural fibres are not recycled into new clothes in general, but down-cycled for application of insulating materials, industrial cleaning cloth, bath mats, industry wipes or oil absorbent mats.

There is limited knowledge of the feasibility of recycling of a number of fibres in mixtures, from an economic and environmental point of view. Challenges include the unavailability of advanced technologies and the lack of a business case for economic operators.

However, various innovating approaches exist for both man-made as well as natural fibres. Currently, the substitution of wood by waste garments from natural fibres as input for the production of viscose fibres is analysed intensively and some of those technologies are on the verge of upscaling and commercialisation. Chemical monomer recycling for non-plastic based fibres like cotton and wool is currently in the research stage. The EU project RESYNTEX funded under Horizon 2020 (H2020) addressed this issue.

Different studies have been focussed on circularity in textile and clothing, addressing directly or tangentially the issue of recycling. The Ellen MacArthur Foundation study “A New Textiles Economy: Redesigning fashion’s future” investigated circularity in the fashion industry by providing an analysis of how to rethink the global textiles system, starting with clothing. The study highlighted how there is a compelling need for radically improving recycling to allow the industry to capture the value of the materials in clothes that can no longer be used. A study for the German Federal Ministry for Economic Cooperation and Development (BMZ) “Circular Economy in the Textile Sector” also provided a similar analysis.

In this regard, further challenges in transition to circular business models were also highlighted by the study “Support Report Mapping Sustainable Fashion Opportunities for SMEs” commissioned by the European Commission. The study highlighted how challenges are also linked to recycling technology and infrastructure. Economically viable recycling options remain scarce for the low-quality of materials and the competition based on cheaper prices of virgin fibres. Further to the above, there is an infrastructure challenge, as the economic viability of recycling of used textiles and clothing depends on both national and international conditions because collections are organized on local/regional/national levels but recycling relies on global infrastructure.

2. Goal of the project

The aims and objectives of this study are to provide substantial knowledge about the state of play and state of the art of textile waste recycling on global level, and a clear and well-defined analysis of opportunities and challenges for European textile and clothing industry. The results of this study will be used as evidence base to improve the knowledge of the effectiveness and potential of existing and emerging recycling capabilities of most common fibres used singularly or in mixtures in the EU market. It will also provide an analysis of the economic and environmental effectiveness of those recycling technologies and a roadmap of the textile recycling technologies under development in order to support their industrial uptake. Finally, the study will also provide an analysis on relevant policy initiatives in order to tackle potential regulatory barriers to and scale up of textile waste recycling activities in the EU.

The study will provide the following different analyses:

- Technical analysis – mapping of textile recycling activities and technologies (**Chapter 3**),
- Analysis of the economic and environmental aspects of the identified textile recycling technologies (**Chapter 4**),
- Definition of roadmaps and recommendations for potential supporting initiatives for textile recycling technologies under development and those almost ready or ready for scale up at industrial level in the EU (**Chapter 5**),
- Analysis of the existing EU regulatory framework and identification of policy solutions (e.g. regulatory initiatives, European standards) to existing or potential regulatory barriers (**Chapter 6**).

3. Technical analysis – Mapping of textile recycling activities and technologies

The mapping of technologies aims to give an overview of the available technologies to recycle textile waste into recycled textile fibres. It should result in an overview for every technology of a number of elements: the input requirements of the textile waste, possible pre-treatments, a description of the process steps, the possible output, the advantages and disadvantages of the technology, and an evaluation of the status and future prognosis.

In order to create this mapping, a desktop study was performed, further complemented with information from technology holders and relevant stakeholders, collected via a questionnaire and interviews. The partners identified in total 85 technology holders and projects, that are or have been developing a relevant technology. During the process of information and data collection, 78 technology holders and project leaders were contacted with the request to fill out a questionnaire; 32 technology holders and project leaders responded to this questionnaire. Out of those 32, 10 technology holders, of which some held more than one specific technology, were interviewed to collect more in-depth data.

3.1. Mapping of the recycling technologies

According to the Waste Framework Directive Art 3(17) ‘recycling’ means any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations.

The ISO standard draft “DIS 5157Textiles – Environmental Aspects – Vocabulary’ defines recycling as follows:

> *Action of reprocessing a material or component which has previously been processed for inclusion in a product.*
>
> *Note 1 to entry: The process may be chemical, mechanical, thermal/thermo mechanical.*
>
> [SOURCE: ISO 8887-1:2017, 3.1.6., modified - Note 1 to entry has been added.]

In the draft DIS 5157 Textiles - Environmental Aspects – Vocabulary 3, the main recycling technologies are identified as being mechanical, thermo-mechanical and chemical. Moreover, two additional recycling technologies were identified for the purpose of this project: biochemical recycling and thermo-chemical recycling. Due to the nature of the medium used to depolymerize, biochemical recycling is not always categorised as chemical recycling. However, as it shows a lot of similarities with chemical recycling, throughout this project, biochemical recycling will be included within chemical recycling. Thermo-chemical recycling could also be categorized as chemical recycling, but due to the high temperature used in the process, it was decided that the thermal part is the main factor driving the process. An overview of the categorization of textile recycling technologies is presented in Figure 1.

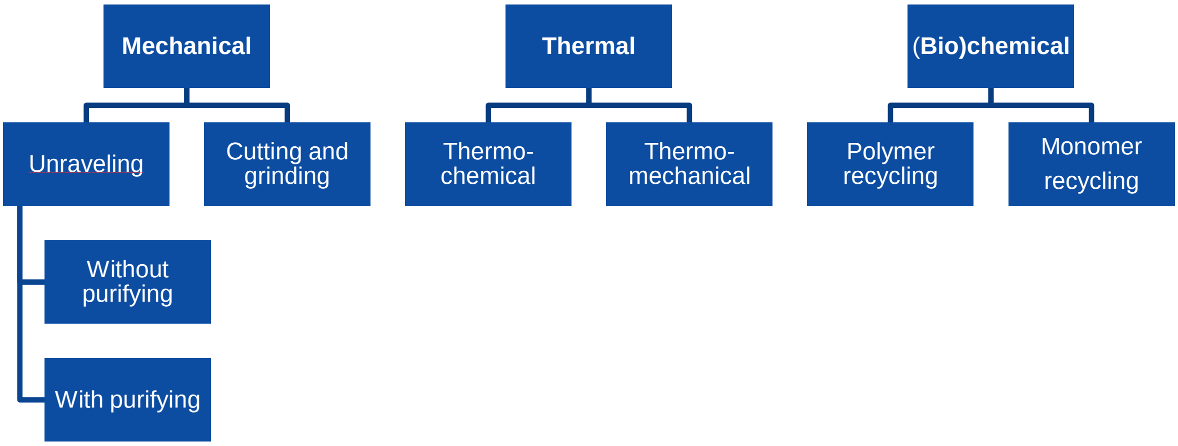


Figure 1: Categorization of textile recycling technologies.

In addition to the actual recycling technologies there are facilitating technologies that help to improve the input in order to reach a higher quality of output. These technologies include sorting and automatic disintegration of textile products (see section 3.5 Facilitating technologies).

3.2. Mechanical recycling process

3.2.1. Definition according to DRAFT DIS 5157

A process, used in a recycling system, based on physical forces, which may be used in isolation for fabric or fibre recycling or as pre-processing for thermo mechanical or chemical and biochemical recycling processes.

3.2.2. Input

Basically, all kinds of textile waste, material type (natural, synthetic or blends), types of textile products (yarns, fabrics, used garments, carpets) and structures (knitted, woven or non-woven) can be processed via mechanical recycling. However, the type of fibre (i.e., synthetic or natural, blends, technical fibres, etc.) in combination with the textile structure (i.e., yarn twist and fabric construction) determines the required machinery and the potential output. For example, aramid (e.g., Kevlar®) fibres are very durable and specialized machinery is needed since the regular machines would be damaged when processing such strong material. Moreover, knitwear is in general very easily opened with tearing machines, while woven fabrics are a tighter construction which is more difficult to open and will lead to shorter fibres. (Aronsson en Persson 2020) Very tightly woven structures can only be processed by milling, resulting into much shorter fibres compared to tearing.

Some technology holders focus on a selection of fibre types, for example only wool, only cellulose-based fibres (cotton, jute, sisal, flax, kenaf, etc.) or only synthetics (polyester, polyamide, polypropylene…), while others process a broad range of materials. In addition, some companies prefer to work with knitwear, others only process production waste, and so on.

In general, the more uniform, untreated, undamaged, and uncontaminated the input is, the higher the amount and quality of the fibre output from the mechanical recycling process will be. Textiles are preferably sorted by material and colour as this process cannot separate blends or filter out dyes (Ellen MacArthur Foundation, A new textiles economy: Redesigning fashion's future 2017). Unfortunately, several technology owners have indicated the lack of good-quality waste available in the market and more specifically, the scarcity of monostreams. Another recurrent comment is the lack of traceability of the origin of the input. End-of-life consumer textiles with different fibre blends and of unknown origin will mostly lead to fluff material with an undetermined content that can only be used as filling material (e.g. for insulation in the construction industry) or in non-woven production. Whereas a monostream of production waste from garment manufacturing (e.g., 100% wool in one colour) might result in a certain amount of spinnable fibres in addition to fluff material.

Coated and laminated products are undesirable in the inputs to the process: coatings and glues keep the textile structure together and as such complicate the unravelling of textiles into individual fibres. Spinnable fibres cannot be obtained from mechanical recycling of these materials.

For most mechanical recycling technologies, the presence of more than 10% of elastane can be problematic as well. Elastic textiles are more difficult to shred or unravel as they will stretch, and greater forces are needed to destroy the fabric and obtain individual fibres. However, some technology holders claim to be able to process elastane-containing textiles without problems. Moreover, the research project "Re:Mix –Separation and recycling of textile" focuses on the topic of separation of polyamide and elastane fibres from other fibres in blends (Östlund, et al. 2017).

Another common problem is the poor quality of post-consumer fabric waste which can be damaged due to the use, washing and maintenance processes. If the fabric is too weak to resist the mechanical recycling process a lot of material goes to waste as dust, especially for cotton. This is mainly a problem for the cotton fraction (content) in industrially washed textile (e.g., hotel/hospital linen, workwear), less for household clothing waste. (EuraMaterials, et al. 2021)

Next to the textile input and machinery, electricity is needed to run the machines and in some cases water, chemicals and heat will be needed for a pre- or intermediate cleansing process (see "pre-treatment" in section 3.2.3). Some examples of the chemicals used are ozone, detergents, bleaching agents, organic solvents. In the future, liquid/supercritical CO_2 might be used for the extraction of (organic) contaminants. It has already been proven that liquid CO_2 washing (non-supercritical) can remove for example polyaromatic hydrocarbon (PAH) substances from firefighter clothes (see disadvantages at 3.2.5). Supercritical CO_2 is used to dye polyester fabrics, which is why it is thought to potentially also remove colorants and/or other chemicals from the polyester. Further research is, however, needed to investigate this.

When colour-sorting the garments, re-dyeing or bleaching is not necessary and the environmental impact of the process can be reduced. (S. Roos, et al. 2019) (Ellen MacArthur Foundation, A new textiles economy: Redesigning fashion's future 2017)

3.2.3. Process steps

The general process diagram for mechanical recycling of textiles is presented in Figure 2.

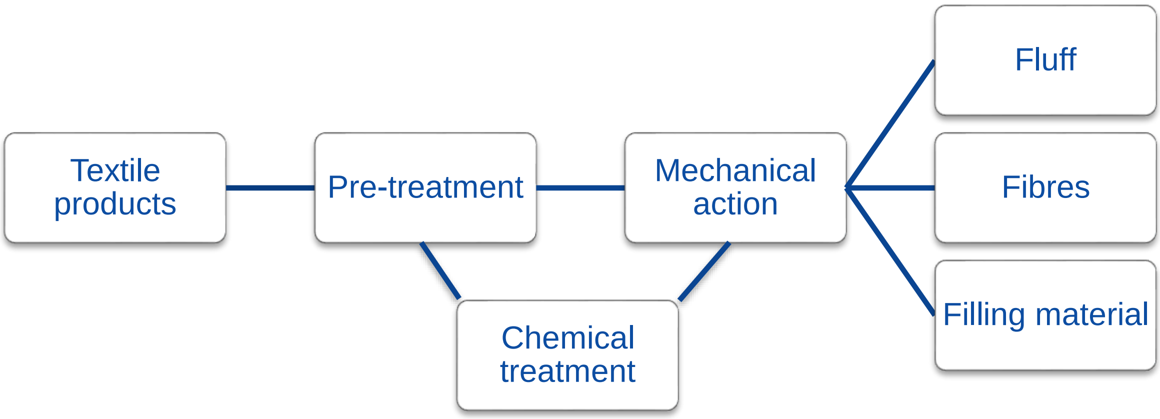


Figure 2: General process scheme for the mechanical recycling of textiles

The main steps consist of a pre-treatment followed by a set of mechanical actions. However, the specific actions needed to obtain a useable output strongly depend on the type, structure and size of the textile product that is used as input.

Pre-treatment

In this step, the textile product will be dismantled and cut to an appropriate size. This can include manual or automatic removal of unwanted accessories.

Soft parts such as coatings, prints and labels are to be avoided. These can cause visual variations (e.g. labels with a different colour), lower the quality of the output (because they consist of a different material) or hinder further processing (because the fibres can't be split). Hard parts, such as buttons and zippers, can damage the machines during processing. Moreover, the metallic parts especially pose a risk of fire: a spark caused by a metal part like a press fastener hitting machine parts could cause the cotton to ignite. Removing these components can ensure a better and more gentle unravelling, since hard parts would damage machinery that is needed to avoid damage to the fibres. The removal would also prevent further problems during respinning, when hard pieces would still be present in the fibre mass. (EuraMaterials, et al. 2021)

Currently, most technology providers rely on manual removal of these unwanted parts. In this case, a fraction of the textile material is lost as it is economically unviable to spend a lot of time on the precise removal of the part. Some metallic components can be easily removed thanks to their magnetic properties by a magnet, while non-ferro hard parts can be separated based on density by means of centrifugal force after fragmentation. (Margasa, Beater Cleaner sd) In this respect a certain degree of automation is possible (see section 3.5 Facilitating technologies). Automated removal and eco-design (i.e. buttons/labels placement designed for easier removal) could thus greatly increase the amount of textile that can be processed via mechanical recycling.

For contaminated textiles (e.g., unwashed clothing, dirty carpets or soiled workwear) the pre-treatment step may also include sanitation via an industrial cleaning/washing process . These processes are similar to the industrial maintenance processes of textile like for workwear and include cleaning with detergents, ozone or liquid CO_2 to remove sweat and sand for example. The nature of the contamination and the further process steps will determine if sanitation is needed and which method is most suitable. Additional resources such as water, chemicals, heat, etc. will be required. It should be noted that this step is generally not needed for industrial/pre-consumer waste. In addition, textile products maintained by industrial laundries are mostly discarded after the cleaning process as the quality control happens directly before packing for shipment. Therefore, this type of textile is often cleaner and free of contaminations. One might find them also as an in-between step.

Mechanical action

The actual mechanical recycling process consists of a number of consecutive actions. First, the material is cut into smaller pieces, typically 15-40 cm² (Aronsson en Persson 2020). One of the technology holders contacted, claims to be able to process larger pieces (250 - 400 cm²), improving the fibre length of the output. After cutting, the smaller pieces are fed into a textile tearing machine. This tearing machine consists of a sequence of high-speed rotating cylinders or drums, covered with saw wires or steel pins which will tear the textile, causing the structure to open up and releasing the individual fibres. The first cylinder(s) have coarse spikes and when the opening is sufficient, the fibres will pass through a series of cylinders with more and finer spikes or saw wires in every step. As illustrated in Figure 3 (LAROCHE sd), a typical tearing line consist of 3 to 6 (sometimes up to 9) cylinders. (Aronsson en Persson 2020) (S. Roos, et al. 2019) Different terminology is used to describe this process, such as opening, tearing, pulling, garneting, and unravelling.

Figure 3: Example of a tearing line from LAROCHE designed for recycling of hard textile waste, consisting of 6 opening sections. (https://www.laroche.fr/en/domaines-dactivites/recycling.html)

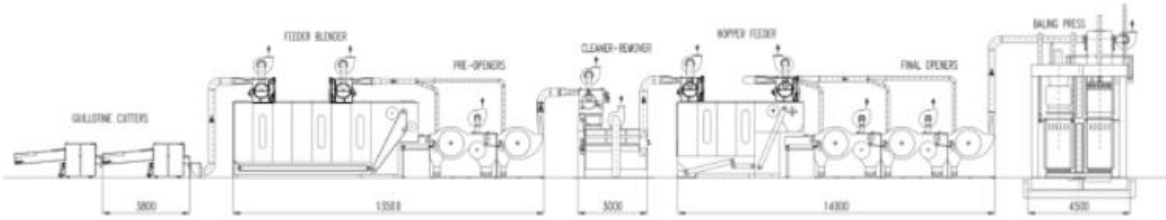
After the tearing machines, the baling presses will compress fibres into bales for transport. Additional to the cutters, tearing machines and baling presses, pre-openers and fine-openers, blending boxes and cleaning drums can be included. Pre-openers perform a first opening of the textile before entering the actual tearing machine, while fine-openers are used at the end of the line to open the last unopened yarns/pieces. Moreover, in order to ensure the recycling into yarn, the opened fibres are carded, a process that disentangles, orients, cleans and intermixes fibres, producing a continuous web or sliver. The opened fibres can also pass through extra steps in order to remove the fraction of fibres which are too short for spinning. Blending boxes can be used in order to ensure a more consistent input by blending the fibres or fabric input intensely so that the quality of the output is more consistent. This is also possible later in the process when mixing the recycled fibres with other virgin or recycled fibres. A cleaning drum can be included in the recycling line for automatic removal of remaining contaminations (metal or plastic parts, stones, seeds, etc.) that were not removed during pre-treatment.

Larger textile pieces can yield longer fibres but are more difficult to open. However, the size of the textile input is not the only factor determining the final length of the output fibres as the mechanical tearing will cause a reduction of the fibre length. The extent of this length reduction depends on the nature of the fibre (natural vs. synthetic) and the structure of the textile (loosely knitted vs. tightly woven) (S. Roos, et al. 2019). The machinery and process steps will often be tailored to maintain the fibre length as much as possible to obtain a high-quality output suitable for respinning into yarn.

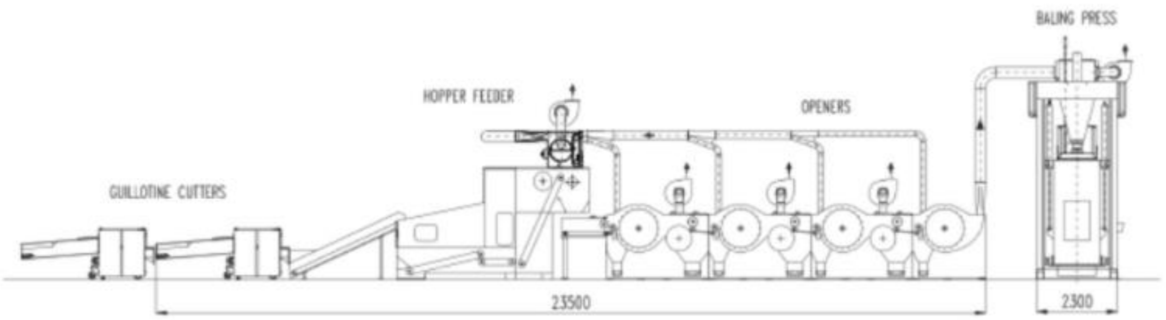
Some technology holders implement a novel chemical treatment, without altering the fibre to large extents (e.g., cotton remains cotton). This can enable a more gentle recycling process or make the fibres more resistant to the process, resulting in stronger fibres with a length almost comparable to virgin ones. Contaminations such as dust, unwanted particles or fibre fragments, etc. are sometimes chemically removed from the fibre mass in order to obtain a higher purity and better fibre quality. The chemicals used, such as for example organic solvents, will depend on the exact contamination one wants to remove. Knowledge of the input composition is thus extremely important, because you want a selective removal without influencing the fibres one wants to regain.

Different textile wastes might require a different line-up of machinery as illustrated by the various standard recycling lines available from Dell'Orco & Villani (shown in Figure 4) and by the diverse range of machinery and lines offered by other machine manufacturers such as LAROCHE and Margasa. (LAROCHE sd) (https://www.dellorco-villani.it/en/plants/textile-recycling/) sd) (Margasa, http://www.margasa.com/en/productos/lineas-de-reciclaje-textil sd) (Balkan Textile Machinery sd) How various machines and technologies are combined depends firstly on the input material and secondly on the intended output. Moreover, process parameters such as speed of material transport and speed of drum rotation, can be adjusted to optimize productivity and fibre quality (Gulich 2006). Therefore, not all technology holders are able to process all kinds of textiles and choices must be made. This leads to specialisation in certain waste streams and an increased need of knowhow.

- Used clothing



- Tailoring clippings



- Post production hard waste

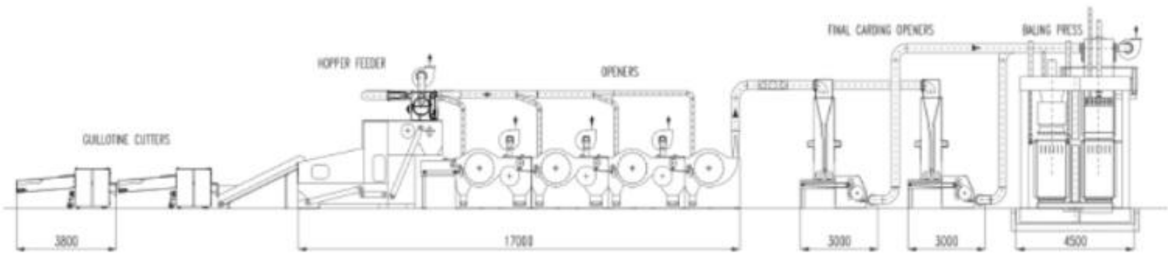


Figure 4: Standard recycling lines from Dell'Orco & Villani for processing different types of textile waste. (https://www.dellorco-villani.it/en/plants/textile-recycling/)

For textile that has a structure that can't be opened or for technical fibres such as aramid and carbon, milling or precision cutting can be performed to obtain short fibres or particles that can be used as filling material in compounding applications for example.

3.2.4. Output

During mechanical recycling the overall fibre properties (including material content and colour) are retained, apart from the fibre length and strength. Due to the tearing process materials can suffer severe damage, leading to a significant reduction in fibre length compared to virgin fibres. This means that the quality of the output depends both on the input material and on the recycling process. The better the process is adapted to the input material the higher the quality of the output. The process yields a variety of fibre lengths, including a considerable share of short fibres and dust. Pieces of fabric and threads can be present as well, in that case, the material requires another (or several) pass(es) through the tearing machine in order to obtain single fibres (Aronsson en Persson 2020) (S. Roos, et al. 2019). Due to the decrease in fibre quality, blending with virgin fibres is necessary to enable respinning into yarns (S. Roos, et al. 2019) (Lindström, et al. 2020). It has been estimated that current tearing technologies generate between 25% and 55% of fibres longer than 10 mm (Gulich 2006). When the fibre length has become too short, respinning will be impossible (Lindström, et al. 2020). These short fibres are also referred to as flock or fluff. The minimum fibre length required for spinning depends on several factors (i.e., the spinning technology: ring yarn vs. rotor yarn, the desired yarn properties: strength, fineness, evenness, etc.). Generally, fibres longer than 15 mm are preferred, while fibres with lengths from 10 to 15 mm can be spinnable but they will not or rarely contribute to the yarn strength. Unfortunately, the majority of the recovered fibres (i.e. about 80 - 95% for cotton) are currently not respun into yarn but processed into non-wovens instead. Although no prove was delivered, some technology holders claim to be able to recover 90% of spinnable fibre in specific cases of cotton waste, this is due to the use of larger pieces of textile, improved technology and better performing machinery. There is a believe amongst experts that this might be the case for stronger fibres like polyester fibres. Nonetheless, the industry is clearly still working on developments to increase the output of spinnable fibres.

Alternatively, the short fibres can be used as filling material or for non-woven production to produce insulation material or technical nonwovens for the automotive industry. Therefore, mechanical recycling is sometimes seen as downcycling. Moreover, any substances, including hazardous ones, remain in the material (S. Roos, et al. 2019) (Piribauer en Bartl 2019).

In terms of fibre content, the output purity solely depends on the input material. In case of material blends the output is very difficult to identify and might also be very inconsistent, depending on the number of different blends that are processed together or even in the same line. A textile input of 100% cotton fibres (e.g. when using 100% cotton denim only) will lead to a certain amount of spinnable fibres that are 100% cotton. However, when other materials were previously processed in the processing line, residues might remain in the machinery and contaminate the 100% cotton batch. The same applies for colours.

The possible outputs are delivered to producers in the form of a bale or in containers. We can categorise the different outputs as spinnable fibres, fluff material or flock for non-woven production, fillers and additional waste streams of non-textile materials.

Spinnable fibres / fibres of high quality and length

The spinnable fibre fraction is the output fraction made of long fibres of a good enough quality to be used in a spinning process. This output can only be obtained when the fibres from the textile input are of a good quality and the textile material is easy to open in the tearing process. Mechanical recycling of laminated, coated, printed or contaminated input will not result into fibres for spinning. These materials, once mechanically recycled, will result in fluff or filling material.

In case of natural fibres, between 5 – 20% of a good quality textile inputs can be recovered as spinnable fibres. As mentioned before, some technology holders claim to be able to recover a much higher percentage of cotton fibres from end-of-life textile. It is needless to say that the more fibres can be used as spinnable fibre, the lower the environmental impact will be when taking into account the replacement of virgin material. For synthetic fibres such as polyester, the amount will be higher but never 100% of the total material. There will always be a part of the textile material that will be recovered as short fibres or dust and thus cannot serve as input for a spinning process.

The removal of contaminants upfront of the recycling process might increase the amount of spinnable fibres but certain contaminants e.g., paint stains, are not removable. Therefore, rags used to clean up paint or clothing of a professional painter will have a lower output of spinnable fibres than hospital clothing. Depending on the nature and amount of contaminants, mechanical recycling is not an option for some textiles and they should be recycled with another technology that can purify the textiles of this contamination.

Fluff / un-spinnable fibre material

This output is still a fibre but they are too short and/or too entangled to be used in a spinning process. Fluff material is typically used in the non-woven industry to produce filling products like insulation for the construction industry or technical non-wovens for the automotive industry.

Fillers

In some processes (e.g. milling) the fibre shape is drastically altered, leading to small particles instead of fibres. This is not always intentional but due to the disintegration of the fibre during the recycling process. For example, cotton fibres that are present in a garment that is washed over 100 maintenance cycles can become so fragile that it pulverises, resulting in cotton dust. This fraction is now mainly compressed and used as burning fuel but could also potentially serve as raw material for a viscose process resulting in a viscose-type fibre.

Depending on the shape, size, and material, these particles can be used as filling or reinforcements in plastics and composites.

Regarding dust production, one technology holder estimated that more or less 20 kg dust is produced for each ton of input material. Another technology holder indicated 50 to 250 kg/h of dust leading to 80 to 400 tonnes a year.

Additional waste streams

Non-fibrous material is unwanted for further processing and thus removed. These are especially hard parts, such as coatings, backings, buttons, zippers or prints, or contaminants present on the textile product such as sand, dried paint or washing residues. Since these parts could also damage the machines, they will be removed resulting in metal and plastic waste fractions. One technology holder estimated this is less than 10% of the total weight in the case of a garment.

The cleansing processes will lead to contaminated cleansing mediums like organic solvents, water, etc.

3.2.5. Advantages vs disadvantages

Advantages

Mechanical recycling technologies require a relatively low level of investment and space, and less highly skilled personnel than chemical recycling technologies (see section 0).

As mentioned before, practically any textile waste stream (material and structure) can be processed via mechanical recycling. Hence, textiles that are not recyclable via other (i.e., chemical or thermo-mechanical) technologies can most probably be recycled mechanically. This leads to additional materials finding their way to new products replacing virgin material instead of going to incineration or landfill.

For natural fibres, mechanical recycling is the only way to preserve the fibre type, for example cotton fibres remain cotton without being converted into regenerated cellulose fibres such as viscose, which is the case in a chemical recycling process (see 3.4.2 Polymer recycling of cotton via a pulping process). This means the original properties of the fibre remain although this might be altered depending on the state of the fibre.

The process uses a relatively low number of resources. Interviews with the technology holders revealed that between 0.3 to 0.5 kW per kg input material is used. Also, the water usage is limited as this is only related to an occasional cleansing process as pre-treatment, but this is not always needed, e.g., production waste like cutting scraps form the confection industry.

Another advantage is that relatively small quantities of waste material can be processed with this technology. However, these small quantities may have as a disadvantage that material can stay behind in the machinery contaminating the following productions leading to quality issues.

Disadvantages

The different problems indicated in section 3.2.2 lead to an output consisting of mostly textile fibres of a (much) lower quality than virgin fibres or worse, non-fibrous material which is unsuitable for textile production without further processing. The use of the spinnable recycled fibre fraction will have an inevitable impact on the quality of the final textile product and blending with virgin material might be needed to reach an acceptable quality.

It is difficult to claim conformity to certain legislation like the Regulation (EC) No 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) and the Regulation (EU) No 1007/2011 of the European Parliament and of the Council of 27 September 2011 on textile fibre names and related labelling and marking of the fibre composition of textile products.

There are two major concerns regarding the REACH Regulation:

- A product that came to the market years ago will not automatically be compliant with the regulation of today, because several chemical substances have been included in the Candidate List of Substances of Very High Concern" (SVHC)-list, have become the object of restriction or are subjected to authorisations. As additives, dyes, contaminants, etc. are not removed during mechanical recycling, it is possible that some recycled materials contain chemicals that are no longer allowed by the REACH-regulation. This can result in a non-compliance although they are not intentionally incorporated during recycling.
- Textile might become contaminated with chemical substances during use. For example, research has shown that firefighter suits contain a high amount of polyaromatic hydrocarbon (PAH) substances that can't be washed out with a conventional cleansing process (Stec, et al. 2018). These PAH substances remain in the textile when mechanically recycled. Since the output can be very inconsistent depending on the input material it is practically impossible to guarantee the compliancy via testing of batches. Only a watertight supply chain could potentially solve this. One would need to know the complete history of the input materials.

Due to practical reasons it is hard to check the fibre content of every product that goes into the process (fibre contents might have changed during use, labels are removed…) and it is too costly and time-consuming to test every product. This problem can be tackled by having full knowledge on the input material in additional to the use of certification systems e.g. STANDARD 100 by OEKO-TEX®, bluesign®, QA-CER or other certification system with a profound testing system.

It is difficult to maintain a stable output when the input is not fully under control. With fully under control is meant that the complete history of the textile is known, including production and use. This is mainly due to the different state of the input even when the original pieces were of the same composition. E.g. a batch of garments consisting out of polyester and cotton staple fibres that are intimately blended will be irregular in composition depending on the fibre loss during use. So, despite the same composition of all pieces, the use can lead to a different composition for every piece. Additionally, it is possible that fibre material from previous recycled textile stay behind in the recycling equipment and will contaminate future production batches. This all leads to an irregular output of materials. The fibre content can, therefore, differ within one batch.

In this regard, article 9 paragraph 4 of Regulation (EU) n° 1007/2011 states that *without prejudice to article 5(1), for textile products the composition of which is hard to state at the time of their manufacture, the term 'mixed fibres' or the term 'unspecified textile composition' may be used on the label or marking*. A manufacturer can declare that the textile product contains "mixed fibres" or "unspecified textile composition", however this would influence the provision of precise information on the fibre content to the consumer.

A fibre composition declaration of a textile product made of virgin fibres and recycled fibres may identify the latter as mixed fibres. This might alert market surveillance authorities in case of compliance checks with Regulation (EU) n°1007/2011 to conclude that the product is not compliant because the declaration of fibre content would exceed the manufacturing tolerance of 3% established in article 20 paragraph 3 of Regulation (EU) n° 1007/2011. Therefore, it is important that the textile fibre content declaration provides clear information about the textile recycled content so that market surveillance authorities which check the conformity with Regulation (EU) n° 1007/2011 can take these deviations into account.

Also, the remaining of colorants might be experienced as a disadvantage. It is very difficult to obtain a uniform colour when different fibre colours are obtained as an output. One can only try dyeing the fibres in a darker shade but then still some fibres might appear darker in colour than others or have a different colour. This will result in irregular and random coloured textiles. Bleaching could be considered but it depends on the colorant if this is possible and even if it would be possible, it would probably damage the fibre too much.

3.2.6. Status & prognosis

Mechanical recycling, currently at Technology Readiness Level 9 (TRL 9), is an established technology in the market with already decades of experience, for example, for wool in the Prato region in Italy or other natural fibres (cellulose-based such as cotton, jute, sisal, flax, etc.) and also synthetic fibres (polyester, polyamide, acryl, viscose, PP, etc.) in various European regions (Belgium, France, Germany, Sweden, etc.). The survey conducted among technology holders revealed a wide range in production capacities, going from 5 000 to 10 000 tonnes/year to as much as 36 000 tonnes per year (see Table 1). New developments, starting from TRL 7, are mainly focusing on increasing the amount of spinnable fibre and improving the quality of the fibres that are recycled. These developments mainly focus on adjustments to the machinery or recycling line set-up, additional (chemical) treatments and better sorting of the input material.

When the input is highly pure and of good quality, it could be a first step to obtain a fraction of spinnable fibres that are (partially) used in a new textile product at a low cost and probably also at a lower environmental footprint. The other fractions could be used as input for other recycling technologies, for example, cotton dust for a pulping process. Thanks to the improving technology and machinery, the amount of spinnable fibres will probably increase in the future.

Table 1: Overview of current and future process capacities of the mechanical recycling technology holders participating in the survey

Company	TRL	Current process capacity (t/year)	Future process capacity (t/year)
1	9	10 000	/
2	9	36 000	/
3	9	6000	/
4	7	0.6	Not provided
5	9	6000	21 000
6	9	> 20 000	/
7	7	1600-5000	Not provided

3.2.7. Technology holders

Several mechanical recycling technology holders, recycling companies as well as developers/manufacturers of machinery, were identified, some are presented in Table 2.

Table 2 : Examples of mechanical recycling process technology holders

Company name	Website
ALTEX Textil-Recycling GmbH & Co. KG	www.altex.de
Cormatex	www.cormatex.it/en
Concordia textiles/PurFi joint-venture	www.concordiatextiles.com purfiglobal.com
Dell'Orco & Villani SRL	www.dellorco-villani.it/en/
Derotex NV	www.derotex.be
HKRITA Garment-to-Garment	www.garment2garment.com
Nova Fides	www.novafides.it
Procotex SA Corporation NV	en.procotex.com/index.php
Recover Textile Systems S.L.	www.recovertex.com/
Vanotex NV	www.vanotex.be

3.3. Thermal recycling process

3.3.1. Definition according to draft DIS 5157

Thermal recycling as such has not (yet) been defined in the draft DIS 5157. However, in the current study it is considered a recycling process based on heating with the aim to recover either polymers or low molecular weight building blocks. Not to be mistaken with thermal recovery, an altogether different process which is not considered a recycling technology by the waste regulation. In the draft DIS 5157, thermal recovery is described as a combustion process for extracting the fuel value of materials, and deliver heat to another process.

Under thermal recycling, a key distinction should be made between thermo-mechanical and thermo-chemical processes (i.e. gasification, pyrolysis, cracking).The thermo-mechanical process will merely melt the polymer, keeping the chains intact, while the thermo-chemical process will break them down into low molecular weight building blocks. At present, the draft DIS 5157 only includes a definition for thermo-mechanical recycling:

Thermo-mechanical recycling process

process used in a recycling system that melts a polymer, typically employed to permit polymer recycling

These are technologies for recycling thermoplastic textiles, e.g. polyester, polyamide, polypropylene, etc. by melt processing them into a regranulate and/or new fibres.

However, recently also thermo-chemical processes are gaining attention for material recovery, more specifically for the recovery of base molecules (e.g., monomers, syn gas, oils) that serve as feedstock for the chemical industry. The ISO 15270 Plastics – Guidelines for the recovery and recycling of plastics waste, already includes cracking and gasification as chemical recycling technologies for conversion of plastic waste into monomers or new raw materials (excluding energy recovery and incineration as well as conversion into fuels for energy purposes). Although this is not yet included in the draft DIS 5157, the processes are in theory also applicable to textiles and some research as well as larger scale initiatives are considering textiles as input material. Hence, it was decided to include those processes in the current project, whereby it is defined as follows:

Thermo-chemical recycling process

Recycling process using partial oxidation reaction of polymers to produce low molar mass components or heat to degrade polymers to monomers that can be used as feedstock for the chemical industry, with the exclusion of fuels used for energy production or other combustion or energy recovery processes.

Thermo-chemical recycling could be considered a chemical recycling process, but due to the high temprature needed, it was decided that the thermal part is the main influence in the process.

An overview of the definitions of thermal recycling and recovery processes is presented in Figure 5.

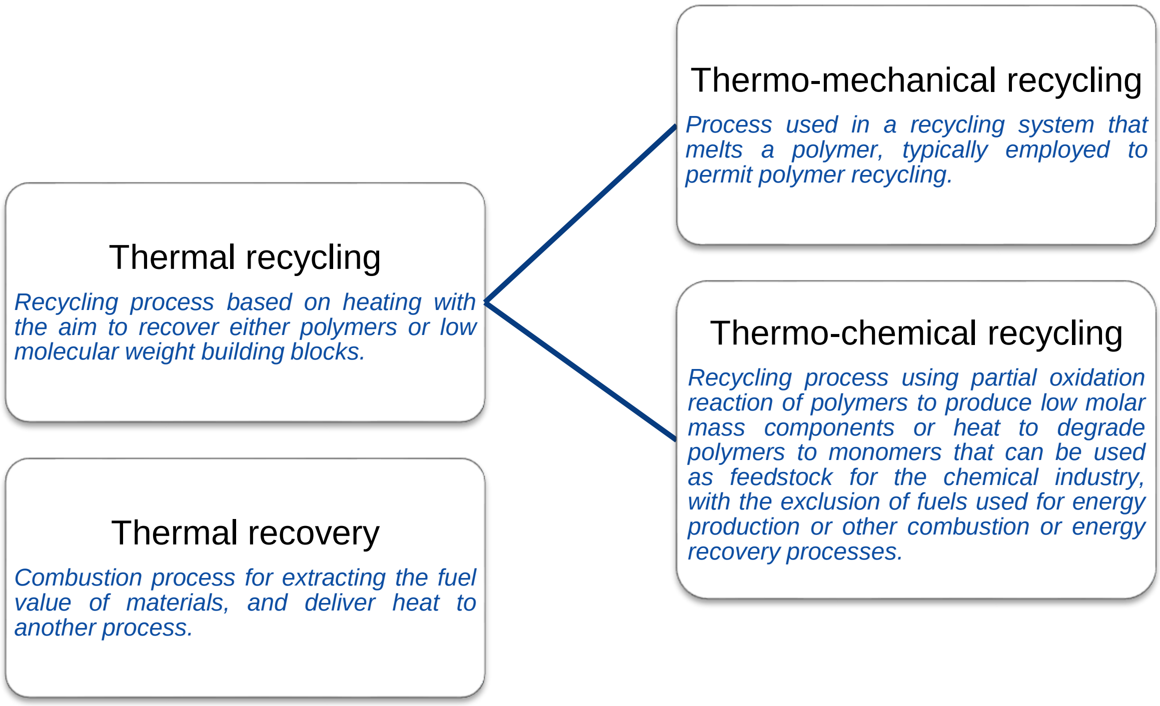


Figure 5: Overview of definitions regarding thermal recycling and recovery.

3.3.2. Thermo-mechanical recycling

Thermo-mechanical recycling is a process using heat to melt thermoplastic textiles and recover the polymers in the form of regranulate or fibres.

3.3.2.1. Input

Theoretically, any thermoplastic fibre or textile, both pre- and post-consumer, can be reprocessed into a new fibre via thermo-mechanical reycling. Examples include PET, PA6, PP and PA6,6. However, it is important that the input material consists of only one polymer type or of compatible polymer types. Incompatible polymers will not blend properly which will cause problems in processing, resulting in fibres of lower strength or even prevent fibre production altogether.

It should be noted that one fibre type or name can refer to different types of polymers. For example, “polyester” is typically used to refer to fibres or textiles made from polyethylene terephtalate (PET), however it can also refer to polybutylene terephtalate (PBT) or polytrimethylene terephtalate (PTT). Blending these different types of polyester can also adversely affect the processing and the quality of the output.

Fibre spinning is a very delicate process and the presence of even a small amount of an incompatible polymer can cause problems in processing and reduce output properties. In mechanical recycling of solid plastic waste, the immiscibility of polymer blends is typically mitigated by the addition of compatibilizers (Koning, et al. 1998). These are polymers (either block/graft copolymers, non-reactive polymers with polar functionalities or reactive functionalized polymers) that promote the interfacial adhesion between immiscible polymers leading to a more uniform and smaller distribution of the dispersed phase and a stable morphology (Ragaert, Delva en Geem 2017). The practice of using compatibilizers is being studied for thermo-mechanical recycling of textiles as well. However it is not yet common practice and technology holders prefer an input consisting of 1 polymer type, 100% pure.

Other contaminants such as pigments, prints, wash residues, flame retardants, coatings, etc. that are present in or on the fibre or textile, can also hinder the spinning process and/or result in severely reduced output quality. For example, some products (like flame retardants) can cause hydrolysis of the polymer chain, resulting in reduced viscosity. Moreover, mixing of different coloured materials can lead to undesirable colours as dyes and pigments remain present. Hence, knowledge of the composition, type and amount of contamination and separation and sorting of the input material are extremely important (Ragaert, Delva en Geem 2017). Thermo-mechanical recyclers prefer production waste or large batches of known origin. Due to the high risk of contamination, clothing waste from households or fashion in general is not considered as a suitable input.

Additional important parameters include the intrinsic viscosity and molecular weight of the thermoplastic material. A great challenge in thermo-mechanical recycling is polymer degradation caused by the reprocessing itself (i.e. a combination of heat and mechanical shear during melt processing) and long-time exposure to environmental factors (mainly (UV) light and oxygen causing photo-oxidation) during lifetime (Ragaert, Delva en Geem 2017) (La Mantia 1996). Polymer degradation leads to variations in mechanical (e.g. reduced elongation at break), rheological (e.g. reduced viscosity occurs with every reprocessing cycle), thermal (melting temperature, crystallization, etc.) and physical (surface properties, colour, etc.) properties. Different additives, such as heat stabilizers, crosslinkers/chain extenders (or “viscosity boosters”), compatibilizers, etc. as well as virgin material can be added to improve the processing and output properties (Ragaert, Delva en Geem 2017) (Murphy 2001). Chain extenders are low (or moderate) molar mass compounds with different functional groups that react with the end-groups of polyesters or polyamides. This results in crosslinking of the polymer chains and therefore an increase in molar mass and viscosity. Moreover, in the specific case of PET the melt strength and mechanical properties can be improved by post-condensation as well (see section 3.3.2.2 Process steps) (Ragaert, Delva en Geem 2017). For this technology to be succesfull, it is important that certain parameters are taken into account (see section 3.3.2.4 Advantages vs disadvantages).

3.3.2.2. Process steps

The general process diagram for thermo-mechanical recycling is presented in Figure 6. It is very similar to the extrusion process of virgin thermoplastic polymers with the exception of the pre-treatment step.

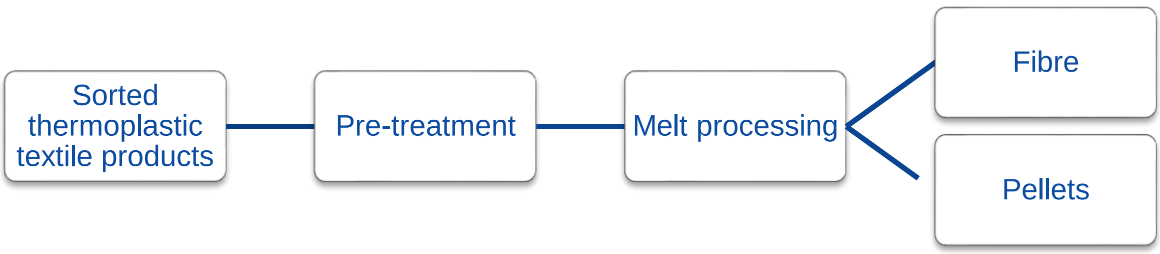


Figure 6: General process scheme for thermo-mechanical recycling

Pre-treatment

Removal of non-textile parts, washing/cleaning, drying and shredding/grinding to fibres is needed. This can be done in the same way as for mechanical recycling (see section 3.2.3 Process steps). For moisture sensitive materials such as polyester and polyamide, the drying step is very important to avoid material degradation due to hydrolysis during processing at increased temperatures.

Melt processing

Similar to mechanical recycling of solid plastic waste, thermoplastic textile waste is processed via compounding and regranulation. This involves reprocessing into a granulate which can be further processed into fibres via melt spinning or other processing techniques (Ragaert, Delva en Geem 2017). It should be noted that processing of fibre/textile fluff is generally more challenging because of the low bulk density. Therefore, specialized shredding, feeding and/or compacting equipment is often required to maintain a constant supply of textile or fibrous input. Granulate or pellets are easier to process by converters than fibre/textile fluff (Ragaert, Delva en Geem 2017).

The production of textile fibres is achieved by melt spinning of the regranulate. Melt spinning of thermoplastic fibres is performed as illustrated in Figure 7: the polymer is fed from a hopper to a single-screw extruder where it is melted to a suitable viscosity by means of heat and shear. The polymer melt is extruded through a spin pack with spinneret (i.e., a metal plate with holes) and subsequently cooled for solidification into continuous filaments. In addition to the spinneret (which is responsible for the filament formation), the spin pack also comprises parts for polymer filtering (to remove non-melting particles and build up pressure) and distribution. A melt pump is applied to ensure a controlled throughput. After cooling, the filaments are drawn by heated godets to increase molecular orientation and therefore fibre strength, and finally spooled onto a bobbin with a winder (Hufenus, et al. 2020).

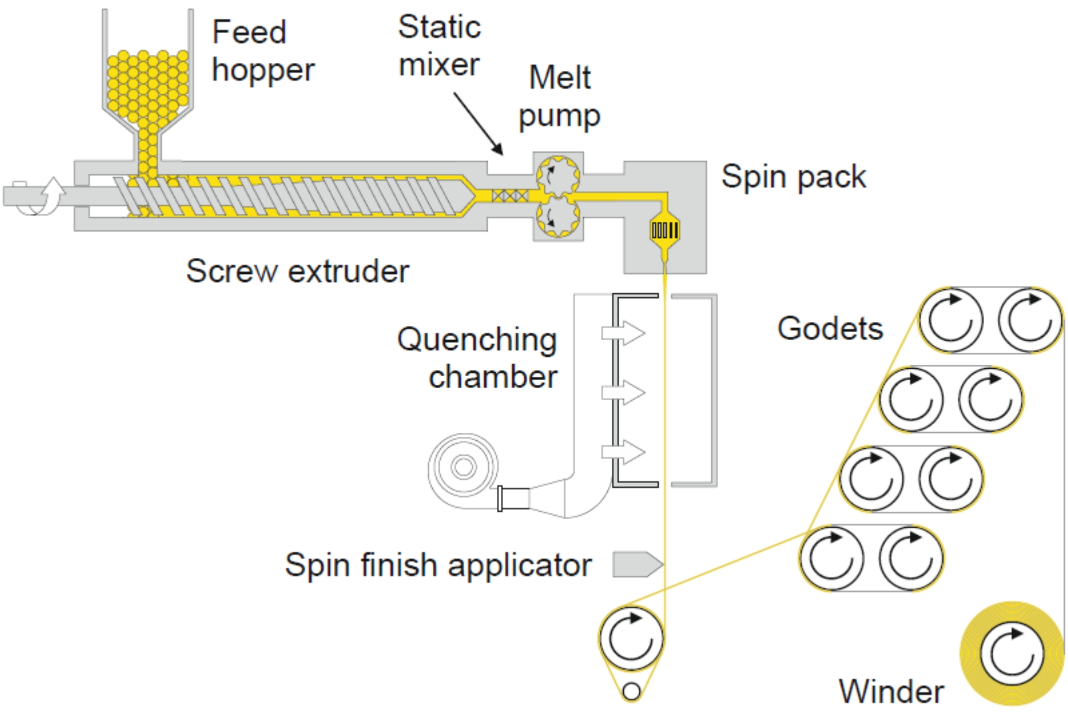


Figure 7: Schematic overview of the melt spinning process. By way of illustration, the polymer is represented in yellow. (Hufenus, et al. 2020)

In mechanical recycling of solid plastic waste, including processing of PET bottles into textile fibres, melt filtration is typically applied to remove small quantities of contaminants and impurities (such as wood, paper, cellulose fibres, chemicals, rubbers, and higher melting polymers) from the polymer melt. This can be done during regranulation or reprocessing to improve the polymer quality and process stability (Ragaert, Delva en Geem 2017). This technology is currently being evaluated by thermo-mechanical textile recyclers as well. However, when there are too many contaminants and impurities, the filters will be constantly blocked and thus hinder the production process.

As mentioned before, polymer degradation is a substantial issue. Not only because of the accompanied reduction in molar mass and viscosity but also due to the generation of molecular volatile compounds (small, oxygenated fragments of the original polymer). These can diffuse through the melt and hinder processing, reduce output properties, or even corrode processing equipment. A (vacuum) degassing unit may be required (Ragaert, Delva en Geem 2017).

In PET recycling an additional solid-state post-condensation step is mostly included after regranulation and before spinning. This process serves to improve the melt strength and mitigate the viscosity loss accompanied by thermal (re)processing in addition to or as an alternative to the use of chain extenders. The PET pellets are heated in a reactor to a temperature between the glass transition temperature and melting temperature (typically 200-240°C) and under vacuum (to remove by-products). At this temperature condensation reactions occur between the end groups of the polymer chains in the amorphous PET phase (Ragaert, Delva en Geem 2017) (Welle 2011).

In theory, the regranulation step could be omitted and the (clean) shredded textile fluff melt spun into fibres immediately in a one-step process. However, in practice this will be very difficult due to issues with feeding fluffy textile materials, the presence of (non-melting) contaminations and reduced polymer viscosities. For PET materials, specialized recycling lines (including systems for melt filtration, vacuum degassing, and viscosity enhancement) exist that can be installed in line with the melt spinning line (BB Engineering GmbH 2019).

3.3.2.3. Output

Textile yarn (continuous filaments in case of high-quality input: no contamination or degradation, or staple fibre in case of lower quality input) or thermoplastic polymer pellets (regranulate) for other applications (in case fibre spinning is not possible).

Contaminants such as pigments, dyes and other chemicals remain in the material. The output colour is thus dependent on the colours of the input materials and of possible colour changes during processing due to degradation or thermochromic dyes. Hence, to avoid irregular and unwanted colours either the input textile should be colour sorted or a dark dye or pigment should be added. Moreover, some remaining contaminants may be in violation with the REACH regulation, as already described in the chapter on the mechanical recycling process, section 3.2.5.

3.3.2.4. Advantages vs disadvantages

Advantages

The process is similar to melt processing of virgin material (with the exception of shredding, cleaning, feeding and degassing steps), even more similar to the more established mechanical recycling of solid plastic waste. It is also a cost-effective, efficient and well-known process which means it can be easily implemented.

Next to this there are little emissions that could emerge during the process, only volatile contaminants (e.g. from disperse dyestuff or polymer degradation).

The output are fibres can be used in various textile applications, depending on the quality. High quality materials can be used in a higher amount when blended with virgin polymer and/or lead to filament yarns. The lower quality can be blended with virgin material which leads to staple fibres.

Disadvantages

The polymer/fibre properties deteriorate after each cycle. So, despite the similarities with the melt processing of virgin or waste plastics, specialised equipment or components are required to ensure a stable and continuous process. This depends on the material and state of the material that is being processed. For example, equipment for the polycondensation of polyester might be implemented to increase the quality of the output.

In addition, the technology is very sensitive to even low levels of contamination and the state (molar mass/viscosity) of the polymer. Technology holders have also indicated that they are only willing to use production waste or large batches of known origin because of this reason.

Since the colorants remain in the polymer material, only dark colours are possible, unless the input is colour-sorted and no colour changes occur during processing: some colorants are thermochromic, meaning that they change colour at a certain temperature.

Just like colorants, chemicals, if not volatile, remain in the recycled material and can conflict with the REACH regulation as explained in section 3.2.5.

3.3.2.5. Status & prognosis

The process is very interesting for the recycling of production waste and some specific consumer waste that has been collected in specialized centres.

One of the technology holders, with a current production capacity of 5000 tonnes/year (see Table 3) expects to reach TRL 7 soon for post-industrial textile waste. However, the addition of virgin material is required and only a limited amount of recycled material will be present in the final fibre. One of the technology holders blends 20% of recycled polyester with virgin material. Further research will be done in an attempt to use chemicals to increase the quality of the polymer. TRL 9, meaning proven and ready for commercial deployment, is expected to be reached in about 1 to 2 years, with still a limited percentage of recycled content and the same input material limitations.

The recycling of blends of thermoplastic materials into hybrid yarn is being investigated, although currently at low TRL (2-3) (Kunchimon, et al. 2019) (Afshari, et al. 2005) (Aslan, et al. 1996).

Table 3: Overview of current and future process capacities of the thermo-mechanical recycling technology holders participating in the survey.

Company	TRL	Current process capacity (t/year)	Future process capacity (t/year)
1	3	Not provided	Not provided
2	6	5000	Not provided

3.3.3. Thermo-chemical recycling

The thermo-chemical recycling processes pyrolysis and gasification differ from one another and from combustion in several ways. Combustion is performed at temperatures in between 800 and 1200°C with sufficient oxygen in order to completely oxidize the material and is mainly used to generate steam for electricity production or for heating. Hence, it is not considered a recycling/material recovery process. Gasification occurs typically at 700-

1100°C with insufficient oxygen or steam to achieve partial oxidation and pyrolysis at 350-700°C in the absence of oxygen (C. Roos 2010) (Pohjakallio, Vuorinen en Oasmaa 2020). The output products (gas and oil) generated by gasification and pyrolysis can be used for heat and power purposes, however, with subsequent purification/upgrading steps these can also be converted into chemical intermediates and therefore serve as feedstock for the chemical industry (Pohjakallio, Vuorinen en Oasmaa 2020) (C. Roos 2010).

The pyrolysis technology is already used to convert plastic waste into solid, liquid and gaseous fuels (Miandad, et al. 2019). Moreover, several industrial players are developing new or modified pyrolysis processes with the intention to produce not only fuels but also raw materials for the chemical industry (Pohjakallio, Vuorinen en Oasmaa 2020). However, as there currently seems to be little focus on textiles, this report will not cover pyrolysis. It should be noted that this technology is already being used commercially for the recovery of the reinforcing fibres (generally carbon) from composites (Blazsó 2010). Nonetheless, this was considered out of scope of the present study as the composite matrix is burnt and not (yet) recycled.

More recently gasification has also started attracting more attention as a recycling technology for plastic as well as textile waste (Pohjakallio, Vuorinen en Oasmaa 2020). Moreover, one of the interviewed technology holders is already processing polyester carpet waste via a gasification process. Hence, this process will be covered in the upcoming sections.

3.3.3.1. Input

In theory any waste can be processed via thermo-chemical recycling as long as it consists of organic/carbon-based material, including biomass, plastics (thermoplastics as well as thermosets) and textiles. The ability to treat heterogeneous and contaminated waste is one of the main advantages of gasification, the flexibility of feedstock is higher than for other recycling technologies. In the gasification process the targeted molecules are carbon and hydrogen, and as most commercially produced polymers contain high amounts of carbon and hydrogen, they are optimal feedstocks for forming syngas through gasification. However, the overall composition of the feedstock can incluence the product mix when it carries high amounts of inorganic material. An example of an inorganic component is nitrogen present in polyamide, which will influence the process to the extent that the amount of polyamide in a production batch will be limited. Moreover, as with any chemical process, depending on the input, the process conditions need to be adjusted to ensure a well-functioning process and high yield.

Therefore, also for this technology, it is imporant to know the composition of the input material. One of the questioned technology holders is capable of processing practically all plastic types (n°1 to 7: PET, HDPE, LDPE, PP, PS and other) with the exception of PVC (plastic type 3) and other plastics with high halogen content due to existing processing limitations, and not technology limits. The gasification process is capable of dealing with small amounts of PVC, however, due to the corrosive nature of chlorine, it is not a desirable feedstock. Nevertheless, some processable materials (like polyamide) are only wanted in limited quantities and they mainly focus on plastics and textiles made from polyester and blends with polyester, as of today. In addition to plastics they are also able to process cellulosic materials. Technology holders have stated that contamination with certain chemicals can influence the process but it is generally not a main concern as most contaminants don't cause major problems. Hence, the input textiles don't require washing or cleaning. Nevertheless, extra gas treatment/cleaning steps might be necessary depending on the desired chemical intermediate, which will increase the investment and operational costs. Therefore, feedstock requirements can also be guided by economical concerns.

In addition to textile feeds, further input materials for the gasification, such as fossil fuel, industrial CO_2 or other organic sources, are currently used for scale. In the future, more fossil input will be replaced with waste. In addition, energy, both from external sources and a portion that is captured from the process itself (auto-consumption), and air,oxygen or steam (depending on the type of gasifier) are needed to run the process.

3.3.3.2. Process steps

The general process scheme for thermo-chemical recycling via gasification is shown in Figure 8.

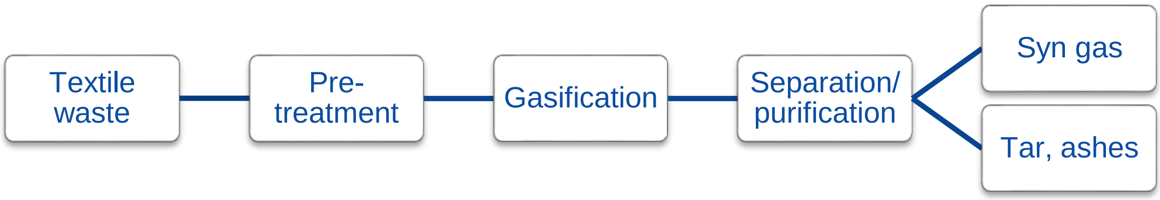


Figure 8: General process scheme for thermo-chemical recycling via gasification.

Pre-treatment

Non textile parts such as metal buttons are removed as they can cause problems during processing. This can be done in the same way as for mechanical recycling (see section 3.2.3). Drying can be necessary when the input material is wet. Size reduction to homogenize and compact the input textiles is required as well.

Gasification

The actual gasification step entails heating the waste to temperatures of 700 to 1100°C with a controlled amount of oxygen, air, oxygen enriched air and/or steam (Pohjakallio, Vuorinen en Oasmaa 2020). During the process a series of complex endothermic chemical reactions occur, resulting in the production of volatiles (i.e. gases and tars) and a solid residue (i.e. char or ash). The composition of the resulting volatiles depends on the polymer reaction mechanisms, which in turn determines the subsequent cracking and reforming reactions happening in the gaseous phase. The gasifying agent is also an important determinant for the output. Air gasification will result in a syngas mainly suitable for energy production, while steam gasification leads to nitrogen free syngas with a composition appropriate for chemical synthesis applications (Lopez, Artetxe, et al., Recent advances in the gasification of waste plastics. A critical overview 2018).

The process can be performed in different types of reactors, such as bubbling fluidized bed (BFB) gasifiers; circulating fluidized bed gasifiers; dual fluidized bed gasifiers; plasma gasifiers; and entrained flow gasifiers. The general design includes the gasification reactor with feeding system and the difference between the various types lies in the heating mechanism, the inlet for gasification agents and the location of the syngas output (Pohjakallio, Vuorinen en Oasmaa 2020) (Brems, et al. 2013).

The ideal reactor design depends on the input and output, for example gasifiers for plastic waste need other features than biomass/coal gasifiers. More specifically, they need to be able to provide high heat transfer rates to promote fast depolymerisation, be able to handle the sticky nature of plastics, allow an appropriate residence time distribution to favour tar cracking, and so on. Fluidized bed reactors are mostly used for waste plastics, altough other reactors have been used as well (Lopez, Artetxe, et al., Recent advances in the gasification of waste plastics. A critical overview 2018).

Separation/Purification

A series of traps/separators each collect a fraction of the reaction products. This can be achieved via condensation by cooling in ice-water, using liquid nitrogen, etc. (e.g., for the tar) or the simple capture of the gasses (e.g., for the syngas). In order for the syngas to meet the requirements for the production of chemical intermediates, components containing sulfur, halogens, nitrogen, etc. need to be removed. Hence, a very efficient gas cleaning system is needed (Lopez, Artetxe, et al., Recent advances in the gasification of waste plastics. A critical overview 2018).

3.3.3.3. Output

Different fractions coming out of the process can be viscous liquids (also called oil or tar fraction), condensable and non-condensable/permanent gases (syngas) and inorganic residue such as carbon soot, metals and minerals (also called ash). The specific output of the gasification process depends on the input waste (type and composition), the reactor type and process parameters (gasifying agent, temperature, heating rate, residence time, etc.), meaning that fractions might have a different content and the quantities might also shift (Pohjakallio, Vuorinen en Oasmaa 2020). The obtained fractions can serve as feedstock for the chemical industry, but also as fuel.

Syngas is a mixture of hydrogen (H_2) and carbon monoxide (CO) including lower concentrations of carbon dioxide (CO_2), methane (CH_4) and potentially other hydrocarbons. After purification it can be further refined to chemical intermediates via different steps. Figure 9 illustrates how syngas can serve as feedstock for the chemical industry through various refining steps (Pohjakallio, Vuorinen en Oasmaa 2020) (Punkkinen, et al. 2017). For this purpose conditioning of the syngas may be required, for example by water-gas shift (i.e. adjustment of the H_2/CO ratio) and CO_2 removal (H.S.Tay, T.L.Ng en K.S.Ng 2012). One of the main products derived from syngas is methanol, which in turn can be converted into a range of chemical intermediates (Punkkinen, et al. 2017). Steam gasification results in a N_2-free syngas with high H_2/CO ratios which is better suited for chemical synthesis than the syngas produced by gasification from direct air (Pohjakallio, Vuorinen en Oasmaa 2020) (Lopez, Artetxe, et al., Recent advances in the gasification of waste plastics. A critical overview 2018). Gasification with pure oxygen (O_2) combines the advantages of both gasifying agents, resulting in a high-quality syngas but is more complex and expensive due to the need for air separation (Xiao, et al. 2007).

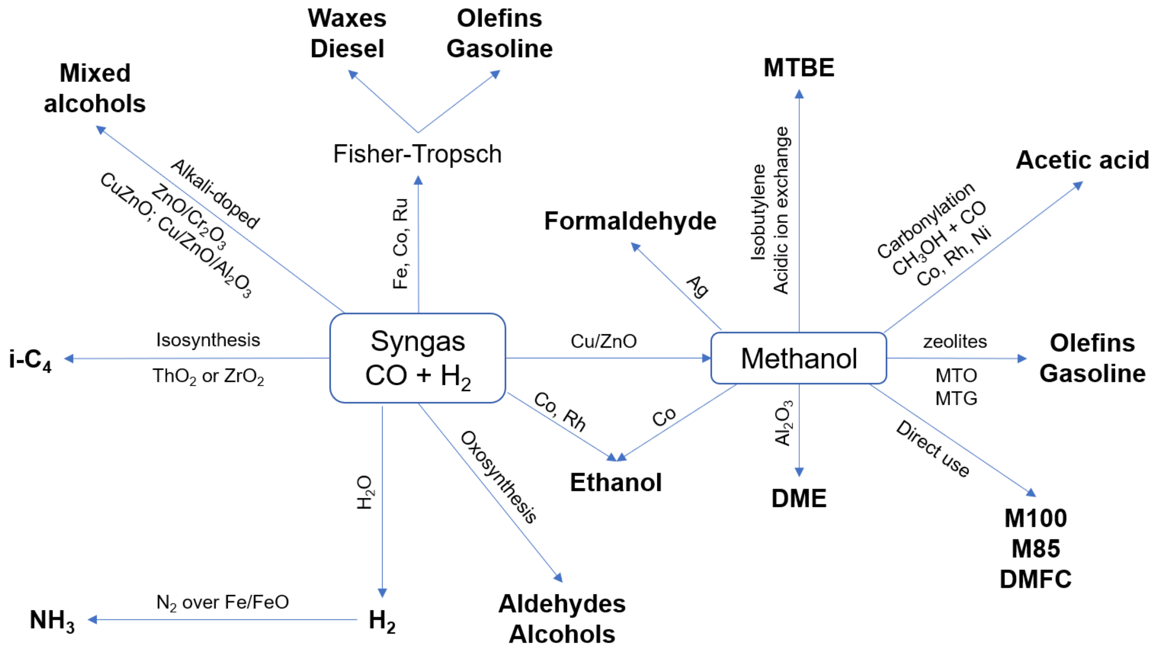


Figure 9: Potential syngas refining pathways (Pohjakallio, Vuorinen en Oasmaa 2020) (Punkkinen, et al. 2017) (Abbreviations: MTBE methyl tert-butyl ether, DME dimethyl ether, M100 fuel methanol, M85 85% methanol and 15% petrol fuel, DMFC direct methanol to fuel cell, MTO methanol to olefins, MTG methanol to gasoline)

One of the technology holders processes polyester textile material into CO and H_2 which is subsequently converted into methanol. The methanol is converted into acetic acid later used in combination with wood pulp to produce cellulose acetate which is dry spun into fibres for textile applications.

Research on the gasification of textiles in a fluidized bed reactor showed that 100% cotton produced high yields (0.8-0.9 kg/kgdaff; kg dry ash free fuel, excluding all moisture and ash) of permanent gas (the non-condensable fraction of syngas) suitable for chemical synthesis, while 100% polyester yielded not only permanent gas (0.7-0.8 kg/kgdaff) but also aromatics (0.1 kg/kgdaff), making valorisation of benzene, toluene, xylene and styrene (BTXS) an option as well. Altough textile blends resulted in lower yields (0.5-0.7 kg/kgdaff permanent gas and 0.1 kg/kgdaff BTXS), the uncoverted fraction could be utilized to produce the energy required for the gasification process (Vela, Maric en Seemann 2019).

3.3.3.4. Advantages vs disadvantages

Advantages

The main advantage of this technology is the ability to process more complex, heterogeneous waste streams, including fibres and blends of fibres that can't be recycled by any other technology or would be downcycled as best option (e.g., thermosets, composites, coated and laminated textiles…). Hence it does not need high-quality, sorted textile waste. It is also more tolerant to contaminants compared to thermo-mechanical or chemical recycling technologies and therefore does not require thorough cleaning and decontamination pre-treatment of the input textiles (Qureshi, et al. 2020) (Council en Association 2004). Unlike mechanical and thermo-mechanical recycling, gasification is less sensitive to material degradation happening during the product lifetime or recycling (Kamińska-Pietrzak en Smoliński 2013).

The input doesn't need to consist solely of textiles material. Materials from different industries (biomass, plastics, textiles…) can be blended, as the carbon and hydrogen content are the molecular targets. This gives a significant advantage as the larger scale of waste material allows to set up an economically viable recycling process. In this way also smaller textile fractions that can't be processed by another technology because it is economical not feasible to develop and scale up a production process, could still be treated.

The technology leads to pure, uncontaminated, virgin-like feedstocks, making it ideal for textiles containing non-REACH compliant chemicals that cannot be removed via other recycling technologies. Moreover, the main output, syngas, has many application possibilities in chemical synthesis reactions leading to a whole range of desirable products.

The gasification process is a relatively straightforward and mature process (TRL 9) with commercial installations already existing for biomass, plastics and even textiles (Qureshi, et al. 2020) (Enerkem 2021) (Company 2021).

It should be noted that thermo-chemical recycling or other textile recycling technologies are not substitutes to one another. All technologies complement each other and, in the future, it is likely that the most sustainable solution to handle textile waste will be to integrate different technologies.

Disadvantages

The process of thermo-chemical recycling is energy consuming due to the high temperatures needed.Together with the required separation and purification steps, the enviromental impact is expected to be higher compared to mechanical and thermo-mechanical recycling of thermoplastic polymers. However, processing (textile) waste requires less energy than processing fossil input, hence the environmental impact is lower than for the traditional gasification of fossil feedstock.

Most gasification plants are optimized for energy recovery and fuel production from biomass or plastic waste and need adaptations and additional purification steps in order to be suitable for textiles as input and clean syngas for chemical synthesis as output. These additional cleaning steps increase investment and operational costs. Moreover, there is a risk for greenwashing when gasification is claimed for recycling because a major part of the input material can go to fuel production instead of feedstock for the chemical industry. This is technology dependent so clarification is required to ensure credibility of claims. It is important to note that this technology is still evolving and developments are focusing on increasing the yield of output suitable as chemical feedstock.

The fact that the output can serve many applications and is not limited to the textile industry, can be seen as an advantage, but it also makes it more difficult to make solid claims on the actual recycled content in the final product. It is therefore necessary for legislation to accept and acknowledge mass balance as a chain of custody model with specified guidelines and restrictions. Here an appropriate amount of flexibility is needed in order to achieve scalability without compromising sustainability or credibility. The overarching goal is to enable a fast and massive diversion of waste materials away from disposal (e.g. landfill and incineration) and into material recycling under the management of chain of custody systems that avoid fraud.

3.3.3.5. Status & prognosis

Because of the low price of oil, thermo-chemical recycling has not been very economically interesting. However this has changed thanks to the pressure to move towards a circular economy (Pohjakallio, Vuorinen en Oasmaa 2020).

Gasification for energy production has already been applied for 180 years, first using coal and biomass, while today several companies and consortia are developing thermochemical routes for recycling plastics and textile waste. It is therefore considered a mature technology, although developments to allow the production of raw materials for the chemical industry (as opposed to energy recovery or fuel production) are very recent. Up to now, not many waste gasification processes have been piloted and tested but there are a few that have already been implemented as industrial plants (TRL 9) processing actual waste

(Pohjakallio, Vuorinen en Oasmaa 2020). One of the interviewed technology holders is able to process 22 million tonnes of plastic waste, including polyester textiles and carpets. Moreover, a Canadian company has commercialized a gasification process for municipal solid waste in which the produced syngas is used for methanol production. Their first commercial-scale facility in Edmonton has a capacity of 100 000 tonnes/year (Edmonton, Innovates en Enerkem sd). There are also plans for a facility in Rotterdam with a capacity for processing up to 360 000 tonnes of waste per year (Enerkem; 2019).

The process is especially interesting for textile waste that is untreatable by mechanical, thermo-mechanical or (bio)chemical recycling and for textile fractions that are too little in quantity. Considering the need to safely and efficiently process these difficult wastes and the need to produce high-quality recycled materials, the gasification process has the potential to become an important recycling technology which is complementary to (thermo-)mechanical and chemical recycling technologies (Pohjakallio, Vuorinen en Oasmaa 2020).

3.3.4. Technology holders

Several thermal recycling technology holders were identified, some are presented in Table 4.

Table 4: Examples of thermal recycling process technology holders

Company name	Website
Antex (thermo-mechanical)	antex.net
DS Fibres (thermo-mechanical)	www.dstg.com/ds-fibres
Eastman Carbon Renewal Technology (Thermo-chemical)	www.eastman.com/Company/Circular-Economy/Solutions/Pages/Carbon-Renewal.aspx

3.4. Chemical recycling process

3.4.1. Definition according to draft DIS 5157

A process using chemical dissolution or chemical reactions which is employed in polymer or monomer recycling. There are several possibilities within this recycling technology.

- monomer recycling:

  system for breaking down polymeric textile materials into their constituent monomers and rebuilding polymeric fibres for new uses

- polymer recycling:

  system for disassembling used fibres, extracting polymers and re-spinning them for new uses

Three major technologies can be identified in this respect: (i) Polymer recycling of cotton via a pulping process, (ii) Monomer recycling of PA6 or PET via (partial) degradation into oligomers or monomers, and (iii) technologies focusing on the recovery of both cellulose and PET from polycotton blends. Due to the large differences between these technologies, they will be treated separately in the following sections.

We want to note that some technology holders only pulp the cellulosic materials by grinding the cellulose into nano cellulose and dispersing it in a liquid without breaking down the cellulose into single polymers chains. This could be seen as mechanical recycling.

However, from this point on, the pulp needs chemical processing to obtain a regenerated cellulose fibre. In addition, the outcome is a different fibre when the cellulose comes from cotton or other natural fibre. Therefore, it was decided to categorise also this type of pulping under chemical recycling.

3.4.2. Polymer recycling of cotton via a pulping process

Cellulosic fibres such as cotton can be chemically recycled via a pulping process. This process can be categorized as polymer recycling, as the cellulose chain is not broken down to monomer level (i.e., glucose), although it can be partially degraded.

Regenerated cellulosic fibres are produced from the pulp via solution spinning processes (e.g., viscose, lyocell, ioncell-F process, etc.). These fibres should have the same properties as other regenerated cellulose fibres (e.g., from wood pulp or other cellulosic sources) (S. Roos, et al. 2019).

3.4.2.1. Input

Theoretically, any cellulosic material could be recycled into regenerated cellulose fibres via a pulping process. However, as cellulose from different sources (e.g., wood, cotton, viscose, cardboard) can differ in chemical structure and viscosity, most technology holders indicated that changing the source would require adaptations to the pulping process or pre-treatment. Hence the need for a pre-treatment step or independent/specific pulping process for processing cotton waste, compared to wood as input material. Moreover, if the viscose or in general all regenerated cellulose fibres would be recycled via pulping, adaptations to the pre-treatment or pulping process would be required as well.

Technology holders prefer textile waste with a cotton content of at least 50%, preferably as high as possible. Most processes could technically handle lower cotton levels, however this would not be economically feasible. Some technologies can separate PET from cotton, but most are still working on the recovery of PET and currently only the cotton fraction of blends can be recycled.

In contrast to mechanical recycling, the fabric structure (knitwear, woven, non-woven…) has no influence on the chemical recycling process via pulping. The tolerance to dyed textiles depends on the process, but most technologies include a decolouring and/or bleaching step, although with varying efficiencies. The colorant which is present in the material determines if bleaching is possible. The removal of any hard parts (buttons, zippers…) is required and can be done in the same way as for mechanical recycling (see section 3.2.3). Most technology holders indicated that both pre- and post-consumer textile waste can be handled.

The efficiency of the recycling process depends highly on the purity of the input material as any contamination (i.e. non-cellulosic content) will reduce the yield or require additional separation or purification steps, which increase both the economic and environmental cost. The application of sorted textile waste is thus very important (S. Roos, et al. 2019). Knowledge of the applied dyes and additives would allow a more efficient removal.

Theoretically the cellulose recovery process can be repeated several times, however the polymer chain degrades with each repetition (Ellen MacArthur Foundation, A new textiles economy: Redesigning fashion’s future 2017). Hence the quality of the input should be monitored closely.

Additional input that is required besides cotton textiles are chemicals for dye removal and bleaching, water for washing, water and chemicals for pulping, electricity, and steam. Some technologies process 100% waste but most of them add at least 50% virgin wood pulp to the cotton pulp to achieve better fibre properties or because the process requires a too big adjustment/optimization to be viable for higher cotton pulp contents.

3.4.2.2. Process steps

The general process diagram for the recycling of cotton (or other cellulosic textiles/materials) into man-made cellulose fibres is presented in Figure 10.

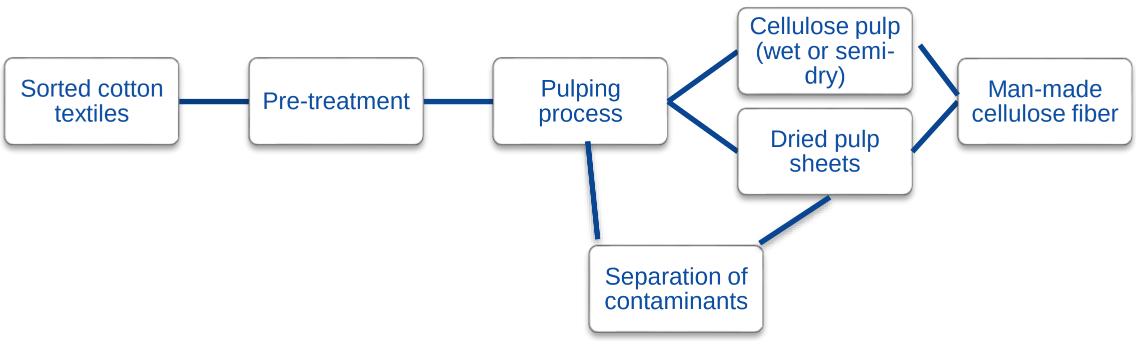


Figure 10: General process scheme for the recycling of cotton textiles via a pulping process.

Pre-treatment

Like for the other technologies, mechanical removal of non-textile parts and shredding/grinding to a fibrous material is needed.

Pulping process

The cotton cellulose is suspended in a liquid with chemicals and can be depolymerized to a certain extent depending on the specific technology, turning the material into a slurry/pulp called dissolving pulp. This can include several steps to adjust the viscosity and reactivity of the cellulose. The process often includes a chemical treatment to remove dyes and finishes as well as a bleaching step of which the latter is similar to the traditional wood pulp production process.

Separation of contaminants

Some technology holders implement an additional stage for the removal of polyester, elastane, etc. through several steps. Details on these steps are not available, since these are part of company IP.

3.4.2.3. Output

The output consists of wet or semi-dried cellulose pulp that, depending on the technology, can be blended with wood pulp and processed in traditional spinning processes for man-made cellulosic fibres. In some cases, the pulp is not immediately used but dried and shaped into sheets for storage and transport to a spinning company. One of the technology holders claims to use only pulp originated from cotton waste for his fibre production while most blend it with virgin material to obtain a continuous quality and production flow. The technology holders indicated that the process produces little waste, which originates mostly from contaminations and non-cotton fibres present in the textiles.

It should be noted that there are various processes for spinning regenerated cellulose fibres of which the newer technologies (Lyocell, carbamate and ioncell) use more environmentally friendly and safer chemicals, often in closed-loop systems. These processes should be considered separately from the pulping process of cellulose textile waste because they are similar to the virgin regenerated cellulose fibre production. The pulping of the cellulosic textile waste is the actual recycling step. A non-exhaustive overview of such spinning processes is provided in Table 5.

Table 5: Overview of spinning processes for the production of regenerated fibres from cellulosic pulp.

Technology	Description	TRL	Environmental impact
Viscose	Treatment with carbon disulfide which results in a cellulose-xanthate intermediate, followed by dissolution in sodium hydroxide and wet spinning into a sulfuric acid bath	9	Toxic chemicals
Modal	Modified viscose process resulting in fibres with higher breaking force and wet modulus	9	Toxic chemicals
Cuprammonium	Dissolution in cuprammonium solution (mixture of copper and ammonium in sodium hydroxide) and wet spinning into a sulfuric acid bath	9	Toxic chemicals
Lyocell	Dissolution using a solvent, N-methylmorpholine N-oxide (NMMO) without chemically changing the cellulose, and dry-jet wet spinning into a water bath	9	Non-toxic solvent in closed-loop system
Carbamate	Treatment with urea forming a cellulose-carbamate intermediate, followed by dissolution in sodium hydroxide and wet spinning into a sulfuric acid bath	7-8(1)	Safer chemicals
Ioncell-F	Dissolution using an ionic liquid as solvent, followed by dry-jet wet spinning	4-5(2)	Non-toxic solvent, working on closed-loop system

(1) TRL 9 expected by 2022
(2) TRL 9 expected by 2023

3.4.2.4. Status & prognosis

At present, most technologies have already reached a high TRL of 7 to 9, at least for pure cotton textiles as input material. The TRL 7-8 technologies are expected to reach TRL 9 by 2025 at the latest. Process capacities range from 10 kg/day to thousands of tonnes/year, as presented in Table 6. The main requirements for further upscaling are more production time and customer feedback for optimization of the process and continuous deliveries of suitable textile waste (in terms of purity and composition) as feedstock. Some technology holders have indicated that they are exploring the recycling of polycotton blends, however it is currently less appealing economically due to the additional separation and purification steps that need to be implemented/developed.

Table 6: Overview of current and future process capacities of the cotton polymer recycling technology holders participating in the survey.

Company	TRL	Current process capacity (t/year)	Future process capacity (t/year)
1	4	Max. 10 kg/day	50 000-100 000 (planned industrial scale unit)
2	9	1000 (27 tonnes/day)	100 tonnes/day
3	6	10-20	Not provided
4	7	200	2000 (by 2022) up to 25 000 (by 2025)
5	7	30 000-150 000	/
6	9	>3000	Not provided
7	8	4500	Not provided

3.4.3. Monomer recycling of PA6 and PET

Chemical recycling via depolymerization implies that the polymer chains are completely broken down into monomers and is thus classified as monomer recycling. These monomers are separated and purified before entering the polymerization process again to produce new virgin-quality polymers.

In theory many polymers can be depolymerized, but efficient, practical processes have not (yet) been developed, e.g. for PA6,6 a polymer with similar applications as PA6. Therefore the following sections focus on PET and PA6 (nylon 6) as these are the only synthetic fibres that are currently recycled via depolymerization on a commercial, though still limited, scale (S. Roos, et al. 2019).

3.4.3.1. Input

In theory any PA6 or PET textiles or plastics can serve as input. However, in practice:

- For PET: generally post-consumer food packaging materials and (pre-consumer) industrial waste (S. Roos, et al. 2019), PET textiles recycling is still under development.
- For PA6: mainly post-consumer PA6 from carpets, also fishing nets and industrial waste (oligomers+plastic waste generated by polymer industries) (S. Roos, et al. 2019) (Aquafil S.p.A. 2020).

Depending on the process, “light” contamination with other materials is allowed, generally dyes and prints and even certain finishes and coatings can be accepted. Nevertheless, most technology holders request a minimum of 80-90% PET or PA6 content for economic reasons. One technology holder did stress that the nature of the contamination is also important as certain specific chemicals can have a large impact on the depolymerization reaction. Knowledge of the composition and adequate sorting of the input is thus of great importance. Another technology holder even indicated to only work with materials that have a product passport including the exact composition.

The majority of technology holders indicated that both pre- and post-consumer PA6 textile waste can be handled but as with most technologies, the removal of any hard parts (buttons, zippers…) is required. For chemical recycling via depolymerization, the fabric structure (knitwear, woven, non-woven…) is not relevant.

Additional required resources depend on the process, but generally include a solvent (i.e. water in the case of enzymatic and hydrolytic processes, glycol for glycolysis and methanol for methanolysis), one or more catalysts and electricity, natural gas and/or steam.

3.4.3.2. Process steps

The general process diagram for the recycling of synthetic fibres like polyamide and polyester into the same synthetic fibres is presented in Figure 11.

Figure 11: General process scheme for the recycling of synthetic fibres like polyamide and polyester into the same synthetic fibres

Pre-treatment

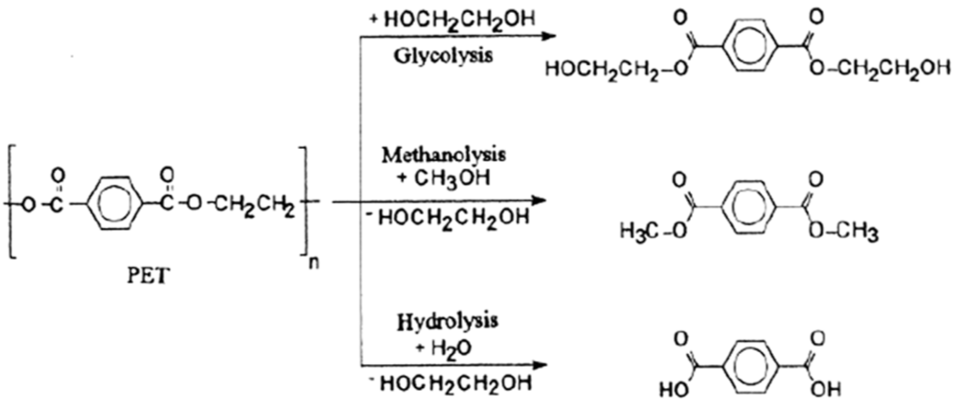
The pre-treatment can include several of the following steps, depending on the type and shape of the waste: cleaning, sorting, mechanical removal of non-textile parts and by extension non-PET or -PA6 parts (e.g. the backing of carpets), shredding/grinding, washing, granulation and/or pelletizing (Aquafil S.p.A. 2020) (Hoenderdaal 2017).

Depolymerization

The PA6 or PET materials are depolymerized, some after first dissolving the polymer, via different technologies and various reaction conditions (temperatures/ pressures/ time/ catalysts). PA6 and PET polymers contain functional groups that can be cleaved by certain reagents also acting as the solvent of the reaction. These types of chemical reactions in which the solvent is one of the reagents and is present in great excess, are called solvolysis reactions. The applied solvents are typically water (i.e., hydrolysis), alcohols (i.e., methanolysis) or glycols (i.e., glycolysis) (Achilias, et al. 2012) (Bartolome, et al. 2012).

In practice PA6 is generally depolymerized via hydrolysis, e.g. using high pressure steam (AlliedSignal patents (Sifniades, Levy en Hendrix, Process for depolymerizing nylon-containing waste to form caprolactam 1999) (Sifniades, Levy en Hendrix, Process for depolymerizing nylon-containing whole carpet to form caprolactam 1999)), via acid hydrolysis and super-heated steam (BASF patent (Corbin, et al. 1999)), or via glycolysis (Aquafil patents (Karasiak en Karasiak, Process and device for the treatment of polymers 2014) (Karasiak en Karasiak, Method and apparatus for handling polymer 2019)) (Achilias, et al. 2012). Although Aquafil has a patent for glycolysis, in practice, it has implemented a hydrolysis process.

For PET all three of the reaction mechanisms, being hydrolysis (alkaline, acid or neutral), methanolysis and glycolysis are used for depolymerization, although the latter is the most common. The final output depends on the reagent (Achilias, et al. 2012). The most important characteristics of each process are presented in Figure 12 (Bartolome, et al. 2012).



Mechanism	**Hydrolysis**	**Methanolysis**	**Glycolysis**
Reagent	Water, acidic (e.g. using concentrated sulfuric acid), alkaline (e.g. using caustic soda) or neutral (water or steam) environment	Methanol	ethylene glycol, but diethylene glycol, triethylene glycol, propylene glycol or dipropylene glycol may be used as well
Main output	PTA + MEG	DMT + MEG	BHET + oligomers
+/ -	Slower reaction, high temperatures and pressures, PTA monomer recovery requires numerous steps to reach required purity	Costly separation and refining or reaction products mixture, water can perturb the process, less or even no longer used	Flexible, simple, mature and least capital-intensive process, can be followed by adding water to make PTA/MEG

PTA = purified terephtalic acid, MEG = Monoethylene glycol, DMT = dimethyl therephtalate (methyl ester of PTA), BHET = Bishydroxylethylene terephtalate (bis(hydroxyethyl) ester of PTA, PTA with 2 MEG)

Figure 12: Illustration (top, (Janssen and van Santen 1999) and characteristics (bottom, (Bartolome, et al. 2012)) of the different methods for the depolymerization of PET.

It should be noted that in addition to the three solvolysis methods, recently a fourth method has become available, namely an enzymatic depolymerization reaction. With this technology, the polymer chain is broken down into monomers using an engineered PET-depolymerase enzyme. It allows the recycling of all forms of PET plastics and fibres, even in mixtures as the enzyme is selective for PET. The process runs at low temperature, at atmospheric pressure and without solvents (Tournier, et al. 2020) (DESROUSSEAUX, et al. 2017). The enzymatic depolymerization technology can be considered a biochemical recycling process since the chemical reaction is mediated by a biological catalyst, the enzyme.

Post-treatment

The post-treatment typically includes one or more of the following steps:

- Purification
    - Separation of contaminants (e.g., removal of insoluble substances via (micro)filtration)
    - Removal of colorants (e.g., using activated carbon, activated clay minerals such as clay, bentonite, montmorillonite, zeolites)

- Separation
    - Distillation of caprolactam or removal of solvent via evaporation. Not in all processes a solvent is used. When there is no solvent used this implicates there is also no need to remove it.
    - Crystallization of BHET/PTA (Hoenderdaal 2017)
- Drying

3.4.3.3. Output

PTA and MEG are the traditional monomers obtained from PET, but the final output depends on the reagent. The main output options are (i) regeneration of base monomers (in case of the methanolysis mechanism for dimethyl terephthalate (DMT) and hydrolysis or enzymatic mechanism for producing pure terephthalic acid (PTA) and ethylene glycol (EG)); (ii) conversion into oligomers and bis(hydroxyethyl) ester of PTA (BHET) (via glycolysis) (Achilias, et al. 2012). See Figure 12 (bottom) for the specific output per process. These monomers can be repolymerized to obtain high purity, virgin grade PET.

Concerning PA6 recycling, the output is caprolactam which can be repolymerized to virgin grade PA6.

Just like the pulping process of cellulose fibres, the efficiency of the chemical recycling of synthetic fibres depends highly on the purity of the input material (S. Roos, et al. 2019). The waste that is generated is a non-PET/PA6 solid residue or sludge consisting of other synthetic or natural fibres, dyes, chemicals from finishings/coatings/prints, etc. depending on the input composition.

3.4.3.4. Status & prognosis

Chemical recycling of PA6 textiles via depolymerization is already an established technology, being at TRL 9 for a decade. For PET textiles the TRL-levels vary from 4 up to 7, with 500 tonnes/year being the largest available production capacity to date (see Table 7). The first technologies are expected to reach TRL 9 by 2023 as currently an industrial production line is being built. For the lower TRL technologies, funding and more R&D at the pilot level are mainly needed to make further progress.

Moreover, there have been new developments in order to improve the solvolysis processes:

- Depolymerization by microwave technology: Hydrolysis process using microwave radiation instead of traditional heating which claims to be an economically efficient chemical recycling method for PET (Parravicini, Crippa en BERTELE 2013) (gr3n recycling sd). This technology is currently at TRL 6, a demonstration plant with capacity of 60 kg/h is being constructed (Demeto 2021).

- Ionic liquid technology: accelerated solvolysis process based on a catalyst complex consisting of a magnetic ionic liquid. It claims to be able to remove colorants and other additives, allowing the upcycling of all types and colors of PET waste into feedstock for virgin-quality recycled PET (HOOGHOUDT, PHILIPPI en ARTIGAS 2016) (Ioniqa Technologies, Ioniqa sd). The technology has reached TRL 8 and has raised sufficient funds to further scale up their 10 kt plant to full capacity. TRL 9 expected in early 2022 (Ioniqa Technologies, Ioniqa attracts € 10 million funding 2021).

Table 7: Overview of current and future process capacities of the PET and PA6 monomer recycling technology holders participating in the survey.

Company	TRL	Current process capacity (t/year)	Future process capacity (t/year)
1 (PET)	6	/	100 at TRL 7, industrial unit of 10 000-15 000 in 2024 at TRL8
2 (PET)	5	500	20 000-25 000
3 (PET)	4	To be defined	/
4 (PA6)	9	Not provided	Not provided

3.4.4. Recycling of polycotton blends

Several technologies focus on the recycling of both cotton and PET from polycotton blends via different approaches.

A first method applies solvent-based dissolution and filtration processes to separate different materials and extract the desired components. In principle the polymers chains should remain unaffected, hence this method is categorized as polymer recycling. The recovered cellulose can be applied in a typical pulping and wet spinning process, while the PET polymers remain largely intact (Worn Again Technologies 2021).

A second type of technology consist of a hydrothermal approach to (partially) degrade either cotton or PET or both. These processes rely on water, pressure, temperature and green chemistry: the final output depends on the specific process applied (HKRITA en H&M Foundation, The Green Machine 2021) (Ross en Jones 2020) (Majeranowski 2021).

A third approach focuses on (partial) degradation of cotton from polycotton blends via an enzymatic route (i.e., biochemical recycling) resulting in glucose, cellulose powder and PET fibres (HKRITA en H&M Foundation, The Brewery - a biological mehtod to recycle garments 2021).

3.4.4.1. Input

Any polycotton-polycellulose material, but depending on the technology also pure polyester and/or pure cotton/cellulose can be processed. Most technologies can deal with a certain percentage of contamination with other materials (nylon, acrylic, wool, elastane…), however hard/metallic accessories such as zippers and buttons and generally also coatings must be removed. Again, sorting of textiles waste is required as knowledge of the composition (e.g. 100% cellulose or PET or the cellulose/PET ratio for blends) is often required for a good process efficiency.

3.4.4.2. Process steps

Pre-treatment

The pre-treatment requires mechanical removal of hard, non-textile parts, cutting and shredding of the fabric to smaller pieces

Separation and recovery

a) Cotton and PET polymer recycling via a dissolution process

Pure polyester and polycotton textiles enter the process together, but the PET/cotton ratio is balanced in order to ensure a good process yield. Almost any contaminant (dyes, elastane, TiO_2) can be removed during the process. PET and cotton are both dissolved, each with a different solvent, used in a closed loop system. The PET pathway includes dye-removal, polymer solvent separation, purification and polymer restoration steps. Although the PET polymers are kept largely intact (i.e. no depolymerization to oligomer of monomer level), the final process step is meant to increase the molecular weight and achieve virgin quality. The output of the cotton pathway is cellulose pulp for man-made cellulose fibre production.

b) Hydrothermal recycling processes

A hydrothermal process can be defined as a process in an aqueous system under pressure and increased temperature. It typically involves subcritical water which is liquid water at a temperature between 100°C (i.e., the atmospheric boiling point of water) and 374°C (i.e., the critical point of water).

Textiles are treated with water containing one or more green acids (e.g., an organic acid or sulfuric acid), no organic solvents, under increased temperature and pressure. Some technologies result in the decomposition of cotton which is recovered as cellulose powder. Next, the polyester fibres are separated via filtration with no depolymerization, retaining the quality of the fibres, ready for spinning (Post-consumer Blended Textile Separation and Recycling by Hydrothermal Treatment 2018). However, the fibres can also be melted, extruded and pelletized, while chain extenders and/or stabilizers can be added to obtain virgin quality PET pellets (SPEIGHT, et al. 2020). Final steps include water removal and drying.

Other hydrothermal technologies result in the depolymerization of PET to TPA and ethylene glycol, and subsequent recovery of the cellulose fraction via a dissolution process or via a second subcritical water treatment. In order to improve the efficiency and reduce energy consumption, a co-solvent with or without phase transfer catalyst can be used during the subcritical water treatment. The exact processing conditions depend on the input: an acidic (e.g., using acetic acid or other organic acids) medium is used for cotton and cotton-polyester blends, while an alkaline environment (e.g., using sodium or potassium hydroxide) is required for PET and polyester-cotton blends. TPA is precipitated and crystallized after which it can be repolymerized and melt spun to PET filament. The recovered cellulose can be further treated to produce pulp for wet spinning of regenerated cellulose fibres (Barla, et al. 2019).

The different processes can include a colour removal/bleaching step as well.

c) Enzymatic recycling process

The first step consists of a pre-treatment to modify the textile structure, more specifically to reduce the crystallinity of the cellulosic fibres and enhance its susceptibility to enzymatic hydrolysis. Next, a fungus is grown onto the textile waste. This fungus will secrete enzymes in situ through solid state fermentation or submerged fermentation. These enzymes are then recovered for use in textile waste hydrolysis. For the textile waste hydrolysis step the recovered enzyme solution is thoroughly blended with the pre-treated textile waste in a bioreactor. Cotton is hydrolysed into cellulose and soluble glucose, while PET (or another non-biodegradable material) remains intact and is separated as fibre via filtration. Finally, PET is re-spun into yarns, while the cotton hydrolysate is purified by activated carbon to obtain a glucose-rich syrup. This syrup can be converted into plastics, surfactants, and chemicals (via industrial biotechnologies) (Textile Waste Recycling Using a Biological Method 2018).

3.4.4.3. Output

The dissolution process results in PET resin (pellets) which can be respun to filaments and cellulosic pulp or powder which can be further processed into regenerated cellulose filaments. The different hydrothermal-type technologies have different outputs, including cellulose powder or pulp and either polyester fibres (applicable as such or remelted and granulated to PET pellets) or PET monomers that can be repolymerized to virgin PET resin. The enzymatic process produces cellulose powder and glucose syrup which can be converted into plastics, surfactants, and chemicals (via industrial biotechnologies) as well as PET fibres that can be re-spun (HKRITA en H&M Foundation, The Green Machine 2021) (Ross en Jones 2020) (HKRITA en H&M Foundation, The Brewery - a biological mehtod to recycle garments 2021) (Majeranowski 2021) (Textile Waste Recycling Using a Biological Method 2018).

3.4.4.4. Status & prognosis

The solvent-based dissolution and filtration technology is currently at TRL 5 and is expected to reach TRL 6 in 2022 and TRL 9 in 2024/2025. A demonstration facility is currently being designed and will be built in 2022. The different hydrothermal technologies are at TRL 6 to 7, approximately. They are expected to reach TRL9 in 2023/2024 (Circ 2021) (Waste Management World 2021), while the enzymatic approach is at TRL 5, expected to reach the next TRL in 2021 Q3 and TRL9 in 2023. Current process capacities range from 15 to 2800 tonnes/year, as presented in Table 8.

Table 8: Overview of current and future process capacities of the polycotton recycling technology holders participating in the survey.

Company	TRL	Current process capacity (t/year)	Future process capacity (t/year)
1	5	13.8	Not provided
2	6	54	550
3	5	2800	/
4	5	To be defined	70 000 for an industrial plant

3.4.5. Advantages vs disadvantages of chemical recycling

Advantages

The main advantage is that the recycled material can be purified and separated to obtain a pure, colourless polymer of good or even virgin-like quality.

This technology is the only option for degraded or contaminated polymers and heavily damaged fibres if they can’t be processed by other technologies such as mechanical or thermo-mechanical recycling. Chemical recycling can restore the polymer.

Disadvantages

Some technology holders claim that the cost of the chemical recycling process is more or less equal to the corresponding virgin production process. In addition, when the input material is heavily contaminated additional purification steps might be required, which will further increase the production cost. In addition, compared to the mechanical and thermo-mechanical recycling processes, chemical recycling technologies are more expensive.

Looking at the environmental impact, chemical recycling processes are expected to have the highest impact due to the additives/chemicals/solvents needed in the dissolution or de- and repolymerisation processes. This is less of an issue for the enzymatic depolymerisation as enzymes are used for the depolymerisation process. However, it is still valid for the repolymerization. Like all other technologies, improvements of recycling of polycotton blends are being made, for example, solvent-free process steps are implemented which have a positive influence on the environmental impact.

Although some contaminations can be handled in the process, material blends are less preferred, except for polyester/cotton. This is mainly due to economic reasons – for example because of too small quantities on the market such as polyester cotton blends with acrylic fibres. Sometimes, also technical issues make material blends less preferred: elastane for example, can cause issues when it is present in the cotton polyester blend.

3.4.6. Technology holders

A variety of chemical recycling technology holders were identified, some are presented in Table 9.

Table 9: Examples of chemical recycling process technology holders

Company name	Website
Antex	antex.net/
Aquafil	www.aquafil.com/ www.econyl.com/
Birla Cellulose	www.birlacellulose.com/
Carbios	carbios.fr/en/
CLS-Tex International	www.cls-tex.com/
CuRe Technology	curetechnology.com/
HKRITA The Brewery	hmfoundation.com/project/recycling-biological-method/ www.hkrita.com/commercial-opportunities-detail.php?id=63
HKRITA/Planet First The Green Machine	www.planetfirst.one/greenmachine
Infinited Fiber Company	infinitedfiber.com/
Ioncell®	ioncell.fi/
Lenzing	www.lenzing.com/ www.tencel.com/refibra
Renewcell	www.renewcell.com/en/ circulo.se/
SaXcell	saxcell.com/
Södra	www.sodra.com/en/gb/
Worn Again Technologies	wornagain.co.uk/

3.5. Facilitating technologies

3.5.1. Automated sorting

The quality of the output of all recycling processes is overall highly dependent on the quality of the input material. Therefore, sorting textiles according to their material content is an important pre-treatment step in the recycling process (Cura, et al. 2021). This is especially the case for post-consumer textile waste that often consists of a larger variety of fibre types and material blends than industrial or pre-consumer waste (Elander 2019).

Textile sorting is typically done manually, based on clothing type and product labels. Unfortunately, manual sorting is a very slow process with limited reliability as labels can be removed, faded or even incorrect (Cura, et al. 2021). In order to increase textile recycling and establish a circular textile value chain, sufficient amounts of accurately sorted textiles should be readily available. Hence, automated sorting processes are imperative (Ellen MacArthur Foundation, A new textiles economy: Redesigning fashion's future 2017).

There are various methods available for the accurate determination of textile material contents, but they often require sample preparation and are too time-consuming for automation (e.g. ISO 1833-1 chemical analysis via dissolution, microscopy, differential scanning calorimetry, gas chromatography, etc.). In this respect, near infrared spectroscopy (NIR) is an interesting technique which is already widely used in industry for different applications, including automated sorting of paper and plastics (Cura, et al. 2021). It should be noted that for household clothing waste manual sorting into a reusable and non-reusable fraction suitable for recycling, will (for now) remain the first step in the pre-treatment of textiles.

Of course, the NIR technology has some limitations as well. Due to the limited penetration depth of NIR light, only the surface composition of textiles can be detected and finishings and coatings can influence the result. Identification of (complex) material blends can be difficult due to overlap of spectra or when a certain type of fibre is incorporated in the core of a yarn (e.g. as is often the case for elastane-containing yarns), this fibre is "invisible" to the NIR. Moreover, chemical changes due to ageing of cotton complicates the detection (Cura, et al. 2021). A technology holder experienced with NIR indicates that also darker colours could affect the identification.

There are several automated NIR-based recognition and sorting lines under development and even close to commercialization. Fibersort by Valvan Baling Systems and Wieland Textiles, and SIPTex which is using TOMRA sorting technology are currently at TRL 7-8 and are expected to evolve to TRL 9 by the end of 2021/early 2022, if the necessary research and financial support can be found. In addition, technologies based on hyperspectral imaging (HSI) and radio frequency identification (RFID) are being developed as well. An overview of technologies that are currently under development is given in Table 10. The review of sorting technologies has been performed on a more superficial level. The reader can consult the 2021 published JRC technical report "Circular economy perspectives in the EU textile sector" for a more comprehensive overview (Köhler, et al. 2021).

Table 10: Overview of the different automated sorting technologies under development

Technology	Type	Current TRL	Country
Fibersort	NIR	7	The Netherlands
SIPTex	NIR	8	Sweden
Resyntex	HSI	4-5	Germany
Tex.IT	RFID	unknown	Sweden

3.5.2. Facilitated disintegration of a textile product

Textiles are rarely mono materials as they can consist of different components (textile and non-textile parts or accessories such as buttons and zippers) and can be coated, laminated or printed on. Several disintegration technologies are being developed to accommodate these issues. The current section presents several examples of these technologies, however, it is not exhaustive.

Novel sewing/stitching yarns to facilitate textile disassembly

The yarn disintegrates under a certain influence so that stitched parts of a textile product or components stitched on a product can be removed. This results in separate fractions that can be reused, refurbished or recycled.

- Wear2Go

A patented sewing thread (Wear2®) combined with innovative microwave technology to disassemble end-of-life clothing and other textile products. Various types of textile and accessories including logos, tags, labels, zippers, buttons, high visibility tape, etc. can be separated within 60 seconds without damaging the components (WEAR2GO B.V., Circular textile sd).

The Wear2 yarn and industrial microwave for assembly and disassembly is being further developed to TRL7 in the Circtex project (2019-2022). The yarns that have already been developed are currently mostly applied to work and corporate clothing but will become widely available to the clothing industry soon. The goal is to produce an extensive range of Wear2 threads for various applications and to set-up a separation hub where large volumes of clothes can be automatically disassembled via the advanced microwave technology (WEAR2GO B.V., INTERREG - Project CircTex sd).

- Resortecs

A melting stitching thread combined with industrial disassembling ovens to facilitate recycling and repair (Resortecs, Resortecs(r) Recycling & sorting technologies sd). Different threads available for denim and workwear, for accessories, sportswear and footwear and for thermal sensitive material applications with melting temperatures going from 195°C down to 115°C (Resortecs(r) sd).

Currently, there are industrial pilot activities available for brands and manufacturers to help validate their circular supply chain at a larger scale (Resortecs, Try out with industrial pilots sd). Funds are being raised for the construction of the first industrial disassembling oven, including sorting equipment which will be connected to the oven as well as to launch the Resortecs® dismantlable rivet buttons (Vanhoeck 2021).

Technologies for the removal of coatings and laminated layers

- Dissolution of the adhesive layer, coating or textile

Recycling of PVC-coated polyester textiles is already being done today, where the PVC is selectively dissolved and recovered as granules. The polyester textile is recovered as fibres suitable for non-woven, thermal and sound insulation applications (Ferrari sd). Moreover, in the DECOAT project solvation trials for the debonding of polyester and polyamide textiles with PU, acrylic and PVC coatings were already conducted with very promising results (Buyle sd) (ISWA, DECOAT Progress Overview 2020 2021).

- Triggerable smart polymer material systems

The application of microcapsules or specific additives activated by heat, humidity, microwave or chemical triggers for debonding of coated or laminated textiles is being investigated in the DECOAT project as well. This approach is illustrated in Figure 13 (Buyle sd).

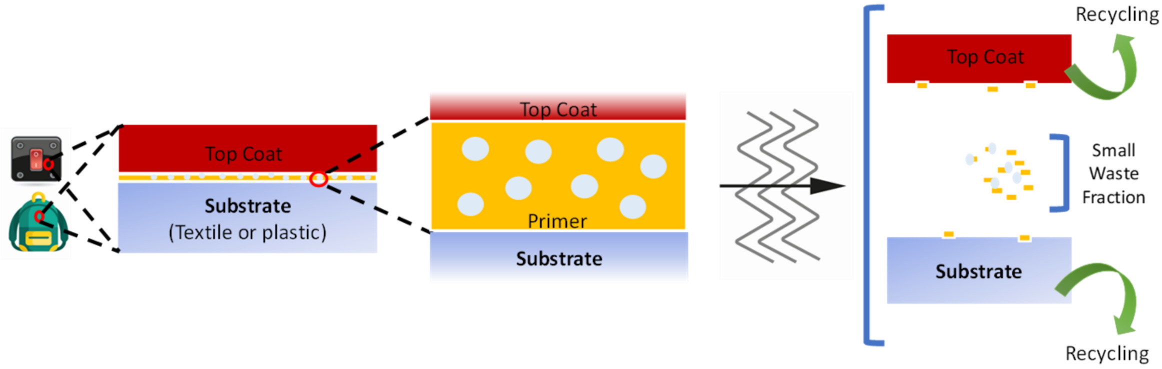


Figure 13: Illustration of the debonding approach using triggerable coatings. (Buyle sd)

In this project, various types of triggerable materials are being developed, including heat triggered core/shell materials, microwave activated particles, super absorbing polymers, etc. Currently, the Indar Inside® debonding technology based on heat triggered blowing agents, developed and patented by RESCOLL, has shown very promising results (ISWA, Work Package 2 : Development of coating debonding systems - Progress June 2021 2021) (Bergara 2011).

- Reversible crosslinking-decrosslinking systems

Several universities are putting efforts into research on reversible crosslinking-decrosslinking systems. These systems can bond-debond reversibly and could be used in a design-for-recycling approach (Oku, Furusho en Takata 2004). One reactive part needs to be incorporated in the substrate, while the other reactant needs to be present in the coating layer. Several different chemistries show this behaviour and could potentially be useful. Depending on the used chemistry, a different triggering mechanism needs to be applied (e.g., acid, heat, UV, thiols etc.).

- Supramolecular polymer adhesives

Supramolecular systems are complexes of molecules held together by non-covalent bonds which are known for their dynamic, stimuli-responsive nature. These assemblies are found in many natural molecular processes or materials because of their adaptive behaviour and reversible connectivity. This has inspired researchers to develop synthetic stimuli-responsive polymers for different applications, including adhesives for bonding-debonding on demand. Supramolecular adhesives can be based on hydrogen bonding, host-guest interactions, or metal-ligand complexation. However, other non-covalent interactions (such as hydrophobic/hydrophilic effects and ionic interactions) can also play a role (Heinzmann, Weder en and De Espinosa 2016). The use of supramolecular polymers for (reversible) adhesives shows great potential but so far it is only emerging with a few customized products (Sajot, Brunet en Lachhab 2009) (SupraPolix BV sd) (Leon, et al. 2011).

4. Analysis of the economic and environmental aspects of the textile recycling technologies

The objective of this chapter is to analyse economic and environmental aspects of different textile fibres recycling technologies, with the final aim to improve and consolidate the knowledge about economic and environmental effectiveness of recycling technologies. The analyses are performed on the combinations of input streams and recycling techniques identified and described in Chapter 3.

Recycling can take place on different levels in the value chain, from fabric recycling to chemical monomer recycling and from reuse in the same application to an open-loop recycling for use in other applications. The focus of this chapter is on closed-loop textile-to-textile recycling: fibre recycling and recycling of textile into polymers, oligomers and monomers. Downcycling to other applications is not considered, unless it concerns by-products of the recycling process. The combinations of recycling technologies and input streams identified in Chapter 3 for further assessment are summarized below in Table 11.

Table 11: Overview of technologies and output materials as identified in Chapter 3

Input material	Recycling technology	Output product
Cotton	Mechanical recycling	Spinnable fibres Fluff Filling materials/ dust
	Chemical - Polymer recycling	Cellulose pulp
Polycotton	Mechanical recycling	Spinnable fibres Fluff Filling materials/ dust
	Chemical recycling	Cellulose pulp PET or monomers
	Biochemical - Enzymatic recycling	PET fibres Glucose syrup
Polyester	Mechanical recycling	Spinnable fibres Fluff Filling materials/ dust
	Thermo-chemical recycling	Small gas molecules Gases, oil, tar
	Thermo-mechanical recycling	PET pellets
	Chemical - Monomer recycling	TA, MEG, DMT and BHET
Polyamide	Mechanical recycling	Spinnable fibres Fluff Filling materials/ dust

	Chemical - Monomer recycling	Caprolactam

The original purpose of this part of the project was to create an environmental profile by means of life cycle assessment (LCA) for each of the recycling techniques in Table 11. In order to perform a life cycle assessment, a life cycle inventory is needed with input and output streams for the subject of the study, in this case the recycling process. In this project, part of the activities focused on obtaining inventory data through stakeholder interviews and cooperation and through literature review. However, in many cases this turned out not to be possible. At present, the textile recycling sector is still under full development. Only a few technology holders were able to provide life cycle inventory (LCI) data. There are various reasons why data cannot be shared. Some processes are still at a low TRL level. In this case, LCI data is often of little relevance and can change significantly throughout the further development of the technology. It may also concern information that companies wish to keep confidential in order to guarantee ownership of a technology in development. Furthermore, collecting the requested information requires a time commitment from these companies, time that is not always available. For some recycling technologies, values are published in literature. Yet, for many recycling technologies it was not possible to gather information which is detailed enough for a proper LCA. This lack of data makes quantitative analyses impossible. Therefore, this chapter consists of two parts:

(1) a qualitative evaluation of the recycling processes on key criteria. The assessment methodology is explained in section 4.1, and section 4.2 contains the evaluation itself. The qualitative evaluation is supported by as much as possible quantitative data. The data used for this purpose are either derived from literature or provided by technology holders contacted within the framework of this study.

(2) an evaluation of the impact on climate change using published results of life cycle assessment studies or, if life cycle inventory data were available, the results of the life cycle assessment carried out within the framework of this project. The results are presented in section 4.3. The reporting focusses on the impact on climate change, which is the environmental impact category for which the most robust results are reported in literature.

In addition, a brief macro-economic perspective is introduced in section 4.4. This section sketches the current fibre and fabrics market, with a focus on EU-activities.

The draft report was circulated among technology holders, with at least one representative from each of the analysed recycling technologies. Relevant feedback was incorporated into the final version.

4.1. Assessment methodology

Per input stream, the recycling technologies identified in Chapter 3 are assessed based on different environmental and economic criteria. The main input streams are cotton, polycotton, polyester and polyamide. The evaluation criteria are ‘quality and quantity of the output product’, ‘consumption of chemical substances’, ‘energy consumption’, ‘water consumption’, and ‘process cost’.

In the following paragraphs, the different assessment criteria are discussed in more detail.

4.1.1. Quality and quantity of the output product

To assess the effectiveness of a recycling technology and the value of the output product, two dimensions are of equal importance: the quantity and quality of the output products. For each combination of input stream and recycling technology, the output products are identified, including the side products/waste which are part of the recycling process. If available, also the quantity of non-waste and waste output generated per tonne of textile input is reported. The quality of the output products is evaluated by its possible application(s).

4.1.2. Use of chemical substances, energy and water

Another criterion used to evaluate the recycling technologies is their **use of chemical substances**. Chemical types are reported and, if data are available, the consumption of the different chemicals by a certain recycling technology. The latter concerns the total consumption of chemicals, excluding their environmental impact or potential toxicity. Chemicals in a fully closed-loop system are not considered to be consumed and are not included in the reported amounts.

Furthermore, the textile recycling processes' **energy consumption** is assessed. Energy intensive steps (e.g. requirements for high temperature or high pressure) in the recycling process are identified and, where possible, quantified.

Similarly, the overall **consumption of water** is evaluated. Does the recycling process require water and, if so, in which quantities? The use of water in closed loop systems are not considered to be consumed and are not included in the reported amounts.

4.1.3. Process cost

For each of the unit operations and to the extent possible, a life cycle costing (LCC) model is constructed where the economic outcomes (CAPEX and OPEX) for each year are related to the process and flowsheet model of each unit operation. Based on this, the projected cash flows for the evaluation period (typically 10 years) can be calculated.

Since a single unit process will not be economically viable on its own, the cost and revenues have to be considered over the entire textile system in order to provide insights on the economic viability of the technologies that are being developed. The main revenues can be only determined at a later stage in a textile system, where fabrics, fibres or poly-/oligo-/monomers are extracted and valorised, whereas costs will arise at each stage of the system.

However, for most processes the lack of sufficiently detailed data or only access to confidential data forces us to fall back on publicly available data via a literature review.

4.2. Evaluation per input stream

This section qualitatively assesses the recycling technologies per input stream on key criteria according to the assessment method set out in section 4.1. The qualitative assessment is supported as much as possible by quantitative data. The data used for this purpose come from literature or were provided by technology holders contacted in the context of this study. For each input stream, an overview figure has been generated (Figure 14, Figure 15, Figure 20, Figure 22). The figures visualise how a certain recycling technology scores on different parameters: energy use, water use, use of chemicals and process cost in comparison with other available recycling technologies. The basis for the assessment is the treatment of a certain amount of textile. The figures show, for example, which recycling technology uses more or less energy per X tonne of treated textile. The symbols used to express energy use, water use, chemical use and process costs are strictly intended for ranking technologies among each other, not for quantifying them. For instance, 3 droplets of water for technology A and 1 droplet for technology B does *not* imply technology A uses three times as much water as B. What cannot be deducted from the figures is which recycling technology would require more or less energy input per tonne of a given end product (e.g. per tonne of spinnable fibre) as the evaluation is done per tonne of input into the recycling process. However, the figures do include the main output products/materials of the recycling process and the products/materials that could potentially be avoided by using the recycled products/materials. A better evaluation based on the key parameters energy use, water use, chemicals use and process cost does not necessarily imply that this technology is 'the better option', since the output quality and quantity are to be taken into account as an equally important aspect. This should be kept in mind by the reader when interpreting the figures.

4.2.1. Cotton

In Chapter 3, two main recycling technologies were identified to recycle cotton: **mechanical recycling** and **chemical polymer recycling**. A wide variety of chemical recycling technologies exist. These can be differentiated based on their key attribute: biochemical or enzymatic, solvent-based, hydrothermal and pulping. This section evaluates the pulping technology. Biochemical, solvent-based dissolution and hydrothermal techniques are discussed in the next section on polycotton. The recycling techniques were described in more detail in Chapter 3. In this chapter, the recycling techniques are evaluated on each of the criteria described in section 4.1. Figure 14 shows an overview of the results of this assessment and further justification is provided in the following sub-chapters.

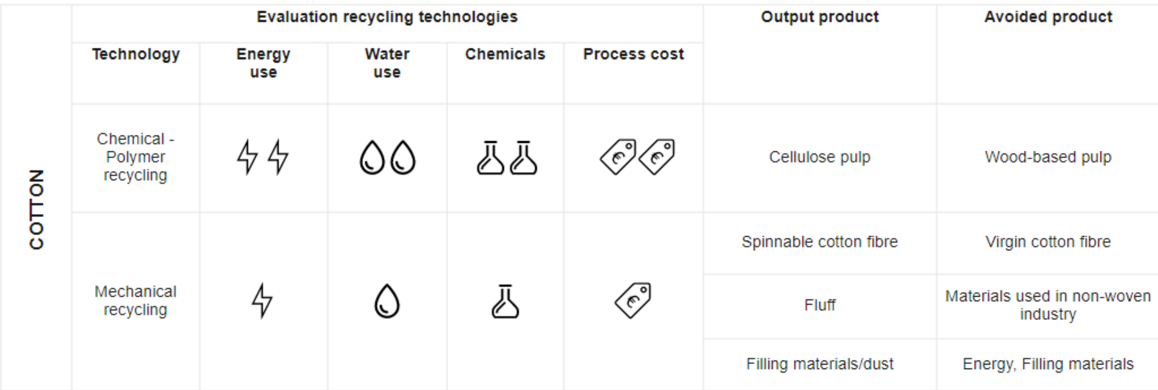


Figure 14: Evaluation of recycling technologies for cotton

Output product

The outputs of the **mechanical recycling process** are spinnable fibres, fluff, filling materials and dust. The fraction of spinnable fibres is 5-20%[1] of the textile material input in case of natural fibres (see Chapter 3). The quality of these fibres depends on the input product's quality, but is lower than the quality of virgin fibres (see Chapter 3). Mechanically recycled fibres can replace virgin cotton fibres, but need to be blended with virgin material to reach a yarn of an acceptable quality (see Chapter 3). The remaining output fraction (fluff, filling materials and dust) has a lower quality than the spinnable fibre fraction and can be used in the non-woven industry, as a filling material or as reinforcement in composites of artificial material or burned with energy recovery (see Chapter 3). Other outputs of the mechanical recycling process are outputs of non-textile origin such as zippers and buttons. Their share is reported to be around 5% of the input material by one technology holder, another technology holder, using automatic removal reports a share of non-textile parts of 7-12%. Spathas (2017) reports a higher share (> 30%) and Paunonen et al. (2019) report

[1] This is the fraction of spinnable fibres long enough to be respun in to yarn. The recycling process may lead to a higher amount of spinnable fibres (up to 90 % (Technology holder)), but they are too short to be respun and will drop out from the spinning process.

a lower share (+/- 1%). Zippers and buttons are typically made of different alloys and are difficult to recycle.

The output of the **pulping process (chemical polymer recycling process)** is cellulose pulp, which can be obtained via different types of pulping processes: sulphate, sulphite and sulphur-free. The pulp, when used as input in a viscose or lyocell process can be blended with wood pulp before it can be processed in a traditional spinning process for man-made cellulosic fibres. A technology holder reports that up to 40-50% wood based pulp can be replaced. Some technologies process 100% waste but mix with virgin wood pulp for better fibre properties, to avoid process modifications (shee Chapter 3) or simply because the production capacity of recycled cellulose pulp is low (technology holder). The necessary pre-treatment, taking place before the cotton enters the pulping plant, depends largely on the type of input material. For post-consumer input material, the pre-treatment step is assumed to be is similar to the mechanical recycling process and similarly also results in losses of non-textile parts. After the pre-treatment, when pure cotton streams enter the recycling process about 10% losses occur during the pulping process[2]. Losses are higher for mixed input streams (see Chapter 3).

Chemicals

In the **mechanical recycling** process little or no chemicals are deployed. If chemicals are used, it concerns e.g. ozone, detergents, bleaching agents, organic solvents, etc. (see Chapter 3).

All types of **pulping processes (polymer recycling)** use a larger amount of chemicals compared to the mechanical recycling process. Typical chemicals used in a sulphur-free pulping process are hydrogen peroxide, sodium hydroxide and sulphuric acid. Sometimes ozone is used for bleaching and specific chemicals are applied for dye removal. The amount of chemicals used in the sulphur-free pulping process depends on the raw material composition and ranges between 70 kg and 240 kg[3] of chemicals per tonne of processed cotton. The higher the cotton content in the input stream, the lower the amount of chemicals required for the pulping process. Oelerich et al. (2017) report the use of the chemical sodium hydroxide and sulphuric acid for the production of dissolving pulp from 100% secondary cotton. 66 kg of chemicals are used for a 100% pure cotton input per tonne of dissolving pulp. When the input consists only for 90% of cotton and the remaining 10% is PET, the chemical use increases to 201 kg per tonne of dissolving pulp. Katajainen (2016) published a life cycle inventory for recycling of cotton into cellulose carbamate fibres. Chemicals involved in pre-treatment and pulping to produce cellulose pulp from cotton are: sodium hydroxide, ozone, hydrogen peroxide and sulphuric acid.

Energy

Mechanical recycling requires an electricity input of approximately 500 kWh per tonne of treated cotton according to a technology holder. Another technology holder reports an electricity use between 300 and 500 kWh per tonne. This includes the processing steps of cutting, metal & heavy part sorting, blending, pulling, tearing and pressing in bales. Esteve-Turrilas and de la Guardia (2017) report an electricity consumption of 364 kWh per tonne of treated cotton for the cutting and shredding process. Rengel (2017) states that the energy requirements for mechanically recycled cotton are almost 20% lower than for conventional cotton.

[2] Communicated by a technology holder – value for a sulphur-free pulping process

[3] Communicated by a technology holder

The **pulping process** requires higher energy inputs compared to a mechanical recycling process. Material entering the pulping process already went through a mechanical pre-treatment step. Additional energy requirements for the subsequent pulping process of the cotton are unknown. The energy requirements for a traditional pulping process proceeding from wood-based input are situated around 860 kWh per tonne of wood input[4]. The energy requirements for the pulping process are higher when using a cotton input compared to a wood input; the wood input material also delivers energy to the pulping process. One technology holder reports that the energy requirements are 10% higher compared to the standard production process using a wood-based input material. However, there is no consensus among technology holders that the pulping process with cotton input has a higher energy consumption than the pulping process with wood input. Oelerich et al. (2017) report a total energy use of 1 050 kWh per tonne of output for the production of dissolving pulp.

Water

Very little water is used in the **mechanical recycling** process, a water consumption of 20 litre per tonne of cotton treated was mentioned by a technology holder. The sulphur-free **pulping process** requires around 45 m^3 water per tonne of cotton input[3]. Oelerich et al. (2017) report a water use of 15 to 27 m^3 per tonne of output of dissolving pulp.

Process cost

Currently, less than 1 percent of all clothing is recycled back into apparel (Ellen MacArthur Foundation, A new textiles economy: Redesigning fashion's future 2017) and with a global virgin cotton market production estimated up to 26 million tonnes in 2018/19 (Textile Exchange, Preferred Fiber Material Market Report 2020 2020), leaving huge room for improvements. At the same time, around 12.5 percent of the global fashion market has made a public commitment to circularity by signing the Circular Fashion System Commitment (Textile Exchange, Preferred Fiber Material Market Report 2020 2020), showing at least the willingness to improve. The recycling of cotton is one approach towards a more circular textile industry.

The **mechanical recycling** of cotton is considered to be economically viable under the condition that the input to the recycling process is uniform and of good quality. Lower quality is a consequence of, for example, industrial washing and high-intensity maintenance processes, resulting in cotton fibres that are too damaged and as such hampering high-quality reuse of the recycled fibres. Therefore, the mechanical recycling of, for example, industrial cutting losses is considered viable. Next to the input quality, also the quality of recycled fibre will not have the same properties as the original fibre. Specifically, a deteriorated fibre length and a lack of length uniformity will limit the potential in end-use applications.

This finding is underpinned by a cost analysis of the mechanical recycling process, for which two scenario's have been investigated. In the worst case scenario (only 5% of the input being transformed into recycable spinnable fibres) the cost amounts to ca. 2 500 EUR per tonne of output spinnable fibres, while in the best-case scenario (up to 20% of the input being transformed into recyclable spinnable fibres) the cost sums up to ca. 560 EUR per tonne of output spinnable fibres (based on the LCI presented in Annex 1). Nevertheless, it is critical to mention that potential costs or revenues from the fluff and filling materials are

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[4] Calculated value using the ecoinvent datasets 'sulfate pulp from hardwood' (Zidmars, Sulfate pulp production, from hardwood, bleached RER. Allocation, cut-off by classification. ecoinvent version 3.6 2020) and 'sulfate pulp from softwood' (Zidmars, Sulfate pulp production, from softwood, bleached RER. allocation cut-off by classification. ecoinvent version 3.6 2020). The value represents the combined energy input of based on the combined energy input of wood chips, electricity, natural gas and fuel oil.

excluded from this analysis. Indeed, their share can vary between 78% and 87% in the output. In comparison, the global market price for cotton varies between 500 to 800 EUR per tonne (Markets Insider n.d.). The prices for cotton yarns are estimated to be 1.5 to 2.5 times this price (Centre International Trade n.d.). Based on Eurostat's trade statistics, the EU27 trade[5] in cotton (CN 5201 – cotton, neither carded nor combed) monthly import price varies between 1 462 and 2 014 EUR per tonne with an average import trade price of 1 706 EUR in the 01/2018 to 05/2021 period.

Determining factors in the cost for mechanical recycling are the cost and quality of the input stream. Ranging from a negative price (payment by the waste producer) to a positive price (payment to the waste producer) this has a huge impact on the economic viability of the recycling process. Also, the price of the virgin equivalent is of equal importance.

The challenges for recycling textiles are summarised by Ellen MacArthur Foundation (2017): aligning clothing design and recycling processes; pursuing technological innovation to improve the economics and quality of recycling; stimulating demand for recycled materials; and implementing clothing collection at scale.

Mechanical recycling of other cotton streams (non-uniform and/or washed) has the potential to become economically viable, but currently it is not. Mechanical recycling degrades the fibres with each cycle, limiting the number of times the fibres can be recycled. As a result, it is often cascaded down to "lower value" materials (materials that are less sensitive to shorter fibres), such as non-woven products used for filling materials and insulation. However, it is reported that mechanical recycling methods have gradually been refined to produce fibres of sufficient quality to be regarded as closed-loop fibre-to-fibre processing rather than downcycling. Some of the more refined mechanical fibre-to-fibre processes for cotton recycling can deliver cotton fibres that are about 25% to 30% shorter than virgin fibre (China Importal n.d.).

One of the setbacks is that the majority of the consumer waste is made of blended materials and the different blends need to be segregated before being recycled. At this moment, it is not possible to segregate the fibre types mechanically. Therefore, most recyclers only accept 100% homogenous materials (from collectors for closed-loop mechanical recycling). However, if the goal of recycling is to produce non-woven products, such requirement may not be applicable. In the upcoming EU strategy for sustainable textiles, it is recommended that the garments are designed for circularity. Considering the cost for incineration as the alternative route can (partly) close this gap.

The recycling technology of Re:newcell is an example of a technique for the **chemical recycling** of cotton. It is stated by the technology holder that its technology has the potential to become a commercial and scalable solution.

The cost of the chemical recycling of cotton to cellulose pulp via a pulping process (i.e. not the above mentioned Re:newcell recycling technology) is estimated at around 900 EUR per tonne (based on the ecoinvent database, see Annex 1), while the market value of its substitute, i.e. wood pulp, fluctuates around 1000 to 1200 EUR per ton, however, with a current low price level of around 750 EUR per tonne.

4.2.2. Polycotton

In Chapter 3, four different recycling techniques were identified to recycle polycotton waste streams: **mechanical recycling**, **chemical recycling (solvent-based dissolution)**, **enzymatic (or biochemical) recycling** and **hydrothermal degradation**. The technologies are described in more detail in Chapter 3. In this section, the impact of the recycling techniques is assessed on various criteria. Figure 15 shows an overview of the results of this assessment and further justification is provided in the following subsections. Little

[5] Trade of EU27_2020 countries with extra EU27_2020 countries.

information is available on hydrothermal degradation. This recycling technique is therefore not further discussed in this section.

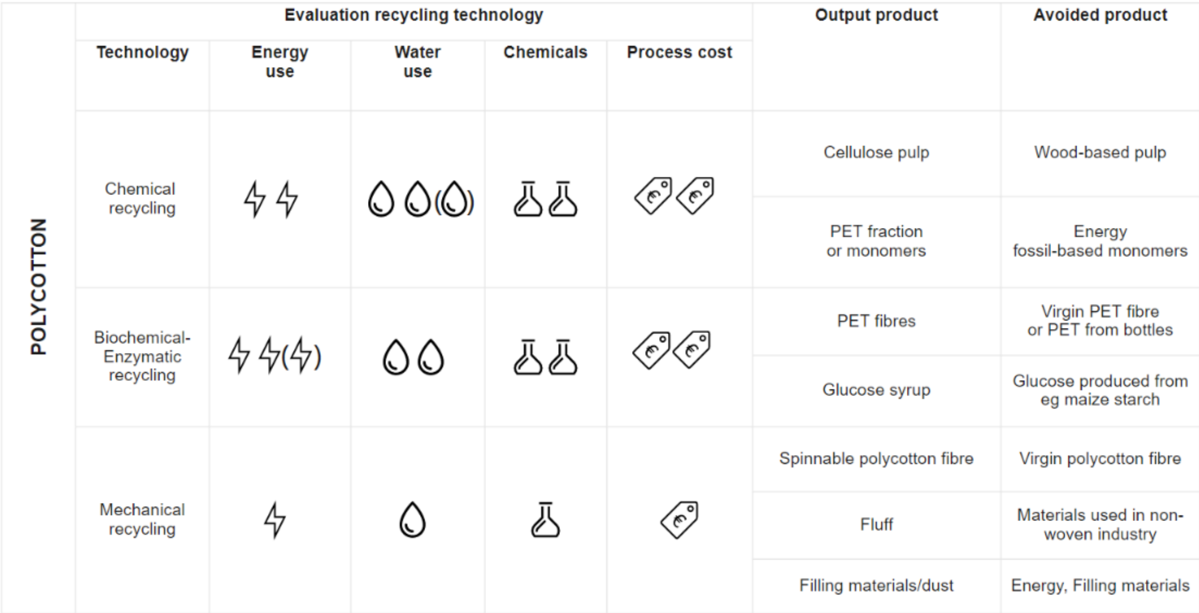

Figure 15 : Evaluation of recycling technologies for polycotton

Output product

Similar to the **mechanical recycling** process of pure cotton streams, the outputs of the mechanical recycling process of polycotton are spinnable fibres, fluff, filling materials and dust. The fraction of spinnable fibres largely depends on the quality of the input product. 25 - 55% of the recycled fibres is longer than 10 mm and therefore sufficiently long for respinning into a yarn (see Chapter 3). The other process outputs are similar to the output streams obtained by recycling pure cotton streams and are discussed in section 4.2.1.

A second method is a **chemical recycling** process which separates the polyester and cotton fractions. This separation can be done by dissolving the cotton and recovering the remaining PET fraction (Worn Again Technologies 2021) or, alternatively, by dissolving PET and recovering the remaining cotton fraction (Peters, Spark and Sandin 2019). In the former case, the output products are recovered cellulose and PET polymers (H&M Foundation 2021), while a solid fraction of cotton and the monomers terephthalic acid (TA) and glycol (which can be further purified to ethylene glycol (EG)) (Peters, Spark and Sandin 2019) or DMT and EG (S. Roos, et al. 2019) are obtained in the latter case. The recovered cellulose can be applied in typical pulping and wet-spinning processes (e.g. lyocell, viscose…). According to a technology holder, the quality of the output dissolving pulp is of 100% purity. PET resins can be respun to filaments, but, in today’s practice, they are incinerated for energy recovery. One technology holder is currently developing a technique which would enable the reuse of the PET fraction (technology at TRL 5). TA and EG or DMT and EG can be repolymerised to polyester, while the solid cotton fraction can be reused as input in a pulping process.

A third approach focuses on (partial) degradation of cotton from polycotton blends via an enzymatic route (i.e. **enzymatic recycling**) resulting in glucose syrup, cellulose powder and PET fibers. (H&M Foundation, HKRITA 2021) The glucose syrup can be used in other industrial applications; for instance it can be converted into plastics, surfactants and chemicals (Chapter 3). In order to obtain PET fibres (through a melt-spinning process) which are suitable for textile applications, PET bottle chips have to be added to the recovered polyester fibres in a 80-20 ratio (Subramanian, et al. 2020). This leads to the conclusion that the quality of the recovered polyester pellets is rather low. Per ton polycotton textile (50-50% cotton-polyester blended textile fabric) the recycling process yields 0.41 tonne recovered polyester fibres (Subramanian, et al. 2020) and 0.41 ton glucose syrup (technolgy holder), meaning that 18% could not be recovered into a useful end product.

The three recycling techniques start with a pre-treatment and shredding step, in essence a mechanical recycling process, which results in approximately 5% losses (non-textile parts).

Chemicals

Similar to the mechanical recycling of pure cotton, the **mechanical recycling** of polycotton uses little to no chemicals. Polymer recycling and enzymatic recycling require a larger amount of chemicals.

In **chemical recycling** of polycotton, cotton is separated from polyester by using chemical substances. For the technology where cotton is dissolved, the same chemicals as used in the pulping process of a pure cotton stream are deployed. The substances identified in section 4.2.1 are hydrogen peroxide, sodium hydroxide and sulphuric acid. Most probably other additional chemicals are used to separate the PET input from the cotton input. No further information was obtained from the technology holders via the surveys conducted in the course of this project. Zamani et al. (2014) report the use of NMMO (N-methylmorpholine-N-oxide) to separate cellulose from polyester. NMMO is mixed with shredded textile, the amount of NMMO required in the process is between 0.01 to 0.05 kg/kg cellulose thread (Zamani, et al. 2014). Zamani et al. (2014) assume that 98% of NMMO solvent is recovered and reused after the spinning step.

The chemicals used in the technology where PET is depolymerised are reported in Peters et al. (2019). PET is sensitive to alkali and is degraded into its monomers by means of hydrolysis using sodium hydroxide. The outputs of hydrolysis and filtration are a stream of recovered cotton and a stream containing sodium terephthalate (Na_2TP) and EG[6]. Separation of Na_2TP and EG is done by the process steps: nanofiltration, acidification and filtration. During acidification H_2SO_4 is deployed. TA (terephthalate) is removed from the neutralised solution, leaving EG in solution with sodium sulphate. Separation of ethylene glycol from sodium sulphate is an energy intensive step. (Peters, Spark and Sandin 2019)

Similar to polymer recycling of pure cotton, sometimes ozone is used for bleaching and specific chemicals are applied for dye removal.

Subramanian et al. (2020) report on the **enzymatic recycling** of cotton-polyester textile in a 50-50 blend. Sodium hydroxide, citric acid, cellulase and beta glucosidase are used during enzymatic hydrolysis; activated carbon, sulphuric acid, sodium hydroxide, cationic resin and anionic resin are used during PET recovery/purification of hydrolysate. Subramanian et al. (2020) mention a pre-treatment step. Communication with the technology holder revealed that this pre-treatment step is not as effective as anticipated and will be taken out in the further development of the technology. The total amount of chemicals used for the process per tonne of textile treated is 1.3 tonnes[7]. Technically, this amount is representative for an industrial scale process, however the technology is currently at TRL 5/6 and further improvements are possible. Chemicals not running in closed loop are sent to a waste water treatment plant.

[6] In the Blend Re:wind process (BRW), where catalyst-free alkaline hydrolysis of polyester from a polycotton input stream is carried out, about 280 tonnes of EG, 1 650 tonnes of sodium hydroxide and 500 tonnes of sodium terephthalate (Na_2TP) enter the reaction to depolymerise 380 tonnes of PET fiber (Peters, Spark and Sandin 2019). Of these input chemicals, 160 tonne EG, 1 100 ton sodium hydroxideand 90 tonnes of Na_2TP are considered to be recycled. Important to mention is that the BRW process is currently a labscale operation, that was theoretically scaled up to pilot plant scale in order to perform a prospective LCA. Therefore, the data provided (such as the aforementioned numbers) and assumptions made by the authors concerns pilot or bench scale data combined with rough estimates on what is feasable in terms of efficiencies (Peters, Spark and Sandin 2019).

[7] Including 0.47 ton cationic and anionic resins

From the aforementioned, it can be concluded that the consumption of chemicals is high for both chemical recycling and enzymatic recycling of polycotton.

Energy

The energy requirements for **mechanical recycling** of polycotton input streams are assumed to be equal to those for pure cotton input streams (see section 4.2.1).

The **chemical recycling** processes are more energy-demanding compared to the mechanical recycling processes as in any case the materials undergo a mechanical step first, comparable to the mechanical recycling processes.

With regards to the process where cotton is dissolved, Zamani et al. (2014) report an energy use (mainly heat) of approximately 1 400 kWh per tonne of textile input for the dissolution process (using NMMO).

Peters et al. (2019) report an electricity use of 3 770 kWh per tonne treated textile to yield PTA, purified EG and recovered cotton[8]. The purification of EG is the most energy intensive step in the process. If EG would not be recovered from the solution with sodium sulphate, the electricity use would drop to 712 kWh per tonne processed textile.

Subramanian et al. (2020) report the use of electricity and steam during the **enzymatic recycling** process. The electricity use is 22 160 kWh per tonne, however this electricity consumption mainly takes place in the pre-treatment step. This step will be left out in the further development of the technology. Without pre-treatment, the electricity consumption drops to 165 kWh per tonne of treated textile. In addition to the electricity consumption, also steam is necessary for enzymatic hydrolysis (7.3 tonne of steam per tonne of textile input (Subramanian, et al. 2020)). To generate steam, additional energy is required.

Water

Very little water is used in the **mechanical recycling** process, a water consumption of 20 litre per tonne of treated polycotton was mentioned by a technology holder.

Subramanian et al. (2020) report a water use of 38 m^3 per tonne of textile input for the **enzymatic recycling** process.

Chemical recycling of polycotton into a cotton output stream and monomers requires quite some water in the washing steps Peters et al. (2019) report water losses of 272 m^3 per tonne polycotton input).

Process cost

For the life cycle costing of **mechanical recycling** of polycotton streams, the same input data can be used as for mechanical recycling of pure cotton streams. The impact per tonne processed polycotton is thus the same as for an input consisting of pure cotton. As stated above, the fraction of spinnable fibres largely depends on the quality of the input product resulting in a range of 25 - 55% of fibres sufficiently long for respinning into a yarn. The fraction of spinnable fibres leaving the mechanical recycling process can only be roughly estimated as it depends largely on the quality of the input material. The other materials that come out of the process are fluff, filling materials and dust. The spinnable fibres are assumed to replace virgin polycotton fibres. The estimated process cost, based on the LCI, is 180 EUR per tonne (best case, 55%) to 500 EUR per tonne (worst case, 25%) of output of spinnable polycotton fibres.

Polycotton fibres, that are recycled via **chemical recycling** into cellulose, replace wood pulp, and the monomers TA and EG or DMT and EG can replace the virgin production of

[8] Cellulose production not included.

these monomers. No life cycle inventory data about this technology were obtained, meaning no LCC could be performed. An indication of the market value of TA, EG and DMT are provided in Figure 16 to Figure 18. The market value of (purified) TA fluctuated between 450 and 700 EUR per tonne in 2019/20; the market value of (mono)EG varied between 500 and 800 EUR per tonne in 2019/20; and the market value of DMT varied between 800 and 1050 EUR per tonne in 2018/19.

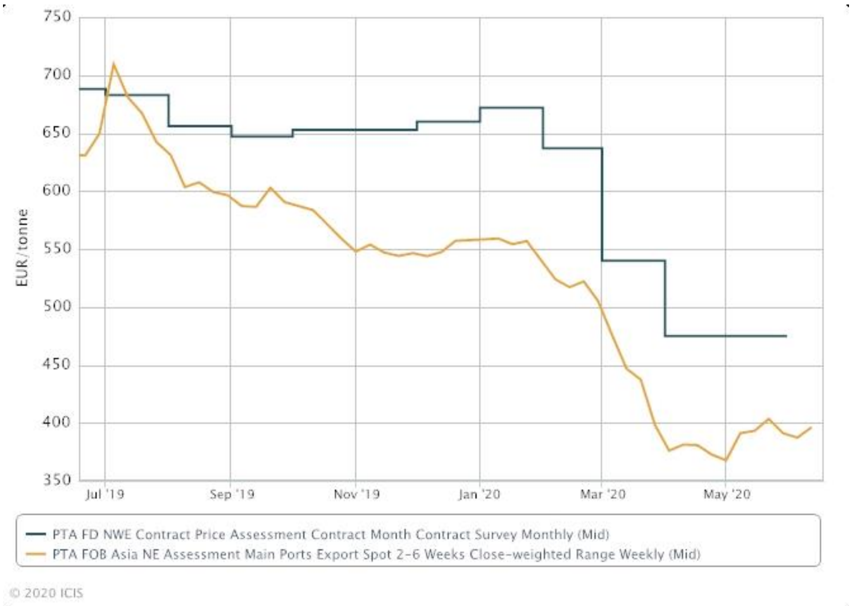

Figure 16: Market value of purified terephthalic acid (PTA). Source : ICIS (ICIS, Europe PET buyers relying on domestic supply but local PX, PTA offtake struggling as pandemic effects linger 2020).

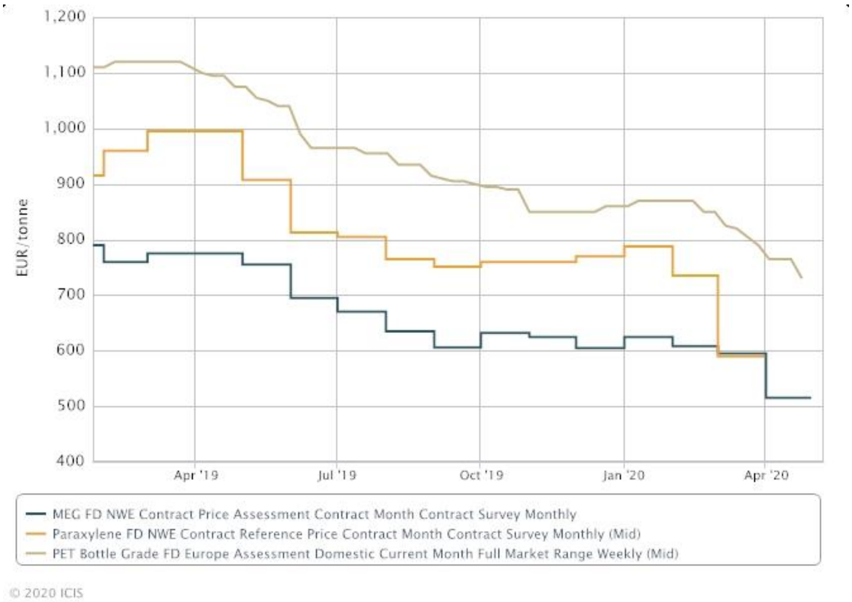

Figure 17: Market value of monoethylene glycol (MEG), paraxylene (PX) and PET. Source : ICIS (ICIS, Europe PTA, PET benefit from lockdowns but threat from fragile economies looms large 2020).

Figure 18: Market value of dimethyl terephthalate (DMT). Source : ICIS (ICIS, Downstream expectations of production cost increases may affect Europe PTA, DMT 2019).

The (partial) degradation of cotton from polycotton blends via an enzymatic route (i.e. **enzymatic recycling**) results in glucose syrup, cellulose powder and PET fibres. Per tonne polycotton textile (50-50% cotton-polyester blended textile fabric) the recycling process yields 0.41 tonne recovered polyester fibres and 0.41 tonne glucose syrup (technology holder), meaning that 18% could not be recovered into a useful end product. Based on Eurostat's trade statistics, the EU27 trade in glucose syrup (CN 17023 - Glucose in solid form and glucose syrup, not containing added flavouring or colouring matter and not containing fructose or containing in the dry state, < 20% by weight of fructose) monthly import price heavily varies between 327 and 1 735 EUR per tonne with an average import trade price of 1 008 EUR in the 01/2018 to 05/2021 period. The market value of recycled PET flakes is indicated on Figure 19, and varies between 900 and 1 100 EUR per tonne in the 2019/20 period. Based on the LCI, the estimated costs of this recycling process are 1 950 EUR per tonne of recycled PET fibres output. Comparing to an expected revenue of around 1 000 EUR per tonne of recycled PET fibres and an equivalent volume of glucose syrup (also around 1 000 EUR) of textile input treated reveals the current economic challenges. Currently, the market values of recycled PET and glucose syrup result in a process close to break-even. However, the value fluctuations introduce huge uncertainties.

Figure 19: Market value of PET, rPET flakes and rPET pellets in Europe. Source : ICIS (ICIS, INSIGHT: Different views on pricing, supply and demand split Europe R-PET market 2020).

4.2.3. Polyester

Textiles consisting of polyester can be processed in 4 different recycling techniques: **mechanical recycling**, **thermo-mechanical recycling, thermo-chemical recycling** and **chemical monomer recycling through solvolysis**. The details of these recycling techniques were discussed in Chapter 3. A fifth recycling technique, enzymatic monomer recycling, is currently being studied and developed, however it is not discussed here since it is still at pilot stage and not sufficiently mature at this moment for an environmental impact assessment or cost assessment. In this report, thermomechanical recycling refers to a melting and extrusion process (see Chapter 3). Figure 20 gives an overview of the different recycling processes and their outputs, evaluated according to their chemical consumption, energy and water use, avoided product and process cost.

	Evaluation recycling technology					Output product	Avoided product
	Technology	**Energy use**	**Water use**	**Chemicals**	**Process cost**		
POLYESTER	Chemical - Monomer recycling	ϟϟϟ	💧💧💧	⚗⚗⚗	🏷🏷🏷	PTA, MEG, DMT & BHET	Fossil-based PTA, MEG, DMT & BHET
	Thermo-chemical recycling	ϟϟϟϟ	💧	⚗	🏷🏷*	Syngas (CO, CO2, H2 & CH4)	Fossil-based syngas
						Gases, oil, tar	Fuels
	Thermo-mechanical recycling	ϟϟ	💧💧	⚗⚗	🏷🏷	PET pellets	Virgin PET
	Mechanical recycling	ϟ	💧	⚗	🏷	Spinnable PET fibre	Virgin PET fibre
						Fluff	Materials used in non-woven industry
						Filling materials/dust	Energy, Filling materials

Figure 20: Evaluation of recycling technologies for polyester
(*) Limited information available.

Output product

As a result of the **mechanical recycling** process, the output material's fibre strength and length are severely impacted; only 55% (at most) of the recycled fibres has a sufficient length to get respun to yarn (see Chapter 3). Furthermore, due to their decreased quality, recycled fibres need to be mixed with virgin fibres. On the other hand, the polyester content is preserved and the colour remains unchanged, which means re-dyeing of the recycled fibres may be avoided when the feedstock is sorted by colour (S. Roos, et al. 2019).

Thermo-mechanical recycling yields either polyester textile yarn (from high-quality, high-purity input) or PET staple fibres (from lower-quality input), or PET pellets (when spinning is impossible) (see Chapter 3). This technique does not tolerate any contamination (such as dust and dirt but also certain surface treatments) due to the sensitivity of the spinning process. This requires a thoroughly sorted and cleaned PET input. Furthermore, the number of recycling stages is limited due to degradation of the polymer, causing the fibre strength to decrease. Contaminants such as pigments, dyes and other chemicals (which are possibly hazardous) remain present in the output. Hence, the output material's colour is determined by the input material and by degradation of certain dyes, shifting colours in the process.

Chemical recycling starting from polyester textiles as an input is currently still being developed. Current practices proceed from packaging waste PET (polyethylene terephthalate) and industrial waste PET. For economic reasons, the PET content of the input should be around 80-90%. Chemical recycling is also referred to as monomer recycling, since, as opposed to (thermo)mechanical recycling, it yields the polyester's constituent monomers as the output. With regards to the output quality, it is beneficial that the impurities in the input material are known since (depending on the chemicals involved) they might negatively impact the depolymerisation reaction. In any case, the lower the input PET content, the lower the yield of recycling and the more additional purification/separation steps required (S. Roos, et al. 2019). Nevertheless, the monomer yield is high (DMT yield after methanolysis is around 90% (Zamani, et al. 2014)) and the recycled monomers can be repolymerized to obtain high-purity, virgin grade PET. Contrary to mechanical recycling, the type of input textile (knitwear, woven, non-woven) does not affect the output quality.

Thermo-chemical recycling yields multiple output fractions, of which the desired recycled content consists of small molecules in gaseous state, such as CO, CO_2, H_2 and CH_4 (a feedstock referred to as synthesis gas or syngas in industry). A technology holder reports a yield of 74% syngas (gas mixture of CO and H_2), which is then converted into acetic acid using steam and subsequently into cellulose acetate by addition of wood pulp. Cellulose acetate can eventually be processed into new textile fibres. The rest of the output consists of heavy liquids (oil or tar) and light liquids (gases and inorganic residue), which can be reused as fuels.

Chemicals

The **chemical monomer recycling** technique from PET is essentially a chemical reaction, depending on a solvent to dissolve the PET polymer chain into its constituent monomers. Frequently used solvents are glycol (glycolysis), methanol (methanolysis, a specific case of alcoholysis) or water (hydrolysis and enzymatic process), of which the former is commercially more established (Hann and Connock 2020). It should be noted that amines and ammonia could be used as solvents as well (resp. in aminolysis and ammonolysis), however there is no evidence proving that these processes have evolved beyond laboratory scale (Hann and Connock 2020). Apart from the solvent, a catalyst is involved to improve the reaction conditions. Catalysts may be used during multiple reaction runs (the number of runs depend on the catalyst type) before they need regeneration (Barnard, Rubio Arias and Thielemans 2021). Since it is difficult to separate from the reaction products and since a catalyst gradually loses its activity (European catalyst manufacturers association 2018), a certain catalyst consumption is expected.

The *glycolysis* mechanism, yielding oligomers and BHET (an ester of purified terephtalic acid (PTA) containing two hydroxyethyl groups), usually involves (mono-)ethylene glycol (MEG) as a solvent (Barnard, Rubio Arias and Thielemans 2021). Other glycols such as diethylene glycol, propylene glycol, dipropylene glycol and 1,4-butanediols may also be used (Barnard, Rubio Arias and Thielemans 2021). In a second reaction step, the oligomers can be cleaved further into monomers by the addition of water, yielding PTA monomers and MEG. These reaction products equal the ones obtained in the hydrolysis mechanism. For every TA unit of the input PET polymer, a molecule of MEG solvent is required. Although most of the MEG is recovered and reused (closed-loop), losses of 2-5% are reported by a technology holder. Furthermore, metal-based catalysts are frequently used to increase the (otherwise very slow) reaction rate (Bartolome, et al. 2012) and to allow for milder reaction conditions (Barnard, Rubio Arias and Thielemans 2021). In a PET/catalyst weight ratio varying between 0.003 and 0.05 (Bartolome, et al. 2012), this means that 3 to 50 kg of catalyst is required for every tonne of PET. A technology holder mentions the use of monoethylene glycol, nitrogen and activated carbon for the partial depolymerisation and afterwards repolymerisation of PES (both industrial and EOL textiles) into new PES.

The *hydrolysis* reaction uses water as a solvent. The depolymerization reaction can be done under neutral conditions (no additional chemicals added) on the one hand or in acidic medium (in which case for instance concentrated H_2SO_4 is added) or alkaline medium (addition of a strong base such as NaOH) on the other. The reaction is slow, even more so when performed in neutral medium, slower than glycolysis and methanolysis and, in order to obtain the required output purity of PTA, multiple recovery steps may be necessary (Bartolome, et al. 2012). H_2SO_4 and NaOH can be recovered and reused, however small losses are assumed.

The *methanolysis* mechanism degrades PET to dimethyl terephtalate (DMT, a methylester of PTA) and MEG using methanol as a solvent. 333 kg of methanol is required to depolymerize one tonne of polyester (Shen, Worell and Patel 2010). As in glycolysis, a catalyst is usually involved to speed up the process.

Due to the cleaning steps during pre-treatment and, for the most part, the purification steps to recover purified monomers, additional chemicals (such as HCl for precipitation of PTA (Hoenderdaal, W.G. 2017)) and filter aids (such as activated carbon and clay minerals) are involved. These materials can be regenerated and reused.

Chemicals consumption in **thermo-mechanical recycling** is low. A technology holder claims that, apart from the polyester input, no additional inputs are required in this process. It is assumed, however, that additional chemicals such as detergents and/or solvents may be involved during pre-treatment, since the polyester input needs to be of high purity and cleanliness not to perturb the melt-spinning process. Another technology holder reports only an antistatic chemical as an additional input for their process. According to Geyer et al. (2016) specific additives can be involved in thermomechanical recycling to improve viscosity and impact strength of recycled PET. These additives may include heat stabilizers, crosslinkers or chain extenders and compatibilizers.

It should be noted that chemicals may be released from polyester textiles during the recycling process (i.e., there is a certain output of chemicals). These chemicals are present in the input material as a result of treatment with dyes and pigments, flame retardants, solvents, softeners etc. during textile production to enhance their properties. Thermal treatment in the thermomechanical and chemical recycling processes of polyester may release chlorinated organic compounds, silicones and alkylphenols through evaporation (Ostlund , et al. 2015).

The use of chemicals in **mechanical recycling** of polyester is very low, as for any textile input material. If chemicals are used, it concerns, for example, ozone, detergents, bleaching agents, organic solvents, etc. (see Chapter 3).

Thermo-chemical recycling can be performed using (only) nitrogen gas (N_2) as an input chemical, in order to establish an inert atmosphere to perform gasification. A catalyst is required in the reactor to convert the polyester input into gas molecules. Some catalysts that have been reported in literature are olivine, sand, Ni-Al_2O_3 and γ-Al_2O_3 (Lopez, Artetxe, et al., Recent advances in the gasification of waste plastics. A critical overview. 2018). Since this recycling technique can handle more contaminated waste streams, no cleaning steps are assumed during pre-treatment, avoiding the use of additional chemicals to decontaminate the input.

Energy

Chemical monomer recycling from PET is energy demanding due to the required conditions for the depolymerization reaction; it is carried out at high temperatures and pressures (for instance, in the case of hydrolysis, water usually enters the reaction as steam). Even when depolymerization is catalyst-mediated, the required reaction temperature remains high. Studies report reaction temperatures in catalyst-mediated glycolysis ranging from 190-300°C and reaction times of 80 to 480 minutes have been reported (Bartolome, et al. 2012). A technology holder reports reaction temperatures of ca. 150 °C for hydrolysis and ca. 180 °C for glycolysis. Another source reports a reaction temperature of 200 °C for both glycolysis and methanolysis, both carried out under pressure (Petcore Europe n.d.). Even higher temperatures for glycolysis (170-300 °C) have been reported (Barnard, Rubio Arias and Thielemans 2021). The sources of energy for monomer recycling (glycolysis process) mentioned by a technology holder are electricity, natural gas and steam. Depolymerization is usually followed by purification to separate the different monomers from the reaction mixture, which further elevates the energy demand of the technology (C. Pudack 2020). In the case of methanolysis, purification of DMT and MEG entails two industrial distillation steps (recovery of methanol and MEG), followed by crystallization (further purification of DMT) (Pudack, Stepanski and Fässler 2020). Similar purification steps are expected for monomer recovery following glycolysis and hydrolysis. Bernard et al. (2021) additionally note that acid hydrolysis in an industrial context seems to be more energy demanding than alkaline hydrolysis, and that the treatment of residual acid (neutralization) could imply an additional energy requirement when concentrated acids are used.

Thermo-mechanical recycling of polyester involves multiple energy-consuming process steps. Firstly, the inputs (textiles or PET bottles) are pre-treated (washing, cleaning and drying) and shredded or ground into smaller pieces. These shreds subsequently undergo some processing steps including heating, melt filtration, degassing and viscosity increase. The resulting polymer melt is then chopped into pellets. The viscosity enhancement may as well take place after pellet production, in a separate solid-state post-condensation. In the case of a low quality input, the recycling process ends there. When the PET input quality is sufficiently high, the obtained PET pellets are fed to a processing machine (see Figure 7) where melt-spinning takes place in order to produce a continuous filament. This step entails melting and extrusion of the polymer, spinning the melt into a filament and subsequent cooling. As mentioned in Chapter 3, the pelletization step might even be skipped by using a specialized recycling line which includes systems for melt filtration, vacuum degassing and viscosity enhancement, before melt-spinning. Hereby the energy required for chopping the polymer and remelting the pellets afterwards is saved. It is assumed that a large part of the energy consumption can be attributed to the temperature profile during melt-spinning. PET melting in the extruder takes place at high process temperatures; PET polymer melting temperatures are situated around 255 °C (Bartolome, et al. 2012), followed by quenching (rapid temperature fall) to produce a filament and then reheating again to enhance fibre strength. In addition, the potential solid-state post-condensation step is energy-demanding as well; it is carried out in a vacuum and at temperatures between 200 to 240 °C. However, no exact data on energy consumption by thermomechanical recycling is at hand.

Mechanical recycling has a relatively low energy demand, the process steps involved (bale opening, cutting, blending, tearing and baling) are performed at ambient temperature and pressure. The energy requirements are assumed to be equal to those for cotton input streams (see section 0).

The energy requirements for **thermo-chemical recycling** are very high. The process consists of extrusion, PET gasificationinside a reactor at high temperatures (up to 1 000 °C), separation (e.g. by condensation) and purification through a series of distillation stages (depending on the desired output). Lastly, chemical treatment of the output yields the desired feedstock (Chapter 3). For each of the unit processes, a considerable amount of energy is needed to heat up or cool down the reaction mixture and/or operate the machinery. Additionally, in case supercritical water is used for PET gasification the energy demand will be greater since the water temperature and pressure need to be increased to 400 °C and 25 – 50 MPa, respectively, to reach its supercritical state (Xiaoli, et al. 2004).

Water

In **mechanical recycling**, water consumption is very low. According to a technology holder, only 20 litres of water are used per tonne of input material.

In **chemical monomer recycling**, water is used in the hydrolysis protocol. For every TA unit in the PET input polymer, a water molecule is consumed. In the Blend Re:wind process 20 800 tonnes of water (of which 16 000 tonnes are considered to be recovered) are used during the hydrolysis step for depolymerization of 380 tonnes of PET fibre (Peters, Spark and Sandin 2019). The glycolysis reaction only consumes water if a second reaction stage (cleaving oligomers to monomers) is applied. Methanolysis does not (and *must* not, in fact, due to poisoning of the catalyst) involve water. However, during pre-treatment a washing step is included to remove stains and impurities, which elevates the water use for chemical recycling.

It is assumed that no water is consumed in **thermo-mechanical recycling**, except during the pre-treatment phase where the input material is washed and cleaned.

Thermo-chemical recycling requires water during condensation, although this cooling water is assumed to circulate in a closed loop. In gasification, steam can be used as a gasification agent instead of air, in which case water consumption will be higher. Also supercritical water may be applied during PET cracking. As previously mentioned, no cleaning steps are assumed during the pre-treatment phase of this technology, hence no water use is considered there.

Process cost

For the life cycle costing of **mechanical recycling** of polyester streams, the same input data can be used as for the mechanical recycling of pure cotton streams. The impact of the recycling process per tonne of polyester processed is thus the same as for an input of (poly)cotton. The fraction of spinnable fibres largely depends on the quality of the input product resulting in a range of 25 - 55% of fibres sufficiently long for respinning into a yarn. The fraction of spinnable fibres leaving the mechanical recycling process can only be roughly estimated as it depends largely on the quality of the input material. The other materials that come out of the process are fluff, filling materials and dust. The spinnable fibres are assumed to replace virgin polyester fibres. The estimated process costs, based on the LCI, are 180 EUR per tonne (best case, 55%) to 500 EUR per tonne (worst case, 25%) of output of spinnable polyester fibres.

The output product of **thermo-mechanical recycling** is either PET fibre (best-case scenario) or PET pellets (worst-case scenario). rPET (recycled polyethylene terephthalate) markets remain complex: increasing consumer demand, developments on regulation and the COVID-pandemic, are just some of the challenges that put enormous pressure on this industry. Figure 19 shows the fluctuation in market prices for PET, rPET flakes and rPET pellets. The spread between virgin PET bottle grade and colourless rPET flakes was around 230 EUR per tonne, compared to May 2019, when flake prices were 8 EUR per tonne below virgin. The crash in crude oil prices has pulled PET down with it, while unchanged (factory) prices and limited supply have kept rPET flake prices in a much more limited range. (ICIS, INSIGHT: Different views on pricing, supply and demand split Europe R-PET market 2020)

Chemical monomer recycling of PET, as mentioned before, yields PTA, MEG, DMT and BHET monomers. PTA is largely used in the production of polyester fibre, which in turn is used to make fabrics for apparel and home furnishings such as bed sheets, bedspreads, curtains and draperies. DMT is used to make polyester fibres for textiles, resins for drink bottles and films for audio-visual equipment and packaging. Prices of these products show a downward trend in the period 2019-2020 (see Figure 16 to Figure 18). PTA price changes are closely related to those of PX (paraxylene). (ICIS, Europe PTA, PET benefit from lockdowns but threat from fragile economies looms large 2020) Clearly, the economy viability of both monomer recycling and thermomechanical recycling are uncertain due to the large fluctuation in the market value of the output of their virgin alternatives.

Life cycle inventory data for monomer recycling and thermomechanical recycling could not be obtained from technology holders, therefore performing a life cycle costing analysis was not possible.

Comparting the different routes of chemical recycling, the glycolysis mechanism is the least capital-intensive option, due to its simplicity and flexibility. Whereas the hydrolysis and methanolysis require numerous production steps and/or complex separation techniques.

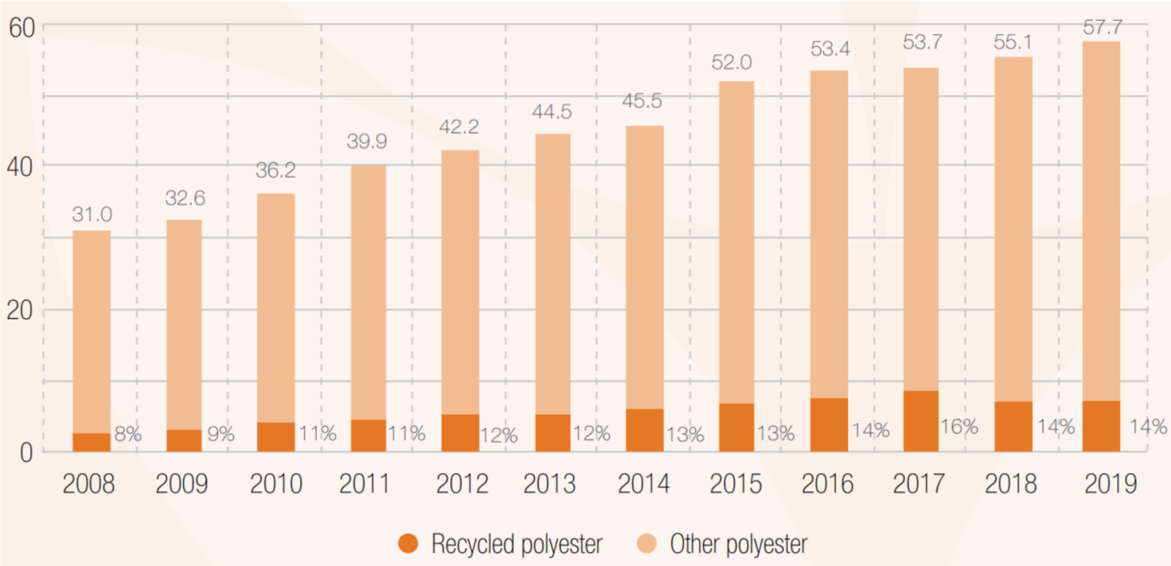

Figure 21: Global production of polyester, including the supply of recycled polyester. Source : Textile Exchange (Textile Exchange, Preferred Fiber Material Market Report 2020 2020).

The estimated recycled polyester (rPET) share of polyester staple fibre is estimated at 30 percent in 2019 (36 percent from 2014 onwards up to the 2018 decline). However, as the rPET share for polyester filament is much lower at around 6 to 7 percent in 2019, the total rPET share of polyester fibre, including staple fibre and filament is lower as well. (Textile Exchange, Preferred Fiber Material Market Report 2020 2020)

Most polyester is currently mechanically recycled. The market share of chemically or biologically recycled polyester is still very low. With new operations starting the commercial production of chemically recycled polyester and further companies in the research and development phase, the market share of chemically recycled polyester is expected to grow in the coming years. (Textile Exchange, Preferred Fiber Material Market Report 2020 2020)

4.2.4. Polyamide

In Chapter 3, two different recycling techniques were identified to recycle polyamide (i.e. nylon) streams: **mechanical recycling** and **monomer or chemical recycling** via a (acid) hydrolyses, glycolyse or methanolyse process. These recycling techniques are described in more detail in Chapter 3. Though in principle all polyamides could be depolymerized, today the only feasible chemical recycling process is for PA6. For other polyamides (e.g. PA6.6, PA11) monomers degrade during the depolymerization step, making monomer recycling impossible. The impact of the recycling techniques is assessed on various parameters. Figure 22 shows an overview of the results. Each parameter is discussed in more detail in the following sub-chapters.

	Evaluation recycling technologies					Output product	Avoided product
	Technology	Energy use	Water use	Chemicals	Process cost		
POLYAMIDE	Chemical - Monomer recycling	⚡⚡	💧💧	⚗⚗	🏷🏷	Caprolactam	Virgin caprolactam
	Mechanical recycling	⚡	💧	⚗	🏷	Spinnable PA fibre	Virgin PA fibre
						Fluff	Materials used in non-woven industry
						Filling materials/dust	Energy, Filling materials

Figure 22 : Evaluation of recycling technologies for polyamide (monomer recycling applies to PA6)

Mechanical recycling of polyamide is typically done with post-consumer polyamide. It includes a cleaning and pelletisation stage. Chemical or monomer recycling of PA6 includes a depolymerisation break down into its monomer component, caprolactam, which can be repolymerized to virgin grade PA6 and afterwards respun into a new yarn. Polyamide 6 is generally depolymerized via hydrolysis, e.g. using high pressure steam, via acid hydrolysis and super-heated steam (Chapter 3).

Output product

Mechanical recycling of polyamide is hardly done in the industry (Rengel 2017). Only a limited number of companies currently mechanically recycle post-industrial nylon for reuse as a fibre. The output are PA6-fibres with a fraction spinnable fibres, a fraction non-spinnable filling material and a fraction which can be used in non-woven applications.

Chemical recycling of PA6 delivers high quality fibres due to technical advancement and expertise (Rengel 2017). The material properties of recycled PA6 can be similar to virgin fibres, yet the input material is usually not ideal for recycling (because of too many different polyamide types). Only a few suppliers are performing chemical recycling of PA6. (Rengel 2017). The output of chemical recycling of PA6 is caprolactam which can be repolymerized to virgin grade PA6. One technology holder, treating an input stream consisting of carpets, fishing nets and textile and plastic scraps (which consists of other components than PA6, such as PP, backing, coating etc.), recovers an average of 65% of the input stream into PA6 (Aquafil S.p.A. 2020). The efficiency of monomer recycling of synthetic fibres highly depends on the purity of the input material. To reach a high efficiency in the monomer recycling process, the concentration of PA6 in the input material should be as high as possible and preferably some pre-separation steps have taken place.

Chemicals

Mechanical recycling uses little or no chemicals. If chemicals are used, it concerns e.g. ozone, detergents, bleaching agents, organic solvents, etc. (see Chapter 3).

Chemical recycling is performed at high temperature and at high pressure of overheated steam. One technology holder performing hydrolysis mentions the use of water, a catalyst for the depolymerization and alkaline compounds. According to the technology holder, chemicals and auxiliaries cannot be recovered entirely (not further specified) and the catalyst has to be added sometimes.

Energy

The energy demand for chemical recycling is higher in comparison to mechanical recycling, due to the high temperature and high pressure requirements. However, the Econyl® process (chemical recycling of PA6) uses up to 60% less energy in comparison to virgin production of nylon. (Rengel 2017). The sources of energy mentioned by a technology holder performing hydrolysis are electricity and thermal energy used to heat diathermic oil and to produce overheated steam.

Water

Hydrolysis (chemical recycling) is performed in a water or steam environment (acidic or neutral). Aquafil S.p.A. (2020) reports a water use of 30 m^3 per tonne recycled PA6 pellet. The water use volumes are comparable to water use in the virgin production of polyamides. (Rengel 2017)

Process cost

For the life cycle costing analysis of **mechanical recycling** of polyamide, the same input data can be used as for the mechanical recycling of the previously discussed streams. The cost structure of the recycling process per ton PA6 processed is thus the same as for the other streams. The fraction of spinnable fibres largely depends on the quality of the input product resulting in a range of 25 - 55% of fibres sufficiently long for respinning into a yarn. The fraction of spinnable fibres leaving the mechanical recycling process can only be roughly estimated as it depends largely on the quality of the input material. The other materials that come out of the process are fluff, filling materials and dust. The spinnable fibres are assumed to replace virgin PA6 fibres. The estimated process cost, based on the LCI, is 180 EUR per tonne (best case, 55%) to 500 EUR per tonne (worst case, 25%) of output of spinnable PA6 fibres. Of course, if the share of PA6 in the input stream is at the bottom of the approximated range 20-65% the process costs per ton of spinnable PA6 output fibre will be much higher. The historical value of these fibres is presented in Figure 23.

The **chemical (monomer) recycling** of PA6 focusses on the production of polyamide resins which can be extruded to polyamide fibres. A full LCI for this recycling process could not be obtained from technology holders for use in this project, therefore performing a life cycle costing assessment was not possible.

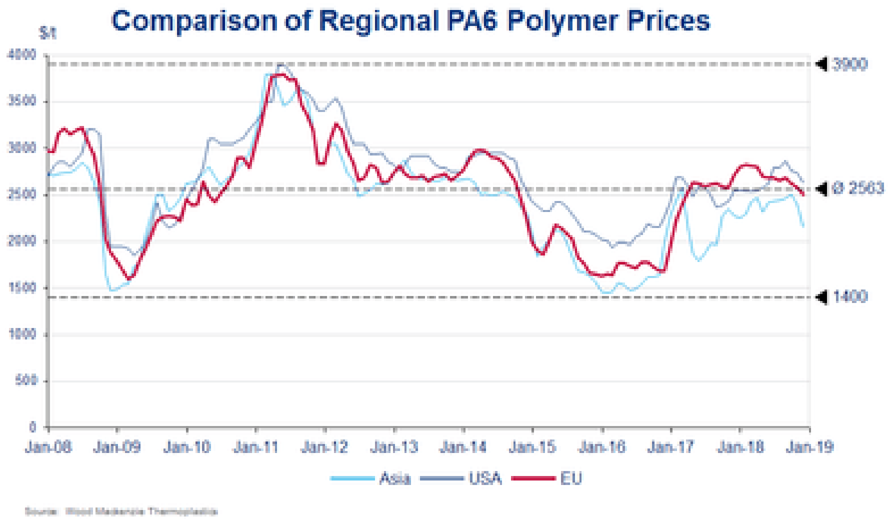

Figure 23 : The market value of PA6 polymers, in dollar per ton. Source : DOMO (DOMO 2019).

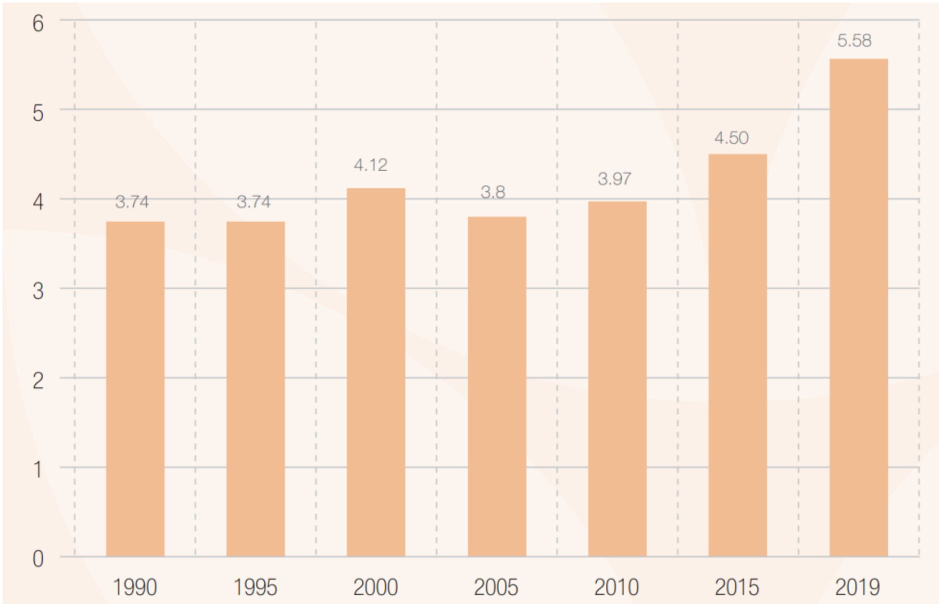

Figure 24: Global production of polyamide, including the supply of recycled polyester. Source : Textile Exchange (Textile Exchange, Preferred Fiber Material Market Report 2020 2020).

The market share of recycled polyamide is challenging to estimate. Reliable numbers on the global recycled polyamide production volume are currently not publicly available. As polyamide is more difficult to recycle than polyester, the market share of recycled polyamide is much lower than the one for recycled polyester. Indicative, we added the global production volumes of polyamide in Figure 24.

4.3. Impact on climate change calculated by means of life cycle assessment (LCA)

This section provides the figures regarding the impact on climate change (expressed in kg CO_2 equivalents) as calculated or as reported in the identified literature resources. For textile recycling technologies for which life cycle inventory data were obtained from technology holders, this section reports the climate change impact calculated by means of a life cycle assessment. For other technologies, the authors established a life cycle inventory dataset based on information available in databases. Sometimes values for the impact on climate change of a certain recycling technology are available in literature, in this case, these values are also mentioned in this section. The authors acknowledge that life cycle assessment methodologies (e.g. goal and scope, system boundaries) might vary across studies and that results are highly dependent on the assumptions taken in the studies. Yet, given the lack of life cycle inventory data, this is often the only source of information available. The methodology followed for the life cycle assessments in this study is described in Annex 1. The considered functional unit is defined as **'the treatment of one tonne of textile material'**. The assessment starts with the reception of the materials at the recycling plant and ends at the point where the output products of the recycling process can substitute primary products. Assumptions are made regarding the type and quantity of materials and/or products that can be avoided by making a recycled equivalent available. Credits are awarded for the avoided production of these materials or products. The eventual impact on climate change and more specifically of the impact that can be avoided of the recycling technology depends, amongst others, on the replacement rate of new products by recycled products. This replacement rate depends on the recycled product's quality compared to that of the virgin product and also on the market demand for the recycled material.

Whenever possible, the impact on climate change is reported per functional unit, being one tonne of treated textile material. Some literature sources report the climate change impact per tonne of output product. A recalculation to the functional unit of one tonne of treated textile material has been done in case the necessary information was available in the source.

The focus of this section is on climate change. This impact category is reported most often in literature and its calculation method is robust. When life cycle inventory data are available, results for sixteen environmental impact categories were calculated, resulting in a more complete environmental profile of the recycling technology. The sixteen environmental impact categories are the categories as defined in the product environmental footprint (PEF) method (Zampori and Pant 2019). These results have been calculated because environmental aspects other than climate change could also be of importance for the sector. The results are reported in Annex 1.

For the cases where information on the impact on climate change of a particular recycling technology is not available, this section reports the impact on climate change of the production of virgin products and/or materials that are being avoided by recycling textile materials. This approach provides an insight into the maximum savings that can be achieved by recycling a certain material. Indeed, the advantage of recycling lies in the fact that the production of new materials or products is avoided. The environmental impact of production of the new materials, which are being substituted by recycled materials, gives an indication of the maximum savings. Of course, the recycling process itself consumes energy, water and/or chemicals which in turn have an environmental impact. This impact must be lower than the impact of the avoided products in order for the recycling process to result in a net saving. However, without life cycle inventory data, this impact cannot be determined.

4.3.1. Recycling of cotton

For the recycling of cotton, two main recycling technologies were identified in Chapter 3: **mechanical recycling** and **chemical (polymer) recycling**. For the mechanical recycling process and also for a pulping process, which is a certain type of polymer recycling, life cycle inventory ballpark figures are available (see Annex 1). The impact on climate change, calculated using these ballpark figures, gives a first indication of the environmental performance of the technology, but should be interpreted with caution as it is not based on a detailed life cycle inventory. Figure 25 shows the impact on climate change of the mechanical recycling process of cotton using two different situations for output products and avoided materials. When cotton fibres are mechanically recycled, they are recycled into different output products, which differ in quality and thus in possible application. The fraction of spinnable fibres is 5-20% of the textile material input in case of natural fibres (see Chapter 3). The other output products are fluff, filling materials and dust. The spinnable fibres replace virgin cotton fibres[9]. In a worst case scenario it is assumed that 5% of the spinnable fibres are recovered, replacing virgin cotton fibres, the remaining output materials are burned with energy recovery. In a best case scenario 20% spinnable fibres are recovered and the remaining output materials replace virgin input materials in the non-woven industry. In both cases, recycling the textile means that a waste treatment step is avoided. The avoided waste treatment is incineration with energy recovery. The two scenarios are given in Table 12.

The impact on climate change of the mechanical recycling process is the same in both scenarios and is approximately 215 kg CO_2 equivalents per tonne of cotton treated. The incineration of the non-spinnable fraction (relevant in the worst case scenario) has an additional impact of 115 kg CO_2 equivalents per tonne cotton treated. The avoided climate change impact due to the avoided heat and electricity production because of this incineration is 278 kg CO_2 equivalents. The avoided climate change impact due to products that can be avoided by recycling the cotton into spinnable fibres is around 190 kg CO_2 equivalents per tonne of cotton input (worst case scenario: 5% spinnable cotton fibres recovered). The total avoided climate change impact could increase in the best case scenario to 1 660 kg CO_2 equivalents per tonne of input if 20% of spinnable fibres can be recovered and if the fluff and filling materials replace virgin PET / PP / cotton fluff / cellulose fluff. The best case scenario entails that the waste cannot be incinerated with energy recovery and consequently no benefits from energy recovery processes are generated which results in a net burden (black coloured part in second bar)[10]. A clear conclusion is that the largest benefits are generated when the recycling process results in as high as possible amount of spinnable fibres which can replace virgin fibres. A possible drawback of the mechanical recycling process is that it does not allow to change the properties (e.g. colour) of fibres.

9

10 Emissions of biogenic carbon are assumed to be neutral in the EF method (uptake during plant growth equals release), the incineration process itself has a low impact on climate change, the impact of the avoided products (heat and electricity) is larger. Due to the use of the cotton in a pulping process, it cannot be incinerated with energy recovery and consequently the avoided impacts from this incineration are visible as a burden.

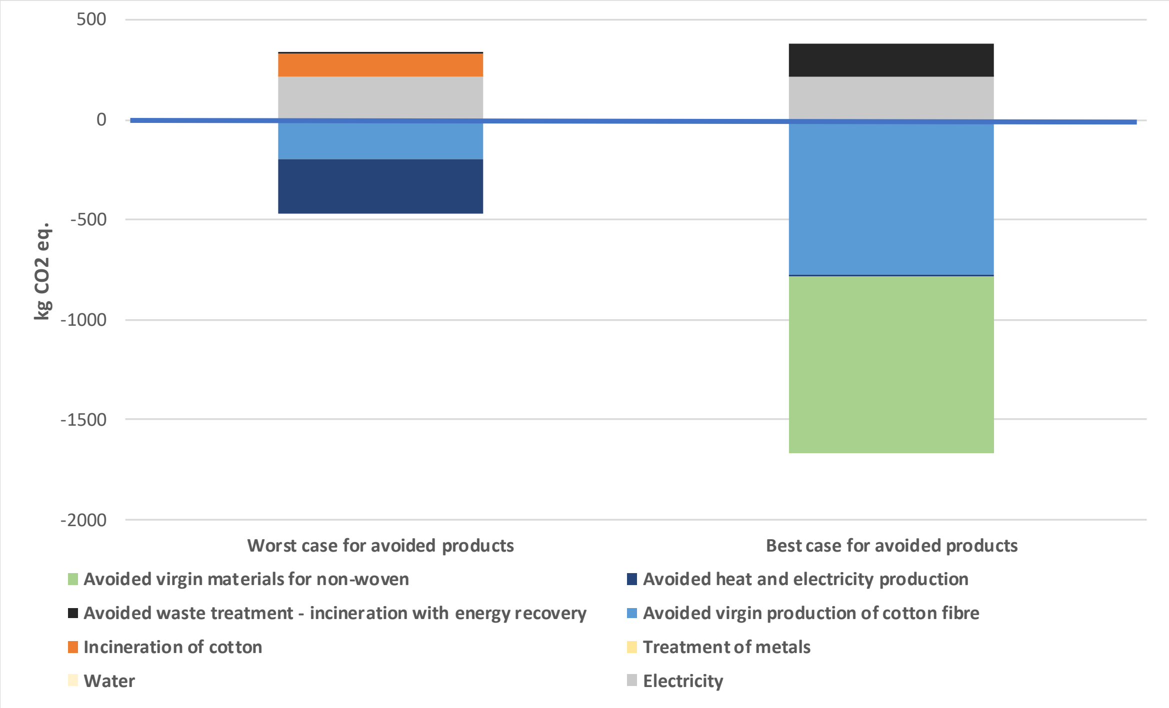

Figure 25 : mechanical recycling of cotton – impact on climate change expressed in kg CO_2 equivalents.

Table 12 : Overview of scenario's for avoided products of mechanical recycling of cotton

Worst case for avoided products	Best case for avoided products
5% spinnable fibres replace virgin cotton fibres	20% spinnable fibres replace virgin cotton fibres
Remaining output of the recycling process is burned with energy recovery	Remaining output of the recycling process replaces virgin materials use in the non-woven industry (25% PET, 25% PP; 25% cotton fluff and 25% cellulose fluff)
5% avoided waste treatment - incineration with energy recovery.	93% avoided waste treatment – incineration with energy recovery

The climate change impact of **cotton recycling via a pulping process (chemical polymer recycling)** to cellulose pulp, calculated with the proxy inventory data set, is approximately 361 kg CO_2 equivalents or 1 090 kg CO_2 equivalents per ton cotton treated for respectively sulphate pulp and sulphite pulp. Cotton, which is recycled for further use in a viscose, lyocell or carbamation process, replaces wood pulp. The avoided climate change impact due to the products that can be avoided by recycling cotton into pulp is around 261 kg CO_2 equivalents per tonne of cotton input (sulphate pulp avoided). This could increase to 950 kg CO_2 equivalents per tonne input (sulphite pulp avoided). Recycling the cotton textile via a pulping process also entails that the waste cannot be incinerated with energy recovery and consequently no benefits from energy recovery processes are generated which results in a net burden[11]. This result is visualized in Figure 26. The two different scenarios are given in

[11] Emissions of biogenic carbon are assumed to be neutral in the EF method (uptake during plant growth equals release), the incineration process itself has a low impact on climate change, the impact of the avoided products (heat and electricity) is

Table 13. In both of the investigated situations, the impact on climate change of the recycling process is higher than the avoided impact due to the avoided primary production of the recycled product. As explained earlier, the life cycle inventory data used for this evaluation are of low quality leading to a high uncertainty on the results. In literature, some values are available for the climate change impact of textile recycling via a pulping process. Oelerich et al. (2017) report an impact on climate change of 480 kg CO_2 equivalents for the production of one tonne of dissolving pulp made from textile input material[12]. The use of a biocatalyst in the degree polymerisation (DP) reduction step reduces the impact to 390 kg CO_2 equivalents per tonne of dissolving pulp. The values are applicable to the recycling process itself, avoided impacts were not considered in Oelerich et al. (2017). Finally, dissolving pulp from textile material holding a certain PET content has a higher impact on climate change, which is calculated by Oelerich et al. (2017) to be 860 kg CO_2 equivalents per tonne of output. This is due to the use of more process chemicals and the need for additional processes to separate PET from cellulose.

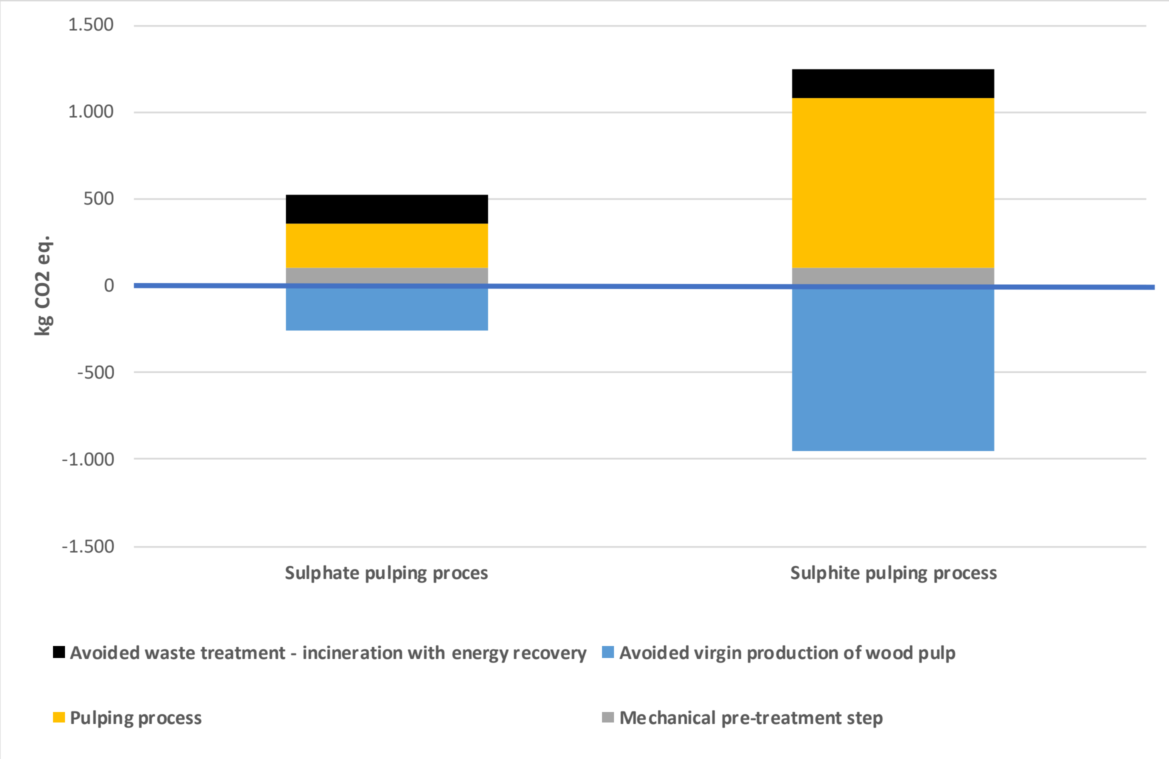

Figure 26 : recycling of cotton via a pulping process– impact on climate change expressed in kg CO_2 equivalents.

Table 13 : Overview of scenario's for recycling of cotton via a pulping process

Cotton recycling via sulphate pulping process	**Cotton recycling via sulphite pulping process**
Recycling via sulphate pulping process	Recycling via sulphite pulping process
Avoided product is wood pulp generated via a sulphate pulping process	Avoided product is wood based pulp generated via a sulphite pulping process

larger. Due to the use of the cotton in a pulping process, it cannot be incinerated with energy recovery and consequently the avoided impacts from this incineration are visible as a burden.

[12] Impact on climate change per ton output. The paper does not mention how much textile input material is needed to produce 1 ton of output. Values cannot be recalculated to one ton of textile input.

93% avoided waste treatment - incineration with energy recovery.	93% avoided waste treatment – incineration with energy recovery

4.3.2. Recycling of polycotton

For the recycling of polycotton, this chapter looks at three different recycling technologies: **mechanical recycling**, **chemical recycling (solvent-based dissolution) and enzymatic (or biochemical) recycling**. For the mechanical recycling process as well as the enzymatic recycling process ballpark life cycle inventory figures are available (see Annex 1). The impact on climate change, calculated using these ballpark figures, gives a first indication of the performance of the technologies. The results should however be interpreted with caution as they are not based on a detailed life cycle inventory.

For the life cycle assessment of **mechanical recycling** of polycotton streams (see Annex 1), the same input data as for mechanical recycling from pure cotton input streams can be used. Again two scenarios are investigated, covering a best case and a worst case situation for the avoided materials (see Table 14). The impact on climate change of the recycling process itself is approximately 215 kg CO_2 equivalents per tonne of polycotton treated and is the same in both scenarios. In the worst case scenario, output that cannot be recovered as spinnable fibres is incinerated with energy recovery. The impact of the incineration process on climate change is 1 090 kg CO_2 equivalents, the benefits for the avoided electricity and heat production due to this incineration are 495 kg CO_2 equivalents. The avoided impact on climate change of the avoided virgin fibre production is around 1 050 kg CO_2 equivalents per tonne of polycotton input in the worst case scenario and could increase to 2 300 kg CO_2 equivalents per tonne of input if 55% of the input material is recovered as spinnable fibre (best case scenario). The results are graphically presented in Figure 27.

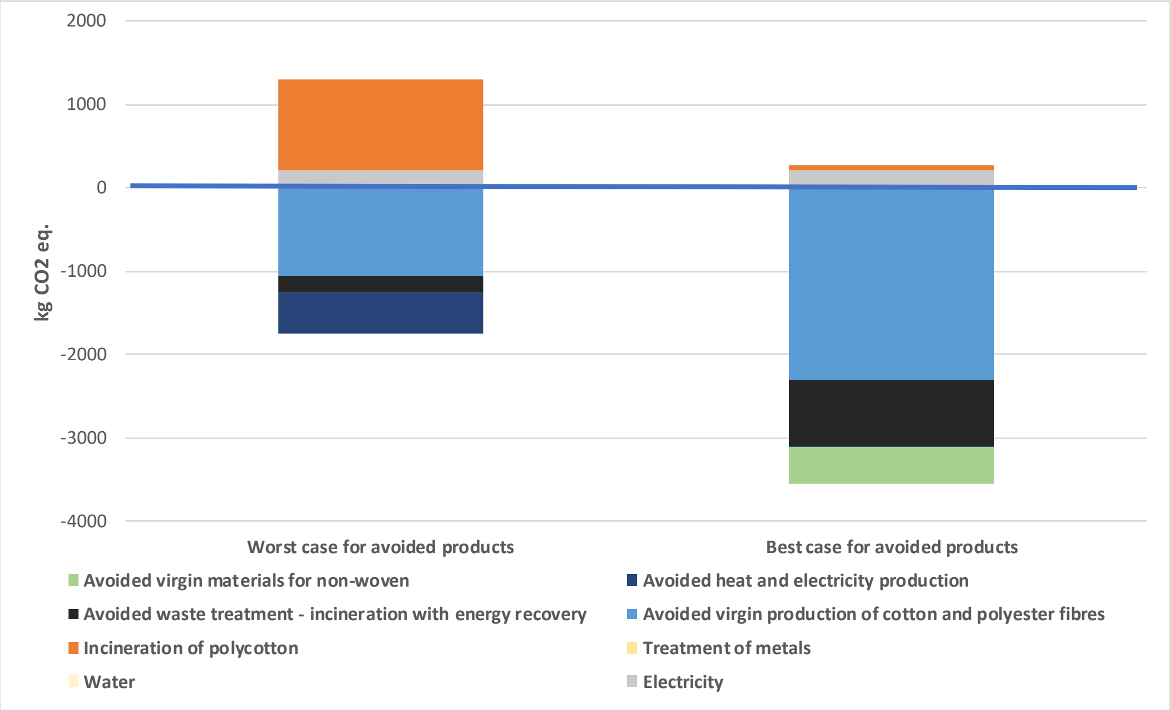

Figure 27 : mechanical recycling of polycotton – impact on climate change expressed in kg CO_2 equivalents.

Table 14 : Overview of scenario's for avoided products of mechanical recycling of polycotton

Worst case for avoided products	Best case for avoided products
25% spinnable fibres replace virgin cotton fibres (50%) and virgin polyester fibres (50%)	55% spinnable fibres replace virgin cotton fibres (50%) and virgin polyester fibres (50%)
Remaining output of the recycling process (70%) is burned with energy recovery	Remaining output of the recycling process (40%) replaces virgin materials use in the non-woven industry (25% PET, 25% PP; 25% cotton fluff and 25% cellulose fluff)
25% avoided waste treatment - incineration with energy recovery.	93% avoided waste treatment – incineration with energy recovery

The life cycle assessment of **enzymatic recycling** reveals that this recycling process results in a climate change impact of 9 180 kg CO_2 equivalents per tonne of input treated. The avoided products are PET resins and glucose syrup, of which the avoided production can result in an avoided impact on climate change of 2 120 kg CO_2 equivalents per tonne of treated textile input into the enzymatic recycling process. It is important to note that the process is currently at TRL5/6 level and a validation of life cycle inventory data at industrial scale has therefore not yet taken place. Possible changes in the life cycle inventory when the technique is effectively used at industrial scale will of course result in changes in the impact on climate change. The result is visualised in Figure 28.

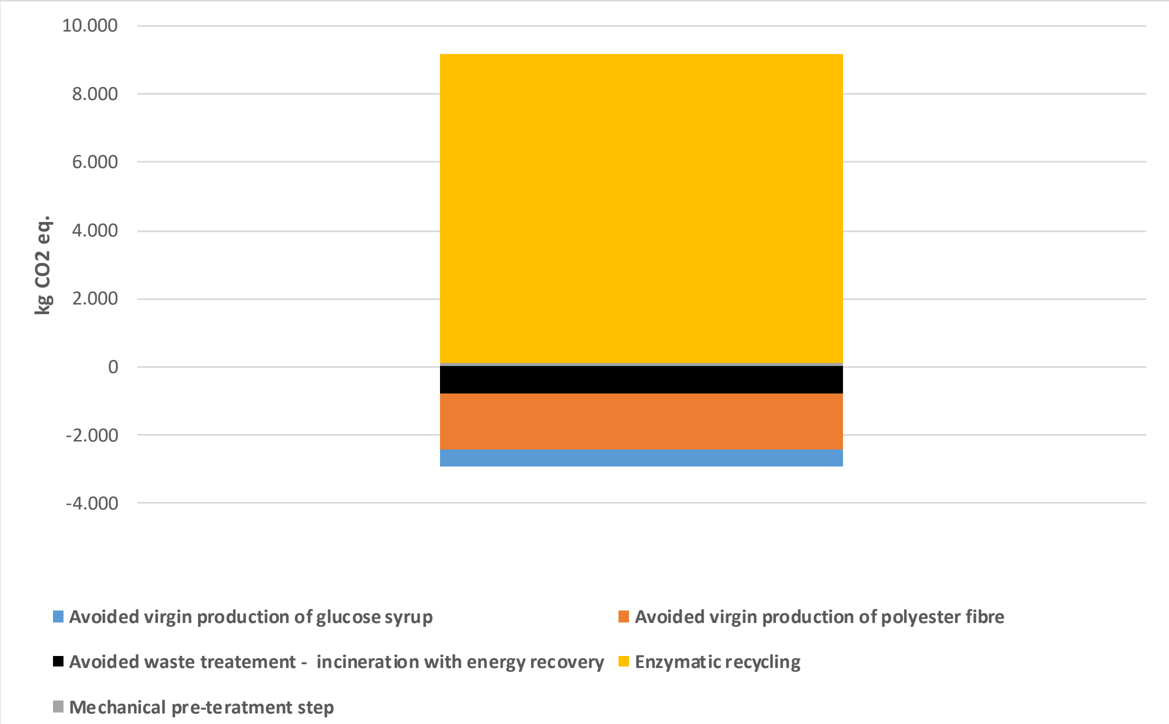

Figure 28 : enzymatic recycling of polycotton – impact on climate change expressed in kg CO_2 equivalents.

Life cycle inventory data for **chemical polymer recycling – solvent-based dissolution** could not be obtained from technology holders, therefore performing a life cycle assessment was not possible. Zamani et al. (2014) report the climate change impact of polymer recycling with NMMO as a solvent. This recycling process results in substantial savings due to the avoided primary production of cellulose and polyester yarns, namely 5.5 tonnes of CO_2 equivalents would be saved in total per tonne of textile material (Zamani, et al. 2014). The climate change impact from the recycling processes (but including yarn spinning) are approximately 1.25 tonnes of CO_2 equivalents per tonne of material processed.[13]

Polycotton fibres, that are recycled via a **pulping process (chemical polymer recycling) into cellulose**, replace wood pulp. No life cycle inventory data about this technology were obtained. The reader is referred to section 4.3.1 where the climate change impact of polymer recycling of a pure cotton stream into cellulose pulp is mentioned. Treatment of polycotton streams requires an additional step to separate the cotton and polyester fraction.

Polycotton fibres that are recycled via **chemical recycling into the monomers** TA and EG or DMT and EG can replace the virgin production of these monomers. Unfortunately, life cycle inventory data for the recycling process are not available. The impact on climate change of the avoided products PTA and MEG from fossil resources is respectively 1 840 kg CO_2 equivalents and 1 600 kg CO_2 equivalents per tonne PTA or MEG. This is the maximum impact that can be avoided by recycling polycotton streams into PTA and MEG. Evidently the recycling processes have their own energy and chemical requirements. No data on the environmental impact of the production of DMT is available in life cycle assessment databases.

4.3.3. Recycling of polyester

For the life cycle assessment of **mechanical recycling** of polyester (see Annex 1), the same input data as for the mechanical recycling of cotton and polycotton can be used. Again two scenarios are investigated, covering a best case and a worst case situation for the avoided materials (see Table 15). The impact on climate change of this recycling process is approximately 215 kg CO_2 equivalents per tonne of polyester treated. The climate change impact of the virgin polyester fibre production that can be avoided by recycling polyester is around 1 080 kg CO_2 equivalents per tonne of polyester input (worst case: 25% spinnable polyester fibres recovered). The main impact in this worst case scenario comes from incineration of the polyester output which cannot be recovered as spinnable fibre. The incineration process also produces a useful output in the form of electricity and heat. However, the climate change impact of these avoided products is lower than the impact of the incineration process itself. In the best case scenario, this incineration process is avoided because fluff and filling materials are assumed to be used in the nonwoven industry. The results are presented in Figure 29.

[13] The number was read from the graph published in (Zamani, et al. 2014). A precise reading was not possible due to the low resolution of the graph. – (Zamani, et al. 2014) used other data for the production of cellulose and polyester yarns from primary production as used in this report.

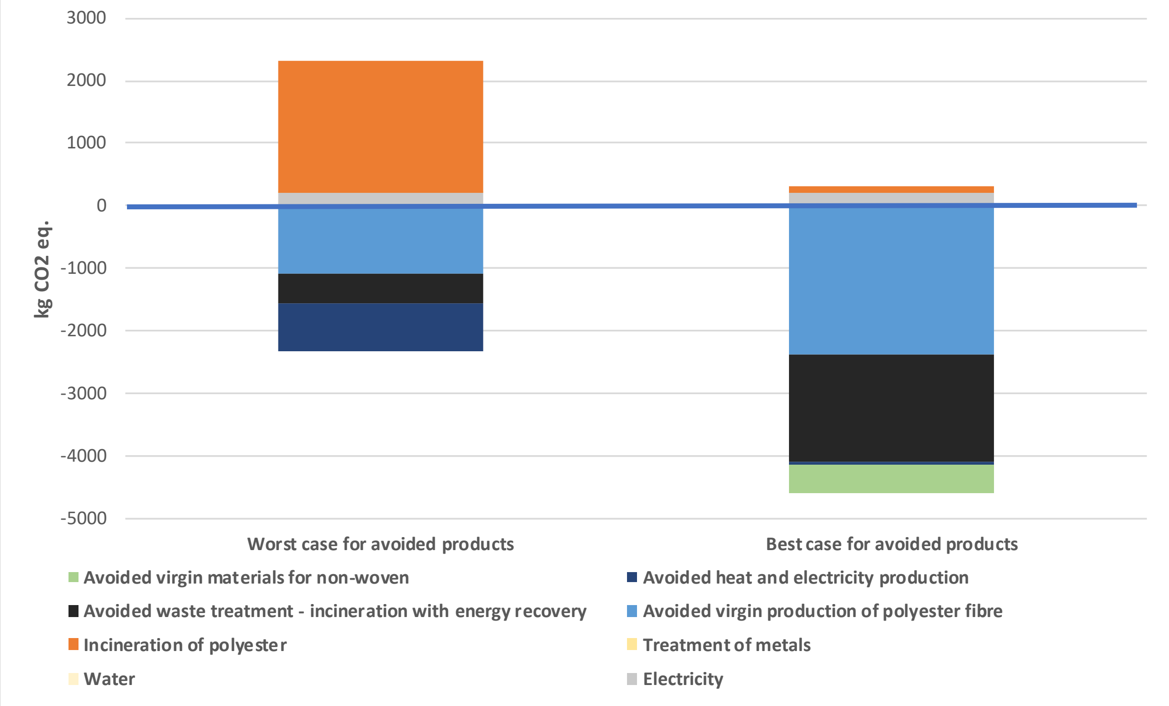

Figure 29 : mechanical recycling of polyester – impact on climate change expressed in kg CO_2 equivalents.

Table 15 : Overview of scenario's for avoided products of mechanical recycling of polyester

Worst case for avoided products	**Best case for avoided products**
25% spinnable fibres replace virgin polyester fibres	55% spinnable fibres replace virgin polyester fibres
Remaining output of the recycling process (70%) is burned with energy recovery	Remaining output of the recycling process (40%) replaces virgin materials use in the nonwoven industry (25% PET, 25% PP; 25% cotton fluff and 25% cellulose fluff)
25% avoided waste treatment - incineration with energy recovery.	93% avoided waste treatment – incineration with energy recovery

LCI data are not available for **chemical monomer recycling** and **thermo-mechanical recycling**. Therefore, only the climate change impact of the avoided products can be reported for these technologies. Obviously, this is an incomplete analysis as the recycling process itself also has an impact on climate change.

Monomer recycling of PET, as mentioned before, yields PTA, MEG, DMT and BHET monomers. In virgin polyester production, these monomers are used directly as inputs but originate from fossil resources. Hence, fossil-based terephthalic acid, monoethylene glycol and terephthalates DMT and BHET are the avoided products. For the production of PTA and MEG, the avoided impact on climate change corresponds to 1 840 and 1 600 kg CO_2 equivalents per tonne PTA or MEG, respectively. No data on the environmental impact of the production of DMT and BHET is available in life cycle assessment databases.

From here on the repolymerization of the recycled monomers and spinning into new polyester fabrics are identical to the primary PET production process.

Since per tonne of produced PET, about 0.862 tonnes of PTA and 0.335 tonnes of MEG are needed, the impact of virgin monomer production is equal to about 2 122 kg CO_2

equivalents per tonne of PET output (0.862*1 840 + 0.335*1 600). In other words, by monomer recycling through hydrolysis, a maximum of 2 122 kg CO_2 equivalents is avoided per tonne of PET. Of course also the recycling process has an environmental impact which could not be quantified.

The output product of **thermo-mechanical recycling** is either PET fibre (best-case scenario) or PET pellets (worst-case scenario). In the former case, the production process of PET as well as melting and spinning into fibres are avoided, resulting in a large benefit towards the carbon footprint; namely the emission of 4 320 kg CO_2 equivalents[14] . In the case where PET pellets are produced, the carbon footprint per tonne of produced PET pellets will be lower than in the former case, since only polymerization into PET is involved. This scenario results in an avoided carbon footprint of 3 040 to 2 840 kg CO_2 equivalents[15], depending on the chemical state of the polymer (amorphous or bottle grade, respectively).

No LCI data on **thermo-chemical recycling** could be shared by technology holders either. However, Coleman et al. (2020) conducted a life cycle assessment of their own, using data from 2020 as a reference year. The LCA was critically reviewed and it is ISO 14040 and ISO 14044 conform. In this cradle-to-gate study, the functional unit was defined as 1 kg of syngas at the specific composition, temperature and pressure, as used by the company to further process into intermediates and products (Coleman, et al. 2020). The processes within scope are transportation of plastic waste to the factory, mechanical pre-processing and thermochemical recycling itself, including supply of energy, utilities and auxiliary materials. This scenario was compared to the situation where fossil-based syngas is produced. Alternatively, a best-case scenario considering an optimal feedstock mix (as opposed to the 2020 average feedstock mix that was used in the main scenario) was assessed as well. The impact on climate change of syngas production by thermo-chemical recycling was calculated to be 22% lower than for traditional syngas production (i.e. by coal gasification). In the optimal scenario, a carbon footprint reduction of 50% would be obtained. No other environmental impact categories were assessed in the study.

4.3.4. Recycling of polyamide

For the life cycle assessment of **mechanical recycling** of polyamide (see Annex 1), the same input data as for the mechanical recycling of cotton, polycotton and polyester can be used. Again two scenarios are investigated, covering a best case and a worst case situation for the avoided materials (see Table 16). The impact on climate change of this recycling process is approximately 215 kg CO_2 equivalents per tonne of polyamide treated. The climate change impact of the virgin polyamide fibre production that can be avoided by recycling polyester is around 2 770 kg CO_2 equivalents per tonne of polyamide input in the recycling process (worst case: 25% spinnable polyamide fibres recovered). The main impact in this worst case scenario comes from incineration of the polyamide output which cannot be recovered as spinnable fibre. The avoided impact for heat and electricity production due to the energy recovery of the incineration process does not outweigh the impacts of incineration. In the best case scenario, this incineration process is avoided because fluff and filling materials are assumed to be used in the non-woven industry. The avoided impact of the recovered spinnable polyamide fibres increases to 6 090 kg CO2 equivalents per tonne polyamide treated. The results are visualised in Figure 30.

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[14] Calculated with the ecoinvent record for polyester fibres

[15] Calculated with the ecoinvent record for polyethylene terephthalate granulates

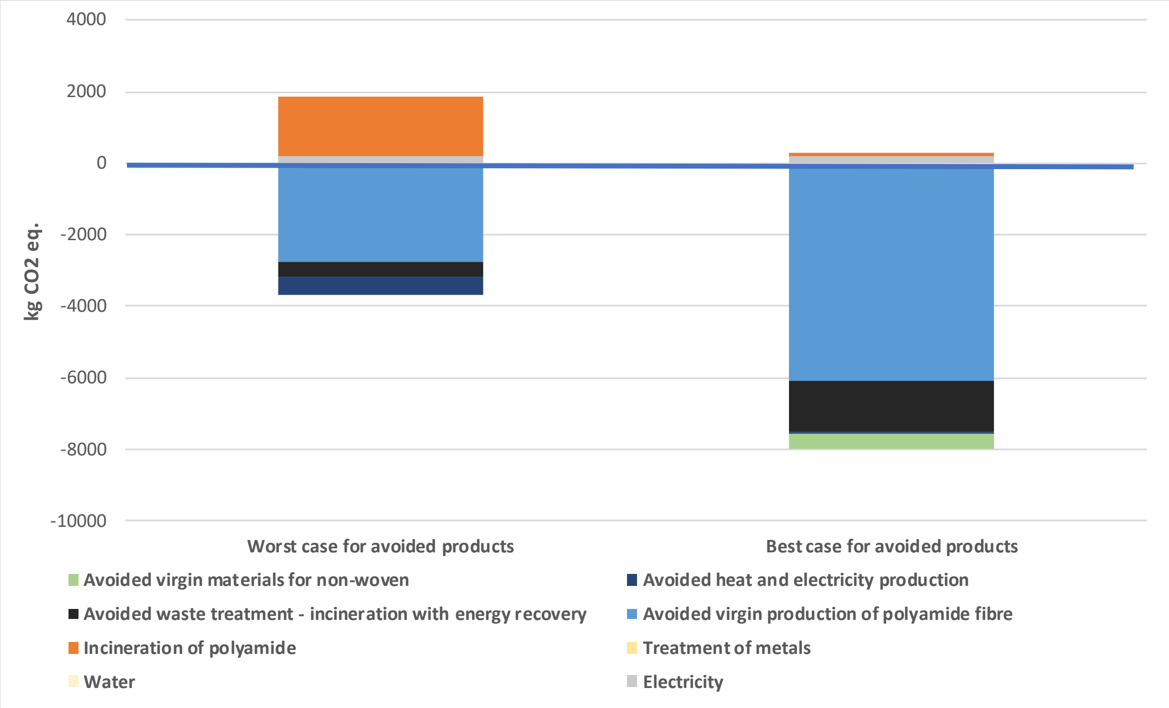

Figure 30 : mechanical recycling of polyamide – impact on climate change expressed in kg CO_2 equivalents.

Table 16 : Overview of scenario's for avoided products of mechanical recycling of polyamide

Worst case for avoided products	Best case for avoided products
25% spinnable fibres replace virgin polyamide fibres	55% spinnable fibres replace virgin polyamide fibres
Remaining output of the recycling process (70%) is burned with energy recovery	Remaining output of the recycling process (40%) replaces virgin materials use in the nonwoven industry (25% PET, 25% PP; 25% cotton fluff and 25% cellulose fluff)
25% avoided waste treatment - incineration with energy recovery.	93% avoided waste treatment – incineration with energy recovery

A technology holder reports by means of an environmental product declaration (EPD) the climate change impact of **chemical recycling (monomer recycling)** of PA6 via hydrolysis into PA6. The input stream consists of post-consumer carpets, fishing nets, plastic scraps and other PA6 waste. The climate change impact of chemical recycling followed by polymerization of PA6 is 600 kg CO_2 equivalents per tonne of input. However, only 65% of the input stream is recovered as PA6 (the climate change impact per ton PA6 polymer output is 920 kg CO_2 equivalents) (Aquafil S.p.A. 2020). The remaining part of the input stream is either recycled or burned for energy recovery. The reported climate change impact for the production of Bulk Continous Filament (BCF) yarns (for textile flooring applications) made from the recovered PA6 is between 1 670 kg CO_2 equivalents and 1 110 kg CO_2 equivalents per tonne of yarn (Aquafil S.p.A. 2020). This is well below the impact on climate change of the avoided virgin fibre, which is 11 060 kg CO_2 equivalents per ton polyamide fibre[16]. This comparison should be seen as a first indication, as the results for the recycled PA6 fibre and the virgin fibre are not calculated within the same LCA study.

4.4. A wider economic perspective

The global textile fibre production in 2020 is estimated at 109 million tonnes which equals 14 kilograms per person. Textile Exchange (2021) estimates that 55% to 81% of these fibres originate from fossil-based sources and from unknown or non-recognized (potentially) renewable sources. 10.7% originates from renewable recognized programs. 7.6% originates from recycled bottles and only 0.5% from recycled pre- or post-consumer textiles and other non-bottle feedstock. Looking at the level of the different textile fibres, the share of recycled fibres differs:

- Cotton: the share of recycled cotton is 0.96%;
- Polyester: the share of recycled PET is estimated at 15%;
- Polyamide: the share of recycled PA is estimated at 2%
- Man-made cellulosic: the share of recycled man-made cellulosic fibres (MMCFs) is estimated at 0.4%; and
- Synthetic fibres: the share of recycled synthetic fibres is 0.6%.

It is clear from these numbers that the global fibre production based on recycled textiles is currently very small.

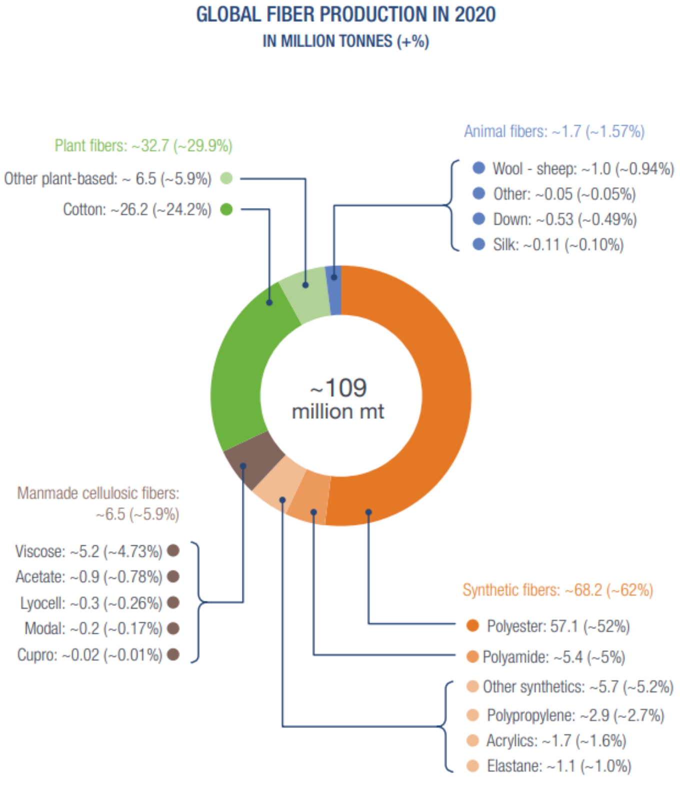

Figure 31: Global fibre production. Source: (Textile Exchange, Preferred Fiber & Materials - Market Report 2021 2021).

[16] Calculated by means of the ecoinvent record 'market for fibre, polyester GLO' in which the polyester input has been replaced with a polyamide input.

In 2020, 2.9 million tonnes of finished textile products[17] were produced in EU27, representing a value of almost 41 billion EUR. EU production specializes in carpets[18], household textiles[19] and other textiles[20] (including non-wovens, technical and industrial textiles, ropes and fabrics). Apart from finished textile products, the EU27 is a significant producer of intermediate products for textiles, such as fibres, yarns and fabrics (see Figure 32). In 2019, The EU27 produced 0.9 million tonnes of fibres, 0.7 million tonnes of yarns and 0.3 million tonnes of fabrics for both domestic and foreign markets. The trade volumes of fibres, yarns and fabrics are smaller compared to these production volumes: the import and export of fibres are both 0.2 million tonnes; the import and export of yarns 0.6 and 0.1 million tonnes respectively; and the import and export of fabrics are 0.2 and 0.1 million tonnes, respectively. The trade volumes are lower compared to the production volumes, implying a large domestic use/consumption of the production output. The higher trade volumes are within the product groups of clothing and household textiles.

In 2020, 6.2 million tonnes of finished textile products[17] were imported in EU27, representing a value of 101 billion EUR (i.e. extra-EU27_2020 trade). About one-third of this volume are made-up textile articles (except apparel) like household textiles and bedding articles and one-third is outerwear. In 2020, 1.3 million tonnes of finished textiles were exported, representing a value of 38 billion EUR. Carpets and rugs are the largest category within this export volume.

[17] Included are the CPA 2.1 product groups 13.92, 13.93, 14.12, 14.13, 14.14, 14.19, 14.31 and 14.39.

[18] 'Carpets' refers to product group 13.93 'Carpets and rugs'.

[19] 'Household textiles' refers to product group 13.92 'Made-up textile articles, except apparel', which consists of blankets, including travelling rugs; bed, table, toilet or kitchen linen; quilts, eiderdowns, cushions, pouffes, pillows, sleeping bags etc.; curtains, valances, blinds, bedspreads, furniture or machine covers etc.; tarpaulins, tents, camping goods, sails, sunblinds, loose covers for cars, machines or furniture etc.; flags, banners, pennants etc.; dust cloths, dishcloths and similar articles, life jackets, parachutes etc.

[20] 'Other textiles refers to product groups 13.91 (knitted and crocheted fabrics), 13.94 (cordage, rope, twinage and netting), 13.95 (Non-wovens and articles made from non-wovens, except apparel), 13.96 (Other technical and industrial textiles) and 13.99 Other (textiles n.e.c.).

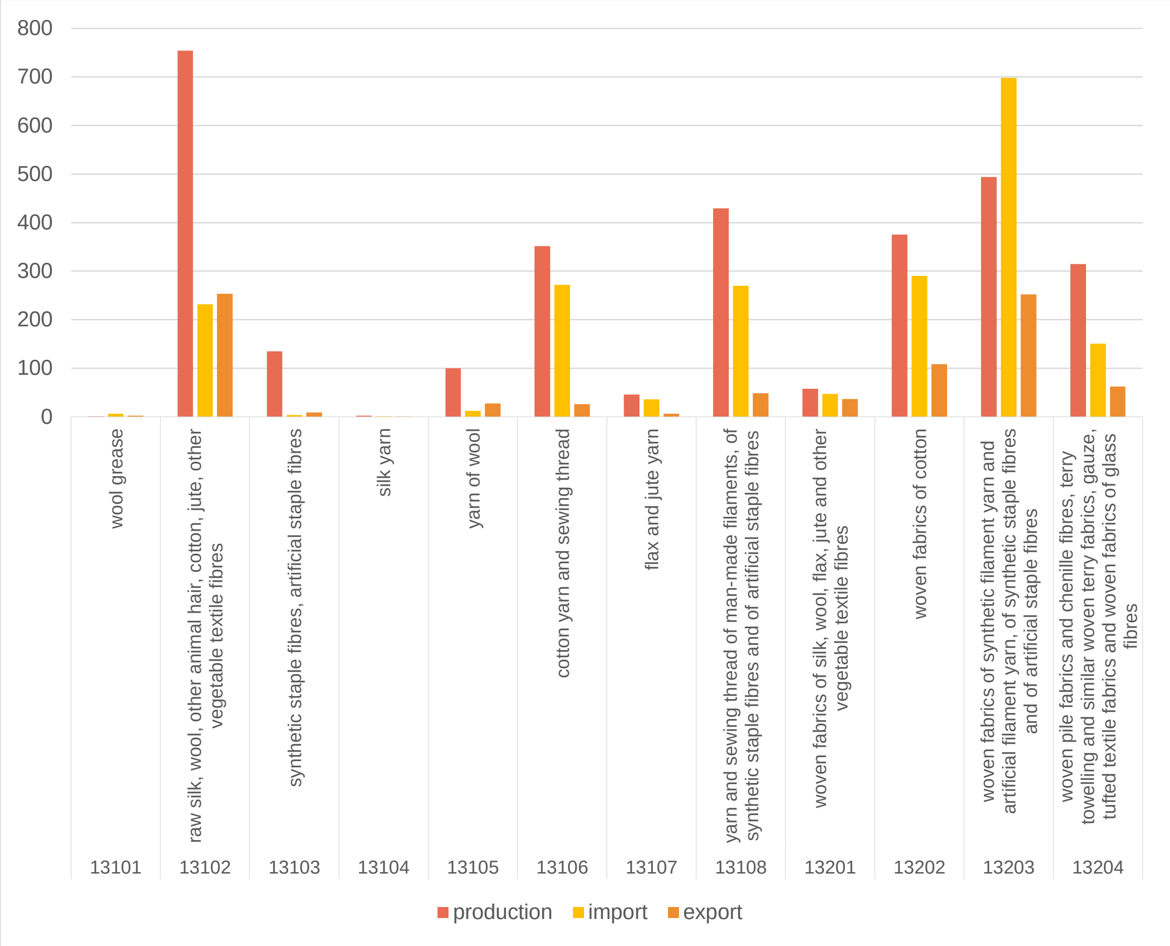

Figure 32:Production, import and export volumes of textiles fibres, yarns and fabrics, EU27_2020, 2019, in 1,000 tonnes. 5-digit PRC-codes are added for clarity. Source: Eurostat [DS-066341].

The EU27 production volume of cotton (carded or combed) is estimated in 2019 at 87 kilotonnes. In comparison, the global production volume is estimated at nearly 26 million tonnes. The trade volumes of this product are estimated at an import of 22 kilotonnes and an export of 3 kilotonnes. The production of cotton yarn is higher: 350 kilotonnes. Also, the import volume of this product is higher: 271 kilotonnes import and 25 kilotonnes export. From these numbers, it is clear that Europe's role at the production side of cotton is relatively small. (Textile Exchange, Preferred Fiber Material Market Report 2020 2020) estimates the European share (taking into account Egypt, Turkey, Israel and Greece) in global volume at 3.5%.

The EU27 production of synthetic and artificial staple fibres (carded, combed or processed for spinning) is estimated in 2019 at 135 kilotonnes. The trade volumes of this product are estimated at an import of 4 kilotonnes and an export of 9 kilotonnes. The production of yarn and sewing thread of man-made filaments, of synthetic staple fibres and of artificial staple fibres is higher: 429 kilotonnes. Also, the import volume of this product is higher: 270 kilotonnes import and 48 kilotonnes export. Again, these European volumes are small compared to global production volumes (e.g. the global production volume of polyester is 58 million tonnes).

The EU27 reported amount of textile waste (both industrial and household waste) is 2.2 million tonnes in 2018 (Eurostat 2021). In the same year, EU27 reported it treated 1.6 million tonnes of textile waste of which 1.2 million tonnes is classified as being recycled (Eurostat 2021). In these official waste statistics 1.2 million tonnes of textile waste is recycled out of a reported volume of textile waste of 2.2 million tonnes. The type of recycling (fibre-to-fibre, downcycling, …) is not known from these statistics. These materials pose practical limitations to the availability of feedstocks for some fibre-to-fibre recycling technologies requiring a pure/an almost pure feedstock.

The separate collection of waste textiles by 2025 could have a positive effect on both this volume and the quality of the waste stream. The EU27 apparent consumption of finished textile products (i.e. estimated by domestic production volume plus imports minus exports) in 2020 is 11.7 million tonnes. If we assume a target for separate collection of this consumption volume of 50%, the waste volume could increase to 5.8 million tonnes. In the case of mechanical recycling the spinnable fibre output varies between 5 and 55%, resulting in a potential (maximum) volume of recycled fibres of 3.2 million tonnes per year in the EU27. With an average value of fibres of roughly 750 EUR per ton this EU27 business could increase to a yearly revenue of 2.4 billion euro. A higher fraction of spinnable fibres output with other recycling techniques could result in an even higher volume of recycled fibres production. Although this value results from a theoretic exercise, it shows the huge challenge ahead if the volume is compared to the global estimated fibre production volume of 109 million tonnes. Moreover, it is critical to highlight the potential lack of a local market demand for these fibres as most production volumes are located outside the EU27.

Next to this route driven by a waste push, also demand (pull) for recycled textiles can be stimulated. For example, eco-design requirements for recyclability can be pioneered for a small number of textile product groups. According to the online survey conducted for this project (see chapter 6), jeans as well as T-shirts could be suitable product groups to introduce mandatory minimum design requirements. Both product groups are widely circulated on the market and possess potential for circularity. According the calculations based on Eurostat data, the consumption of T-shirts and jeans in the EU27 is estimated at 1.9 million tonnes per year (own calculation based on (Eurostat 2021); it is estimated at 4.5 kg per capita). Assuming a eco-design guideline of 5% recycled content roughly requires a total of 0.1 million tonnes of recycled cotton fibres to produce these jeans and T-shirts. The estimated current global production of recycled cotton fibres is estimated at 0.3 million tonnes showing already the huge effect this guideline could have on this market.

5. Recommendations for potential supporting initiatives and definition of roadmap

The objective of this chapter is to perform an analysis to determine which steps are needed to ensure that the earlier identified and promising textile recycling technologies will in fact reach application and scale-up at industrial level, and thus become reality. The analysis leads to the development of a roadmap with necessary steps and supporting initiatives, and the definition of a timeframe for that to happen.

This chapter further builds upon the outcomes of the previous chapters, being the identified technology – fibre(mix) combinations, their TRL and environmental and economic performance or potential. In order to map the needs and underlying barriers which inhibit the uptake of textile fibres recycling, the information from the previous chapters was complemented with further information available in literature, relevant information from the questionnaire filled out by 32 technology holders, and the 10 in-depth interviews with technology holders conducted in the framework of this study (see Chapter 3). Next to this, a broader stakeholder survey was done, including specific open questions on barriers and policy needs for textile fibres recycling, as well as on possible supporting initiatives. This survey was sent to different stakeholder groups such as collectors and sorters, enablers (e.g. machine builders, certification bodies), industry federations and retailers/users. 15 Stakeholders responded to this survey. A first overview of barriers and possible solutions was presented to technology holders during a webinar organized in June 2021 within the scope of this study to validate and further refine the findings. This chapter will focus on the technology- and market-related issues, the operational and financial issues as well as the potential initiatives to overcome these barriers and issues. The policy issues and recommendations will be separately addressed in Chapter 6 and will also further build upon these identified barriers and needs.

5.1. Mapping of needs and underlying barriers

An overview of the needs and underlying barriers for the different textile fibres recycling technologies can be found in Table 17. In this table, a viable recycling process is considered to depend on having a steady input stream of well-defined materials that results in an output that meets market expectations and demand with regard to quality and price. The scalability of the recycling process impacts the volume that can be processed and the costs. These needs can be (negatively) impacted by underlying barriers. Not all barriers apply to every recycling technology. In the table these are highlighed by different colours. Barriers with a medium impact have a yellow cell colour, barriers with a high impact have an orange cell colour. Grey cells indicate that the barrier (currently) is not relevant for the respective recycling technology. More information about the barriers can be found in Chapter 3.

Table 17: Overview of needs and underlying barriers of the various textile fibres recycling technologies

Needs and underlying barriers	Mechanical	Thermo-mechanical	Thermo-chemical	Chemical / monomer	Chemical / polymer
Well-defined and steady input					
Unknown composition / intolerance to contamination(s)					
Hard parts and trims					
Coatings or (laminated) layers					
Elastane content					
Dyes					
Type (woven / knitted)					
State (due to use and maintenance or the collection process, e.g. wet)					
Consistent output quality					
Lower mechanical properties					
Limited colours (depending on input colours)					
Residues of chemicals of concern				(*)	(*)
Market demand					
Higher price (compared to virgin)					

Competition from other recycled fibres (e.g. recycled PET from bottles)					
Knowledge and expectations from the market					
Scalability					
Lack of adequate and well-defined input quantities					
Costs of logistics					
Currently at low TRL level					
Capital intensive / availability of capital					
Specialized or skilled labour requirements					

(*) at the moment there is not enough information on whether or not all chemicals of concern are removed in this process

Yellow: applicable barrier with a medium impact

Orange: applicable barrier with a high impact

5.2. Potential supporting initiatives

This section will present options for supporting initiatives to foster the industrial uptake of textile fibres recycling in the EU. Using the input gathered via literature, interviews and the online questionnaire and stakeholder survey, a set of initiatives was compiled that could address the barriers as presented in Table 17. In each of the subchapters, one initiative, the barriers it addresses and the potential impact will be outlined.

5.2.1. Further development of advanced sorting technologies

Practically all textile recycling technologies depend on having a well-defined input. This is why some technologies limit themselves to processing post-industrial (or pre-consumer) textile waste streams. As there is a clear need for higher volumes of well-defined inputs for technologies to scale, especially chemical recycling technologies, recyclers will have to start processing post-consumer textiles in order to increase the input volumes. Over the coming years, the collected volumes of post-consumer textile waste are expected to increase by a further 65000 to 90000 tonnes per year due to the increased amounts of textiles placed on the market and the obligation to separately collect textile waste that Member States have to put in place by 1 January 2025 (Köhler et al., 2021). This in its turn will further increase the need for advanced sorting for collecting organizations in order to create economic value out of this (Kohler et al., 2021). At the moment, sorting is still mainly a manual process, having a significant contribution to the total process costs of recycled textile fibres. The cost of manual sorting is a major barrier to cost effective production of feedstock for textile fibres recycling (WRAP, 2019). Next to this, the accuracy of manual sorting is limited due to removed or incorrect labelling (WRAP, 2019). Automated sorting has the potential to deliver sufficient, well-defined and low-cost input to recycling processes, however, to date, this potential is not yet fulfilled.

Most innovative automated sorting technologies currently on the market (see section 3.5.1) use near infrared spectroscopy (NIRS) or hyperspectral imaging to detect fibre type, color and structure (knit or woven). These technologies are based on the fact that different materials react differently to electromagnetic waves of different wavelengths in the way they absorb, reflect or let them pass through. Next to the detection of pure fibres, such as cotton, polyester or wool, also fibre blends such as polycotton can be detected. In theory, the variety of fibre types and color, and its combinations that could be determined are limitless as these are programmed by algorithms. However, due to economical reasons, this is currently limited to market demand as every extra fraction adds costs and lowers the process speed. The sorted fibres have a low level of contamination and could serve as inputs to (thermo-)mechanical and chemical recycling technologies. For the latter, color sorting is not required. However, there are still some barriers that impact the (cost-)effectiveness of these technologies (Cura et al., 2021; Köhler et al., 2021; Specim, 2020):

- NIRS uses surface detection, this means that it can not determine the composition of multi-layered textiles (e.g. lining or padding). Next to this, fabrics having other material in the core of the yarn (e.g. polyester to enforce the yarn) can also not be detected.
- Buttons, rivets or dirt can cause reflections or shadows which could cause problems. Addtionally, these non-textile parts still need to be removed after sorting as they could disturb the textile fibre recycling process.
- The state of the textle products (e.g. wet, damp or dirty) also impacts the recognition and requires additional algorithms. Preferrably, only dry textiles are used as input.

- Black coloured textiles largely absorb the light, making it much more difficult to distinguish between different fibre types. Midwave infrared cameras could partly solve this but are more expensive. (Specim, 2020; Köhler et al, 2021)

Other automated sorting techniques are based on radio-frequency identification (RFID). An RFID tag can carry a large amount of data and is read when it is within range of a reader. It can be used adaptively and allows sorting of textiles based on specified parameters, such as fibre types, color, used dyes or a certain undesired chemical. This can greatly facilitate sorting processes prior to recycling. However, this requires the textile products to carry an RFID tag and an entire system behind, adapted by all parts of the value chain (Englund, F.et al., 2018).

The capacity of automated sorting facilities in Europe is currently just a few thousand tonnes per year (Köhler et al., 2021). This means there is still a huge gap between the amount of discarded textiles and the automated sorting capacity. Upscaling to industrial size and tackling the remaining challenges will be needed in order to close this gap.

Advanced sorting technologies can generate cost savings for the substitution of manual sorting but commonly require high upfront investments as well as large volumes of textiles in order to be cost effective (Norden, 2015). Next to this, there are still some technological and system challenges that need to be tackled. However, increasing the speed and accuracy of sorting (post-consumer) textile waste streams into well-defined input fractions for textile recycling technologies, will increase the input volumes at a lower cost, enabling textile recyling technologies to scale. This in its turn could lower the price of the output fraction(s) making them more price competitive to virgin fibres, which could then have a positive impact on market demand. The potential impact of supporting the further development of advanced sorting technologies could therefore be considered very high.

Case: Fibersort

Fibersort is an automatic sorting system of mixed post-consumer textiles (simultaneously by colour and fibre type) using near infrared spectroscopy (NIRS) which allows the detection of garments from cotton, wool, viscose, polyester, acrylic and nylon (Ellen MacArthur Foundation, 2017). The Fibersort was developed in “The Fibersort project” (2016-2020), an Interreg North-West Europe (NWE) project, a European Territorial Cooperation Program funded by the European Commission with the ambition to make the North-West Europe area a key economic player and an attractive place to work and live, with high levels of innovation, sustainability and cohesion. More information can be found on the project website: https://www.nweurope.eu/projects/project-search/bringing-the-fibersort-technology-to-the-market/

5.2.2. Development of sorting and recycling hubs

High transport costs for gathering sufficient feedstock of specific materials for recycling come on top of the sorting and recycling costs (Manshoven et al. 2021). This is due to the fact that most recycling facilities are specialized to certain materials and need well-defined input fractions. To get sufficient quantitites, they need to source it from various locations. Intermediate storage which is needed to bulk sorted fractions add to the overall cost of logistics. Many of the consulted stakeholders in this study inidcated it would make sense to locate the different recycling technologies together, rather than shipping all the different streams to different locations. Recycling hubs could produce economic and product synergies that could increase the recycling rates. Some stakeholders also reported the desire to sort feedstock for their processes 'as close to home as possible'. The development of sorting and recycling hubs to optimize logistics and align collection, sorting and recycling could support the further uptake of the entire textiles recycling system.

Case: ReHub

In order to upscale recycling, in December 2020 the European Apparel and Textile Confederation (EURATEX) launched with its members an initiative called European Textile Recycling Hubs (ReHub) to create five major hubs to process textile waste across Europe. The hubs would be located in Belgium, Finland, Germany, Italy and Spain and aim to help deal with the extra textile waste that will have to be mandatory separately collected under EU legislation as of 2025. These five initial ReHubs would operate across borders and benefit to other European countries in the short and mid-term. This coordinated, large-scale management of material-streams could create economies of scale and generate new raw materials for the (European) textile value chains. As next steps, the specialization of the ReHubs will have to be further defined, the pool of stakeholders enlarged and adequate financial resources identified to develop feasibility studies to trigger a larger private-public partnership (EURATEX, 2020).

5.2.3. Implementation of eco-design principles and further development of disintegration techniques

Next to the fibre composition affecting recyclability, textile products can also consist of different (non-textile) components or accessories, such as buttons and zippers, and can be coated, laminated or printed on. These hard parts, trims, coatings and (laminated) layers hamper recycling and are a major barrier for practially all textile fibres recycling technologies, especially chemical recycling technologies. The removal of these non-textile components requires disassembly prior to recycling, adding costs to the overall recycling process. Limiting the use of accessories, substituting parts where possible or making them easily removable could lower the disassembly cost and make the input better suitable for textile fibres recycling processes.

According to the Ellen MacArthur Foundation that published its insights after two years of Jeans Redesign Guidelines, the majority of participants (65%) managed to eliminate the metal rivets from their products by substituting it with bar tracks, reinforced stitching or embroidery techniques. 32% of brands managed to use buttons that can be easily disassembled. However, challenges remain with regard to durabilty of the removable hardware and scalability in the production process due to adding labour intensive assembly to the manufacturing process. Also the easy removal of zippers without fabric loss during disassembly remains an obstacle (Ellen MacArthur Foundation, 2021).

The past few years, there have been a number of innovations to accommodate easy disassembly or for the removal of coatings and laminated layers, such as;

- disintegrating stitching/sewing yarn that melts in specialized ovens (e.g. Resortecs) or disintegrates via microwave technology (e.g. Wear2Go),
- reversible crosslinking-decrosslinking systems that can bond-debond reversibly after applying a triggering mechanism (e.g. acid, heat, UV light),

- triggerable smart polymer material systems (e.g. Inside® debonding technology) for debonding of coated or laminated textiles,
- supramolecular polymer adhesives for (reversible) bond-debond.

A more detailed overview and explanation of these techniques can be found in section 3.5.2.

Although there are a number of initiatives and research projects on this topic, the implementation and uptake of these techniques is far from reality. Next to the remaining technological and economical challenges, the implementation of desintegration techniques also requires a system, in which products that are fitted with any of these techniques, are properly collected, recognized and sent towards the right facility to apply the appropriate triggering mechanism. This links with the need for innovative (circular) business models, value chain cooperation (see further), optimized logistics (see development of sorting and recycling hubs) and the implementation of traceability technology (see further) in order for this supporting technology to scale.

Case: Circtex

The objective of the Interreg "Circtex" project is to make a polyester based garment that can be easily disassembled and chemicaly recycled. The Circtex project focuses on chain collaboration with the help of the facilitating technology of disintegrating stiching yarns "Wear2Go". This yarn is used to stich on components to the workwear garments that can not be chemically recycled, e.g. reflextion bands and zippers. An industiral microwave with an integrated RFID system is built to automize the removal of the unwanted parts so that the output is a fraction that can be chemicaly recycled. More information can be found on the project website: https://www.nweurope.eu/projects/project-search/circtex-innovation-towards-a-circular-future-for-nwe-textiles/

5.2.4. Development of an alternative for elastane

Elastane (also known by its trade names Spandex or Lycra) is a synthetic fibre (being a polyurethane and polycondensation polymer) used in fabrics to impart stretch properties, providing comfort and enhancing the appearance of garments. It is typically blended in small amounts (1–5%) with other fibers, such as polyester, cotton or wool, but also in larger amounts (around 20%) with polyamide in sportswear for example. With the exception of thermo-chemical recycling, elastane acts as a contaminant in all textile fibres recycling technologies, impacting the (economical) feasibility and environmental cost of the recycling process. For most mechanical recycling techologies, a presence of more than 10% of elastane can be problematic as these are more difficult to shred or unravel (see section 3.2.2). Chemical recycling processes can remove elastane, however, as described in section 3.4.3.1, monomer recycling technology holders request a minimum of 80-90% PET or PA6 for economic reasons. The elastane ends up as waste in the solid residue or sludge, however, the fate of elastane is unknown as it is possible that elastane is also degraded under solvolysis conditions (Harmsen et al., 2020).

Due to the fact that (a high content of) elastane can hamper textile fibres recycling and at present no methods are available to recycle elastane in case it is removed during the chemical recycling process (Harmsen et al., 2020), the use and need for elastane in new textile products should be carefully considered. Over the past few years there have been a number of industry initiatives to substitute elastane with more sustainable alternatives, such as elastane made of (partly) pre-consumer recycled elastane (e.g. Spanflex and Roica RF), (partly) bio-based (e.g. Lycra EcoMade and Dupont Sorona) or biodegradable elastane (e.g. Roica V550). Although the use of recycled elastane will probably have a lower environmental impact than the use of virgin elastane, it does not address the issues as described above. A bio-based alternative partly addresses the challenges as it prevents non-renewable resources from ending up in the waste fraction, but it will still negatively affect recycling. Adding stretch properties to cotton fabrics is also possible by applying a special mechanical manufacturing process (e.g. Natural Stretch technology) and research of new cotton cultivars that are stretchy is ongoing (e.g. Australia's SynBio project). Also within the Circtex project (see above), ways to make polyester fabrics more stretchable are being explored. However, further research into the potential and processability and behaviour of fully bio-based alternatives and innovative materials and fabrics that have the same properties of elastane are needed in order to assess the total impact of production, use and (closed-loop) recycling.

5.2.5. Development and implementation of fibre- and product traceability technologies

Fibre or product traceability is an important precondition to enable high-quality recyclability as it could provide information to the sorting facility and recycler about used fibres, additives and (hazardous) chemicals in the product in order to ensure a well-defined input. Next to this, it could also enable customers to make conscious decisions when they have easy access to simple and standardized information on social and environmental performance. Traceability assures quality and compliance and mitigates fraud or greenwashing, engaging each actor in the value chain to bear direct consequences for their processes and activities. Collaboration throughout the value chain (see further) and supporting technology are needed to enable traceability (Manshoven et al., 2019).

One of those supporting technologies (or carrier) could be a product passport. According to a report by ECOS, this passport should "include a bill of materials and a bill of chemicals, environmental information, as well as information on repairability, durability, and due diligence (social and environmental), essential information regarding product circularity and links to external valuable data sources (LCAs, certifications, etc.)" (ECOS, 2021).

One of the insights after two years of applying the Jeans Redesign Guidelines, was that only 12% of brands and garment manufacturers opted to use technology as an enabler to track and trace materials to ensure they can be used again. The most commonly used technologies are QR codes and RFID tags (Ellen MacArthur Foundation, 2021). An RFID tag can be integrated in the garment without affecting the quality of the reading. This facilitates handling compared to QR code systems, which can neither be read from a distance nor carry the same amounts of data. An RFID system can be used adaptively and allow sorting of textiles based on the parameters specified, such as colour, fibre type(s), the presence of (undesired) chemical substances,… (RISE, 2021). However, adding non-textile components to textile products such as RFID tags could complicate recycling, although the exact impact of the tags is yet to be determined (Englund, F et al., 2018).

The application of markers to fibres is another technology that is emerging (e.g. FibreTrace®, Tailorlux, AWARE). Upon scanning, this technology redirects the reader to a website where information about the garment's composition, production processes, and fibre sourcing can be easily accessed. However, at the moment it is unclear what the impact of recycling is of textiles to which these markers have been added and how this could potentially hamper recyclability or traceability of the recycled fibres in consecutive material cycles.

The further development of fibre and or product traceability technologies has the potential to sort out textiles in a wide range of fractions according to selected parameters, providing well-defined input for different types of textile fibres recycling techniques in a very efficient and accurate way. However, there are still a number of remaining challenges with regard to the impact of the technology itself on the recycling process and the necessary system conditions in order to implement the technologies. A broad consensus across industry will be needed as well as cross-sectoral cooperation and mutual understanding of the possibilities and limitations in order to standardize and adopt at a large scale (Englund, F. et al., 2018; RISE, 2021).

Case: Tex.IT

Tex.IT is a project funded by Sweden's innovation agency, Vinnova and coordinated by RISE and aims to build the foundation of a digital system based on RFID to reach circular textile value chains. The specific objective of this project is to build knowledge and competence regarding:

- Information system model
- System for data collection
- Overview of existing standards and mapping of standardization need
- Cost calculations and evaluation of ROI (Return on Investment)
- Implications of integrating digital information carriers in textile products

The Tex.IT consortium has been set up with the intention of including the entire value chain and several brands. The project started in 2018 and was due to finish in 2021. (RISE, 2021)

5.2.6. Further research into dispersion and recovery of chemical substances

(Hazardous) chemicals such as additives, dyes, finishes, etc. present in textile products (both through production and product use) can not be removed in a (thermo)mechanical recycling process and stay in the output (see sections 3.2 and 3.3). This creates risk with regard to possible non-compliance to the REACH legislation and a negative perception of the quality of the recycled textile fibres of customers. With chemical recycling processes, the chemical substances present in the recycled textile products can be found in the solid residue or sludge waste output fraction, which indicates that the (hazardous) chemicals are removed during the recycling process (see section 3.4.3.3). However, at the moment it is unclear whether all chemicals are removed with every chemical recycling process. Laboratory trials within the 'Circtex' project (see section 5.2.3) indicated for example that some dyestuff remained in the recycled polymer. Therefor an extra process step was needed to remove all the dyestuff. This raised the question whether all chemicals present in the recycled textiles are actually removed. Further research on the topic is needed.

Detecting unwanted chemical substances present in textile products before they enter the recycling process could be realized by implementing traceability systems (see previous section) that disclose information on the chemicals used and on the product's history. However, this is not yet the case for the vast majority of end-of-life textile products currently entering the recycling system and in the next years to come. In addition, contamination with unwanted chemical substances can also occur during the use phase (see section 3.2.4). Testing every product that enters the recycling process is not feasible due to practical reasons and costs. This means that the risk will need to be managed and contained. To mitigate this risk, certification systems with a profound testing system such as bluesign® or OEKO-TEX® could be used to test the output on the presence of hazardous substances. However, as the input of recycling processes of post-consumer textile products varies with every batch, the exact composition of each output batch will also differ and will have to be tested, adding extra costs to the recycling process. Next to this, the wider effect of (hazardous) chemicals such as dyes, anti-wrinkle agents, water repellents, but also fibre tracers (see section on product and fibre traceability) on circularity needs to be further investigated (ECOS, 2021). Finally, removing, purifying and recovering additives and dyes from the recycled textile fibres and its by-products has also been identified by various industry stakeholders as an important challenge to tackle. These are new processes and will need novel technological solutions and research and development over the coming years.

5.2.7. Support (cross-)value chain collaboration

Many of the described potential initiatives and needs described above, rely on systemic change and collaboration of multiple players in the value chain in order to align processes and implement and scale the initiatives. Collaboration across the value chain, from brand and retailers to garment makers to yarn and fabric suppliers, from collectors to recyclers, as being a key factor for success was also one of the outcomes of the fibre to fibre pilots implemented by the part funded EU LIFE project ECAP (European Clothing Action Plan) that aimed to support the use of recycled post-consumer textile fibres (ECAP, 2019).

Sorted textiles must match textile fibres recyclers' demands with regard to fibre composition, tolerance to contaminations and state when entering the different recycling processes. On its turn, the output of the recycling processes must match producers' and manufacturers' demand on input materials for production of new textile products (Elander, M., Ljungkvist, H., 2016). It is clear from literature and the conducted stakeholder consultation that both on feedstock and output requirements, knowlegde and expectations of the different parties involved need to be improved and better aligned. Improved value chain collaboration linking supply and demand could create a powerful lever in the uptake of the use of recycled textile fibres as brands increase their knowledge on the availability and properties of recycled fibres and on the recyclability of their products (Watson et al., 2017). In many cases however, this requires a new way of working as retailers and brands are used to order ready-made garments and normally do not take part in the development of new yarn and fabric (ECAP, 2019). Also suppliers must gain a better understanding of the reasoning behind the brands' material specifications (Watson et al., 2017). Suppliers and manufacturers, hindered by a lack of knowledge, financial barriers, or low awareness of available alternatives, will struggle to create change in the production processes alone (Rouch, 2021). The fact that many brands have long-term partnerships with their suppliers and a partnership build on trust could be an enabler to jointly develop new fabrics, but could also be a barrier when the brand, due to volume, does not have enough leverage with its supplier. In that case a search in the network of the partners in the existing supply chain and to further build on their relationships could be a succesful strategy (ECAP, 2019). Finding new partners through initiatives such as the Ellen MacArthur Foundation's Jeans Redesign initiative that brings together brands, garment manufacturers and fabric mills that share a common vision of a circular economy for fashion has also proven its effectiveness (Ellen MacArthur Foundation, 2021). Online platforms could also help to bring together supply and demand of recycled textile fibres, yarn or fabric and could help to inform industrial partners on material specifications and application potential (Rouch, 2021; Interreg North-West Europe, 2020). An example of such a plaform is Ellie.Connect that brings together players across the supply chains, to inspire each other, share knowledge and ideas and make new connections to roll-out sustainable projects.

The current lack of coordination and exchange of information in the textile value chain is a major barrier for the uptake of textile fibres recycling. There is a clear need for a joint strategic approach that aligns interests and fosters cooperation along the value chain.

Case: SCIRT

SCIRT (System Circularity and Innovative Recycling of Textiles), a EU-funded innovation project supported under the Horizon2020 programme, aims to support systemic innovation towards a more circular fashion system and bridge the supply-demand gap for recycled textile fibres. Starting from the demand side needs, SCIRT demonstrates an entire textile-to-textile recycling system for post-consumer textiles, focusing on the recycling of natural and synthetic fibres, as well as fibre blends. All relevant players along the value chain are involved, from collector to retailer. By focusing on the recycling of textiles often downcycled today, value retention is improved throughout the value chain. Not only will the business case for individual actors be validated, the overall system implications will be quantified from a financial, environmental and social life-cycle perspective. Besides the technological innovations required, SCIRT addresses enabling conditions and supporting measures facilitating the transition towards a circular system for apparel. A True Cost Model will be developed and a framework for an eco-modulated EPR system will be set up, aiming at increased value chain transparency. Special attention is given to the consumer perspective. A consumer behavioural flow intervention will be developed to impact their decision making on the purchase and disposal of textiles. Throughout the project, stakeholder involvement and validation is guaranteed via an advisory board. SCIRT started in June 2021 and finishes by June 2024. More information and (intermediate) project results can be found on the project website: https://www.scirt.eu.

Case: RETEX

The Interreg Retex project indicated that the use of mechanically recycled fibres of workwear coming from the health sector (hospitals), although more expensive, is economically feasible. Utexbel, a fully integrated yarn and fabric producer, decided to build a circular value chain around their product "Dr. Green" involving the user (hospitals), industrial laundering companies, garment producers, sheltered workplaces and a mechanical shredding company. This value chain recycles end-of-life polycotton garments, of which 33% of the material is re-used in the new fabric. Another third comes from own pre-consumer recycled materials and recycled PET bottles. The remaining third is virgin organic cotton to ensure a garment lifetime of at least 100 washing cycles, to not compromise on product durability.

5.2.8. Create market pull from consumers to drive the industry

Currently, the higher cost of recycled textile fibres compared to virgin fibres is a major barrier for most of the textile fibres recycling technologies, especially for chemical recycling processes. During the stakeholder consultation, one of the indicated reasons was the fact that not all costs are reflected into the price of virgin materials creating a competitive disadvantage. Ensuring price parity with virgin alternatives is considered as an important condition to reduce this economic barrier (Interreg North-West Europe, 2020). An increase of demand for recycled fibres would bring economies of scale and lower the cost.

Increasing the demand for (products made of) recycled textile fibres could be stimulated by manufacturers, brands and end-customers. Increasing knowledge about the possibilities and limitations combined with an alignment of needs and matchmaking mechanisms connecting manufacturers, designers and buyers with producers of recycled materials are needed (see section on value chain collaboration). Setting company goals on the use of recycled textile fibres in new textile products, with backing from the top management, is also of critical importance (Watson et al., 2017).

Concurrently, manufacturers and brands seek long term agreements with feedstock suppliers at reasonable, realistic and stable prices. Multi-year purchasing commitments and suppy contracts of yarn or fabric made of recycled textile fibres could create these conditions and at the same time would support investment from recyclers to further develop its activities (WRAP, 2019). Brands integrating a low percentage of 5% recycled content into some of their products could have a big impact on the overall demand for recycled fibres (see section 4.4). At the same time, this low percentage "enables brands to avoid any potential negative impacts on performance, price and aesthetics" (Interreg North-West Europe, 2020).

Also the end-consumer plays an important role in shifting practises in the textile recycling value chain. Informative campaigns to promote the right diposal practises combined with convenient separate collection infrastructure could influence the amount of separately collected textile products and quality. Excessive washing on high temperatures has a negative impact on the fibre quality of textile products, which in its turn has a negative impact on the amount of spinnable fibres as output faction of mechanical recycling processes (see section 3.2.2). Consumer messaging to reduce over-washing could address this issue (WRAP, 2019). Although consumers will not compromise on quality and performance, knowledge about environmental and social impacts of textiles helps to create a positive perception of recycled textiles (Interreg North-West Europe, 2020).

5.2.9. Financial support for scale-up technologies

During the stakeholder consultation it was clear that many of the recycling technologies are capital intensive and require big upfront investments. Especially in taking the step from prototypes to industrialized processes, a lack of funding currently exists as there are hardly any financial resources available for technologies that reached a higher TRL than a demonstrated proof of concept (Hemkhaus et al., 2019). High upfront costs involve long payback periods that combined with uncertainty about profitability due to the many remaining barriers, hinders private investments (Köhler et al., 2021; WRAP, 2019). Next to the barrier of a lack of well-defined input and regulatory barriers (see Chapter 6), textile recyclers are not likely to invest in scaling up without guaranteed and long-term purchasing commitments from the market (WRAP, 2019). Value chain collaboration between supply and demand could address this (see above).

Long term business relationships and purchasing commitments between recycler and buyer could also be more profound when they are put in a so-called 'offtake' agreement. Such an offtake agreement (e.g. between a textile fibres recycler and a brand) is an agreement to buy or sell, in advance, some of a producer's materials that have not yet been made, making it easier for recyclers to obtain financing. The agreement is normally negotiated before the construction of a factory or facility to secure a market and revenue stream for its future output (Investopedia, 2021). As more and more brands and manufactures are committing to replace virgin materials with recycled ones, the advantage for them is that a price can be locked, anticipating future demand. For textile fibre recyclers, offtake agreements could make it easier to obtain financing to scale.

Case: Renewcell

In 2020, Renewcell signed a five-year deal with Chinese viscose manufacturer Tangshan Sanyou to supply 175,000 tonnes of Circulose dissolving pulp recycled from discarded textiles. Renewcell will deliver its recycled Circulose dissolving pulp from its new plant in Sundsvall (Sweden), of which the commissioning is planned in 2022. This offtake agreement with Tangshan Sanyou was a key element to securing the financing for this new plant (Apparel Insider, 2020).

5.3. Roadmap

Each of the supporting initiatives described above has a different potential impact and feasibility. Some initatives are more difficult to implement due to boundary conditions or need for systemic change, e.g. the implementation of traceability technologies or advanced disintegration techniques. Others are more easy to initiate such as value chain collaboration or further research into the dispersion of chemical substances. As the initiatives are the result of research and stakeholder consultation, all potential initiatives can be considered to have a postive impact on the further uptake of textile fibres recycling technologies. Based upon the stakeholder consultation and expert judgement of the authors of this study, the impact and feasibility of each supporting initiative is mapped in Figure 33.

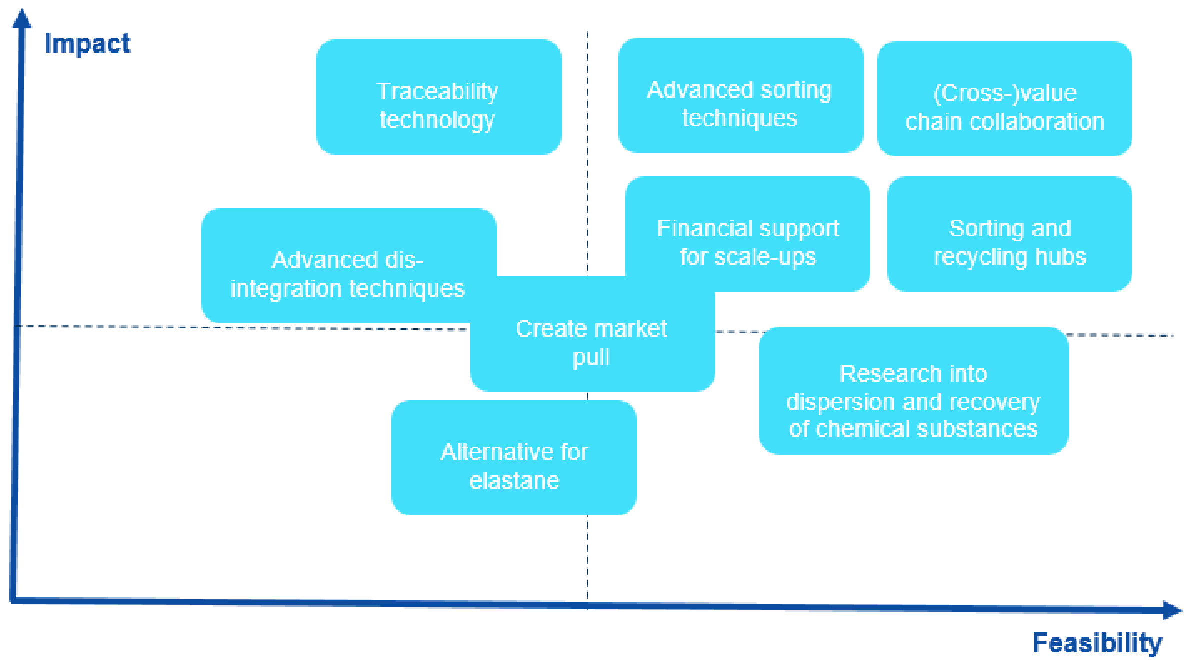

Figure 33: Impact and feasibility of the potential supporting initiatives

In order to develop a roadmap to prioritize the supporting initiatives with a related timeframe, it would make sense to focus on the initiatives that have a high impact and high feasibility (upper right quadrant of Figure 33).

To map the different initiatives over time, it is clear that one of the main needs of textile fibre recycling technologies is to get a high(er) volume of well-defined input at a low(er) cost.

However, at the moment most textile products on the market are not designed to be optimally recycled. Therefore, priority should be given to those initiatives that within the existing context contribute to lowering the cost and improving the accuracy of the input (optimizing the current situation where most disposed textile products are not designed to be recycled). At the same time, initiatives need to be taken to improve the recyclability of disposed textile products over time that further lower the cost of recycling and improve input quality. This can be done by making sure new products entering the market can be recycled (implementing design for recycling principles). This evolution is illustrated in Figure 34.

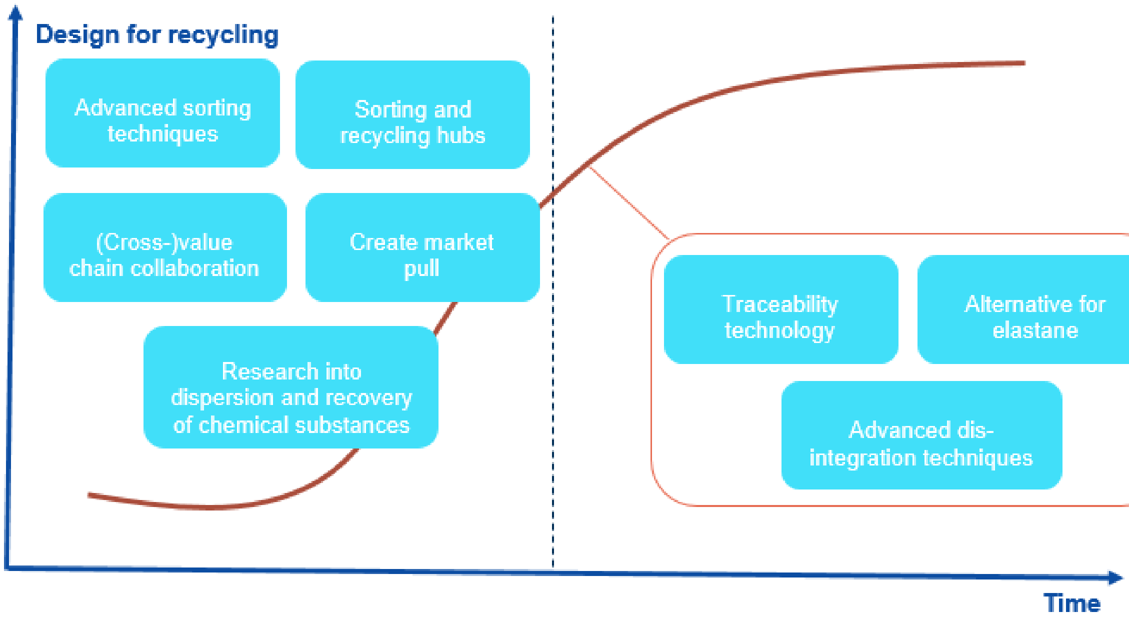

Figure 34: Mapping the supporting initiatives within time

6. Analysis of regulatory framework and identification of policy solutions to foster textile recycling

The objective of this chapter is to analyse the existing EU regulatory framework relevant for textile recycling, and to investigate policy options to foster textile-to-textile recycling in the European Union. This part of the study was based on literature and document analysis, expert interviews as well as an online survey with stakeholders of the European textile sector.

6.1. Why analysing regulatory barriers and policy support options?

Textile-to-textile recycling is still in its infancy. Secondary to reuse, it could become a key building block in a competitive and low carbon circular textile economy. The EU could support such a development by establishing policy support measures and regulatory framework conditions that foster textile-to-textile recycling. Specifically, policies could support the industrial take-up and upscaling of recycling technologies, infrastructures and capacities as well as the development and scale-up of appropriate, circular business models.

To support the European Commission on its way to a more circular and sustainable textile economy, the present study investigated the following two research questions:

1. *In how far is the EU regulatory framework fit for supporting and fostering textile fibre recycling?*
2. *What are alternative and coherent policy solutions that could support the industrial uptake and scale-up of textile fibre recycling activities in the EU?*

The first aim of this study was to identify bottlenecks and gather stakeholder perspectives on potential barriers in EU policy that might hamper textile-to-textile recycling or slow down the uptake of innovative technologies and business models. For this, the current EU policy landscape relevant for the textile and textile recycling sector was scanned, looking for regulatory barriers and gaps.

The second aim was to elaborate policy options for alternative and coherent solutions to support textile-to-textile recycling in the EU. Here, different possible options for EU policy to mitigate identified barriers and to close policy gaps were investigated, taking the technological and market reality of textile fibre recycling into account. Stakeholder participation was a central component in the development of the results of this study.

Aim of this analysis is to make proposals regarding which further activities and steps EU policy could undertake to address the barriers identified. The analysis covers a very broad range of policy tools. Taking into account all the related complexities, its aim is to provide subjects for discussion for future policy development. Therefore, its purpose is not to provide an impact assessment of the regulatory framework components analysed. More detailed analysis through feasibiliy studies will be critical to further deepen the understanding of content and implications of such options due to their complexities.

Furthermore, this study builds on the results presented in the previous chapters of this report.

6.2. Methods

As a first step of the analysis, the available literature on textile recycling and textiles in a circular economy was reviewed. The targeted review served to map the EU legislation related to textiles and to identify potential gaps and barriers for the uptake of textile-to-textile recycling. The literature analysis included scientific articles, reports and policy documents. In addition, the stakeholder responses gathered via a survey on barriers and policy needs for textile recycling were considered. Based on this, a “long list” was compiled of the relevant EU regulatory framework components and their potential effects on the industrial uptake of textile waste recycling.

Next, 9 in-depth qualitative expert interviews were conducted. The interviews served to validate and complement our findings on the most important regulatory barriers and policy gaps and to discuss suitable policy solutions. The selected interviewees included policy experts on European level, representatives of key business sectors and their associations, and representatives of civil society organisations. The interviews took place in May and June of 2021 and were conducted online by means of a video conference tool. Table 18 gives an overview of which organisations were represented in the expert interviews. The interview questionnaire that was used can be found in Annex 2.

Table 18 : Overview of expert interviews

Date	Organization of interviewee
May 18, 2021	European Sustainable Business Federation (Ecopreneur)
May 26, 2021	Ellen MacArthur Foundation
May 26, 2021	Environmental Coalition on Standards (ECOS)
May 27, 2021	European Environmental Bureau (EEB)
May 28, 2021	European Environment Agency (EEA)
May 28, 2021	European Recycling Industries' Confederation (EuRIC)
May 31, 2021	Circular.Fashion
June 1, 2021	Municipal Waste Europe (MWE)
June 25, 2021	European Apparel and Textile Confederation (EURATEX)

Following a detailed analysis of the findings from the interviews and the literature review, possible policy options to existing or potential regulatory barriers were drafted. The conclusions aimed at:

- considering possible changes to individual components of the existing regulatory framework, or
- considering overarching pointers for adding alternative solutions to the existing regulatory framework.

Possible policy options developed in the scope of this research project cannot, however, include detailed suggestions for legal texts or formulations for amending existing policies.

As a final step in our analysis, an online survey was designed, targeted at stakeholders of the textile recycling sector. The aim of the survey was to validate and refine the findings. The survey was composed of mostly multiple choice questions and a small number of ranking questions. In addition, open text boxes were included at certain points in the survey to enable respondents to explain or elaborate their answers, to make additions or to leave comments. Furthermore, the survey design took into account that the survey could be answered within 20 minutes. This was considered important by the researchers in order to achieve a high response rate. We aimed for a response rates of at least 40 complete replies.

Invitations to take part in the survey were sent out via email to key actors of the textile and textile recycling sector, with the request to circulate the invitations in their networks. At the same time, the invitations were distributed to over 100 stakeholders, building on contacts from consortium partners, DG GROW and also from some of our interviewees. The survey was open from June to mid August 2021.

Excluding the duplicates and unvalid responses, we received 69 valid responses to the survey. Responses were analysed qualitatively (for content) and quantitatively (for frequencies of responses as well as rankings made). Figure 35 depicts the representation of stakeholders that took part in the survey. More than half of the respondents belong to the business sector (businesses or business associations). Here, the data collected show that the organisations of the respondents cover textile labels and fibre producers as well as recyclers, sorters and waste managers. Next, about a quarter of the respondents were policy representatives from both national and European level. Furthermore, a considerable share of civil society organisations took part in the survey as well as a small number of researchers.

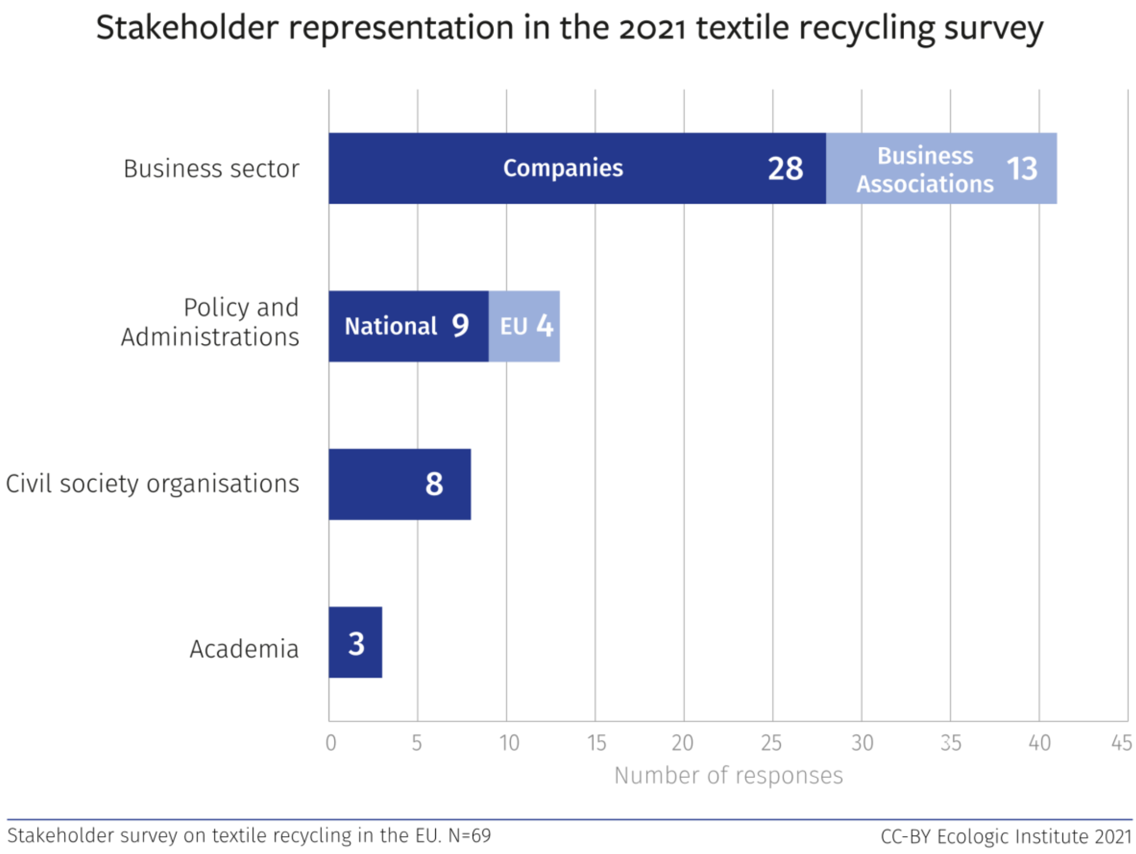

Figure 35 : Stakeholder representation in survey

We consider the representation of stakeholders that took part in the survey to be appropriate for the objectives of this study. As the textile and textile recycling industries are key actors for the industrial uptake of textile fibre recycling technologies, it was important to gain profound insights into their perspective. At the same time, valuable policy and civil society perspectives could be taken into account as well. The survey findings served to revise and further elaborate the analysis results on possible policy options.

6.3. Challenges to textile fibre recycling and analysis of relevant EU regulatory framework

This subchapter looks at the status quo of the EU policy landscape relevant for textile recycling. First, a short overview is given over central EU policy strategies that relate to the textile and textile recycling sector. Second, relevant legislative elements are analysed in detail, showing regulatory barriers and gaps in the existing EU legislation.

6.3.1. Key EU policy strategies pointing the way to the future of the textile sector

There are a number of recent EU policy strategies and initiatives – some still under development – that are relevant for the future direction of the textile industry. These policy documents also give clues as to what role textile recycling should take and how it should be shaped. Moreover, they provide the guidelines for any forthcoming changes to EU legislation.

One key strategy is the "**New Circular Economy Action Plan - For a cleaner and more competitive Europe**" (CEAP; COM(2020) 98). The Action plan declares textiles to be a priority sector for the transformation to a circular economy, seeing large potential to save resources by it becoming more circular. The CEAP announced the preparation of a **comprehensive EU Textile Strategy**, which will be based on input by industry and other stakeholders. It is currently under development and expected to be adopted by the first quarter of 2022. It is foreseen that the Strategy puts in place the following measures that can be expected to have a beneficial effect on recycling activities:

- assess the feasiblity of harmonising separate collection of waste within the EU;
- boost the sorting, reuse and recycling of textiles, including through innovation;
- consider eco-design requirements for textiles, ensuring use of secondary raw-material, addressing the use of hazardous chemicals;
- support circular materials and production processes (European Commission 2020a).

Moreover, the CEAP announced that the European Commission will put forward a **sustainable product policy legislative initiative.** It is planned to be adopted in the first quarter of 2022. At its core, the Sustainable Products Initiative (SPI) aims to widen the scope of the Ecodesign Directive to include non-energy products such as textiles. The goal is to improve durability, reparability and recyclability of products. At the same time, it aims to advance the digitalisation of the EU's product policy. Specifically, it foresees to establish a "European Database for Smart Circular Applications" with data on value chains and product information, and considers the introduction of digital product passports (Pantzar and Suljada 2020).

Also of relevance is the **updated Industrial Strategy** (COM(2021) 350), which was put forward to integrate the lessons learnt from the COVID-19 pandemic to support EU industry resilience. It aims to strengthen the market surveillance, which entails to improve the traceability of traded products and to better monitor product safety. For this, the strategy strives to make greater use of digital solutions. It announces an annual analysis of the state of 14 "industrial ecosystems" in the Single Market, aiming for better traceability and product safety. Textiles present one of those industrial ecosystems.

Finally, in the "**Chemicals Strategy for Sustainabiliy – Towards a toxic-free environment**" (COM(2020) 667), safe recycling is addressed and links to the textile sector are explicitly mentioned. In general, the Strategy aims for a shift to chemicals that are safe and sustainable by design. Regarding the transition to a circular economy, it points out the importance of non-toxic material cycles. To pave the way for this, the strategy stipulates the following actions for the European Commission:

- to improve the availability of information on chemical content and safe use;
- to minimise the presence of substances of concern in products through legal requirements;

- to scrutinize rules under REACH for recycled materials (e.g. ensure that derogations from restrictions are justified);
- particularly for textiles, to support innovations that can decontaminate waste streams, increase safe recycling and reduce the export of waste.

With their objectives, announced measures and vision for the future, the above strategies set the framework for the European legislation. In the following subchapter, a closer look is taken at the relevant existing legislative documents and elements. More specifically, legislative pieces are highlighted that have potential to support the uptake of textile fibre recycling in the EU.

6.3.2. Identified regulatory barriers and gaps in legislation

The analysis of the EU policy landscape relevant for textile recycling revealed a number of regulatory barriers and gaps. These have been summarised in Table 19.[21]

Table 19: Overview of key pieces of EU legislation affecting textile recycling

Piece of legislation	Relevant effects on textile reuse or textile fibre recycling	
	Support	Possible barriers or gaps
Waste Framework Directive 2008/98/EC	Obligation for separate collection of textile waste in all Member States by 2025 (Art. 11). Article 10.4: Separately collected waste is not incinerated. Art: 9 requires notification to the European Chemicals Agency of articles containing substances of very high concern (SVHCs) above 0.1%.	**Lack of EU specific end-of-waste criteria for textiles**. Lack of **sorting criteria for textile waste**.
Waste Shipment Regulation (EC) No 1013/2006	Enables safe and traceable movements of waste (intra-EU shipment, imports & exports). Shipments of non-hazardous wastes within the EU and OECD countries are "green-listed"; information requirements apply.	Classification of certain textile or textile related waste (e.g. shoes) not fully clear. Also, the distinction between used clothes and textiles vs textile waste is not entirely clear. Higher administrative burden for trading textile waste, mixed with for example shoes, destined for recycling within the EU.
Textile Regulation (EU) No 1007/2011	Requiring labelling and marking, e.g. of textile fibre names, thus easing sorting for recycling and marketing for use of textile secondary raw materials	The labels are not adequate to enable smooth sorting and recycling, as • the information given is not sufficiently specific • they do not support an automated sorting of textile waste.
Ecological criteria for the award of the EU Ecolabel for textile products 2014/350/EU with the respective amendment (2017/1392/EU)	Providing a credible label (EU Ecolabel) to help consumers choosing recycling-friendly textile products. Supports recycling by	Shortcomings concerning textile recycling: • **no criteria included for design for recyclability** (such as ease of

[21] The table presents a selection of pieces of legislation that are considered most relevant by the author team. It does not present a complete mapping of EU legislation and policies.

Piece of legislation	Relevant effects on textile reuse or textile fibre recycling	
	Support	**Possible barriers or gaps**
	• setting strict requirements to the use of hazardous substances in EU Ecolabel goods (Article 6.6 and 6.7). • promoting the use of recycled content in polyester and nylon.	dismantling, homogeneous material use) • The use of recycled content in natural fibres (such as cotton, wool, etc.) & secondary resource inputs to cellulose-based semi-synthetics (such as viscose, Tencel) is not rewarded **Limited range:** Only covers products that apply for the EU Ecolabel.
Ecodesign Directive 2009/125/EC		Lack of minimum requirements for circular design & design for recyclability of textiles
Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) Regulation (EC) No 1907/2006	Restricts hazardous chemicals in textile products. Recycling and recyclability is taken into consideration when socio-economic analyses are carried out in the preparation of REACH restrictions or authorisations.	Substances of very high concern below a certain threshold (0.1%) do not have to be communicated along the supply chain. Compatibility of chemicals with recycling technologies is not subject of the Regulation, unless related to safety.

One major factor that hampers the uptake of textile fibre recycling technologies in the EU are the **limited feedstock availabilities** for textile recycling. In order to make recycling economically viable, companies need sufficient volumes of well-sorted textile waste of certain qualities on a regular basis. Here, EU policy has made a major progress by obligating all Member States to collect textile waste separately by 2025. This obligation is stated in Article 11 of the Waste Framework Directive. Article 11 also mandates the European Commission to consider the setting of targets for textile waste on preparing for reuse and recycling . The 2025 target can be expected to increase the volumes of feedstock available for reuse and for recycling (Sajn 2019). In 2018, 2.2 million tonnes of textiles waste were generated in EU27, including both industrial and household waste, of which 1.2 million tonnes have been recycled (Eurostat 2021). This appears to be a good share to build on, yet these figures need to be viewed with caution. First, it has to be pointed out that generally, industrial textile waste (i.e. pre-consumer textile waste) is easier to recycle, as it is more homogenous and identification of the material composition is simpler. Second, for the reported amount of recycled textiles waste of 1.2 million tonnes, no differentiation between textile-to-textile recycling and other recycling is made. In fact, a large part of textile recycling refers to downcycling into lower-value products or applications, such as cleaning wipers, insulation, padding materials or upholstery fillings (Manshoven et al., 2021; Watson, et al. 2020; Leal Filho 2019). It is estimated that currently only about one percent of textile waste is recycled into new textiles, such as clothing (Manshoven, et al. 2019).

The 2025 target entails separate collection of textiles that are not suitable for reuse markets, as for example damaged or worn out clothing (Watson et al. 2020; Köhler et al. 2021). As of today, this type of textile waste often ends up in mixed municipal waste, mostly destined for incineration or landfilling (Manshoven, et al. 2018; Watson, et al. 2018). When collected separately, this fraction of textile waste could be channelled into the recycling stream and be used for the production of new fibres for textiles.

Köhler et al. (2021) have estimated that "annual collection will *increase* by a further 65 000 to 90 000 tonnes annually in coming years as Member States begin to roll out new/adjusted collection systems to implement the Directive" (Köhler et al. 2021, p. 8). In the present study it was estimated that, with the 2025 target entering into force, the volume of collected waste could increase to 5.8 million tonnes in EU27 (assuming that a 50% share of the annual consumption of textiles is collected; compare chapter 4.3). Based on this, it was estimated that mechanical recycling could produce up to 3.2 million tonnes of recycled fibres per year in the EU27 – not yet considering other types of recycling in this calculation (see section 4.4).

Overall, the prospect of increased potential feedstock for recycling is likely to open room for innovation (European Commission 2020c, Niniimäki et al. 2020). Yet, stakeholders consulted for this study pointed out that the 2025 target alone will not suffice to foster the industrial uptake of textile fibre recycling technologies. The reason for this is that several factors complicate the sorting and recycling of textile waste, making it expensive and rather unattractive for companies:

- Common sorting criteria and standards are missing;
- Information on the contents of textile waste is often lacking or too inaccurate for certain recycling technologies;
- The low quality of many textile items presents a problem for various recycling technologies, as recycling would result in low quality outcomes;
- Post-consumer textiles are very heterogenous in their composition regarding materials and accessories used, and frequently fibre blends are used. Recyclability and disassembly have mostly not been considered in the design of textiles products.

Hence, a major challenge lies in "handling the complex bulk of post-consumer textile waste" (Roos et al. 2019, p. 34). This involves the organisation of the separate collection and the sorting of textile waste. Existing infrastructures for the collection and sorting of textile waste vary greatly across Member States regarding their extent and nature, with for example different actors being responsible (charity organisations, companies, public authorities) (Köhler et al. 2021; European Commission 2020c). **Clear and harmonised methodologies for sorting are currently lacking** – including for example common waste sorting classes – which could slow down the accomplishment of consistent feedstock streams for recycling (cf. European Commission 2020c).

A further factor that makes the sourcing of textile waste for recycling difficult, time-consuming and costly are the **legal provisions for trading textile waste**. The central legislation here is the Waste Shipment Regulation ((EC) No 1013/2006), which provides rules for a safe and traceable transboundary movement of waste. While it is important to have such rules in place, in its current form the Regulation poses unnessecary burdens on the shipping of certain post-comsumer textile waste within the EU that could be used for recycling. The smooth movement of sorted and recyclable textile waste in the single market is hampered by different interpretations of the classification of that waste and the related procedures in the Waste Shipment Regulation between Member States (Manshoven, et al. 2019; Watson et al., 2018). Companies hence often struggle with the administrative burden and long permitting processes linked to the shipment of wastes. In practice, this involves for example frequent delays of notification procedures and lengthy procedures in renewals (Confederation of Finnish Industries 2020; cf. also European Commission 2020c). Also, the differentiation between waste and non-waste materials as laid out in the Waste Framework Directive remains unclear for textiles. This results in varied interpretations not only between Member States, but also within Member States (Manshoven et al. 2021, Roos et al. 2019, EURATEX 2017). The Waste Shipment Regulation is currently revised, with the new proposal being adopted by the European Commission in the fourth quarter of 2021.

Furthermore, Article 10.4 of the Waste Framework Directive regulates that separately collected waste should not be incinerated, which applies to separately collected textile waste. In addition, the Landfill Directive (1999/31/EC and Directive (EU) 2018/850 amending 1999/31/EC) restricts the landfilling of all waste that is suitable for recycling or other material or energy recovery from 2030 onwards. Both of these legislative elements can be expected to result in a higher quantity of feedstock that becomes available for the recycling stream. Finally, an aspect which would require more in-depth analysis are **unsold textiles**. Certain amounts of textiles may remain unsold in shops or warehouses, including returned textiles from online trade. The quantitiy of unsold textiles is not statistically recorded. According to estimates, between 6.5% and 33% of garments put onto the EU market remain unsold (Niinimäki et al. 2020). As storage room is expensive and new merchandise arrives every season in the fashion cycle, labels and manufacturers – fast fashion and luxury brands alike – frequently incinerate unsold textile products (Niinimäki et al. 2020, Manshoven et al. 2019). Even in the case of energy recovery, this presents an avoidable loss of resources and is therefore an issue that deserves to be further investigated.

The **lack of traceability** of the materials and additives that have been used to produce a textile can be further improved. One key legislation in this area is the Textile Regulation (EU No 1007/2011). It regulates the use of textile fibre names and the labelling and marking of the fibre composition of textile products. Accordingly, certain information, including fibre composition, needs to be declared on labels attached to the textiles. Its main purpose is to ensure accurate information to consumers. For the purpose of sorting and recycling textile waste, however, there are a number of shortcomings regarding the usefulness of the textile labels:

- Labels in discarded textiles are often missing or washed-out. This disrupts not only the flow of information for recycling, but also for preparation for reuse and re-selling.
- The labels are not machine-readable. This slows down the sorting process, which hinders recycling to become economically viable on a larger scale.
- Information on the labels is not sufficiently specific for certain recycling processes. For example, the labels do not differentiate between different types of nylon – yet this information is crucial for certain recycling processes (Roos et al. 2019; see chapter 3.1.4
- Information on chemicals used during production process (dyes, flame retardants, anti-wrinkle agents, etc) is missing (ECOS, 2021, EllenMcArthur Foundation, 2017).

Regarding chemicals, the REACH Regulation is a central piece of legislation that affects the textile sector. It restricts the presence of certain hazardous chemicals in textile products which are known to be, or have been present in textiles. This essentially contributes to safe recycling. Yet, there are a number of shortcomings from the perspective of recyclers. For example, according to Article 33 of REACH, actors in the EU have to inform the next professional actor in the supply chain about substances of very high concern (SVHC) present in articles at concentrations above 0.1% (weight by weight). Yet, SVHC present in articles below the threshold of 0.1% do not have to be communicated. This leaves a gap for use of hazardous substances which could hamper recycling, or increase the cost of recycling. Moreover, in many cases manufacturers do not disclose information on how to safely remove hazardous components of a product prior to recycling (Hilton et al. 2019). A further, tricky problem for recycling is that textile waste may encompass products that have been placed on the market before certain restrictions under the REACH regime applied (Ellen MacArthur Foundation 2017). This can be particularly problematic for mechanical recycling processes, as additives, dyes, contaminants, etc. are not removed during mechanical recycling (cf. chapter 3.1.4).

Next, the analysis of the EU policy landscape revealed a further policy gap: **incentives to design textiles in a way that makes them easier to recycle are largely lacking** (Watson et al. 2020, EcoP 2019, EuRic 2019, Leal Filho et al. 2019). In the Ecodesign Directive (2009/125/EC), so far material efficiency criteria for textile products are absent. Options to introduce such criteria are currently looked into as part of the upcoming Sustainable Product Initiative. This encompasses for example design criteria that promote durability and repairability of products, as well as recyclability. A further relevant policy instrument is the EU Ecolabel for textile products (amendment 2017/1392/EU). It specifically supports recycling by setting strict requirements to the use of hazardous substances in EU Ecolabel goods and by promoting the use of recycled content in polyester and nylon. In addition, it sets quality and durability requirements, which can also be beneficial for recycling. Despite these supportive features, researchers found that concerning textile recycling the EU Ecolabel does not yet meet its full potential to encourage circularity in awarded textile products (Köhler et al. 2020). For example, there is a gap regarding the use of recycled content in natural fibres (such as cotton, wool, etc.) as well as secondary resource inputs to cellulose-based semi-synthetics (such as viscose, Tencel). Next, to receive the Ecolabel, recycled content can be based entirely on pre-consumer waste. Thus, the Ecolabel provisions fail to incentive the recycling of post-consumer textile waste. Finally, criteria for a design for recyclability – such as ease of dismantling or a homogenous material use – are lacking (Köhler et al. 2020). Besides, as it is a voluntary instrument that only covers products that apply for the EU Ecolabel, its range in the textile industry is limited.

In addition to obstacles related to supply-side, a **lack of demand for recycled fibres** is hampering the uptake of recycling technologies. This goes hand in hand with a low interest of companies and investors to provide financial resources for textile recycling, as there is no strong market pull. Few EU policy measures are in place to create a market for circular textiles, particularly for recyclable products and recycled fibres. To be mentioned here are the EU Ecolabel and the EU green public procurement (GPP) criteria. However, both are voluntary instruments that have a limited range.

Some Member States have introduced extended producer responsibility (EPR) systems for textiles, which can help financing the needed expansion of infrastructures for collecting, sorting and recycling textile waste (see for example Hemkhaus et al. 2019). Establishing such EPR schemes for textile waste is voluntary. Minimum requirements of how EPR schemes should be set up are laid out in Article 8a of the Waste Framework Directive. Overall, it has to be noted that there are only very few policy incentives in place on the EU level to stimulate a market as well as investments to foster textile recycling.

6.4. Policy solutions to foster textile fibre recycling

This section will present options for policy solutions to foster the industrial uptake of textile fibres recycling in the EU. Using the input gathered via expert interviews and an online stakeholder survey, a set of options were compiled that seem promising to address those regulatory barriers and policy gaps that our literature review and stakeholder feedback identified as most relevant – as presented in section 6.3.

In each of the subchapters, the suggested policy solution, the problems they address and the regulatory framework component they related to will be outlined. While this study did not undertake an impact assessment of the suggested policy solutions, relevant aspects that will be helpful to consider when designing policy solutions are sketched out.

Taken together, the policy solutions result in a policy mix with interlocking and reinforcing elements.

6.4.1. Increasing traceability of materials and chemicals used in textiles

Recyclers are faced with information gaps that make recycling difficult and expensive. To promote the industrial uptake of recycling technologies, it is key to improve the traceability of materials and chemicals used in the textile supply chain. Therefore, it is considered critical to take into account the extension of mandatory product information for textiles on 1) more specific fibre composition as well as presence of accessories and 2) chemical content, making this information easily available for recyclers and sorters. Bearing this in mind, the required information could be digitalised and as such enable an automatic sorting of textile waste. To achieve this, digital product passport for textile products could be a valuable tool to carry key information for recyclers.

Expanding the mandatory information declaration for textiles

Based on literature analysis, stakeholder feedback and expert interviews, it was found that the most important information needs for textile recyclers are 1) more detailed data on fibre content and 2) data on chemical content (e.g. Roos et al. 2019, Manshoven et al. 2021). This was confirmed by the results of our survey, as presented in Figure 36. In addition, many study respondents considered information on the use of recycled fibres, information on accessories and information on design for recyclability to be important to enable recycling.

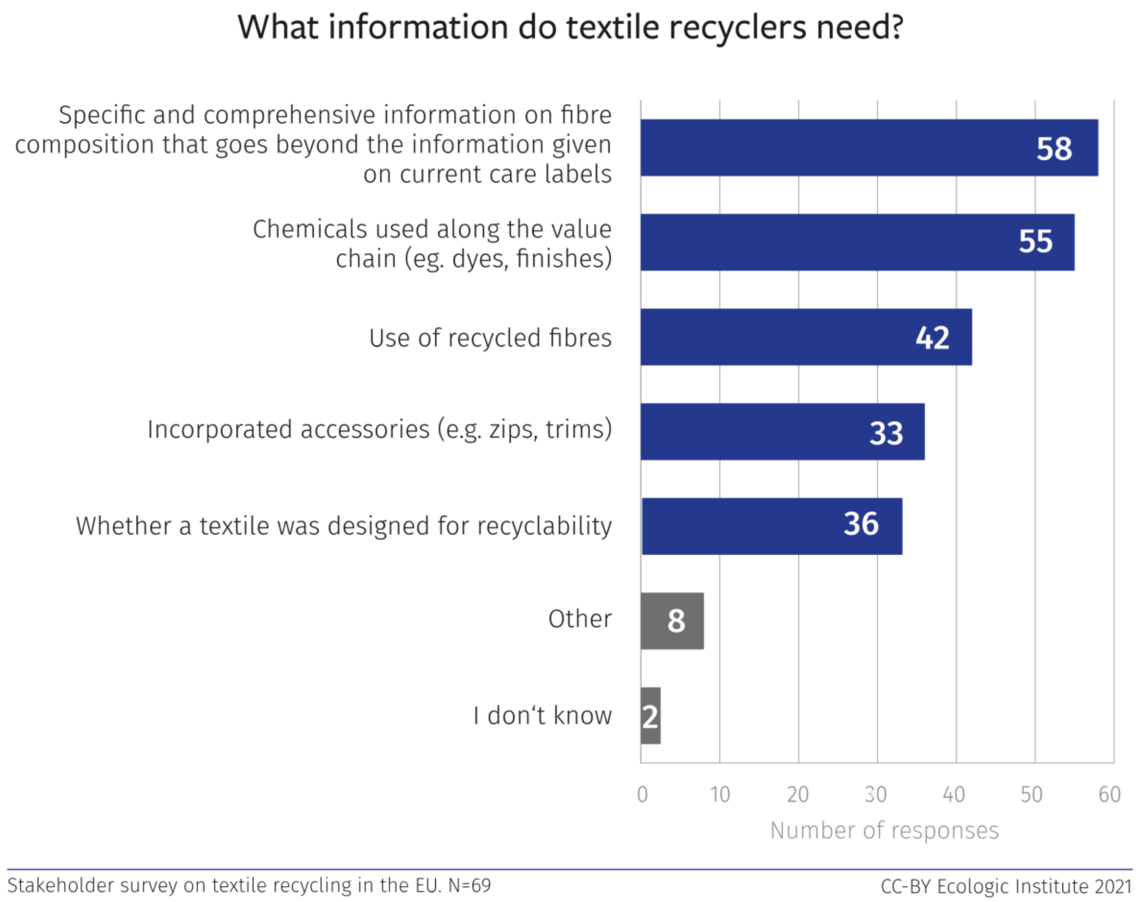

Figure 36: Stakeholder survey results on information needs of recyclers. Multiple replies were possible.

To address these information needs, one policy option could be to make the provision of these information mandatory.

More specifically, regarding the fibre content and composition, it could be considered to expand the current information requirements as laid down in the EU Textile Regulation (EU No

1007/2011). One advantage of this could be that one can build on existing information obligations. Yet, these existing information requirements in the Textile Regulation serve to inform consumers, and more specific and detailed information on fibre composition are most likely not useful for them. Next, the EU could introduce mandatory information declaration of chemicals used in all stages of the value chain. This would present a new element to the existing legislation. Similarly, while important for recyclers, this information is most likely not needed by consumers. Here, it is important to understand which information is needed by different target groups.

Mechanism and expected effects

The suggested policy solutions address the prevalent lack of traceability of materials and chemicals used in textile products along the supply chain. The information gaps often impede or complicate the recycling of textile waste. The mandatory information requirements proposed here would make it transparent for sorters and recyclers which specific fibres and relevant chemicals have been used to produce a textile. This could considerably ease the sorting of waste textiles, enable a better sourcing of specific textile wastes and lower the costs of obtaining information for economic actors.

Moreover, in the envisioned policy mix presented in this study, reliable standard information is considered as the basis to build up recycling streams and new business models. It is a first step to enable high quality recycling. Besides, the reuse stream can also be expected to benefit from the information requirements.

Some limitations of the effects of mandatory information requirements need to be pointed out. First, the envisioned traceability cannot replace the testing and inspection of textile products on the market. Control bodies are needed to check on a regular basis whether false statements are being made – be it intentionally or accidentally. Second, the expanded and new information requirements can only apply to textiles that are newly released on the market. This means that there will be a transition phase during which textiles enter the waste stream that do not have to comply to the information requirements.

Considerations for policy design

Legislative changes could be needed to put the proposed measures forward. Expanding the mandatory product information declaration on fibre content and composition should be one key aspect in the revision.

Next, mandatory information requirements on relevant chemicals used for textile production need to be newly added to the EU legislation. Albeit the authors of this study are no legal experts, in principle different options seem possible. One option could be to include mandatory information requirements on chemicals in the revised Textile Regulation. Alternatively, it could be put forward through the Ecodesign Directive (2009/125/EC) as part of the revisions envisaged under the new Sustainable Product Initiative (cf. Adisorn, Tholen & Götz 2021).

In addition, clear rules need to be established regarding who has access to the delivered information, and how they can be reliably provided to waste managers. Moreover, a key challenge for the expansion of information requirements will be the handling of data flows. This aspect will be elaborated further in the following section.

Digitalisation: Introducing machine-readable data carriers and a digital product passport for textiles

Regarding the expansion of information requirements as depicted above, a key question is how to manage the data flows in a practicable way – both for companies and for EU authorities.

Here, an advantageous option could be to digitalise the process by introducing machine-readable data carriers and a digital product passport for textiles. Importantly, this policy solution would enable automatic sorting of textile wastes. This could present a game-changer, accelerating the uptake of textile recycling technologies by reducing the time and resources needed for sorting (Köhler et al. 2021, Manshoven et al. 2021).

In the survey conducted for this study, stakeholders were asked which medium is in their view best suited to provide information to recyclers (see Figure 37). Results reveal a clear preference for a data carrier that can be automatically recognised and read in the sorting and recycling faciliites. Automatic sorting is a very important aspect for upscaling to industrial scale, as it makes the whole process more efficient. According to stakeholder views, to manually sort garments into different fractions for targeted recycling takes too long to be economically viable on a large scale. Therefore, the data carrier on the textiles should be designed in a way that the sorting and recycling systems can read the information without visual contact. NFC or RFID[22] transponder could be a solution here.

Textile labels, as they are in place on the EU market today, ranked second in the votes of stakeholders, receiving significatly less votes. In the qualitative replies, a number of stakeholders explained that they see a need to keep both systems (digital data carriers and physical labels) as a transitional solution. This is because time was needed to establish automatic sorting on a massive scale and to equip a sufficient number of textiles with the new data carriers. During that time, different recycling and sorting systems need to be served.

As „other“ option, which ranked on a distant third place, respondents mentioned the need to introduce a digital product passport to go along with the digital data carriers.

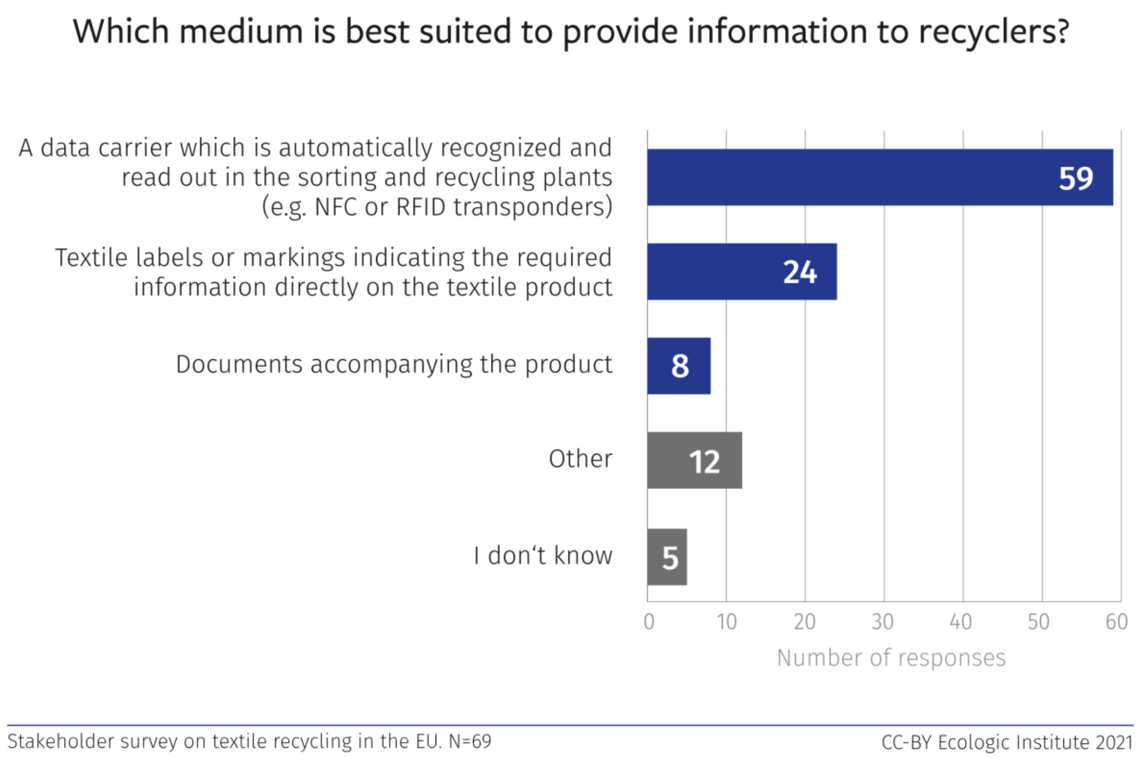

Figure 37 : Stakeholder survey results on options how to provide information to recyclers. Multiple replies were possible.

[22] The abbreviation NFC stands for Near Field Communication ; RFID stands for Radio-Frequency Identification

Next in the survey, we asked stakeholders of the textile and textile recycling industry whether they are in favour of introducing a digital product passport for textile products (see Figure 38). The absolute majority of respondents was in favour, with 65% voting “yes” (in absolute numbers, this presented 45 respondets out of 69). 29% said that “it depends” and only 6% voted “no”. As part of this question, we asked respondents to briefly explain their choice. From the qualitative replies, the most important advantages perceived for a DPP for textiles were that it can

- improve the sorting efficiency,
- ease monitoring and enforcement of REACH,
- increase traceability along the value chain, and
- make the information load manageable.

Most stakeholder who voted for “it depends” stated that they favoured DPP in principle, but it depended on the design of the instrument. They pointed out that for example data security needs have to be taken into account and that the introduction of this new instrument should not results in an additional financial and administrative burden for companies.

The few stakeholders who opposed a DPP for textiles stated that they believed this was technically not possible or not sensible as long as textile recycling was in its initial stages.

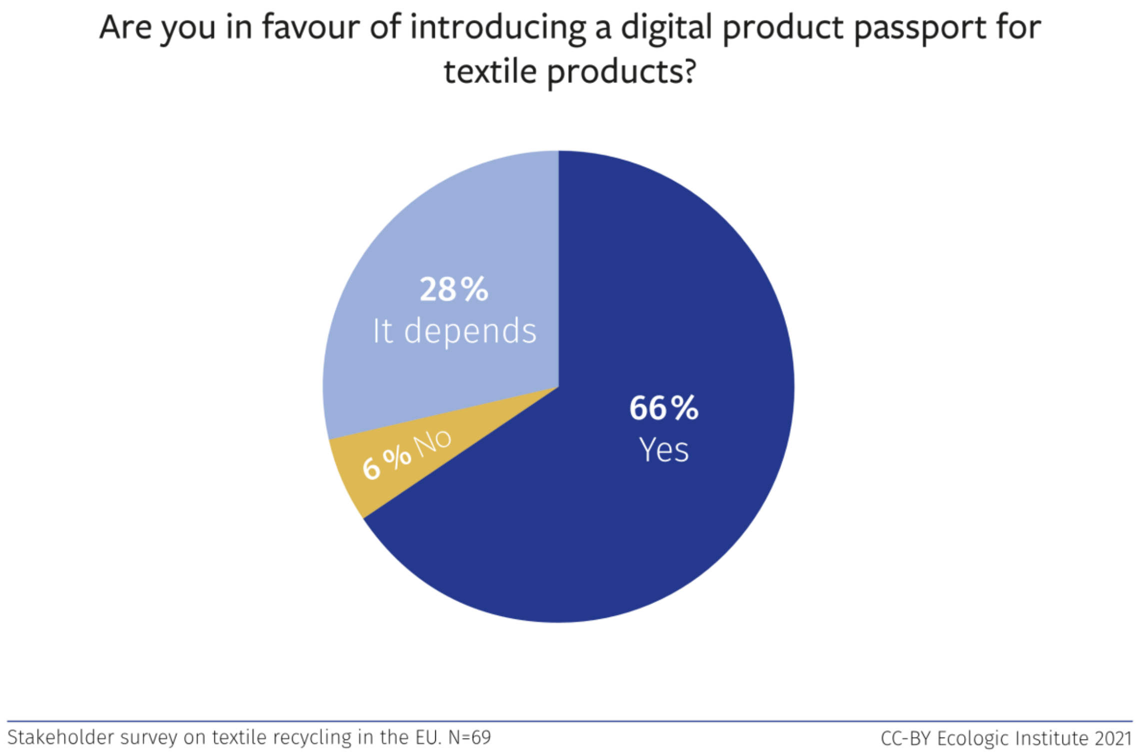

Figure 38: Stakeholder survey results on introducing a digital product passport for textiles

Mechanism and expected effects

A digital product passport (DPP) can be understood as a “data set that summarizes the components, materials and chemical substances or also information on repairability, spare parts or proper disposal for a product. The data originate from all phases of the product life cycle and are to be used for the optimization of design, production, use and disposal” (Adisorn, Tholen & Götz 2021, p. 2). The introduction of a DPP was mentioned in the European Green Deal and in the Circular Economy Action Plan as instrument to foster a more sustainable and circular product policy. A discussion paper by the European Policy Centre has suggested to investigate the set-up of a DPP for textiles, next to other prioritised product value chains (Hedberg and Šipka 2020). At the moment, it is intensely discussed as a policy element for the upcoming Sustainable Product Policy of the EU (Adisorn, Tholen & Götz 2021, EEB 2021, Hilton et al. 2019).

Digital product passports have potential to facilitate the market surveillance and monitoring of information requirements. On the other side, it needs to be considered that SMEs and small economic actors will need support to integrate and exploit the digital tools which require technology integration and digital skills. In addition, DPP for textiles can pave the way for automated sorting of textile waste. It can be a means to ensure that waste managers have access to information that is needed for a high quality recycling.

Besides, a DPP for textiles would not only serve the purpose of recycling. First, information on detailed fibre content and relevant chemicals used can be helpful for organising the sorting as well as the reuse of textile products. Second, the data set that composes the DPP can cetainly include other relevant information on sustainability issues, such as due dilligence or circularity (e.g. durability and repairability of textiles). Against this background, the introduction of a DPP for textiles is considered as a key policy instrument to foster the transformation of the textile sector towards more sustainability.

Consideration for policy design

The stakeholder feedback obtained for this study gives important insights that are relevant for policy design:

- A key challenge for the introduction of digital data carriers and a DPP is data authorisation. Sensitive data need to remain confidential and clear rules must be in place to regulate who has access to which data. Stakeholders emphasised that information requirements should be kept as simple as possible and on a "need-to-know-basis". Recyclers only need to know specific data, and the same applies to other actors, such as reusers or consumers.
- When designing the set-up of digital product passports, it should also be taken into account which information consumers need and how they can access it. One option could be NFC transponders, which can be read out via smartphone. Consumers could thus be directed to a digital twin, i.e. a website with product information relevant for the user (e.g. fibre origin, washing instructions, sustainability aspects of the product).
- To keep the administrative burden for companies low, the digital product passport system should be a "one-stop-shop". This means that there should be only one system where companies need to enter their data. Linked to this, the interoperability with existing databases should be ensured (such as the SCIP database for information on substances of concern in articles as such or in complex objects).
- The data carriers need to be easily removable. This allows to collect them separately and make them available for reuse or recycling. At the same time, they need to be designed for durability, e.g. be standardised to last for many washing cycles.

Overall, before a digital product passport for textiles can be implemented, extensive standardisation efforts and preparatory work are needed. A harmonised approach is key, which entails that data are standardised, machine-readable and accessible for authorised waste managers. In particular, procedures for data authorisation need to be worked out, an adequate and secure central data base needs to be established, data transfer standards need to be developed, and it needs to be agreed on a standard data carrier (cf. Adisorn, Tholen & Götz 2021).

In fact, the private sector has already developed advanced digital solutions, showing that digital product passports can be feasible. One frontrunner in the EU is the start-up Circular.Fashion. It developed the Circularity ID® open data standard (see Circular.Fashion 2020), which presents a standardised format for product and material data. This was built up along the lines of what recyclers need, what sorters need, and what data manufacturers and fashion brands can provide. In other words, the work presents an inventory of what is necessary and what is possible to provide for recycling. The data is stored in a database for which a product page for the end consumers can be generated, containing e.g. information on material composition and return options. Additionally, information from the manufacturers can be provided directly via a physical identifier (e.g. NFC transponder). Circular.Fashion developed a sorting software for waste managers that can access this data and deliver a result for which fraction a sorting company should sort.

Another interesting example from practice is the PRODIS product passport for carpets (European Carpet and Rug Association 2021). It aims to enhance transparency and make information available to different market players. It was based on the GUT-label, which addressed health and environmental aspects, and extends it considerably in order to enable more circular products: "The PRODIS-system add[s] a greater level of technical detail, resulting in the first EU-wide harmonised digital product information system for flooring. At the core of the PRODIS system is a comprehensive database with more than 4,500 registered carpet types. This database allows for the generation of a digital product passport, even for legacy products, by using untapped data sources, and provides information on material composition, technical data and specs, chemical used and absence of hazardous substances, […], basic safety requirements (CE marking) […]" (European Carpet and Rug Association 2021, p 37).

6.4.2 Promoting design for recyclability by introducing minimum design requirements

Currently, policy incentives for a design for recyclability are largely lacking on the EU market. We therefore consider EU actions critical that are able to foster the design of recyclable textile products. Specifically, a possible option could be to introduce minimum design requirements for recyclability. In addition, the EU could further promote the use of safe chemicals in textile production.

Mandatory minimum requirements for circular design of textile products, including recyclability, could be introduced via the EU Ecodesign Directive (2009/125/EC). Consequently, these minimum requirements become applicable to all addressed textile product groups produced in or imported to the EU. This makes the policy very effective and creates an investment opportunity.

The measure addresses an important current shortcoming regarding circularity in the textile sector: the lack of design for recycling. In fact, in the current EU policy landscape there is a complete lack of incentives to design textiles in a way that enables recycling. At the same time, there is a lack of dialogue and cooperation between designers and producers on the one hand and textile waste sorters and recyclers on the other hand. The development of design specifications could bridge this gap and align textile design with basic recycling needs.

Setting up minimum design requirements through the EU Ecodesign Directive is an effective means to ensure that recyclability criteria are considered in the design phase of textiles (Polverini 2021, Pantzar and Suljada 2020, Nordic Council of Ministers 2018). Moreover, it will have the effect to:

- Eliminate the worst performing textile products from the market;
- Increase the share of textile waste that can be recycled into new textile fibres;

- Provide planning security to companies to invest into recycling infrastructures and capacities;
- Reduce amount of textile waste that needs to be incinerated or landfilled (or exported).

In the past, product requirements laid down in the Ecodesign Directive had mostly focused on energy related products. The Circular Economy Action Plan (COM(2020) 98 final) announced that for textiles, ecodesign measures shall be developed “to ensure that textile products are fit for circularity” (European Commission 2020a, p. 10). With the upcoming Sustainable Products Initiative, which was currently under public consutation and is expected to be adopted in the 1st quarter of 2022, it is aimed to widen the scope of the Ecodesign Directive to include non-energy related products such as textiles. Particularly, the planned revisions aim to target material efficiency aspects. This is an opportunity to address the recyclability of textile products.

Recyclability is only one aspect of a circular textile economy, and clearly textile products also need to become more durable and repairable. Minimum design requirements for durability and repairability are likely to have a positive impact on recyclability in certain cases. Yet, to achieve a breakthrough in design for recyclability and to give sufficient planning security for companies to establish textile recycling capacities on a broader scale, we consider it a possible solution to establish minimum design requirements that explicitly address recyclability. This could encompass for example an optimisation of the fibre mix, the use of chemicals that are compatible with established recycling technologies and design for easy disassembly (cf. PACE 2021).

The Ecodesign Directive could allow to address specific textile products with differentiated requirements. Moreover, it could provide the possibility to introduce **minimum or maximum thresholds for certain product characteristics.** Threshold requirements could be used for example to

- limit the use of problematic chemicals to a certain threshold (e.g. maximum threshold for total content of organic fluorine (Nordic Council Ministers 2018))
- promote an easy disassembly, e.g. by setting a maximum of time (in seconds) needed to remove zippers & other accessories (ECOS, 2021, Nordic Council Ministers 2018).
- limit the addition of certain materials in a given fibre mix (e.g. elastane) (ECOS, 2021).

It would go beyond the scope of this study to make concrete proposals for threshold requirements. The level of thresholds for specific product groups should be determined in **close consultation with industrial stakeholders**, and it should go hand in hand with standardisation efforts (cf. Pantzar and Suljada 2020, Nordic Council of Ministers 2018, Watson et al. 2017). Useful initial starting points for how threshold requirements could be drawn up can be found in a study by the Nordic Council of Ministers (2018) as well as in a report by ECOS (2021).

Regarding the threshold requirements for problematic chemicals as mentioned above, it needs to be pointed out that harmful chemicals are subject of the REACH regulation. Yet, a number of chemicals (e.g. dyes or finishes) are frequently used in the production of textiles that are not compatible with established recycling technologies (ECOS, 2021). They either disturb the recycling process or complicate it so that it becomes economically not viable. Therefore, we consider it an option to limit such chemical additives to threshholds that are unproblematic for recycling.

In line with that, stakeholders responses gathered in this study see the compatibility of chemicals – such as dyes, finishes, flame retardants and anti-wrinkle agents – with the vision of a circular economy for textiles as a relevant topic for further research. In particular, stakeholders see need to further investigate the effects of chemical additives on reuse and recycling of textiles. Hence, in order to further promote toxic-free and recycling-friendly textiles, it is important to strengthen the research in safe alternative chemicals for textile production and promote available alternatives. This could be a useful accompanying measure for minimum design requirements. Moreover, based on such research, we see it as important to encourage EU campaigns for the use of safe chemicals on the EU market and beyond. Additionally, in the long term it might be an option to establish a positive list of suitable chemicals that can be safely used in textiles. Role model for inspiration here could be the Cosmetic Regulation (1223/2009).

Consideration for policy design

Ecodesign requirements for recyclability can be pioneered for a small number of textile product groups. According to the online survey conducted for this project, jeans as well as T-shirts could be suitable product groups to introduce mandatory minimum design requirements (see Figure 39). Both product groups are widely circulated on the market and possess potential for circularity. More specifically, both product groups are suitable for a design for recyclability, as they can be produced of a single material (such as cotton) and thus could be suitable for mechanical recycling (Sandvik 2017; see section 3.2).

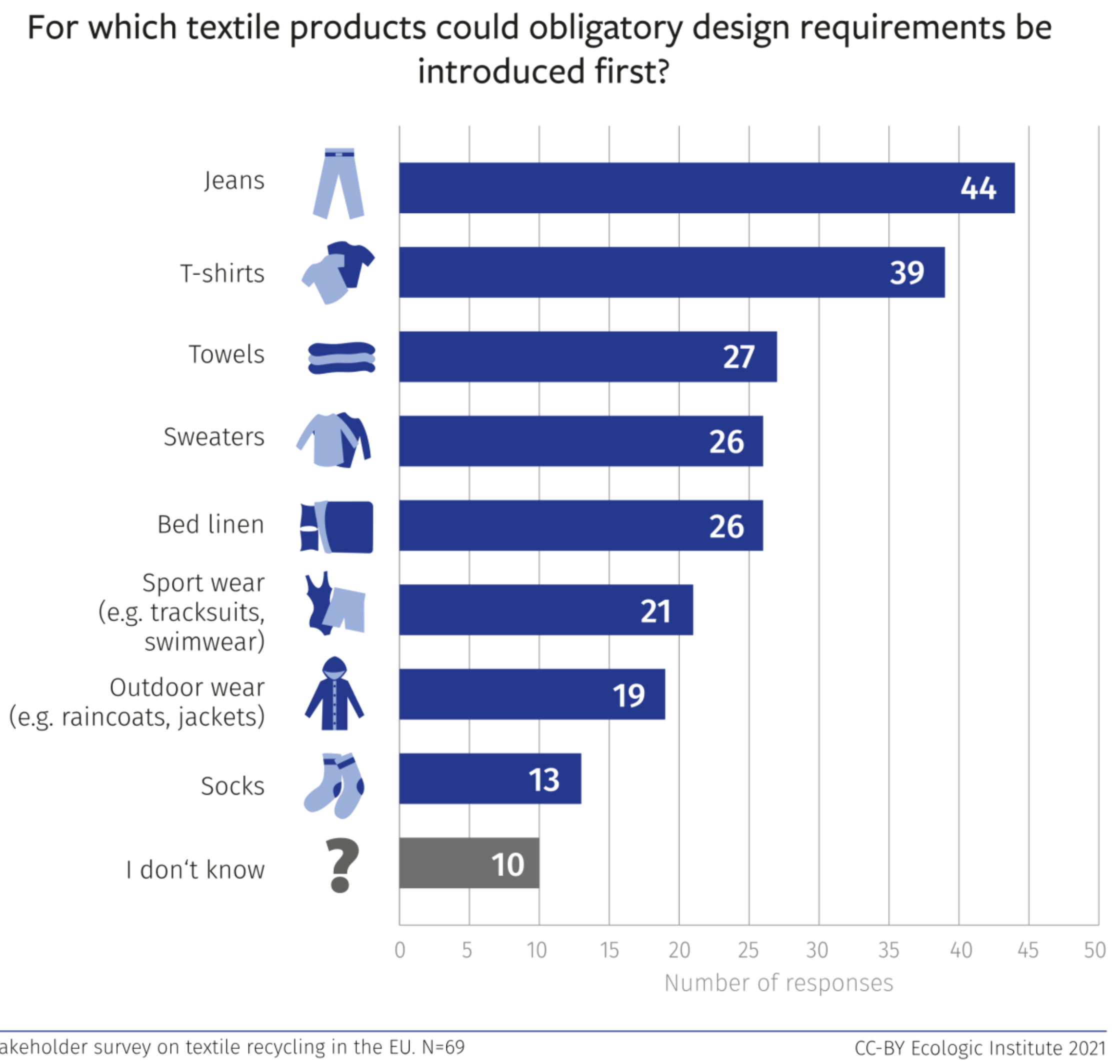

Figure 39 : Stakeholder survey results on obligatory design requirements. Multiple replies were possible.

As a first step to put this measure under way, EU institutions could initiate a dialogue between relevant actors – in particular designers and producers as well as sorters and recyclers of textiles. A starting point can be ongoing procceses for the development and harmonisation of standards (e.g. standardisation working groups CEN, ISO). In the survey and interviews conducted for this study, stakeholders emphasized the urgent need to develop and harmonise standards in order to better align textile design with recycling (e.g. standards that help limiting the use of problematic chemicals, limiting the combinations of different materials, easing the disassembly).

Next, we consider it as crucial to align the minimum design requirements with available recycling technologies on the market. This serves to ensure that textiles are not just (claimed to be) recyclable in theory, but can be recycled in practice. Here, standards play a crucial role to match the requirements to available technologies. Furthermore, as this recommendation is about establishing minimum standards that all addressed products must meet, it is important to

1. Provide advanced warning to producers to allow for preparation
2. Start with manageable requirements and develop the requirements dynamically over time to achieve gradual improvement of products – e.g. though a planned stepwise progression of threshold requirements (cf. Nordic Council 2018).

A specific challenge for the suggested policy could be the market surveillance and enforcement. Here, digital product passports as elaborated above present a key policy to enable the monitoring.

Finally, in the interviews and open text replies as part of the survey, stakeholders stressed that the same standards and restrictions for chemicals should be applied for recycled fibres as for virgin fibres.

6.4.3. Easing trade in textile wastes to foster preparation for re-use and high-value recycling

Several stakeholders shared the view that existing rules regarding the shipment of waste within and beyond Member States complicate access to textile waste materials for preparation for re-use and for recycling. In their feedback, they also linked this to unclear end-of-waste criteria. Against this background, relevant policy options could be to

- Investigate the need and options for specifying end-of-waste criteria for textile wastes in the Waste Framework Directive (WFD) to ease preparation for re-use and recycling of sorted textile wastes;
- Undertake further analyses of mechanisms by which the Waste Shipment Regulation could ease shipment of sorted textile wastes destined for preparation for re-use or for recycling.

According to stakeholder feedback obtained, end-of-waste criteria are perceived as a barrier that complicate trade within and beyond the EU (see Figure 40). Stakeholders perceived definitions of waste and non-waste (i.e., meeting end-of-waste criteria), as well as how administrations interpret them, to differ between EU Member States, thus in their perception complicating approval and permiting procedures for preparation for re-use and recycling operations as well as for trade within the EU.

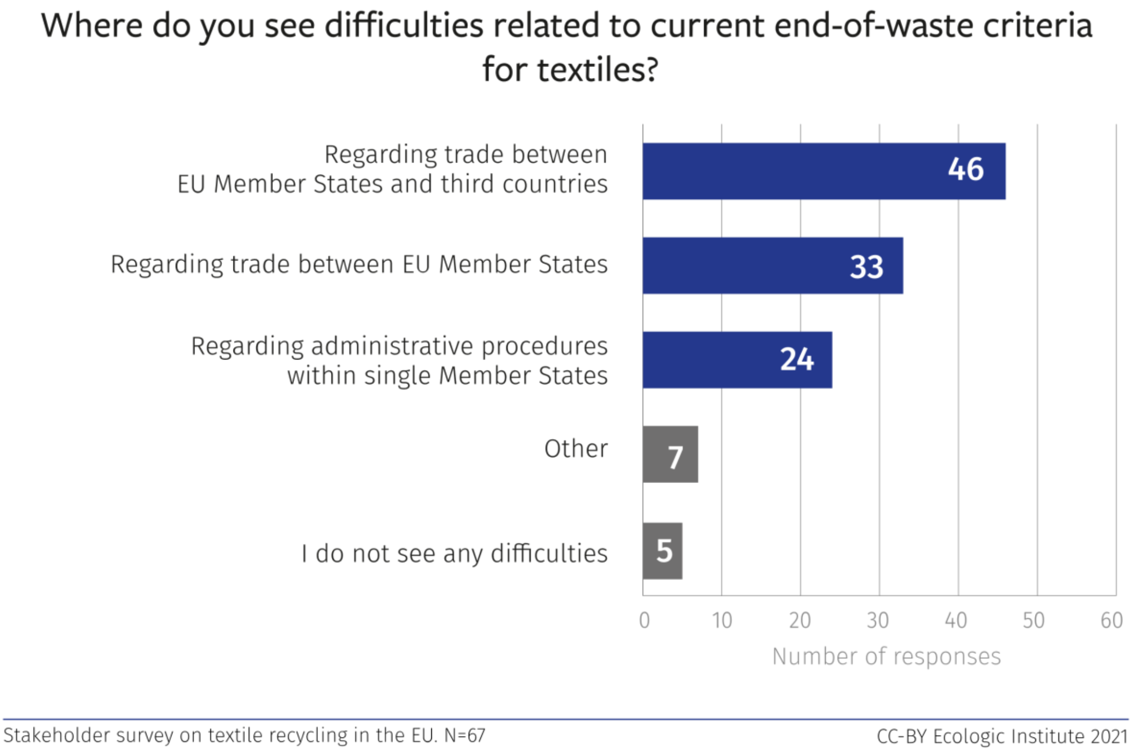

Figure 40 : Stakeholder survey results on difficulties related to current end-of-waste criteria. Multiple replies were possible.

Regarding waste shipments, although the WSR does not foresee a general export prohibition for textile waste – this applies only to some hazardous wastes from the textiles industry, for instance dyestuffs and pigments containing dangerous substances – stakeholders perceived trade barriers in relation to the classification of a certain substance as being waste (or hazardous waste) or not. Furthermore, the WSR does not mention shoes nor accessories, which constitute a relevant part of the textile, footwear and apparel sector and also relevant sources of secondary materials. Therefore, there remains uncertainty of companies wanting to source such materials from other countries as to whether or not these wastes would fall under the WSR, running the risk of illegal shipments of wastes and associated penalties.

This legal uncertainty leads to a lack of available high-quality feedstock for preparation for reuse and for recycling. Stakeholder feedback shows that textile retailers experience such barriers, for instance where export restrictions for collected garments in one country and its administrative procedures to lift such restrictions make trade difficult. In other cases, shipping collected garments outside the EU for re-use or recycling currently requires clothing to be de-constructed in the EU before shipment, which limits the further use options to recycling only. Against this background, more than 80% of respondents of our stakeholder survey were in favour of reviewing the WSR.

Mechanism and expected effects

Against this background, it seems relevant to support a circular textile economy both by

1. Investigating if and how EU-wide end-of-waste criteria in the WFD;
2. Undertaking further analyses of mechanisms by which the WSD

could ease preparation for re-use and recycling of textile wastes so that textile waste can serve as high-value input material for producing textiles in the EU.

Regarding end-of-waste criteria, stakeholder feedback highlights the specification of recovery options ending the waste status for textile wastes as a relevant policy option. Furthermore, stakeholders argued for a definition of recycling that limits downcycling without added value (i.e. not being fibre-to-fibre recycling, such as using textile wastes for filling materials) counting as recycling. Based on this feedback, it appears relevant to investigate whether end-of-waste criteria could

- Explicitly include preparation for re-use in addition to recycling and other recovery operations as an operation, which also ceases the object's waste status;
- Give additional direction to recycling operations by prioritising operations leading to high added-value of outputs of the recycling operation (i.e., the recycled objects, for instance recycled fibres as input materials for fibre-to-fibre recycling rather than using textile waste for filling-material in the sense of downcycling).

Undertaking further analyses of mechanisms by which the WSR could ease shipment of textile wastes destined for preparation for re-use or for recycling could help increasing legal certainty as to when textile wastes can be traded. Furthermore, depending on the results of investigations of the needs and options for specifying end-of-waste criteria for textile wastes, specifications in the WSR could be linked to end-of-waste criteria in the WFD. For instance, Union-wide end-of-waste criteria for textile wastes could also help clarify cases of disagreement between different countries regarding non-waste status of shipments towards enabling the trade of sorted textile material, which has undergone operations related to preparation for re-use or recycling.

Such further investigations and analyses might have the potential to contribute to:

- Facilitating trade of textile waste materials as input into operations for preparation for re-use or for recycling within and beyond the EU – by increasing legal certainty regarding tradeable textile wastes;
- Increasing the share of textile waste that can be prepared for re-use and recycled into new textile fibres – by prioritising preparation for re-use and high-quality recycling and easing shipments of textile wastes destined for preparation for re-use and reycling;
- Providing planning security to companies to invest into recycling and preparation for re-use infrastructures and capacities – by prioritising preparation for re-use and high-quality recycling and increasing legal certainty regarding shipments of textile wastes destined for preparation for re-use and reycling.

Thereby, a circular textile economy could be strengthened, hoping for thus reducing the amount of textile waste that is destined to incineration or landfilling.

Consideration for policy design

Based on the stakeholder feedback, it appears relevant to **investigate if and how end-of-waste criteria can best foster both preparation for re-use and high-value recycling of sorted textile wastes**. According to findings from our stakeholder survey, stakeholders consider it most important to ease shipment of sorted textile wastes destined for preparation for re-use of for recycling. In addition, they argued for recycling operations prioritsing high-quality recycling. In order to foster a circular textile economy, this seems to necessitate clear sorting criteria in the first place.

Currently, sorting criteria or harmonised standards for sorting are largely missing, posing a barrier to effective and comparable sorting routines. Thus, textile wastes are not sorted according to the same standards across different countries, hence leading to a diversity of different textiles materials being sorted. This affects both the quality and the quantity of the feedstock of textile waste available to recyclers in different countires and hence an effective circular uses of textiles wastes. This reflects in the survey findings regarding the focus areas for developing or harmonising standards – here, survey respondents ranked sorting criteria for post consumer textile waste third (see Table 20).

Table 20: Results from stakeholder survey regarding needs for standards. N= 67 ; multiple answers were possible.

Number of votes	Areas in need to develop and harmonise standards for textile recycling
47	Standardisation of product information
47	Limiting the use of problematic chemicals
41	Sorting criteria for post-consumer textile waste (e.g. different fractions depending on material)
39	Limiting the combinations of different materials
36	Disassembly of textiles (e.g. removal of hardware such as trims, zips)
36	Common test methods to declare recycled content in textile products
33	Decision criteria on whether a product should be prepared for reuse or be destined for recycling
33	Definining textile fibre recycling (in distinction to downcycling)

Hence, regarding sorting, there is a clear research need to analyse and identify structures and technologies that can effectively sort pre- and post-consumer textile wastes in a way, which facilitates preparation for re-use or for recycling. For post-consumer textile waste, sorting criteria could for instance be different fractions depending on material.

In addition to the need for clarifying sorting criteria, investigating end-of-waste criteria could look into ways that preparation for re-use and high-quality recycling are prioritised. Learning from the stakeholder feedback, one potential pathway could be to consider including the term “preparation for re-use” into Art. 6 No. 1 WFD in addition to recycling and other recovery options. Furthermore, as Art. 6 No. 1 WFD specified recycling as one recovery option ending the waste status of a treated object, another option could be to consider introducing a definition or prioritisation of recycling output qualities that limits downcycling counting as recycling.

And finally, regarding overall policy design, it could be assessed whether provisions and end-of-waste criteria specific to textile wastes should be introduced in order to foster as much as possible the circular use of textile wastes to be collected separately from 1 January 2025 onwards, i.e. prioritising re-use, preparation for re-use and high-value recycling.

According to stakeholder feedback on the question who should develop textile specific end-of-waste criteria, relevant actors include policy and administration (e.g., public waste management), businesses (e.g., producers and recyclers), academia, civil society and NGOs (see Figure 41). Under the category "other", stakeholders also mentioned international standard setting organisations.

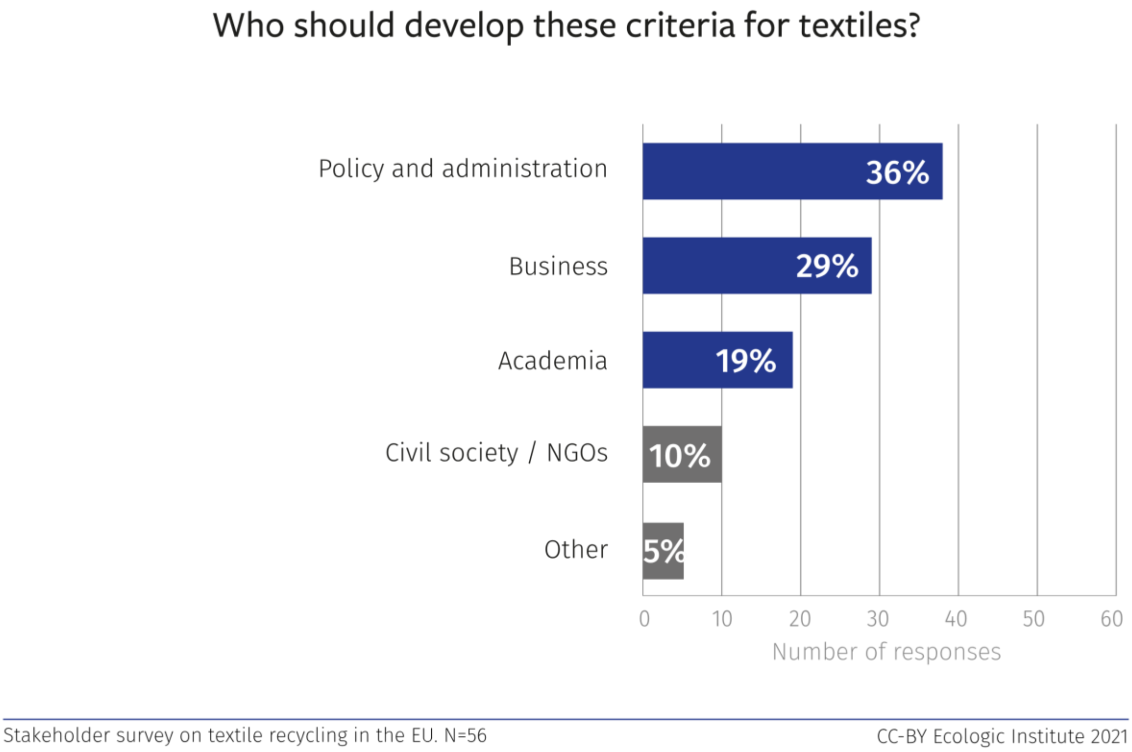

Figure 41 : Stakeholder survey results on actors considered relevant to develop end-of-waste criteria

One relevant starting point for initiating such dialogue can be ongoing processes for the development and harmonisation of standards towards textile designs as well as operations for reuse and high-value recycling (e.g standardisation working groups CEN, ISO).

There appear to be two main avenues for integrating textile waste specific end-of-waste criteria:

1) According to Art. 6 No. 2 WFD the European Commission "*shall monitor the development of national end-of-waste criteria in Member States, and assess the need to develop Union-wide criteria*". Where appropriate, "*the Commission shall adopt implementing acts in order to establish detailed criteria on the uniform application of the conditions laid down [in Art. 6 No. 1] to certain types of waste*".

Therefore, at the level of implementing acts, separate provisions for textile waste could be introduced, which could operationalise this recommendation and provide guidance to Member States.

2) Linked to 1) above, chapter "4.3. Creating a well-functioning EU market for secondary raw materials" of the Circular Economy Action Plan (CEAP) details that the Commission will

"*assess the scope to develop further EU-wide end-of-waste criteria for certain waste streams based on monitoring Member States' application of the revised rules on end-of-waste status* *and by-products, and support cross-border initiatives for cooperation to harmonise national end-of-waste and by-product criteria;*" (CEAP 2020, p. 14).

When **undertaking further analyses of mechanisms by which the WSD could ease trade in sorted textile waste destined for preparation for re-use and recycling** to serve as high-value input material for producing textiles in the EU, it seems relevant to assess if the WSR could

- increase legal certainty as to when non-hazardous sorted textile wastes can be shipped across borders primarily within the EU;
- settle cases of disagreement between EU Member States regarding waste status of shipments.

In both of the above cases, further analyses could explore potential linkages in the WSR to further investigated end-of-waste criteria in the WFD, as suggested above.

The Waste Shipment Regulation (WSR) 1013/2006 is currently under review, with the European Commission elaborating a legislative proposal to revise the WSR. As of end of September 2021, this proposal was planned to be submitted in the fourth quarter of 2021. Hence, it could not be considered within this study.

The WSR revision also responds to the call under the European Green Deal (COM(2019) 640 final) and the Circular Economy Action Plan (COM(2020) 98 final) to revise the WSR with the aim of:

- facilitating shipments of waste for reuse and recycling in the EU;
- ensuring that the EU does not export its waste challenges to third countries; and
- tackling illegal waste shipments.

The Commission's Evaluation of the instrument (European Commission 2020b) concluded that the current rules in the WSR cannot sufficiently ensure that waste shipped to other countries is treated in an environmentally sound manner and in line with the waste hierarchy. Three aspects of this problem were identified:

1. Intra-EU shipment procedures are burdensome and can cause delays that impose costs on waste operators while existing simplification tools are not widely used;
2. The current rules cannot guarantee that exported waste will be soundly managed in a way that addresses the same environmental and health impacts as would treatment in the EU. EU reliance on waste exports makes it vulnerable to global value chain disruptions, including sudden import restrictions and dependencies on the import of secondary materials;
3. Non-comparable resources and insufficient coordination for enforcement lead to large amounts of waste being illegally shipped, within and beyond the EU.

According to findings from our stakeholder survey (see Figure 42), stakeholders consider it most important that when further analysing options to support trade in sorted textile waste destined for preparation for re-use and recycling, the WSR makes a clear link to end-of-waste criteria.

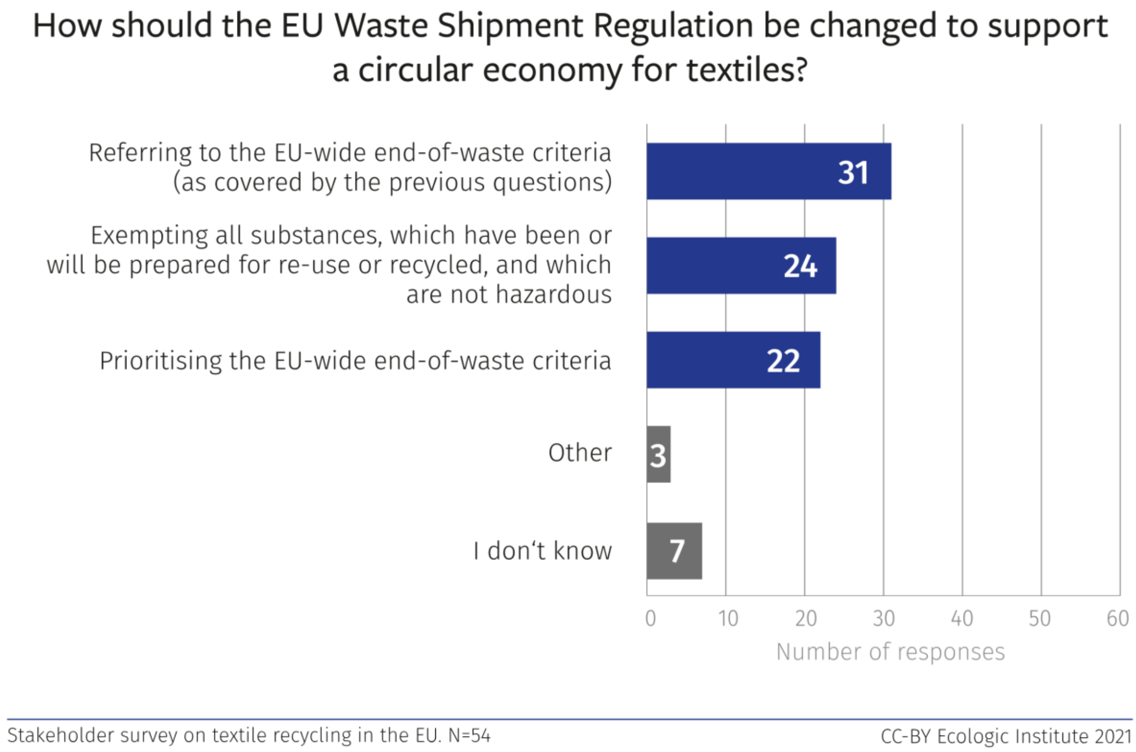

Figure 42 : Stakeholder survey results on suggested changes to the Waste Shipment Regulation. Multiple replies were possible.

Prioritising Union-wide end-of-waste criteria over national waste definitions in case of disagreements ranked third in the stakeholder feedback. Therefore, in case that investigations of Union-wide end-of-waste criteria for textiles highlight a need for revision or further development of such criteria in the WFD or implementing acts, one relevant option could be to refer to these in a revised legal text of the the WSR. In addition, such a reference could also be introduced in Article 28 of the WSR regarding cases of disagreement. Alternatively, the provisions foreseen in Article 28 of the WSR could be supplemented by allowing appeals of actors wanting to ship or import either sorted textile wastes or re-used textiles or recycled fibres to national competent authorities to provide proof of operations that already took place or are foreseen that will end the waste status, thus removing disagreements on waste.

Furthermore, stakeholders suggested to assess whether through the WSR the EU can prioritise shipments of sorted textile wastes destined for preparation for re-use and recycling within the EU, instead of outside the EU, in order to keep waste and secondary material flows circular within the domestic market as much as possible.

In addition, stakeholder feedback obtained highlights the suggestion to include shoes and accessories not containing hazardous substances in List B, item B 3030 of Annex IX of the Basel Convention, which lists wastes not covered by Article 1(1)(a) of the Basel Convention, and therefore not covered by the export proh`ibition of the WSR. Thus, companies wanting to ship such textile wastes for preparation for re-use or recycling could gain legal clarity on what provisions in the WSR apply and could prepare accordingly.

6.4.4. Stimulating demand for recycled fibres

A lack of demand for recycled textiles slows down investments and innovation in textile fibre recycling. In addition, recycled fibres have to compete with cheaper virgin fibres on the EU market. To stimulate the demand and incentivise investments, the EU may consider the introduction of mandatory recycled content for certain textile products and put measures in place that level the playing field for recycled fibres.

Introducing a mandatory recycled content for certain textile products

In order to stimulate the demand for recycled fibres and to set a strong market signal, one policy option could be to consider the mandatory use of a minimum percentage of recycled content for certain textile products. With such a policy element, the EU can provide a clear direction and planning security for companies, incentivising investments into recycling infrastructures and capacities (Roos et al. 2019, Manshoven et al. 2021, EuRIC 2019).

As capacities for textile recyling are currently very low, the key to success for such a policy is to find **a realisitic initial level** so as not to overburden the economy. To achieve this, it is critical to

- involve industry in the process of setting targets for recycled content.
- carefully select and define product groups for which recycling technologies are available on the market.
- start with very low targets in the single-digit percentage range, with differentated targets for the different product groups addressed.
- make the targets dynamic and adapt them over time as recycling technologies and capacities evolve, i.e. aligning targets to what is technically possible.

Regarding the selection of product groups, a first starting point can be to choose homogenous textile products that are massively present on the market, such as jeans, T-shirts or bed linen. About 1.9 million tonnes of T-shirts and jeans are consumed across the EU per year (cf. calculations in section 4.3 based on Eurostat 2021). For such products, a stable incoming waste stream can be expected. Furthermore, the homogenous composition (jeans and T-Shirts are usually composed of mainly cotton) eases a fibre-to-fibre recycling. Besides, from an environmental point of view it makes sense to address mass products, as an overall high amount of virgin fibres and the associated resource consumption could be saved – even when the recycled content in a single article is low. As an illustration, if a legal requirement entailed a share of 5% recycled cotton content in jeans and T-Shirts, roughly about 0.1 million tonnes of recycled cotton fibres would be needed to produce the T-Shirts and jeans consumed in the EU Member States in one year (see calculations in section 4.3 of this report). Even though this is a very rough estimation and involves some uncertainty, it demonstrates that **a considerable demand pull could be generated** by such a policy approach.

In the online survey, stakeholders were asked for which textile products it would be most sensible and feasible to introduce a low mandatory recycled content by the year 2024. T-shirts and jeans were most frequently selected, with a clear lead over other product groups. Textiles for furniture landed on third place (see Figure 43).

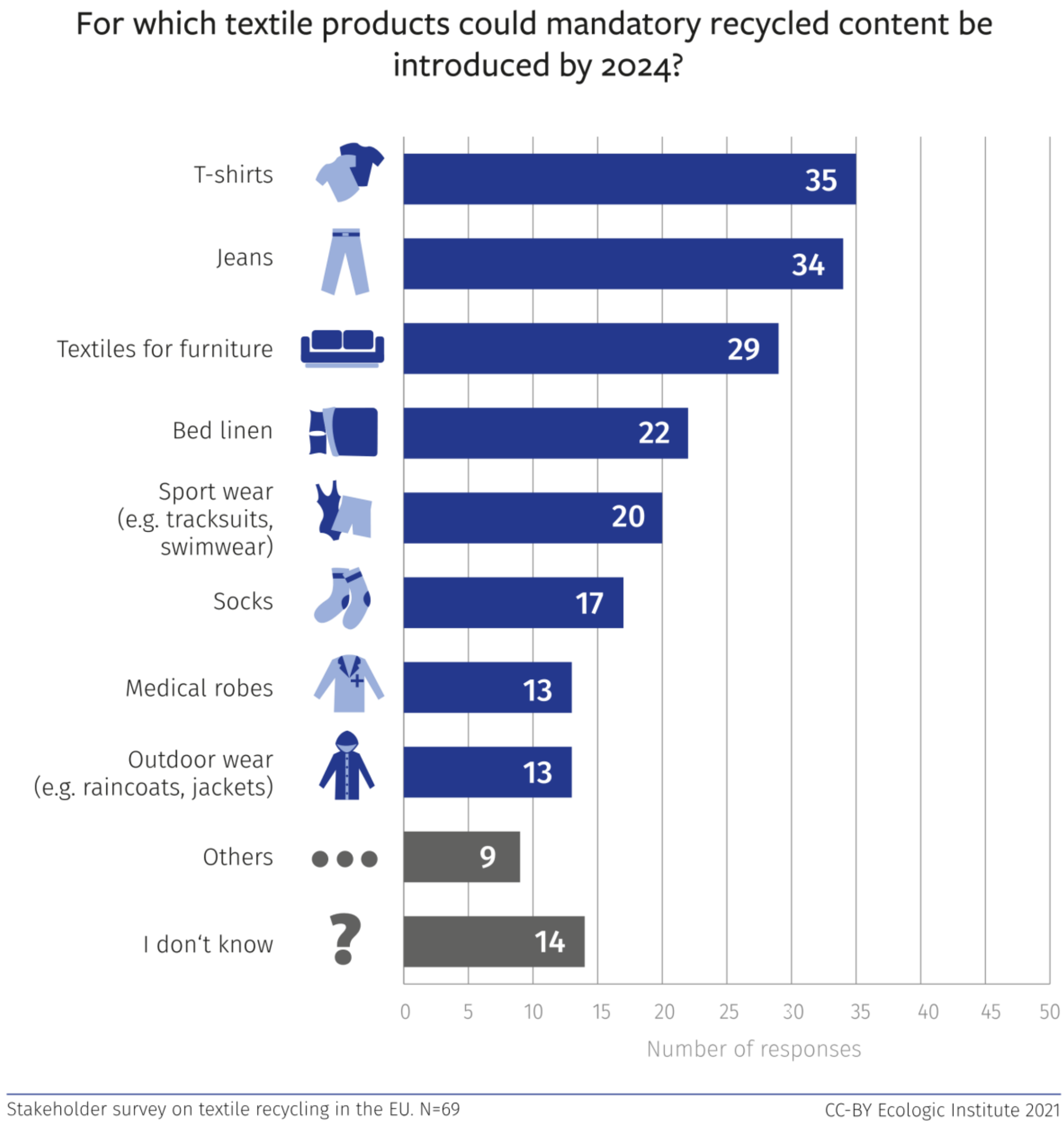

Figure 43 : Stakeholder survey results on mandatory recycled content. Multiple replies were possible.

Overall, in the stakeholder feedback received, a mandatory recycled content was perceived as a useful policy incentive to stimulate demand for recycled fibres. As outlined above, it could start with few carefully selected product groups and low targets that are in line which technical feasibility. Moreover, the stakeholder feedback provides further insights that could be helpful for policy design. One central question that was raised by several stakeholders was: What should qualify as recycled content? Here, the following aspects were emphasised:

- **A life cycle perspective** presents a good basis to define targeted product groups and minimum requirements for recycled content. This could help to prioritise sustainable recycling processes over less sustainable alternatives, taking for example the energy intensity of recycling technologies into account.
- In order to set a strong incentive to recycle separately collected textile waste from households, it is important that to fulfill the mandatory recycled content, a **certain share of post-consumer waste** is required. This issue needs to be addressed explicitly,

otherwise companies that recycle post-consumer waste are put in a worse position on the market than companies that focus on pre-consumer waste recycling.

- More generally, when introducing targets for recycled content, it is important to consider the **number of cycles that specific materials can undergo**. This could faciliate the identification of recycled content quantity in relation to the fibre type and recycling technologies available for it.
- There is a need to clarify how recycled content in a product should be declared. This entails for example to define how recycled material quotas apply to the total amount of the product.[23] As the technical analysis of recycling technologies showed (cf. chapter 3), this issue is particularly important for thermo-chemical recycling processes.

The discussion above shows that clear rules are needed regarding what qualifies as recycled content in textiles products on the EU market. One way forward to address these issues could be supporting and promoting standardisation processes. Together with industry, central terms and rules could be defined to ensure the establishment of high quality recycling streams. In the end, to distinctly advance textile recycling activities, the standards could be taken up in the legal texts.

Regarding the preferred timing of implementation, the survey and stakeholder replies did not deliver a clear result. There was overall little disagreement about the introduction of low targets for recycled content by 2024. Yet, one policy expert among the stakeholders remarked that producing the necessary legal text would take longer. In addition, one of the interviewed experts argued that it makes sense to set targets over a longer timeline, e.g. for 2030, as this serves to stimulate the ambition level.

Finally, this study revealed further research needs related to the use of recycled content in textile products. In particular, the EU could promote closer investigation into the following issues:

- Life cycle analysis for different recycling technologies and different product groups and types, taking into account the number of recycling cycles that are possible.
- Effects on durability of textile products when applying recycled content, as recycling often leads – depending on the recycling technology apllied – to shorter or weaker fibres.
- The potential risk of increased microplastic sheddings
    - from textiles with recycled content (due to higher fibre strain from first product life and recycling process), as opposed to textiles made from virgin fibres with the same fibre composition.
    - due to displacement from the market of degradable natural fibres (e.g. cotton, flay, hemp or algae-based fibres), as to achieve the minimum recycled content, it could be more attractive for market actors to use synthetic fibres that are available in sufficient quantities and for a reasonable price (e.g. polyester or polyamide).

Accompanying measure to stimulate demand for recycled fibres: Creating a level playing field

[23] One discussed method for this is the mass balance approach. A detailed description on the approach can be found in Tabrizi, Crêpy & Rateau (2021).

To further stimulate the demand for recycled fibres, the EU could consider putting policies in place to improve the difficult market position of recycled fibres, which have to compete with the often cheaper virgin fibres. This is important to help establish innovative recycling technologies on the market.

Costs of producing recycled fibres are currently considerably higher than those for virgin fibres – especially when recycled fibres are made from post-consumer textile waste. Most importantly, high transport costs for gathering sufficient feedstock of specific materials for recycling come on top of production costs (Manshoven et al. 2021). This is due to the fact that most recycling facilities are specialized to certain materials. To get sufficient quantitites, they need to source it from various locations. It can be expected, however, that the price differences will no longer be very significant once the sorting and recyling infrastructures and capacities have grown to scale.

In the stakeholder feedback, it was frequently emphasised that policy incentives to stimulate the demand are needed. In a recent strategy paper, the European Carpet and Rug Association (ECRA) highlighted this aptly by demanding “new policies making recycling more competitive or indeed preferable from a cost perspective“ (European Carpet and Rug Association 2021, p. 38). One option on EU level could be to further investigate the necessity and feasibility of promoting and strengthening green public procurement (GPP) (cf. Köhler et al. 2021). GPP criteria that address ease of recycling or recycled content could guide decisions on large-scale public purchasing (Ellen MacArthur Foundation 2017).

In addition, in the open text replies of the survey as well as in the expert interviews, stakeholders pointed out the importance of **regulating unsubstantiated claims regarding recycled content.** Greenwashing claims and consumer confusion regarding recycled content worsen the market position for companies who have high standards for recycled content, as they have to compete with other claims on the market. For companies, this situation makes it less attractive to invest into high quality recycling technologies. Part of the problem is that there is no clear definition of what should qualify as recycled content, and how to differentiate between high quality recycling and downcycling (e.g. of discarded textiles into insulation materials). While various voluntary labels and standards are in place, this situation rather overburdens consumers, who have to weigh between the different claims. Often, consumer information remains incomplete and can be misleading.

One option to improve this situation could be to define in the legal texts what qualifies as ‘recycled content’, and under which conditions brands may use this term. Furthermore, the EU could prove whether a differentiation in terms is sensible, e.g. to delineate textile-to-textile recycling from other forms of recycling. Here, it could be helpful to take into consideration how many cycles specific materials can make and which environmental effects are associated to them from a life cycle perspective. In the end, having more legal clarity in the use of terms could also support the implementation of the Unfair Commercial Practices Directive (2005/29/EC).

6.4.5. Setting the frame and activating businesses

Introducing targets for separate collection, recycling and for preparation for re-use

Based on the feedback gathered in this study, stakeholders highlight that introducing separate targets for collection of textile wastes, for recycling and for preparation for re-use can support the establishment of a circular textile economy in the EU. Such targets could

- Help increase the shares of textile wastes collected separately as a potential feedstock for preparation for re-use or high-value recycling;

- Foster the application of the waste hierarchy, prioritising actions higher up the waste hierarchy, i.e. design for longevity, re-use and recycling (if not conflicting with each other).

Stakeholder feedback obtained indicates that textile design and feedstock availability hamper a circular textile economy because they do not foster the waste hierarchy. Instead, they seem to favour a linear economy and largely limit treatment options to downcycling. Against this background, binding targets could enhance circularity in the textile sectors by covering separate collection of textile waste, recycling and preparation for re-use as separate targets. According to findings from our online survey, a large majority of the respondents is in favour of introducing such separate targets (see Figure 44 below).

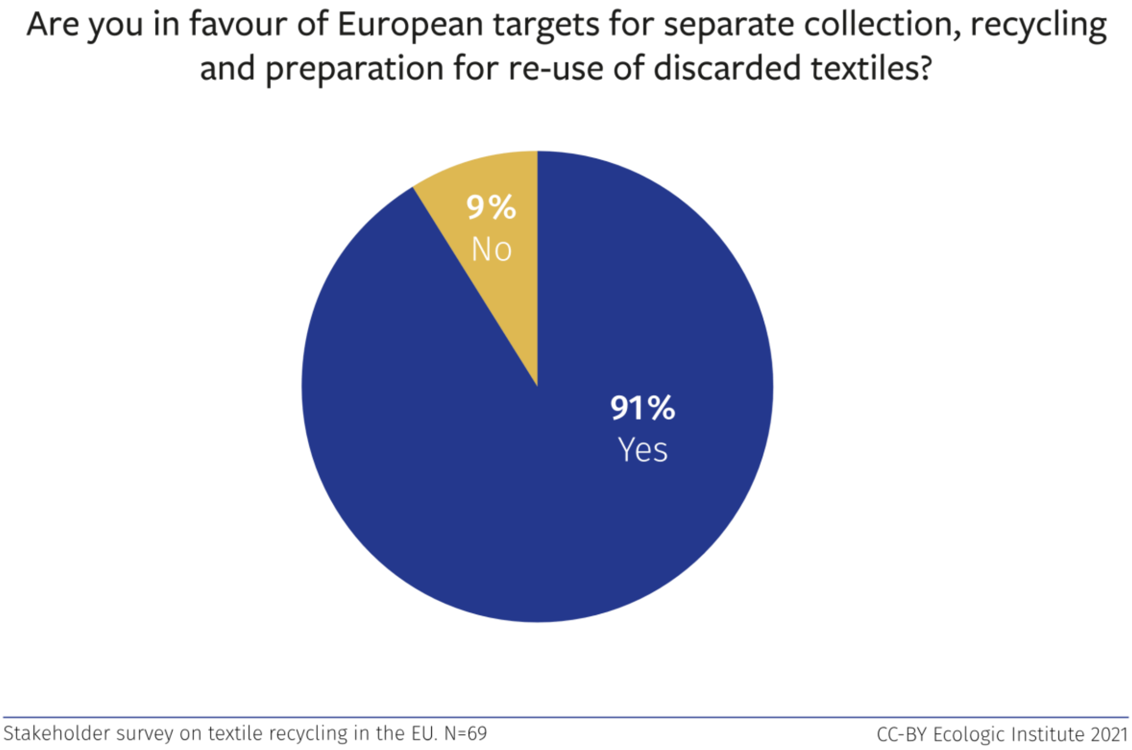

Figure 44 : Stakeholder survey results on the introduction of separate targets

Mechanism and expected effects

Setting targets for separate collection, for prepartion for re-use and for recycling could help increasing the ambition level of circular economy actions in the textiles sector and foster actions higher up the waste hierarchy, i.e. prioritising longevity over preparation for re-use over recycling.

Moreover, introducing such targets could:

- Drive innovations in business models, infrastructures and technologies to help meet these targets;
- Provide planning security to companies to invest into capacities and infrastructure for preparation for re-use and for recycling – to help meet these targets;
- Increase the share of textile waste that is prepared for reuse and that can be recycled into new textile fibres.

Thereby, a circular textile economy could be strengthened, hoping for thus reducing the amount of textile waste that is destined to incineration or landfilling.

Consideration for policy design

When designing separate targets for separate collection, for preparation for re-use and for recycling, it seems relevant that targets

1. become effective in the near future;
2. start at a reasonably feasible level that is within reach given current business models, structures and technologies, but still trigger innovation.

In addition, dynamic targets could be beneficial, i.e. gradually increasing target levels at certain time intervalls to maintain the momentum for innovation – while still being reasonable from a life-cycle perspective.

Regarding the timing of first targets, several stakeholders considered it important to define their introduction in the near future.

Despite the fact that stakeholders considered separate targets overall as a relevant means to support a circular textile economy, stakeholder feedback showed a wide range of potential starting levels – no converging picture emerged regarding target starting levels (see

Box 1). Even across different stakeholder groups providing feedback (representatives from industry, industry associations, policy and administration as well as civil society and academia) target suggestions ranged widely.

Box 1 : Overview of wide ranges for starting levels for targets on separate collection, preparation for re-use and recycling, obtained from stakeholder survey

Responses for targets for separate collection show …

- no clear priority target starting level, but a wide possible range of 30%, 40%, 50% or 60%. Some stakeholders suggested starting levels including 80% and 90%.
- no differentiation between the different stakeholder groups having participated in the survey: representatives from industry, industry associations, policy and administration as well as civil society and academia alike use this range.

Responses for targets for preparation for re-use show …

- no clear priority target starting level, but a wide possible range of 10%, 15% or 20%. Some stakeholders suggested other starting levels including 50% and 60%
- no clear differences regarding stakeholder group specific preferences; however slighty more representatives from academia, civil society and policy and administration among those having selected or suggested higher starting levels.

Responses for targets for recycling show …

- no clear priority target starting level, but a wide possible range of 10%, 15% or 20%. Some stakeholders suggested other starting levels: 30%, 50% and 60%.

- no clear differences regarding stakeholder group specific preferences; however slighty more representatives from academia and civil society among those having selected higher starting levels.
- that stakeholders suggest that recycling should be high-value recycling, hence excluding downcycling from counting towards the recycling target.

This indicates a clear need for further research and dialogue to determine relevant and feasible starting levels for the different targets. Knowledge on existing rates for separate collection, preparation for re-use and recycling appear to support this finding (see Box 2).

Box 2 : Examples for knowledge on rates for separate collection, re-use and recycling in Europe

Separate collection rates	A study by the Danish Environmental Protection Agency (2020[i]) found rates for separate collection[24] in six EU countries to vary considerably: rates ranged from around 20% in Sweden (for 2013) and Finnland (for 2012) to more than 70% in Germany (for 2013) (Danish Environmental Protection Agency 2020). A more recent study by the JRC (Köhler et al. 2021) finds separate collection rates to range from 4.5% in Latvia (for 2018) to 11% in Italy and Lithuania (for 2018) to 30% in the Czech Republic (for 2013) and Estonia (for 2018), with a maximum at 45% in the Netherlands (for 2018) (Köhler et al. 2021). This study also shows that growth rates of separate textile collection for many countries increased since 2006, e.g. for Austria, France, Italy, the Netherlands and Sweden. According to Köhler et al. (2021) the EU-wide textile collection rate in 2019 was estimated to be around 39%.
Re-use rates	Actual figures are hard to come by – according to Euratex (2020) about 50-60% of the textiles collected in the EU in 2019 were still in the condition to be reused or worn again. However, data collected by Manshoven et al. (2019) find lower actual reuse rates, showing that reuse rates in several EU countries (Flanders region in Belgium, Nordic countries and the UK) range between 4 and 30%, averaging a 10% reuse rate.
Recycling rates	Available figures differ depending on whether it is fibre-to-fibre recycling or recycling with lower-value outputs (i.e., downcycling), e.g. using textile waste to produce insulation material, wiping cloths, or mattress stuffing. Less than 1% of textiles collected goes into fibre-to-fibre recycling (Ellen MacArthur Foundation 2017, Manshoven et al. 2019), while recycling rates including downcycling can reach up to 15% (see, e.g., Euratex 2020).

Hence, given widely ranging rates and their seeming dependence on the structures existing in different Member States, further in-depth analyses and feasibility assessments regarding targets are needed.

In addition, this wide range in potentially relevant starting levels for separate targets seems to also point to a need for a multi-stakeholder dialogue on separate targets at EU-level regarding timing and levels of introduction. This dialogue could involve actors from academia, business and industry, civil society and policy and administration, and be made part of the EU's standard processes around better regulation or, more specifically, of the high-level exchanges on the

[24] Refering to separate collection of used textiles as a share of new textiles placed on the market in the same year (Danish Environmental Protection Agency 2020, p. 7).

circular economy and waste with Member States, regions and cities that the Commission will organise under the CEAP from 2020. In addition to discussion possible starting dates and levels of such targets, discussions could also tackle potential competition between textile wastes going to preparation for reuse or towards recycling. Here, according to stakeholder feedback, setting separate targets for preparing for re-use and for recycling could help reducing such competition.

Determining the best starting dates and levels for separate targets as well as intervals for gradually increasing targets is a challenging process because of the different perspectives and interests, which various stakeholders likely bring into a dialogue about targets. Therefore, target setting remains a selective and normative process, trying to reconcile different interests and capacities for a circular textile economy.

There appear to be two main avenues for undertaking further in-depth analyses and holding dialogues on separate targets:

1) According to Art. 9 No. 9 WFD, by 31 December 2014 the European Commission "*shall examine data on re-use provided by Member States in accordance with Article 37(3) with a view to considering the feasibility of measures to encourage the re-use of products, including the setting of quantitative targets. The Commission shall also examine the feasibility of setting other waste prevention measures, including waste reduction targets.*"

2) Linked to 1) above, chapter "4.1. Enhanced waste policy in support of waste prevention and circularity" of the CEAP details that the Commission will

"*put forward waste reduction targets for specific streams as part of a broader set of measures on waste prevention in the context of a review of Directive 2008/98/EC. […] [serving] the objective to significantly reduce total waste generation and halve the amount of residual (non-recycled) municipal waste by 2030."* (CEAP 2020, p. 13).

Therefore, both further data analysis and multi-stakeholder dialogue on separate targets for preparation for re-use and on recycling appear very relevant and timely.

Introducing Extended Producer Responsibility for textiles

EPR is an environmentally policy tool based on polluter's pay principle. It intends to hold the producer responsible for product's entire life-cycle – from desiging sustainable products to the end-of-life (EoL) management of the products. Article 8 of the Waste Framework Directive (WFD) enables Member States to take legislative or non-legislative measures to implement EPR in order to strengthen reuse, prevention, recycling and other recovery of waste. Where a Member State decides to establish EPR schemes, the Member State must do so according to general minimum requirements laid down in Article 8a of the WFD. The minimum requirements stipulate, inter alia, that EPR schemes are in line with the waste hierarchy and that financial contributions paid by the producers in a collective EPR scheme to comply with their EPR obligations *"are modulated, where possible, for individual products or groups of similar products, notably by taking into account their durability, reparability, re-usability and recyclability and the presence of hazardous substances, thereby taking a life-cycle approach […]*".

In EPR, the concept of ecomodulation of fees can be used to improve the product design towards environmental sustainability. Through ecomodulation of fees, economic actors who produce better designed products – such as easy to recycle textiles – would pay lower EPR fees as compared to producers putting products with high environmental impact on the market (such as textiles with low recyclability).

In order to support Member States in implementing the modulation of financial contributions, the European Commission shall publish guidelines – these guidelines have not been published at the time of writing this report. Once these guidelines are published, further analysis of Member States' implementation of EPR schemes and modulation of fees could investigate whether EPR schemes are established covering textiles. If such schemes are not found or if they are insufficient, further steps could be considered.

Mechanism and expected effects

Currently, producers are not obliged to manage the waste arising from their textile product after use, neither financially nor operationally. Introducing textile-specific EPR schemes could help shifting responsibility for product design and product end-of-life (EoL) management to producers. Through such EPR schemes, textile producers can be legally obliged to make sure that discarded textiles are separately collected and managed according to the waste hierarchy. Furthermore, using ecomodulation of fees could incentivise producers to design more circular and sustainable textiles and phase out problematic substances in textiles.

According to the Roadmap on the planned EU strategy for textiles from January 2021 the European Commission intends to consider "the role of extended producer responsibility in promoting sustainable textiles and treatment of textile waste in accordance with the waste hierarchy" (European Commission 2021a, p. 3). As of 2021, France is the only EU Member State to have introduced a mandatory EPR scheme for textiles; Sweden and the Netherlands are in the process of introducing the same (Matthews 2021, Tojo 2019).

Thereby, considering a textile specific EPR scheme with ecomodulation of fees could help

- Ensuring access to increased finances to improve EoL management of discarded textiles including separate collection, sorting, reuse and recycling – by earmarking funds collected via EPR fees for this purpose;
- Facilitating the implementation of separate collection of textiles by 1 January 2025 – by requiring producers to contribute, financially or financially and organisationally, to managing their products' end-of-life, which necessitates separate collection;
- Increasing feedstock availbility for recycling through necessitating improved separate collection and sorting of textile wastes;

In stakeholder feedback received as well as in literature (see, e.g., Sachdeva et al. 2021) ecomodulation of fees is linked to potential contributions to longer term design improvements, including design for longevity and re-use, use of secondary raw materials, and recycling. This, in turn, necessitates criteria for differentiating EPR fees, which cover aspects such as durability, recyclability, sortability, and recycled content). Results from our online survey (see Figure 45) indicate that ecomodulation can play a crucial role in improving textile design requirements.

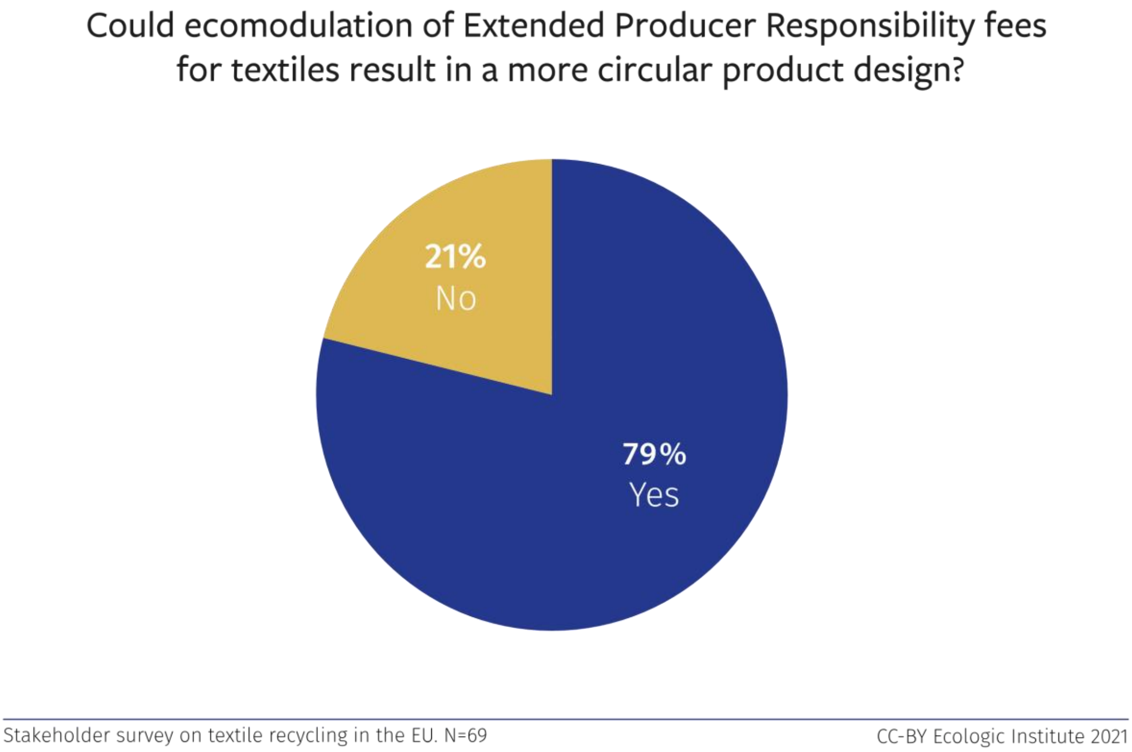

Figure 45 : Stakeholder survey results on ecomodulation of EPR fees

Then, there is the potential that EPR schemes with ecomodulation of fees can contribute to stimulating demand for secondary raw materials and thus for fibre-to-fibre recycling; and to supporting the implementation of minimum design requirements for recyclability. The latter could be linked other policy and regulatory measures such as Ecodesign Directive (see, e.g., Sachdeva et al. 2021).

Consideration for policy design

According to findings from expert interviews there is a risk that textiles, which otherwise can be re-used, end up being recycled if proper sorting methods that can distinguish between textiles for reuse and recycling are not applied. The concern is augmented from experience of EPR schemes for other waste streams, such as waste electrical and electronic equipment (WEEE) and plastic packaging, where priority is given to recycling instead of reuse, both because of lacking focus on re-use in the EPR schemes and because of the absence of targets for preparation for reuse (Sachdeva et al. 2021). Stakeholder feedback suggests that differentiated fees could prioritise both textile design for reuse and collecting textile wastes for preparation for reuse. Here, the organisation responsible for such a textile EPR scheme could set and clearly communicate to its members the criteria, based on which members have to pay lower fees (eco-modulated). Such criteria could include design for reusability and longevity on the one hand and certain shares of textile waste collected being prepared for reuse. The French EPR scheme prioritises reuse and recycling for collected textiles resulting in 57.8% of collected textiles reused in 2019 and 33.5% recycled.[25] Between 2009 and 2019, reuse rates

[25] Eco TLC. (2019, January). Annual Report 2019. Paris: Eco-TLC

increased from 55% to 57.8%, while recycling rates rose from 27% to more than 33% (Eco TLC 2019).

In addition, there is a need to further develop research in sorting methods and technologies, which can ensure that the discarded textile collected is sorted on the basis of reusability and recyclability. This concern was echoed in the online survey, where out of 69 respondents 71% voted that in order to avoid competition between discarded textiles collected for re-use and recycling there should be separate targets for both.

For the other waste streams – packaging, WEEE and batteries – the impact of EPR has been predominantly focused on improving EoL management of the product such as increasing collection and recycling rates. There has not been any considerable impact on improving product design and reuse of products or components. Therefore, in addition to improving the EoL management of the discarded textiles, ecomodulation of EPR fees (i.e. charging producers lower fees for environmentally friendly and more circular textiles) could be included in the design of the EPR schemes to foster design criteria such as reusability, recyclability, and use of recycled content. The French EPR scheme has three scales of ecomodulation of EPR fees to encourage producers to adopt ecodesign practices. For example, it offers a discount of 50% on EPR fee if a textile product contain at least 15% of recycled fibres.[26]

However, uptake of more sustainable design in the French EPR has been slow. In 2019, only 2.16% of the total EPR relevant textiles put on the market were declared as ecomodulated items and qualified for lower EPR fees (Eco TLC 2019). One of the reasons has been reported to be a low incentive per piece of textile, which is not able to cover the cost of certifying the durability and recycled content (Hogg, et al. 2020). This is aggravated by the very small size of EPR fees compared to the product price, which does not have a significant effect on producers' decision to shift to better designed textiles. For a T-shirt costing around 19.50 Euros, the EPR fee is just 0.009 Euros or 0.04% of the product price (Sachdeva, et al. 2021). Therefore, while ecomodulation of EPR fees can be one factor to steer the design of textiles, it alone is not sufficient to establish circular product design as a mainstream in the textile sector. Setting minimum design requirements for textile products via the Ecodesign Directive could be a much more effective method in ensuring textiles put on the market are more circular and environmentally sustainable. Nevertheless, introducing EPR schemes for textiles with ecomodulation of fees can be a helpful tool on the way to more circular product design, including design for recyclability. In order to have a greater impact, the scales in the fees should be more differentiated than is currently the case in the French EPR scheme. This way, stronger incentives for advances in product design can be set.

Apart from steering product design, another potentially more important effect of EPR schemes for textiles is to secure funding for setting up collection, sorting and recycling infrastructures. This is essential in order to handle the increased amount of separately collected textile waste that can be expected due to the 2025 target in Article 11 of the Waste Framework Directive. Linked to this, EPR schemes for textiles could go hand in hand with setting targets for separate collection, recycling and preparation for reuse of textile waste.

When designing an EPR scheme, the questions of who controls the post-consumer governance of textile waste is important. This point was mentioned in the expert interviews as a concern that EPR could replace the existing collection systems if the collection is organised by Producer Responsibility Organisations (PROs). In EPR schemes for other products, such as packaging and WEEE, the producers dispense their EPR responsibility by paying fees to a PRO to organise the collection and sorting of the waste arising from products. Regarding designing an EPR scheme for textiles, our online survey shows that the largest number of respondents, i.e. 48%, prefer that municipalities remain operationally responsible for

[26] https://refashion.fr/pro/en/eco-modulated-scale

separately collecting the textiles from public waste bins, while producers contribute financially (see Figure 46). As an important part of this solution, producers should have the option and freedom of organising individual take-back systems. The producers in this case can choose the best suited method based on the type and quality of the textile. The operational responsibility of collection through PROs was opted as the second best option with 26% of votes. This can be attributed to the reason that in many Member States, municipalities are already collecting discarded textiles separately (e.g. Finland) (Municipal Waste Europe 2021; Lounais-Suomen Jätehuolto 2020; Watson, et al. 2018).

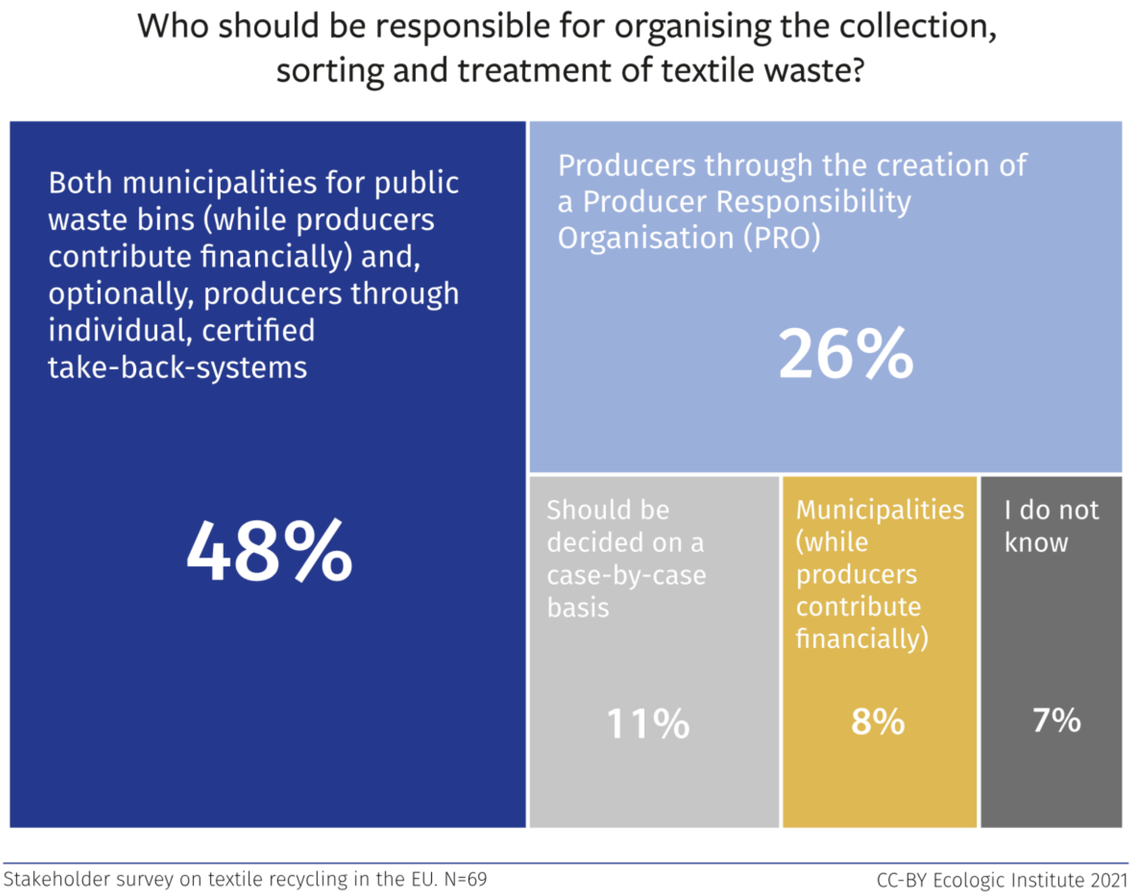

Figure 46 : Stakeholder survey results on responsibility for collection, sorting and treatment of textile waste

EPR schemes from other product streams such as packaging, WEEE and batteries offer insights regarding relevant challenges. Currently, not-for-profits and charity organisations are playing an important role in ensuring reuse of discarded textiles, which otherwise would end up in landfills or incinerators. One of the challenges of EPR implementation would be to ensure priority access of discarded textiles to the existing collection channels of not-for-profits and charity organisations.

According to findings from our online survey, 86% of the respondents were in favour of introducing an EU-wide mandatory EPR scheme for textiles (see Figure 47 below).

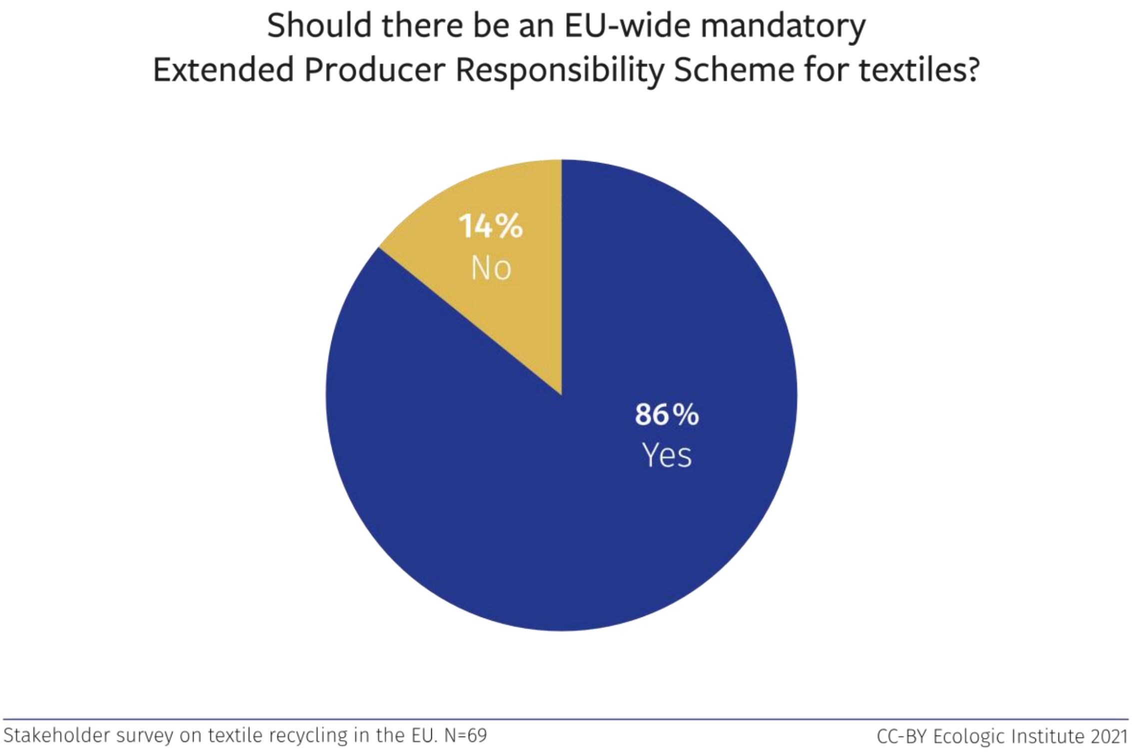

Figure 47: Stakeholder survey responses on mandatory extended producer responsibility schemes for textiles

Nevertheless, as no other textile specific EPR schemes exist in EU Member States, first the situation across EU Member States regarding establishment of textile specific EPR schemes and ecomodulation of fees should be carefully analysed in the near future. It is critical to underline that Article 8 of the WFD foresees the publication of guidelines by the European Commission, in consultation with Member States, on cross-border cooperation concerning extended producer responsibility schemes and on the modulation of financial contributions. Based thereupon and the exchange of information established under the WFD with Member States and actors involved, the European Commission could investigate if further steps in fostering EPR for textiles are needed. This could include investigations as to whether a system of EU-wide harmonised criteria for ecomodulation of EPR fees could be introduced or whether an EU-wide mandatory EPR scheme for textiles could be a relevant option.

6.5 Synthesis of policy options to advance textile-to-textile recycling

In this study, based on literature review and stakeholder feedback from the textile – including textile recycling – sector, we identified existing EU-level regulatory barriers and policy gaps that currently hamper the industrial uptake of textile-to-textile recycling. Next, we elaborated possible EU policy solutions that could foster textile-to-textile recycling.

Overall the analysis results indicate that there is potential to better align EU legislation taking into account Member States' role according to the principle of subsidiarity to enable and incentivize textile-to-textile recycling. Recycling can be a key building block in a circular textile economy, secondary to prepration for re-use. In particular, one key role of textile-to-textile recycling can be to enable the reprocessing of discarded textiles that are not suitable for reuse (e.g. damaged or worn-out garments).

As there are several policy processes with relevance for the textile sector ongoing at EU-level – such as the preparation of a comprehensive EU Textile Strategy as well as a Sustainable Product Initiative and review of the Waste Shipment Regulation – there is potential to pave the way for high quality textile-to-textile recycling in a timely manner. With the target of collecting textile waste separately in all Member States by 1st January 2025, a first and important step is underway. Now, further strong policy signals could facilitate the uptake of advanced textile-to-textile recycling technologies and increase capacities across Member States. In the online survey and expert interviews conducted for this study, key economic stakeholdes distinctly signalled to be open and prepared for ambitious policy approaches.

Along these lines, and building on the findings of the technical as well as economic and environmental analysis of textile recycling technologies, this chapter presented an analysis that provides subjects for discussion for possible future policy development, aiming to promote preparation of textile wastes for reuse and to accelerate the uptake of textile-to-textile recyling technologies and related infrastructures on the EU market. As the present study does not provide any impact assessments of the regulatory framework components analysed, more detailed analysis through feasibiliy studies will be critical to further deepen and develop such policy options.

For the identification and analysis of policy options, stakeholder feedback – including from recycling technology holders, fibre and textile producers and lables, as well as national and EU administrations, civil society organisations and academia – allowed us to reflect on their perspectives and needs. Moreover, we focused on policy options that address existing bottlenecks and gaps, which currently pose an obstacle to textile-to-textile recycling. In particular, this entails to

- improve information and traceability on what has been used to produce textiles,
- continue technical standardisation processes in the area of textile recycling,
- set incentives for designing textiles for recyclability, and
- set market incentives to use recycled fibres in textile products, as well as to
- foster the development of recycling capacity and attract necessary investments.

Table 21 summarises key policy options to enhance textile-to-textile recycling identified, links them to policy support needs from the stakeholder perspective and points out their likely effects on textile recycling activities.

Table 21: Overview of identified policy options with strong signal to textiles market

Policy needs to enhance textile-to-textile recycling from stakeholder perspective	Key policy elements that could be considered to enhance textile-to-textile recycling	Expected contributions of policy elements to a circular textile economy
Enhance traceability of materials and chemicals used in textiles	Considering mandatory information declaration Considering the introduction of machine-readable data carriers and a digital product passport for textiles	Stimulate new, circular business models, increase sorting efficiency, improve availability of pure(r) feedstocks for recycling, ease monitoring and enforcement of EU Chemicals legislation and due dilligence along the textile supply chain
Promote design for recyclability	Considering minimum design requirements	Achieve more circular design of textile products, enable and increase adequate and more regular feedstock volumes for recycling, ease disassembly of textile

		products, provide planning security for economic actors
Ease access to feedstocks for textile fibre recycling	Easing shipment of sorted textile waste destined for preparation for re-use and for recycling Investigating the need for further clarifying end-of-waste criteria	Establish legal clarity, reduce disagreements between textile waste and non-waste classifications across Member States, ease the sourcing of specified feedstocks and improve availability of feedstock volumes for recycling
Stimulate the demand for recycled fibres	Considering mandatory recycled content for specific textile products Adressing greenwashing claims on recycled content in textile products	Create a market for recycled fibres, provide planning security for economic actors, incentivise investments into recycling technologies, capacities and circular business models, level the playing field for recycled fibres on the market
Set a frame with clear long-term direction	Discussing binding targets for separate collection, recycling and preparation of reuse of textile waste Considering Extended Producer Responsibility Schemes for textiles	Provide planning security for economic actors, secure funding for uptake of technologies and infrastructures, improve feedstack availability for recycling, incentivise circular design of textile products

This set of options presents a policy mix with interlocking elements that are likely to work best in combination to foster preparation for re-use and textile-to-textile recycling.

Regarding the timeline of such a policy mix, it appears reasonable to first clarify and set the frame and long-term goals (e.g. through considering separate targets for separate collection, recycling and preparation of re-use of textile waste) and to secure funding (e.g. through considering an EPR scheme for textiles and use of EU funding). Based on this, provision of and access to feedstock for recycling could be simplified. Initiating and further supporting standardisation efforts, e.g. in the area of sorting, appears as a key measure here, and could result in taking up harmonised standards in EU legislation. A further important step could be to enhance the traceability of materials and chemicals used in textiles (see also Chapter 5). Here, enabling automatic sorting of textile waste (see section 5.2.1) could induce a leap forward in the uptake of textile recycling technologies, making it economically much more attractive.

Once a starting position of textile-to-textile recycling is prepared, as a second step, design for recyclability could be facilitated and, at the same time, the market for recycled fibres be stimulated. Here, our findings indicate that jeans and T-shirts could be suitable product groups to pioneer mandatory design requirements as well as mandatory recycled content. Design requirements could ensure that when producing these products, recyclability is taken into account. Over time, this could enable a gradual increase of recycled content.

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List of abbreviations

BHET	Bis(2-Hydroxyethyl) terephthalate
CAPEX	Capital Expenditure
CN	Combined Nomenclature
DMT	Dimethyl terephthalate
EG	Ethylene glycol
EoL	End-of-life
EPD	Environmental Product Declaration
EPR	Extended Producer Responsibility
EU	European Union
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
MEG	Monoethylene glycol
MMCF	man-made cellulosic fibres
n.d.	no date
NACE	Statistical classification of economic activities in the European Community
NMMO	N-methylmorpholine-N-oxide
OPEX	Operational Expenditure
PA	Polyamide
PE	Polyethylene
PES	Polyester
PET	Polyethylene Terephthalate
PP	Polypropylene
PTA	Purified Terephthalic Acid
TA	Terephthalic acid
TP	Terephthalate
TRL	Technology Readiness Level

PEF	Product Environmental Footprint
LCT	Life Cycle Thinking
LCIA	Life Cycle Impact Assessment
PEF	Product Environmental Footprint
WEEE	Waste Electrical and Electronic Equipment
WFD	Waste Framework Directive
WSR	Waste Shipment Regulation

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A. Annex 1: Life Cycle Assessments

A.1 Methodology for Life Cycle Assessment (LCA)

To assess environmental aspects specifically related to the textile recycling technologies following a value (life cycle) chain perspective, the *Life Cycle Assessment (LCA) approach* is a scientifically sound and generally approved methodology. Life Cycle Thinking (LCT) is the consideration of the upstream and downstream benefits and trade-offs. LCT seeks to identify environmental improvement opportunities at all stages across the life cycle: from raw material extraction and conversion, product manufacture, through distribution, use and at the end-of-life stage. Its fundamental aim is to provide a structured and comprehensive approach in support of the overall reduction of environmental impacts. LCT and LCA can be applied in a broad context, e.g. related to legislation or to consumption patterns of specific products, but as well in a specific focus e.g. to specific technologies or to circular business models or strategies.

When performing an LCA, all inputs (resources and energy consumed) and outputs (emissions and waste) are quantified and their potential effects on the environment, human health and resource depletion are determined. One of the strengths of LCA is that it encompasses the total life cycle and a wide range of environmental impacts and thus avoids burden shifting between life cycle phases or types of environmental effect. The results of an LCA can be used, for example, to gain insight into the environmental hotspots or to make a comparison of the environmental impacts of products and processes with a similar function.

According to all relevant guidelines, an LCA must be performed in 4 steps:

- Goal and scope definition: definition of the goal of study, functional unit, system boundaries and modelling choices.
- Life cycle inventory (LCI): data collection and data calculation.
- Life Cycle Impact Assessment (LCIA): inventory results are converted to a number of environmental themes, like climate change, ozone depletion, toxicity, etc.
- Interpretation: interpretation of results, hotspot analysis, robustness of results and conclusions and recommendations.

The relation between the different phases is illustrated in Figure 48.

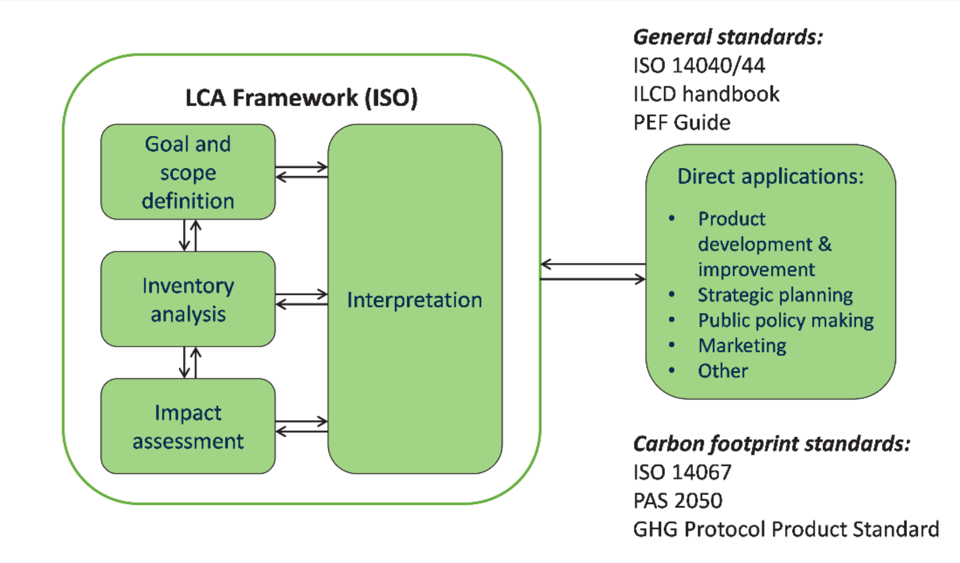

Figure 48: Phases of the LCA methodology (adapted from ISO 14040/44)

A.1.1 Goals and scope

The goal of the life cycle assessments is to gain insight in the environmental aspects of identified recycling technologies for textiles. The recycling processes will be benchmarked against the avoided 'product': depending on type of fibre and the type of recycling process this can be the virgin fibre or pulp for new fibres (fibre to fibre (closed loop) recycling) or virgin polymer or monomer production (open loop recycling).

A.1.2 Functional unit

To allow a fair comparison of the selected recycling processes, a reference basis (called 'functional unit' in LCA) has been defined. This is the reference unit for which environmental and economic parameters have been assessed. The functional unit adopted in this project is **'the treatment of one tonne of textile material'**.

A.1.3 System boundaries

All steps required for the recycling technology are included in the scope and if relevant also steps following the recycling technology when they are different from the traditional processes (e.g. yarn spinning with recycled fibres).

For this study it is important to include <u>the environmental impacts related to the recycling techniques</u> (e.g. due to energy use) and the <u>avoided impacts. Avoided impacts are impacts that can be avoided due to the use of output materials of the recycling process which replace virgin materials</u> like cotton fibres, wood pulp or fossil based PET resins. The life cycle starts at the sorting plant, where used textiles are sorted (end-of-waste point at the sorting facility). The textiles are considered to be burden free. A literature review by Subramanian et al. (2020) revealed that the main methodological assumption in most of the LCA studies of textile recycling approaches is that waste sent for recycling is considered burden free from environmental impacts (cut-off approach or recycled content approach), and the textiles made from recycled materials replace textiles made from virgin fibres (system expansion). In this study the same approach has been followed and as such, the study is in line with other studies on the topic.

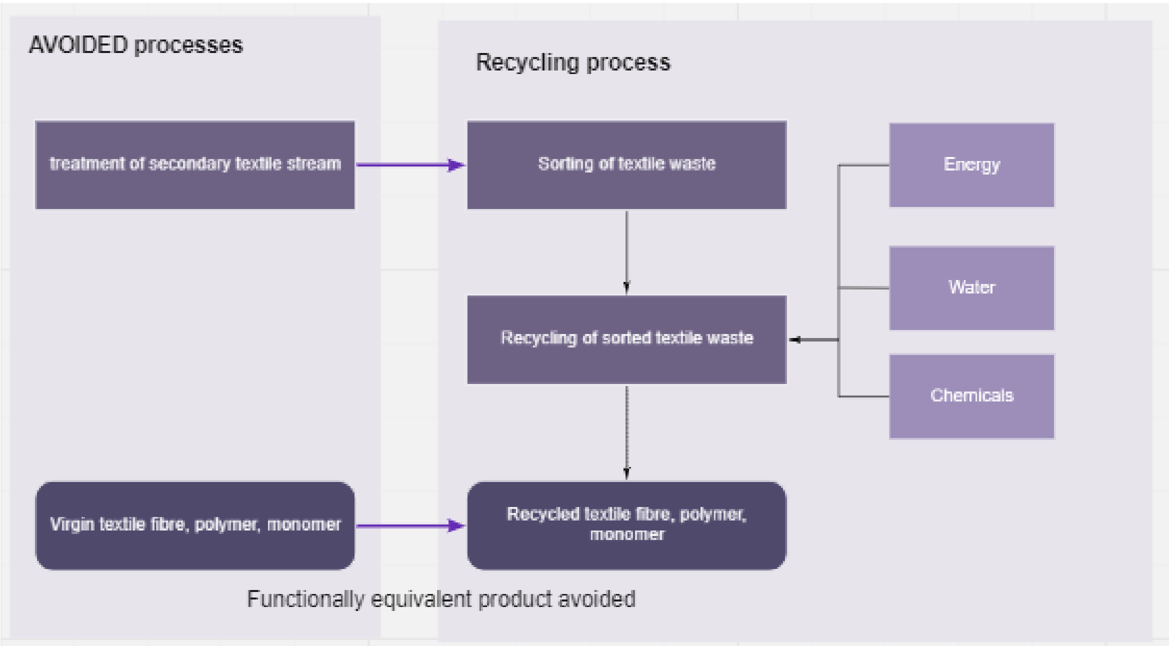

Figure 49 : System boundaries for the life cycle assessment

A.1.4 Types of impact and methodology of impact assessment for LCA

Translating all data into environmental impacts is based on *life cycle impact assessment* (LCIA) methodologies. The LCIA methodology applied in this study is the Environmental Footprint (EF) method, which is developed and supported by the Commission, and defines the environmental indicators listed in Table 22 (Zampori and Pant 2019).

Table 22: Environmental impact categories according to the EF method (version 3.0)

Environmental impact category	Unit
Climate change, total	kg CO_2 eq.
Ozone depletion	kg CFC-11 eq.
Human toxicity, cancer	CTUh
Human toxicity, non-cancer	CTUh
Particulate matter	disease incidence
Ionising radiation, human health	kBq U^{235} eq.
Photochemical ozone formation, human health	kg NMVOC eq.
Acidification	mol H+ eq.
Eutrophication, terrestrial	mol N eq.
Eutrophication, freshwater	mol P eq.
Eutrophication, marine	mol N eq.
Ecotoxicity, freshwater	CTUe
Land use	Pt
Water use[27]	m^3 world eq.
Resource use, minerals and metals	kg Sb eq.
Resource use, fossils	MJ

The impact assessment results in an individual environmental profile for each selected recycling technology, which gives insight in the environmental hot spots and in the ratio of environmental impacts of the recycling process versus the benefits (avoided impacts) due to avoided virgin production ('benchmark').

A.2 Methodology Life Cycle Costing (LCC)

For each of the unit operations a life cycle costing model is constructed where the economic outcomes (CAPEX and OPEX) for each year are related to the process and flowsheet model of each unit operation. Based on this, the projected cash flows for the evaluation period (typically 20 years) can be calculated.

Since a single unit process will not be economically viable on its own, the cost and revenues have to be considered over the entire textile system in order to provide insights on the economic viability of the technologies that are being developed. The main revenues can be only determined at a later stage in a textile system, where fabrics, fibres or poly-/oligo-/monomers are extracted and valorised, whereas costs will arise at each stage of the system.

[27] This is the impact category water use. The calculated values for this impact category represent direct and indirect water use. Direct water use is the water used in the recycling process itself. Indirect water use is water which is for example used during electricity production, where electricity is input into the recycling process. The inventory data are translated into a characterised result using the EF 3.0 method. The method used to translate inventory data to characterised results takes into account a water scarcity level, meaning that the characterisation factor differs for the type of water used and for the country where the water is sourced from.

A.3 Life cycle inventory (LCI)

Ideally during *data inventory*, for each of the textile recycling processes data and information is available that allow to calculate the environmental impacts on a detailed level. This encompasses data for:

Input flows: use of

- Energy (e.g. electricity or natural gas for heating)
- Water (e.g. water for washing step)
- Materials (e.g. solvents for chemical recycling)

Output flows:

- Waste (e.g. efficiency of recycling)
- Emissions to air and water (e.g. related to solvent use)

The original purpose of this study was to obtain life cycle inventory data from technology holders. However, in many cases this proved to be impossible. Only a few technology holders were able to share life cycle inventory data ball park figures. These are the technology holders of the following recycling technologies:

- Mechanical recycling of cotton, polycotton, polyester and polyamide
- Enzymatic recycling of polycotton

There are various reasons why data cannot be shared. Some processes are still at a low TRL level. In this case, LCI data is often of little relevance and can change significantly with the further development of the technology. Often it also concerns information that companies wish to keep confidential in order to guarantee ownership of a technology in development. Furthermore, collecting the requested information also requires a time commitment from the companies, time that is not always available.

In addition to the above mentioned life cycle inventory datasets the authors established a dataset for cotton recycling into cellulose pulp making use of information available in the ecoinvent database (Wernet, et al. 2016).

During the course of this project some publicly available sources of life cycle inventory data were identified. They are listed in the table below. In case the sources also contained calculated results, they are referenced in the main text. In addition to this, Sandin and Peters (2018) published an overview table with reference to publication of life cycle inventory data for textile recycling and reuse.

Overview of sources for life cycle inventory data for recycling of cotton available in literature.

Overview of literature sources for life cycle inventory data on recycling of textile				
Author, year	**Title publication**	**Input material**	**Recycling technology**	**TRL/scale**
Paunonen, S., Kamppuri, T. et al., 2019. (Paunonen, Kamppuri and et al. 2019)	Environmental impact of cellulose carbamate fibres from chemically recycled cotton	Cotton	Polymer recycling – carbamate technology	
Oelerich J. et al. 2017. (Oelerich and et al. 2017)	The life cycle assessment of cellulose pulp from	Cotton	Polymer recycling - pulping	

	waste cotton via the SaXcell TM process			
Subramanian K., Chopra S.S., Cakin E., Li X., Sze Ki Lin C. 2020. (Subramanian, et al. 2020) Please also refer to section A.4.1– the technology holder has communicated updates to the life cycle inventory for use in this study	Environmental life cycle assessment of textile bio-recycling - valorizing cotton-polyester textile waste to pet fiber and glucose syrup.	Polycotton (50/50)	Enzymatic recycling	The amount is technically representative for industrial scale, but technology currently at TRL5/6 – so guaranty on the accuracy of the numbers in actual industrial scale application cannot be given
Peters G., Spak B., Sandin G. 2019 (Peters, Spark and Sandin 2019)	LCA on recycling of blended fiber fabrics	Polycotton	Monomer recycling	Prospective LCA – laboratory scale data upscaled to large pilot plant
Franklin Associates, 2018 (Franklin Associations 2018)	Life Cycle Impacts for postconsumer recycled resins: PET, HDPE and PP	PET	Monomer recycling	Pg25/49

The following sections contain per input stream the life cycle inventory data obtained from or validated by technology holders, except for the life cycle inventory for polymer recycling of cotton which has been established by the authors by modifying a wood pulping process (see section A.4.2).

A.3.1 Life cycle inventory mechanical recycling cotton

Table 23 contains a life cycle inventory for the mechanical recycling of cotton. The inventory represents a worst case situation for the amount of spinnable fibres that will eventually be reused in a textile. Table 24 presents the life cycle assessment for a best case situation with regard to the avoided product. On overview of the two scenarios is provided in Table 12 in the main text. The technology level for which the data are applicable is industrial scale. The life cycle starts with the reception of the raw materials at the sorting facility. It is assumed that sorting is done manually. Other sorting techniques are currently being developed (see Chapter 3). They are however not the focus of this report. For data on collection and sorting, we refer the reader Köhler et al. (2021).

Table 23 : Life cycle inventory for mechanical recycling of cotton – worst case situation for avoided products

Mechanical recycling cotton – Worst case					
Input flow	**Amount**	**Unit**	**Data source**	**Record** (Wernet, et al. 2016)	**Comment**
Textile - cotton	1	ton	/	/	/
Electricity	500	kWh	Technology holder	Electricity, low voltage {RER}| market group for | Cut-off, U	/
Water	20	l	Technology holder	Tap water {RER}| market group for | Cut-off, U	/
Output flow	**Amount**	**Unit**	**Data source**	**Record**	**Comment**
Spinnable fibers	0.0475	ton	Average of the percentage spinnable fibres mentioned in Chapter 3	Avoided virgin cotton fibres: Fibre, cotton {GLO}| market for fibre, cotton | Cut-off, U Avoided waste incineration with energy recovery	5-20% spinnable fibres of the textile input -> worst case: 5% of the textile input, 4,75% of total input
Metals	0.05	ton	Technology holder	Scrap aluminium {Europe without Switzerland}| treatment of scrap aluminium, municipal incineration | Cut-off, U; Scrap copper {Europe without Switzerland}| treatment of scrap copper, municipal incineration | Cut-off, U; Scrap steel {Europe without Switzerland}| treatment of scrap steel, municipal incineration | Cut-off, U Records adapted: credits for material recovery removed	Buttons, zippers consist of different alloys and cannot be recycled, assumption made for the composition: 1/3 copper, 1/3 steel, 1/3 iron
Dust	0,03	ton	Technology holder	Waste textile, soiled {CH}| treatment of, municipal incineration | Cut-off, U Avoided products: Heat, district or industrial, natural gas {RER}| market group for | Cut-off, U; Electricity, medium voltage {RER}| market group for | Cut-off, U	
Fluff	Unknown part of 0.87	ton	Calculated (mass balance)		
Filling materials	Unknown part of 0.87	ton			

Table 24 : Life cycle inventory for mechanical recycling of cotton – best case situation for avoided products

Mechanical recycling cotton – best case for avoided product					
Input flow	**Amount**	**Unit**	**Data source**	**Record** (Wernet, et al. 2016)	**Comment**
Textile - cotton	1	ton	/	/	/
Electricity	500	kWh	Technology holder	Electricity, low voltage {RER}| market group for | Cut-off, U	/
Water	20	l	Technology holder	Tap water {RER}| market group for | Cut-off, U	/
Output flow	**Amount**	**Unit**	**Data source**	**Record**	**Comment**
Spinnable fibers	0.19	ton	Average of the percentage spinnable fibres mentioned in Chapter 3	Avoided virgin cotton fibres: Fibre, cotton {GLO}| market for fibre, cotton | Cut-off, U Avoided waste incineration with energy recovery	5-20% spinnable fibres of the textile input -> best case: 20% of the textile input, 19% of total input
Metals	0.05	ton	Technology holder	Scrap aluminium {Europe without Switzerland}| treatment of scrap aluminium, municipal incineration | Cut-off, U; Scrap copper {Europe without Switzerland}| treatment of scrap copper, municipal incineration | Cut-off, U; Scrap steel {Europe without Switzerland}| treatment of scrap steel, municipal incineration | Cut-off, U Records adapted: credits for material recovery removed	Buttons, zippers consist of different alloys and **cannot be recycled**, assumption made for the composition: 1/3 copper, 1/3 steel, 1/3 iron
Dust	0.03	ton	Technology holder	Waste textile, soiled {CH}| treatment of, municipal incineration | Cut-off, U Avoided products: Heat, district or industrial, natural gas {RER}| market group for | Cut-off, U; Electricity, medium voltage {RER}| market group for | Cut-off, U	
Fluff	Unknown part of 0.73	ton	Calculated (mass balance)	Avoided product: 25% Polyethylene terephthalate, granulate, bottle grade {RER}| production | Cut-off, U; 25% Polypropylene, granulate {RER}| production | Cut-off, U; cotton and cellulose fluff are assumed to enter the	Assumption: fluff and filling materials for use in non-wovens replace PET/PP/cottonfluff and cellulosefluff in equal amounts
Filling materials	Unknown part of 0.73	ton			

				product system burden free. Avoided waste incineration with energy recovery	

A.3.2 Life cycle inventory polymer recycling cotton

For polymer recycling of cotton can be done via a pulping process. It was not possible to obtain life cycle inventory data for polymer recycling of cotton via a pulping process from technology holders, however, several technology holders indicate that the process and chemical use is identical to a traditional pulp mill operation using wood as an input. In the ecoinvent database (Wernet, et al. 2016), life cycle inventory data are available for sulphate pulp and sulphite pulp. As a first attempt to estimate the environmental impact of cotton polymer recycling via pulping, we have replaced the wood input in the dataset for sulphate pulping and sulphite pulping with a cotton textile input. This input first undertakes a mechanical step similar to the mechanical recycling process. Data on this mechanical step are missing and is therefore assumed to be equal to the mechanical recycling process with half of the energy consumption (250 kWh instead of 500 kWh) The avoided products are on the one hand bleached sulphate pulp made from wood (both hardwood and softwood) and on the other hand bleached sulphite pulp made from wood (again, both hardwood and softwood). The textile material input also undergoes a mechanical step where zippers and buttons are removed and large textile parts are teared.

A.3.3 Life cycle inventory mechanical recycling polycotton

The life cycle inventory is identical to the inventory of cotton (see section A.3.1), with the exception of polycotton fibres being the avoided product instead of cotton fibres. Table 25 presents a worst case situation for the amount of spinnable fibres that will eventually be reused in a textile. Table 26 presents the life cycle assessment for a best case situation with regard to the avoided product. The technology level for which the data are applicable is industrial scale.

Table 25 : Life cycle inventory for mechanical recycling of polycotton – worst case situation for avoided products

Mechanical recycling polycotton – worst case for avoided products					
Input flow	**Amount**	**Unit**	**Data source**	**Record** (Wernet, et al. 2016)	**Comment**
Textile - polycotton	1	ton	/	/	/
Electricity	500	kWh	Technology holder	Electricity, low voltage {RER}| market group for | Cut-off, U	/
Water	20	l	Technology holder	Tap water {RER}| market group for | Cut-off, U	/
Output flow	**Amount**	**Unit**	**Data source**	**Record**	**Comment**
Spinnable fibers	0.25	ton	Lower end of the range for spinnable fibres	0.125 ton avoided virgin cotton fibres: Fibre, cotton {GLO}|	25-55% spinnable fibres of the input -> worst case: 25%

			mentioned in Chapter 3	market for fibre, cotton | Cut-off, U 0.125 ton avoided virgin polyester fibres: Fibre, polyester {GLO}| market for fibre, polyester | Cut-off, U Avoided waste incineration with energy recovery	
Metals	0.05	ton	Technology holder	Scrap aluminium {Europe without Switzerland}| treatment of scrap aluminium, municipal incineration | Cut-off, U; Scrap copper {Europe without Switzerland}| treatment of scrap copper, municipal incineration | Cut-off, U; Scrap steel {Europe without Switzerland}| treatment of scrap steel, municipal incineration | Cut-off, U Records adapted: credits for material recovery removed	Buttons, zippers consist of different alloys and cannot be recycled, assumption made for the composition: 1/3 copper, 1/3 steel, 1/3 iron
Dust	0.03	ton	Technology holder	Waste textile, soiled {CH}| treatment of, municipal incineration | Cut-off, U and Waste polyethylene {CH}| treatment of, municipal incineration | Cut-off, U Avoided products: Heat, district or industrial, natural gas {RER}| market group for | Cut-off, U; Electricity, medium voltage {RER}| market group for | Cut-off, U	
Fluff	Unknown part of 0.67	ton	Calculated (mass balance)		
Filling materials	Unknown part of 0.67	ton			

Table 26 : Life cycle inventory for mechanical recycling of polycotton – best case situation for avoided products

Mechanical recycling polycotton – best case for avoided products

Input flow	Amount	Unit	Data source	**Record** (Wernet, et al. 2016)	Comment
Textile - polycotton	1	ton	/	/	/
Electricity	500	kWh	Technology holder	Electricity, low voltage {RER}| market group for | Cut-off, U	/
Water	20	l	Technology holder	Tap water {RER}| market group for | Cut-off, U	/
Output flow	**Amount**	**Unit**	**Data source**	**Record**	**Comment**
Spinnable fibers	0.55	ton	Higher end of the range for spinnable fibres mentioned in Chapter 3	0.275 ton avoided virgin cotton fibres: Fibre, cotton {GLO}| market for fibre, cotton | Cut-off, U 0.275 ton avoided virgin polyester fibres: Fibre, polyester {GLO}| market for fibre, polyester | Cut-off, U Avoided waste incineration with energy recovery	25-55% spinnable fibres of the input -> best case: 55%
Metals	0.05	ton	Technology holder	Scrap aluminium {Europe without Switzerland}| treatment of scrap aluminium, municipal incineration | Cut-off, U; Scrap copper {Europe without Switzerland}| treatment of scrap copper, municipal incineration | Cut-off, U; Scrap steel {Europe without Switzerland}| treatment of scrap steel, municipal incineration | Cut-off, U Records adapted: credits for material recovery removed	Buttons, zippers consist of different alloys and cannot be recycled, assumption made for the composition: 1/3 copper, 1/3 steel, 1/3 iron
Dust	0.03	ton	Technology holder	Waste textile, soiled {CH}| treatment of, municipal incineration | Cut-off, U and Waste polyethylene {CH}| treatment of, municipal	

				incineration | Cut-off, U Avoided products: Heat, district or industrial, natural gas {RER}| market group for | Cut-off, U; Electricity, medium voltage {RER}| market group for | Cut-off, U	
Fluff	Unknown part of 0.37	ton	Calculated (mass balance)	Avoided product: 25% Polyethylene terephthalate, granulate, bottle grade {RER}| production | Cut-off, U; 25% Polypropylene, granulate {RER}| production | Cut-off, U; cotton and cellulose fluff are assumed to enter the product system burden free. Avoided waste incineration with energy recovery	Assumption: fluff and filling materials for use in non-wovens replace PET/PP/cottonfluff and cellulosefluff in equal amounts
Filling materials	Unknown part of 0.37	ton			

A.3.4 Life cycle inventory enzymatic recycling polycotton (50/50)

The values are technically representative an industrial-scale process. The process is currently at TRL5/6 level and a validation of the values at industrial scale has therefore not yet taken place.

Table 27 : Life cycle inventory for enzymatic recycling of polycotton

Enzymatic recycling polycotton (source: (Subramanian, et al. 2020) **and personal communication)**					
Input flow	**Amount**	**Unit**	**Data source**	**Record** (Wernet, et al. 2016)	**Comment**
Textile - polycotton	1	ton	/	/	/
Electricity	250	kWh	Technology holder	Electricity, low voltage {RER}| market group for | Cut-off, U	For tearing, baling… - data on this mechanical step are missing and is therefore assumed to be equal to the mechanical recycling process with half of the energy consumption (250 kWh instead of 500 kWh) same as

					mechanical recycling
Water	20	l	Technology holder	Tap water {RER}| market group for | Cut-off, U	Same as mechanical recycling
NaOH	0.189	ton	Technology holder	Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Cut-off, U	
Citric acid	0.302	ton	Technology holder	Citric acid {GLO}| market for | Cut-off, U	
Cellulase	0.264	ton	Technology holder	Enzymes {GLO}| market for enzymes | Cut-off, U	
Beta glucosidase	0.026	ton	Technology holder	Enzymes {GLO}| market for enzymes | Cut-off, U	
Activated carbon	0.0004	ton	Technology holder	Activated carbon, granular {RER}| activated carbon production, granular from hard coal | Cut-off, U	
H_2SO_4	0.008	ton	Technology holder	Sulfuric acid {GLO}| market for | Cut-off, U	
Monosphere resin 88 (cationic)	0.218	ton	Technology holder	PROXY Polystyrene, general purpose {GLO}| market for | Cut-off, U	Strong acid cation, matrix: styrene, functional group: sulfonate
Monosphere resin 66 (anionic)	0.218	ton	Technology holder	PROXY Polystyrene, general purpose {GLO}| market for | Cut-off, U	Weak base anion, matrix: styrene, functional group: tertiary amine
Water	32.44	ton	Technology holder	Tap water {RER}| market group for | Cut-off, U	
Electricity	151.82	kWh	Technology holder	Electricity, low voltage {RER}| market group for | Cut-off, U	
Steam	6.68	ton	(Subramanian, et al. 2020)	Steam, in chemical industry {RER}| market for steam, in chemical industry | Cut-off, U	

Output flow	Amount	Unit	Data source	Record	Comment
Metals	0.05	ton	Technology holder	Scrap aluminium {Europe without Switzerland}| treatment of scrap aluminium, municipal incineration | Cut-off, U; Scrap copper {Europe without Switzerland}| treatment of scrap copper, municipal incineration | Cut-off, U; Scrap steel {Europe without Switzerland}| treatment of scrap steel, municipal incineration | Cut-off, U Records adapted: credits for material recovery removed	Buttons, zippers consist of different alloys and cannot be recycled, assumption made for the composition: 1/3 copper, 1/3 steel, 1/3 iron
Dust	0.03	ton	Technology holder	Waste textile, soiled {CH}| treatment of, municipal incineration | Cut-off, U Avoided products: Heat, district or industrial, natural gas {RER}| market group for | Cut-off, U; Electricity, medium voltage {RER}| market group for | Cut-off, U	From mechanical recycling process
PET fibres	0.377	ton	Technology holder	Avoided product: Fibre, polyester {GLO}| market for fibre, polyester | Cut-off, U	
Glucose syrup	0.377	ton	Technology holder	Avoided product: Glucose {GLO}| market for glucose | Cut-off, U	
Waste water to treatment	33.397	m3	Calculated based on mass balance	Wastewater from textile production {GLO}| market for wastewater from textile production | Cut-off, U	

A.3.5 Life cycle inventory mechanical recycling polyester

Table 28 contains a life cycle inventory for the mechanical recycling of polyester. The inventory represents a worst case situation for the amount of spinnable fibres that will eventually be reused in a textile. Table 29 presents the life cycle assessment for a best case situation with regard to the avoided product. The technology level for which the data are applicable is industrial scale. The life cycle starts with the reception of the raw materials at the sorting facility. It is assumed that sorting is done manually. Other sorting techniques are currently being developed (see Chapter 3). They are however not the focus of this report. For data on collection and sorting, we refer the reader to Köhler et al. (2021).

Table 28 : Life cycle inventory for mechanical recycling of polyester – worst case situation for avoided products

Mechanical recycling polyester – worst case for avoided products					
Input flow	**Amount**	**Unit**	**Data source**	**Record** (Wernet, et al. 2016)	**Comment**
Textile - polyester	1	ton	/	/	/
Electricity	500	kWh	Technology holder	Electricity, low voltage {RER}| market group for | Cut-off, U	/
Water	20	l	Technology holder	Tap water {RER}| market group for | Cut-off, U	/
Output flow	**Amount**	**Unit**	**Data source**	**Record**	**Comment**
Spinnable fibers	0.25	ton	Average of the percentage spinnable fibres mentioned in Chapter 3	0.25 ton avoided virgin polyester fibres: Fibre, polyester {GLO}| market for fibre, polyester | Cut-off, U Avoided waste incineration with energy recovery	25-55% spinnable fibres of the input -> worst case: 25%
Metals	0.05	ton	Technology holder	Scrap aluminium {Europe without Switzerland}| treatment of scrap aluminium, municipal incineration | Cut-off, U; Scrap copper {Europe without Switzerland}| treatment of scrap copper, municipal incineration | Cut-off, U; Scrap steel {Europe without Switzerland}| treatment of scrap steel, municipal incineration | Cut-off, U Records adapted: credits for material recovery removed	Buttons, zippers consist of different alloys and cannot be recycled, assumption made for the composition: 1/3 copper, 1/3 steel, 1/3 iron
Dust	0.03	ton	Technology holder	Waste polyethylene {CH}| treatment of, municipal	

Fluff	Unknown part of 0.67	ton	Calculated (mass balance)	incineration | Cut-off, U Avoided products: Heat, district or industrial, natural gas {RER}| market group for | Cut-off, U; Electricity, medium voltage {RER}| market group for | Cut-off, U	
Filling materials	Unknown part of 0.67	ton			

Table 29 : Life cycle inventory for mechanical recycling of polyester – best case situation for avoided products

Mechanical recycling polyester – best case for avoided products					
Input flow	**Amount**	**Unit**	**Data source**	**Record** (Wernet, et al. 2016)	**Comment**
Textile - polyester	1	ton	/	/	/
Electricity	500	kWh	Technology holder	Electricity, low voltage {RER}| market group for | Cut-off, U	/
Water	20	l	Technology holder	Tap water {RER}| market group for | Cut-off, U	/
Output flow	**Amount**	**Unit**	**Data source**	**Record**	**Comment**
Spinnable fibers	0.55	ton	Average of the percentage spinnable fibres mentioned in Chapter 3	0.55 ton avoided virgin polyester fibres: Fibre, polyester {GLO}| market for fibre, polyester | Cut-off, U Avoided waste incineration with energy recovery	25-55% spinnable fibres of the input -> best case: 55%
Metals	0.05	ton	Technology holder	Scrap aluminium {Europe without Switzerland}| treatment of scrap aluminium, municipal incineration | Cut-off, U; Scrap copper {Europe without Switzerland}| treatment of scrap copper, municipal incineration | Cut-off, U; Scrap steel {Europe without Switzerland}| treatment of scrap steel, municipal incineration | Cut-off, U	Buttons, zippers consist of different alloys and cannot be recycled, assumption made for the composition: 1/3 copper, 1/3 steel, 1/3 iron

				Records adapted: credits for material recovery removed	
Dust	0.03	ton	Technology holder	Waste polyethylene {CH}| treatment of, municipal incineration | Cut-off, UAvoided products: Heat, district or industrial, natural gas {RER}| market group for | Cut-off, U; Electricity, medium voltage {RER}| market group for | Cut-off, U	
Fluff	Unknown part of 0.37	ton	Calculated (mass balance)	Avoided product: 25% Polyethylene terephthalate, granulate, bottle grade {RER}| production | Cut-off, U; 25% Polypropylene, granulate {RER}| production | Cut-off, U; cotton and cellulose fluff are assumed to enter the product system burden free. Avoided waste incineration with energy recovery	Assumption: fluff and filling materials for use in non-wovens replace PET/PP/cottonfluff and cellulosefluff in equal amounts
Filling materials	Unknown part of 0.37	ton			

A.3.6 Life cycle inventory mechanical recycling polyamide

Table 30 contains a life cycle inventory for the mechanical recycling of polyamide. The inventory represents a worst case situation for the amount of spinnable fibres that will eventually be reused in a textile. Table 31 presents the life cycle assessment for a best case situation with regard to the avoided product. The technology level for which the data are applicable is industrial scale. The life cycle starts with the reception of the raw materials at the sorting facility. It is assumed that sorting is done manually. Other sorting techniques are currently being developed (see Chapter 3). They are however not the focus of this report. For data on collection and sorting, we refer the reader to Köhler et al. (2021).

Table 30: Life cycle inventory for mechanical recycling of polyamide – worst case situation for avoided products

Mechanical recycling polyamide – worst case for avoided products					
Input flow	**Amount**	**Unit**	**Data source**	**Record** (Wernet, et al. 2016)	**Comment**
Textile - polyester	1	ton	/	/	/
Electricity	500	kWh	Technology holder	Electricity, low voltage {RER}|	/

				market group for | Cut-off, U	
Water	20	l	Technology holder	Tap water {RER}| market group for | Cut-off, U	/
Output flow	**Amount**	**Unit**	**Data source**	**Record**	**Comment**
Spinnable fibers	0.25	ton	Average of the percentage spinnable fibres mentioned in Chapter 3	0.25 ton avoided virgin polyester fibres: Fibre, polyester {GLO}| market for fibre, polyester | Cut-off, U_adapted to polyamide fibres (PA6) -> polyester input in ecoinvent record replaced by polyamide 6 input. Avoided waste incineration with energy recovery	25-55% spinnable fibres of the input -> worst case: 25%
Metals	0.05	ton	Technology holder	Scrap aluminium {Europe without Switzerland}| treatment of scrap aluminium, municipal incineration | Cut-off, U; Scrap copper {Europe without Switzerland}| treatment of scrap copper, municipal incineration | Cut-off, U; Scrap steel {Europe without Switzerland}| treatment of scrap steel, municipal incineration | Cut-off, U Records adapted: credits for material recovery removed	Buttons, zippers consist of different alloys and cannot be recycled, assumption made for the composition: 1/3 copper, 1/3 steel, 1/3 iron
Dust	0.03	ton	Technology holder	Waste plastic, mixture {CH}| treatment of, municipal incineration | Cut-off, U Avoided products: Heat, district or industrial, natural gas {RER}| market group for | Cut-off, U; Electricity, medium voltage {RER}| market group for | Cut-off, U	
Fluff	Unknown part of 0.67	ton	Calculated (mass balance)		
Filling materials	Unknown part of 0.67	ton			

Table 31 : Life cycle inventory for mechanical recycling of polyamide – best case situation for avoided products

Mechanical recycling polyamide – best case for avoided products					
Input flow	**Amount**	**Unit**	**Data source**	**Record** (Wernet, et al. 2016)	**Comment**
Textile-polyester	1	ton	/	/	/
Electricity	500	kWh	Technology holder	Electricity, low voltage {RER}| market group for | Cut-off, U	/
Water	20	l	Technology holder	Tap water {RER}| market group for | Cut-off, U	/
Output flow	**Amount**	**Unit**	**Data source**	**Record**	**Comment**
Spinnable fibers	0.55	ton	Average of the percentage spinnable fibres mentioned in Chapter 3	0.55 ton avoided virgin polyester fibres: Fibre, polyester {GLO}| market for fibre, polyester | Cut-off, U_adapted to polyamide fibres (PA6) -> polyester input in ecoinvent record replaced by polyamide 6 input. Avoided waste incineration with energy recovery	25-55% spinnable fibres of the input -> best case: 55%
Metals	0.05	ton	Technology holder	Scrap aluminium {Europe without Switzerland}| treatment of scrap aluminium, municipal incineration | Cut-off, U; Scrap copper {Europe without Switzerland}| treatment of scrap copper, municipal incineration | Cut-off, U; Scrap steel {Europe without Switzerland}| treatment of scrap steel, municipal incineration | Cut-off, U	Buttons, zippers consist of different alloys and cannot be recycled, assumption made for the composition: 1/3 copper, 1/3 steel, 1/3 iron

				Records adapted: credits for material recovery removed	
Dust	0.03	ton	Technology holder	Waste plastic, mixture {CH}| treatment of, municipal incineration | Cut-off, U Avoided products: Heat, district or industrial, natural gas {RER}| market group for | Cut-off, U; Electricity, medium voltage {RER}| market group for | Cut-off, U	
Fluff	Unknown part of 0.37	ton	Calculated (mass balance)	Avoided product: 25% Polyethylene terephthalate, granulate, bottle grade {RER}| production | Cut-off, U; 25% Polypropylene, granulate {RER}| production | Cut-off, U; cotton and cellulose fluff are assumed to enter the product system burden free. Avoided waste incineration with energy recovery	Assumption: fluff and filling materials for use in non-wovens replace PET/PP/cottonfluff and cellulosefluff in equal amounts
Filling materials	Unknown part of 0.37	ton			

A.4 Results life cycle impact assessment

A.4.1 Results life cycle assessment mechanical recycling cotton

Figure 50 shows the environmental profile of the mechanical recycling of 1 tonne of cotton textile, using the worst case situation for the avoided products (5% spinnable fibres, remaining part of cotton output burned with energy recovery). Overall, there are more impact categories where the environmental benefits outweigh the impacts. Figure 51 shows the results for the best case scenario with regard to the avoided products and Table 32 and Table 33 provide the absolute values per tonne of cotton treated for the two scenarios.

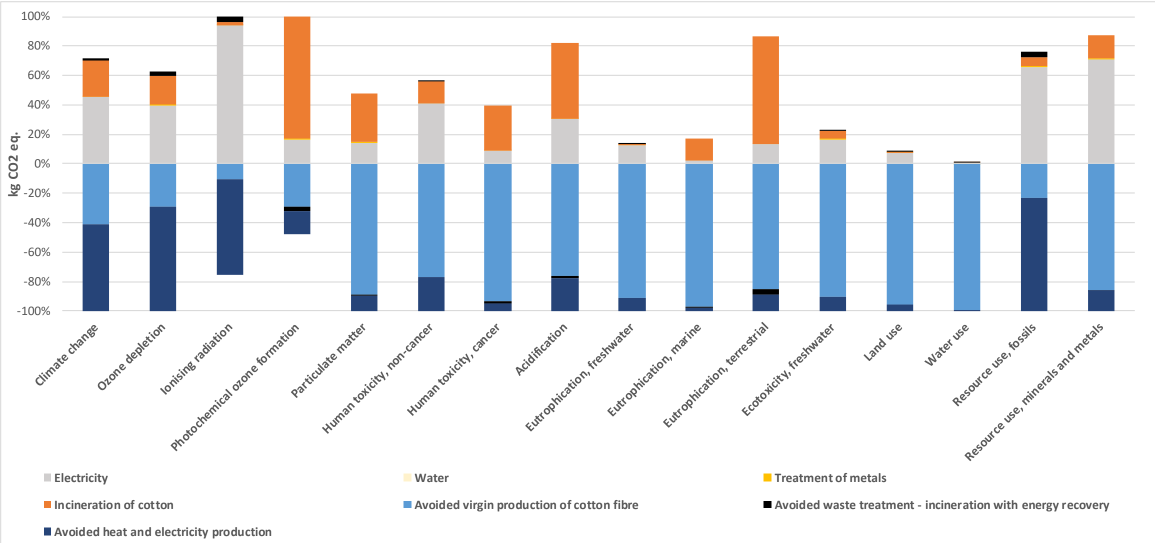

Figure 50 : Characterised environmental profile for the mechanical recycling of cotton – worst case scenario for the avoided material

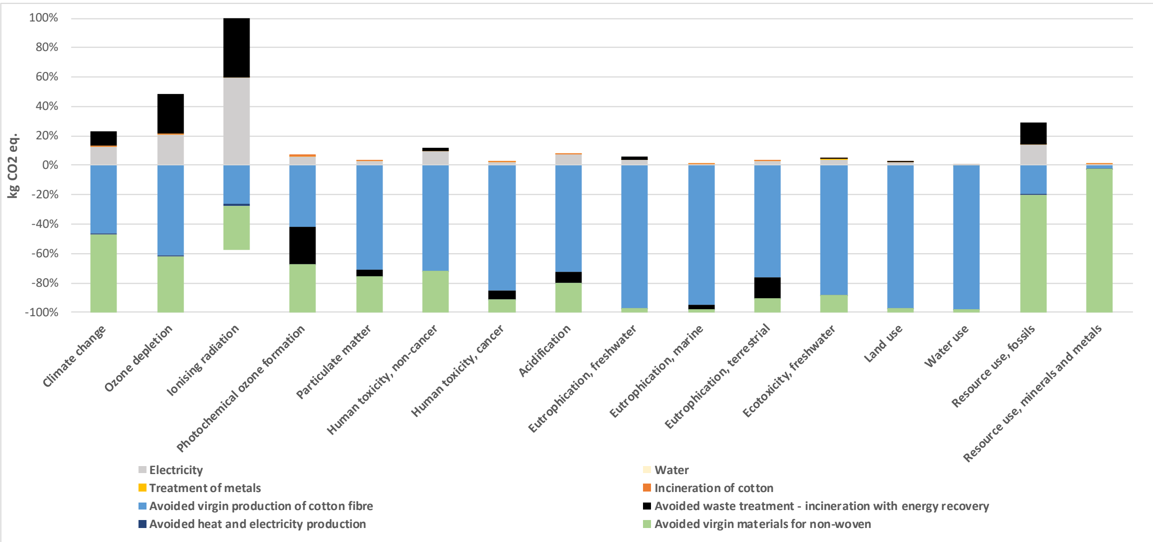

Figure 51 : Characterised environmental profile for the mechanical recycling of cotton – best case scenario for the avoided material

Table 32 : Absolute values for characterized environmental profile of mechanical recycling of cotton – worst case situation for avoided products

Impact category	Unit	Electricity	Water	Treatment of metals	Incineration of cotton	Avoided virgin production of cotton fibre	Avoided waste treatment - incineration with energy recovery	Avoided heat and electricity production
Climate change	kg CO2 eq	2,14E+02	6,90E-03	6,91E-01	1,15E+02	-1,93E+02	8,57E+00	-2,78E+02
Ozone depletion	kg CFC11 eq	1,80E-05	6,07E-10	1,59E-07	8,72E-06	-1,32E-05	1,21E-06	-3,18E-05
Ionising radiation	kBq U-235 eq	3,83E+01	8,10E-04	4,63E-02	1,06E+00	-4,22E+00	1,35E+00	-2,66E+01
Photochemical ozone formation	kg NMVOC eq	4,91E-01	2,32E-05	5,18E-03	2,46E+00	-8,53E-01	-1,06E-01	-4,50E-01
Particulate matter	disease inc.	3,25E-06	3,36E-10	1,55E-07	7,54E-06	-2,02E-05	-2,76E-07	-2,31E-06
Human toxicity, non-cancer	CTUh	2,64E-06	4,19E-10	2,12E-08	9,42E-07	-4,99E-06	2,79E-08	-1,47E-06
Human toxicity, cancer	CTUh	7,75E-08	1,87E-11	1,29E-09	2,73E-07	-8,33E-07	-1,20E-08	-4,66E-08
Acidification	mol H+ eq	1,24E+00	4,00E-05	4,55E-03	2,08E+00	-3,08E+00	-6,18E-02	-9,14E-01
Eutrophication, freshwater	kg P eq	2,26E-02	5,48E-07	1,17E-05	7,60E-04	-1,60E-01	7,62E-04	-1,52E-02
Eutrophication, marine	kg N eq	1,57E-01	6,35E-06	1,51E-03	1,11E+00	-7,22E+00	-5,14E-02	-1,38E-01

Eutrophication, terrestrial	mol N eq	1,94E+00	7,38E-05	1,66E-02	1,09E+01	-1,27E+01	-4,87E-01	-1,66E+00
Ecotoxicity, freshwater	CTUe	3,00E+03	1,29E-01	1,39E+02	1,00E+03	-1,66E+04	4,14E+01	-1,79E+03
Land use	Pt	1,07E+03	3,31E-02	1,97E+01	1,06E+02	-1,41E+04	2,99E+01	-6,75E+02
Water use	m3 depriv.	4,90E+01	8,60E-01	-5,25E-01	1,93E+01	-6,55E+03	8,19E-01	-3,50E+01
Resource use, fossils	MJ	4,38E+03	1,17E-01	1,25E+01	4,46E+02	-1,54E+03	2,45E+02	-5,11E+03
Resource use, minerals and metals	kg Sb eq	2,91E-04	1,03E-08	1,16E-06	6,41E-05	-3,51E-04	-3,63E-07	-5,74E-05

Table 33 : Absolute values for characterized environmental profile of mechanical recycling of cotton – best case situation for avoided products

Impact category	**Unit**	**Electricity**	**Water**	**Treatment of metals**	**Incineration of cotton**	**Avoided virgin production of cotton fibre**	**Avoided waste treatment - incineration with energy recovery**	**Avoided heat and electricity production**	**Avoided virgin materials for non-woven**
Climate change	kg CO2 eq	2,14E+02	6,90E-03	6,91E-01	3,82E+00	-7,74E+02	1,66E+02	-9,23E+00	-8,80E+02
Ozone depletion	kg CFC11 eq	1,80E-05	6,07E-10	1,59E-07	2,91E-07	-5,26E-05	2,35E-05	-1,06E-06	-3,24E-05
Ionising radiation	kBq U-235 eq	3,83E+01	8,10E-04	4,63E-02	3,52E-02	-1,69E+01	2,61E+01	-8,85E-01	-1,96E+01
Photochemical ozone formation	kg NMVOC eq	4,91E-01	2,32E-05	5,18E-03	8,18E-02	-3,41E+00	-2,05E+00	-1,50E-02	-2,68E+00
Particulate matter	disease inc.	3,25E-06	3,36E-10	1,55E-07	2,51E-07	-8,08E-05	-5,35E-06	-7,68E-08	-2,81E-05
Human toxicity, non-cancer	CTUh	2,64E-06	4,19E-10	2,12E-08	3,14E-08	-2,00E-05	5,40E-07	-4,90E-08	-7,76E-06
Human toxicity, cancer	CTUh	7,75E-08	1,87E-11	1,29E-09	9,10E-09	-3,33E-06	-2,32E-07	-1,55E-09	-3,31E-07
Acidification	mol H+ eq	1,24E+00	4,00E-05	4,55E-03	6,94E-02	-1,23E+01	-1,20E+00	-3,04E-02	-3,40E+00
Eutrophication, freshwater	kg P eq	2,26E-02	5,48E-07	1,17E-05	2,53E-05	-6,40E-01	1,48E-02	-5,07E-04	-1,95E-02
Eutrophication, marine	kg N eq	1,57E-01	6,35E-06	1,51E-03	3,71E-02	-2,89E+01	-9,96E-01	-4,60E-03	-6,00E-01
Eutrophication, terrestrial	mol N eq	1,94E+00	7,38E-05	1,66E-02	3,63E-01	-5,08E+01	-9,44E+00	-5,51E-02	-6,53E+00
Ecotoxicity, freshwater	CTUe	3,00E+03	1,29E-01	1,39E+02	3,34E+01	-6,63E+04	8,02E+02	-5,95E+01	-9,07E+03
Land use	Pt	1,07E+03	3,31E-02	1,97E+01	3,54E+00	-5,65E+04	5,80E+02	-2,24E+01	-1,47E+03
Water use	m3 depriv.	4,90E+01	8,60E-01	-5,25E-01	6,45E-01	-2,62E+04	1,59E+01	-1,16E+00	-4,98E+02
Resource use, fossils	MJ	4,38E+03	1,17E-01	1,25E+01	1,49E+01	-6,18E+03	4,75E+03	-1,70E+02	-2,55E+04
Resource use, minerals and metals	kg Sb eq	2,91E-04	1,03E-08	1,16E-06	2,14E-06	-1,40E-03	-7,04E-06	-1,91E-06	-6,40E-02

A.4.2 Results life cycle assessment polymer recycling cotton via pulping

Figure 52 shows the environmental profile of polymer recycling of 1 tonne of cotton via a sulphate pulping process. For the impact categories ‘Climate change’, ‘Ozone depletion’, ‘Ionising radiation’, ‘Ecotoxicity freshwater’ and ‘Resource use, fossils’, treating the cotton textile stream with a pulping process does not lead to a benefit. The opposite is true for the impact categories ‘Photochemical ozone formation’, ‘Human toxicity cancer’, ‘Eutrophication marine’, ‘Eutrophication terrestrial’ and ‘land use’. For some impact categories, the difference between benefits and burdens is small and probably falls within the error margin of the analysis. Also, the results are based on generic life cycle inventory data for a wood pulping process which have been modified to represent a pulping process with cellulose output, without having access to actual life cycle inventory data for polymer recycling of cotton via a pulping process from technology holders. Figure 53 shows the results for cotton recycling via a sulphite process. Table 34 and Table 35 provide the absolute values per tonne of cotton treated with respectively the sulphate and sulphite pulping process.

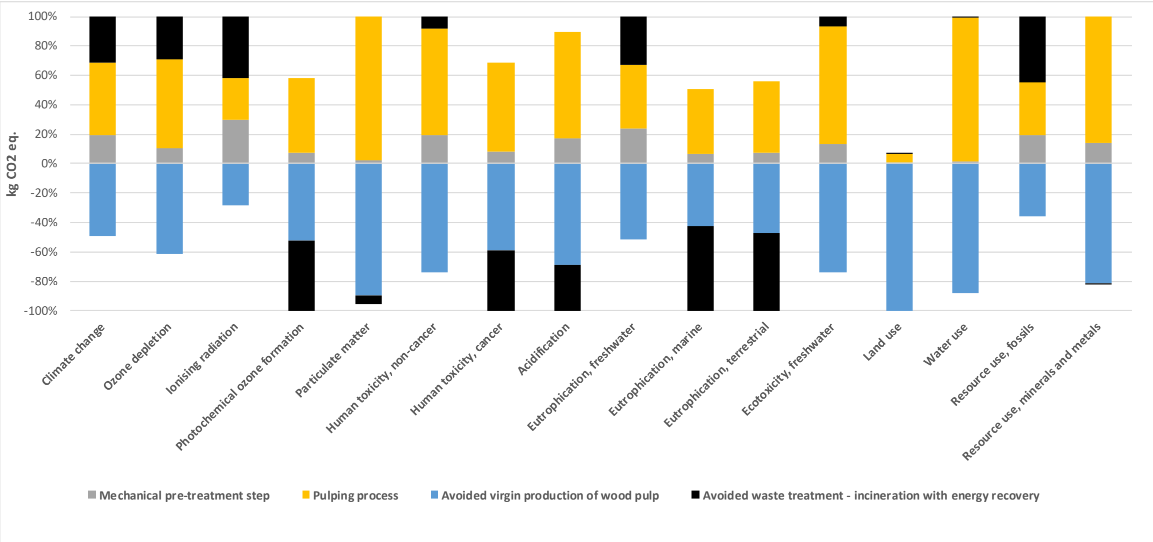

Figure 52 : Characterised environmental profile for the polymer recycling of cotton – sulphate pulping process

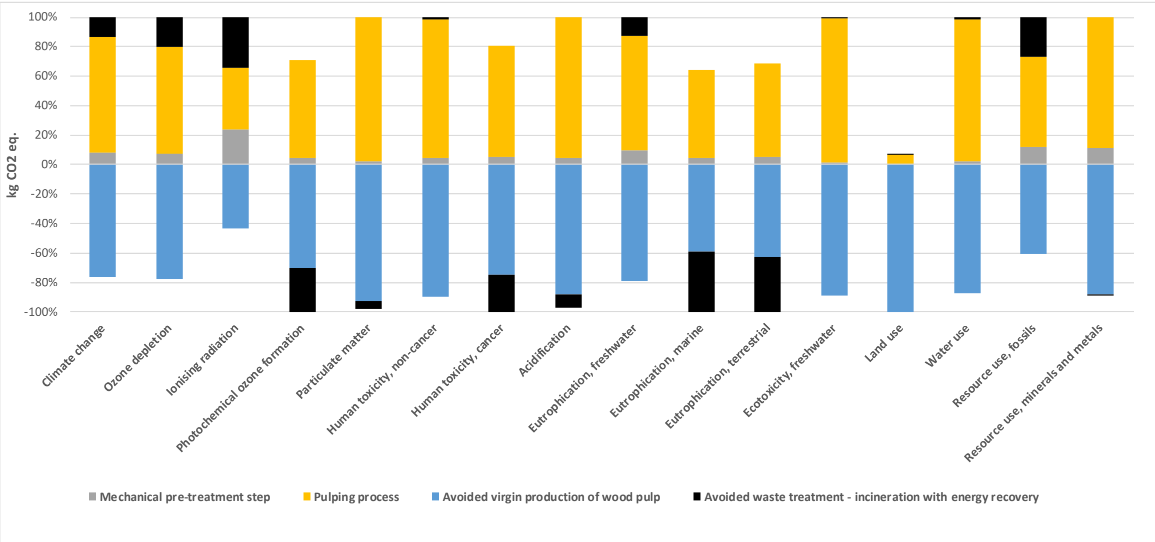

Figure 53 : Characterised environmental profile for the polymer recycling of cotton – sulphite pulping process

Table 34 : Absolute values for characterized environmental profile of polymer recycling of cotton – sulphate pulping process

Impact category	Unit	Mechanical pre-treatment step	Pulping process	Avoided virgin production of wood pulp	Avoided waste treatment - incineration with energy recovery
Climate change	kg CO2 eq	1,02E+02	2,59E+02	-2,61E+02	1,66E+02
Ozone depletion	kg CFC11 eq	8,37E-06	4,85E-05	-4,91E-05	2,35E-05
Ionising radiation	kBq U-235 eq	1,84E+01	1,76E+01	-1,74E+01	2,61E+01
Photochemical ozone formation	kg NMVOC eq	3,18E-01	2,21E+00	-2,28E+00	-2,05E+00
Particulate matter	disease inc.	1,95E-06	8,21E-05	-7,51E-05	-5,35E-06
Human toxicity, non-cancer	CTUh	1,32E-06	5,02E-06	-5,10E-06	5,40E-07
Human toxicity, cancer	CTUh	4,76E-08	3,38E-07	-3,31E-07	-2,32E-07
Acidification	mol H+ eq	6,63E-01	2,81E+00	-2,67E+00	-1,20E+00
Eutrophication, freshwater	kg P eq	1,09E-02	1,94E-02	-2,31E-02	1,48E-02
Eutrophication, marine	kg N eq	1,13E-01	7,67E-01	-7,45E-01	-9,96E-01
Eutrophication, terrestrial	mol N eq	1,29E+00	8,62E+00	-8,31E+00	-9,44E+00
Ecotoxicity, freshwater	CTUe	1,61E+03	9,40E+03	-8,79E+03	8,02E+02
Land use	Pt	5,36E+02	7,52E+03	-1,28E+05	5,80E+02

Water use	m3 depriv.	2,43E+01	1,53E+03	-1,38E+03	1,59E+01
Resource use, fossils	MJ	2,05E+03	3,87E+03	-3,85E+03	4,75E+03
Resource use, minerals and metals	kg Sb eq	1,47E-04	9,10E-04	-8,59E-04	-7,04E-06

Table 35 : Absolute values for characterized environmental profile of polymer recycling of cotton – sulphite pulping process

Impact category	Unit	Mechanical pre-treatment step	Pulping process	Avoided virgin production of wood pulp	Avoided waste treatment - incineration with energy recovery
Climate change	kg CO2 eq	1,02E-01	9,83E-01	-9,54E-01	1,66E-01
Ozone depletion	kg CFC11 eq	8,37E-09	8,66E-08	-9,21E-08	2,35E-08
Ionising radiation	kBq U-235 eq	1,84E-02	3,21E-02	-3,31E-02	2,61E-02
Photochemical ozone formation	kg NMVOC eq	3,18E-04	4,59E-03	-4,85E-03	-2,05E-03
Particulate matter	disease inc.	1,95E-09	9,79E-08	-9,28E-08	-5,35E-09
Human toxicity, non-cancer	CTUh	1,32E-09	2,93E-08	-2,79E-08	5,40E-10
Human toxicity, cancer	CTUh	4,76E-11	6,81E-10	-6,74E-10	-2,32E-10
Acidification	mol H+ eq	6,63E-04	1,36E-02	-1,26E-02	-1,20E-03
Eutrophication, freshwater	kg P eq	1,09E-05	9,04E-05	-9,19E-05	1,48E-05
Eutrophication, marine	kg N eq	1,13E-04	1,46E-03	-1,45E-03	-9,96E-04
Eutrophication, terrestrial	mol N eq	1,29E-03	1,63E-02	-1,61E-02	-9,44E-03
Ecotoxicity, freshwater	CTUe	1,61E+00	1,45E+02	-1,32E+02	8,02E-01
Land use	Pt	5,36E-01	1,27E+01	-1,98E+02	5,80E-01
Water use	m3 depriv.	2,43E-02	1,16E+00	-1,05E+00	1,59E-02
Resource use, fossils	MJ	2,05E+00	1,09E+01	-1,08E+01	4,75E+00
Resource use, minerals and metals	kg Sb eq	1,47E-07	1,14E-06	-1,14E-06	-7,04E-09

A.4.3 Results life cycle assessment mechanical recycling polycotton

Figure 54 shows the environmental profile of the mechanical recycling of 1 tonne of polycotton, using the worst case situation for the avoided materials and Figure 55 shows the results for the best case scenario with regard to the avoided products Overall, there are more impact categories where the environmental benefits outweigh the impacts. Table 36 and Table 37 provide the absolute values per ton polycotton treated.

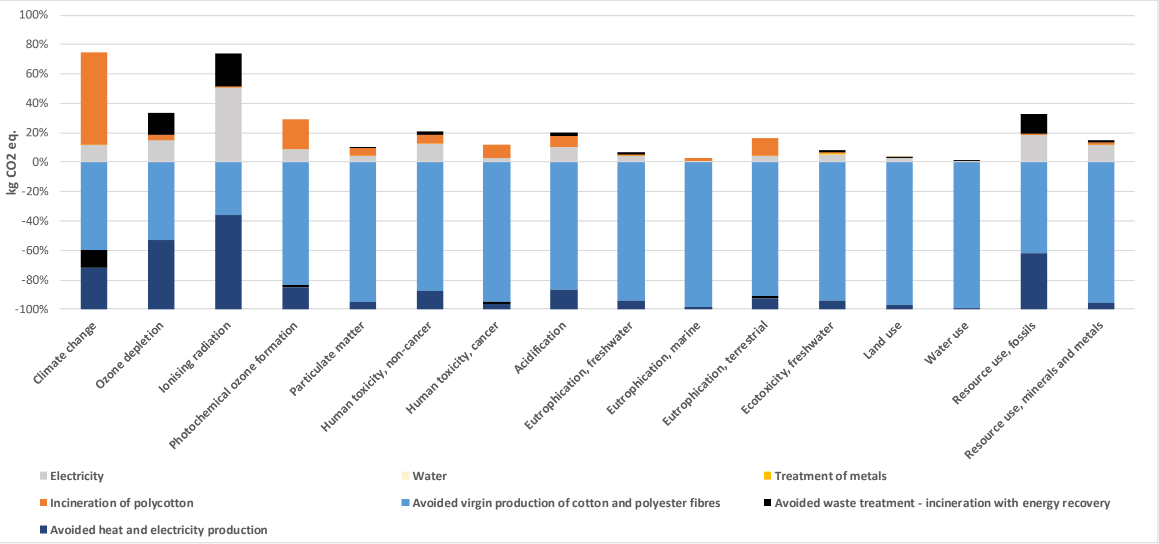

Figure 54 : Characterised environmental profile for the mechanical recycling of polycotton – worst case scenario for the avoided material

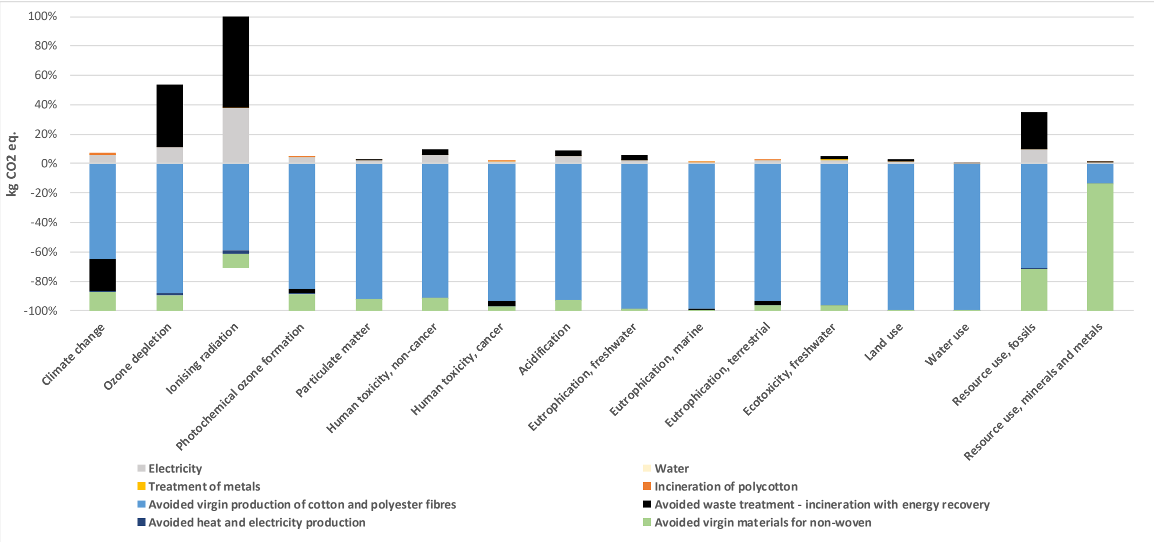

Figure 55 : Characterised environmental profile for the mechanical recycling of polycotton – best case scenario for the avoided material

Table 36 : Absolute values for characterized environmental profile of mechanical recycling of polycotton – worst case scenario for avoided materials

Impact category	Unit	Electricity	Water	Treatment of metals	Incineration of polycotton	Avoided virgin production of cotton and polyester fibre	Avoided waste treatment - incineration with energy recovery	Avoided heat and electricity production
Climate change	kg CO2 eq	2,14E+02	6,90E-03	6,91E-01	1,09E+03	-1,05E+03	-2,13E+02	-4,95E+02
Ozone depletion	kg CFC11 eq	1,80E-05	6,07E-10	1,59E-07	4,18E-06	-6,45E-05	1,86E-05	-5,64E-05
Ionising radiation	kBq U-235 eq	3,83E+01	8,10E-04	4,63E-02	5,41E-01	-2,72E+01	1,70E+01	-4,82E+01
Photochemical ozone formation	kg NMVOC eq	4,91E-01	2,32E-05	5,18E-03	1,12E+00	-4,62E+00	-1,11E-01	-8,07E-01
Particulate matter	disease inc.	3,25E-06	3,36E-10	1,55E-07	3,87E-06	-7,38E-05	1,06E-07	-4,17E-06
Human toxicity, non-cancer	CTUh	2,64E-06	4,19E-10	2,12E-08	1,35E-06	-1,88E-05	4,70E-07	-2,66E-06
Human toxicity, cancer	CTUh	7,75E-08	1,87E-11	1,29E-09	2,33E-07	-2,44E-06	-5,31E-08	-8,39E-08
Acidification	mol H+ eq	1,24E+00	4,00E-05	4,55E-03	9,28E-01	-1,05E+01	2,58E-01	-1,65E+00
Eutrophication, freshwater	kg P eq	2,26E-02	5,48E-07	1,17E-05	3,98E-04	-4,45E-01	9,72E-03	-2,76E-02
Eutrophication, marine	kg N eq	1,57E-01	6,35E-06	1,51E-03	4,86E-01	-1,95E+01	-8,50E-02	-2,48E-01
Eutrophication, terrestrial	mol N eq	1,94E+00	7,38E-05	1,66E-02	4,84E+00	-3,81E+01	-6,65E-01	-2,98E+00
Ecotoxicity, freshwater	CTUe	3,00E+03	1,29E-01	1,39E+02	6,43E+02	-5,29E+04	9,27E+02	-3,24E+03
Land use	Pt	1,07E+03	3,31E-02	1,97E+01	5,90E+01	-3,85E+04	4,15E+02	-1,22E+03
Water use	m3 depriv.	4,90E+01	8,60E-01	-5,25E-01	9,31E+00	-1,75E+04	1,92E+01	-6,32E+01
Resource use, fossils	MJ	4,38E+03	1,17E-01	1,25E+01	2,19E+02	-1,48E+04	3,18E+03	-9,12E+03
Resource use, minerals and metals	kg Sb eq	2,91E-04	1,03E-08	1,16E-06	3,30E-05	-2,30E-03	2,52E-05	-1,04E-04

Table 37 : Absolute values for characterized environmental profile of mechanical recycling of polycotton – best case scenario for avoided materials

Impact category	Unit	Electricity	Water	Treatment of metals	Incineration of polycotton	Avoided virgin production of cotton and polyester fibre	Avoided waste treatment - incineration with energy recovery	Avoided heat and electricity production	Avoided virgin materials for non-woven
Climate change	kg CO2 eq	2,14E+02	6,90E-03	6,91E-01	4,68E+01	-2,31E+03	-7,85E+02	-2,12E+01	-4,46E+02
Ozone depletion	kg CFC11 eq	1,80E-05	6,07E-10	1,59E-07	1,79E-07	-1,42E-04	6,86E-05	-2,42E-06	-1,64E-05
Ionising radiation	kBq U-235 eq	3,83E+01	8,10E-04	4,63E-02	2,32E-02	-5,99E+01	6,27E+01	-2,07E+00	-9,91E+00

Photochemical ozone formation	kg NMVOC eq	4,91E-01	2,32E-05	5,18E-03	4,79E-02	-1,02E+01	-4,08E-01	-3,46E-02	-1,36E+00
Particulate matter	disease inc.	3,25E-06	3,36E-10	1,55E-07	1,66E-07	-1,62E-04	3,92E-07	-1,79E-07	-1,42E-05
Human toxicity, non-cancer	CTUh	2,64E-06	4,19E-10	2,12E-08	5,78E-08	-4,14E-05	1,73E-06	-1,14E-07	-3,93E-06
Human toxicity, cancer	CTUh	7,75E-08	1,87E-11	1,29E-09	9,97E-09	-5,36E-06	-1,95E-07	-3,60E-09	-1,68E-07
Acidification	mol H+ eq	1,24E+00	4,00E-05	4,55E-03	3,98E-02	-2,30E+01	9,48E-01	-7,07E-02	-1,72E+00
Eutrophication, freshwater	kg P eq	2,26E-02	5,48E-07	1,17E-05	1,71E-05	-9,80E-01	3,58E-02	-1,18E-03	-9,87E-03
Eutrophication, marine	kg N eq	1,57E-01	6,35E-06	1,51E-03	2,08E-02	-4,29E+01	-3,13E-01	-1,06E-02	-3,04E-01
Eutrophication, terrestrial	mol N eq	1,94E+00	7,38E-05	1,66E-02	2,08E-01	-8,38E+01	-2,45E+00	-1,28E-01	-3,31E+00
Ecotoxicity, freshwater	CTUe	3,00E+03	1,29E-01	1,39E+02	2,75E+01	-1,16E+05	3,41E+03	-1,39E+02	-4,60E+03
Land use	Pt	1,07E+03	3,31E-02	1,97E+01	2,53E+00	-8,46E+04	1,53E+03	-5,24E+01	-7,45E+02
Water use	m3 depriv.	4,90E+01	8,60E-01	-5,25E-01	3,99E-01	-3,85E+04	7,08E+01	-2,71E+00	-2,52E+02
Resource use, fossils	MJ	4,38E+03	1,17E-01	1,25E+01	9,38E+00	-3,27E+04	1,17E+04	-3,91E+02	-1,29E+04
Resource use, minerals and metals	kg Sb eq	2,91E-04	1,03E-08	1,16E-06	1,41E-06	-5,07E-03	9,28E-05	-4,44E-06	-3,25E-02

A.4.4 Results life cycle assessment enzymatic recycling polycotton

Figure 56 shows the environmental profile of the mechanical recycling of 1 tonne of polycotton. Table 38 provides the absolute values per ton polycotton treated.

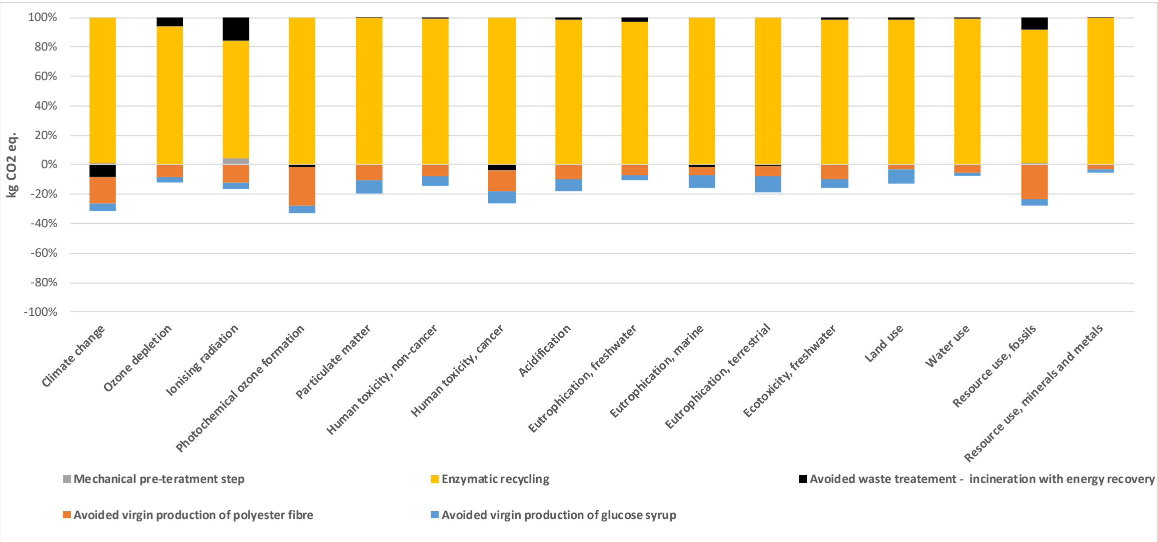

Figure 56 : Characterised environmental profile for the enzymatic recycling of polycotton

Table 38 : Absolute values for characterized environmental profile of enzymatic recycling of polycotton

Impact category	Unit	Mechanical pre-teratment step	Enzymatic recycling	Avoided waste treatement - incineration with energy recovery	Avoided production virgin of polyester fibre	Avoided production virgin of glucose syrup
Climate change	kg CO2 eq	1,33E+02	9,04E+03	-7,85E+02	-1,63E+03	-4,95E+02
Ozone depletion	kg CFC11 eq	6,90E-06	1,02E-03	6,86E-05	-9,01E-05	-4,27E-05
Ionising radiation	kBq U-235 eq	1,72E+01	3,22E+02	6,27E+01	-4,87E+01	-1,86E+01
Photochemical ozone formation	kg NMVOC eq	2,64E-01	2,73E+01	-4,08E-01	-7,16E+00	-1,50E+00
Particulate matter	disease inc.	1,77E-06	5,79E-04	3,92E-07	-6,23E-05	-4,88E-05
Human toxicity, non-cancer	CTUh	1,29E-06	2,24E-04	1,73E-06	-1,71E-05	-1,45E-05

Human toxicity, cancer	CTUh	4,64E-08	5,21E-06	-1,95E-07	-7,41E-07	-4,35E-07
Acidification	mol H+ eq	5,93E-01	7,29E+01	9,48E-01	-7,17E+00	-6,44E+00
Eutrophication, freshwater	kg P eq	1,02E-02	1,04E+00	3,58E-02	-7,44E-02	-3,83E-02
Eutrophication, marine	kg N eq	9,03E-02	2,51E+01	-3,13E-01	-1,45E+00	-2,11E+00
Eutrophication, terrestrial	mol N eq	1,07E+00	2,15E+02	-2,45E+00	-1,40E+01	-2,34E+01
Ecotoxicity, freshwater	CTUe	1,53E+03	2,75E+05	3,41E+03	-2,80E+04	-1,63E+04
Land use	Pt	5,05E+02	1,40E+05	1,53E+03	-3,83E+03	-1,48E+04
Water use	m3 depriv.	2,25E+01	1,48E+04	7,08E+01	-7,56E+02	-4,13E+02
Resource use, fossils	MJ	1,82E+03	1,26E+05	1,17E+04	-3,25E+04	-5,84E+03
Resource use, minerals and metals	kg Sb eq	1,44E-04	1,41E-01	9,28E-05	-4,16E-03	-3,28E-03

A.4.5 Results life cycle assessment mechanical recycling polyester

Figure 57 shows the environmental profile of the mechanical recycling of 1 tonne of polyester, using the worst case situation for the avoided materials. Opposite to the mechanical recycling of cotton and polycotton, the avoided impact of primary production does not outweigh the impact of the recycling process and waste treatment of downcycled materials, which are in the worst case scenario assumed to be incinerated with energy recovery. The main reason for the difference is the impact of the incineration of polyester. Figure 58 shows the results for the best case scenario with regard to the avoided products and Table 39 and Table 40 provides the absolute values per tonne of treated polyester.

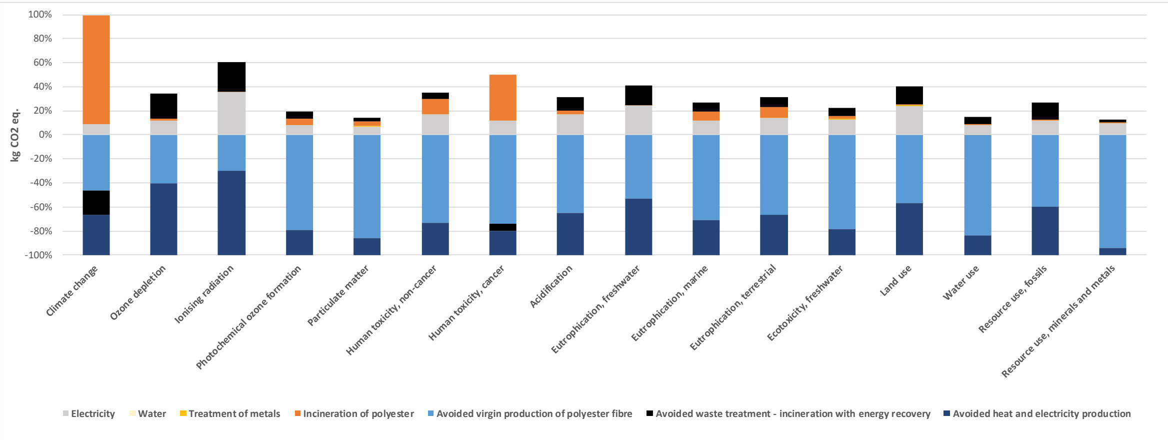

Figure 57 : Characterised environmental profile for the mechanical recycling of polyester – worst case scenario for the avoided material

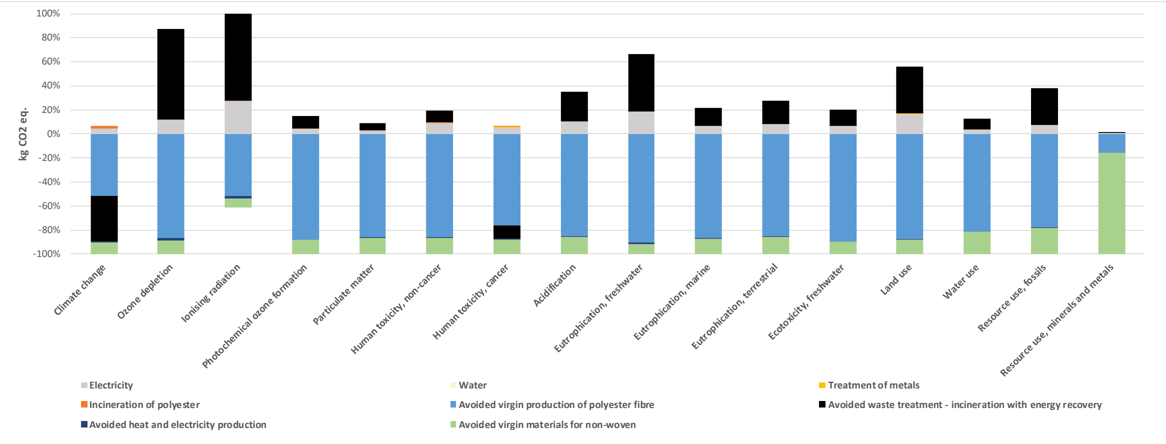

Figure 58 : Characterised environmental profile for the mechanical recycling of polyester – best case scenario for the avoided material

Table 39 : Absolute values for characterized environmental profile of mechanical recycling of polyester – worst case scenario for avoided materials

Impact category	Unit	Electricity	Water	Treatment of metals	Incineration of polyester	Avoided virgin production of polyester fibre	Avoided waste treatment - incineration with energy recovery	Avoided heat and electricity production
Climate change	kg CO2 eq	2,14E+02	6,90E-03	6,91E-01	2,10E+03	-1,08E+03	-4,72E+02	-7,74E+02
Ozone depletion	kg CFC11 eq	1,80E-05	6,07E-10	1,59E-07	1,58E-06	-5,97E-05	3,09E-05	-8,81E-05
Ionising radiation	kBq U-235 eq	3,83E+01	8,10E-04	4,63E-02	2,62E-01	-3,23E+01	2,70E+01	-7,58E+01
Photochemical ozone formation	kg NMVOC eq	4,91E-01	2,32E-05	5,18E-03	3,26E-01	-4,75E+00	3,35E-01	-1,27E+00
Particulate matter	disease inc.	3,25E-06	3,36E-10	1,55E-07	1,87E-06	-4,13E-05	1,67E-06	-6,54E-06
Human toxicity, non-cancer	CTUh	2,64E-06	4,19E-10	2,12E-08	1,97E-06	-1,13E-05	7,93E-07	-4,19E-06
Human toxicity, cancer	CTUh	7,75E-08	1,87E-11	1,29E-09	2,53E-07	-4,91E-07	-4,33E-08	-1,32E-07
Acidification	mol H+ eq	1,24E+00	4,00E-05	4,55E-03	2,36E-01	-4,75E+00	8,41E-01	-2,59E+00
Eutrophication, freshwater	kg P eq	2,26E-02	5,48E-07	1,17E-05	2,06E-04	-4,93E-02	1,54E-02	-4,34E-02
Eutrophication, marine	kg N eq	1,57E-01	6,35E-06	1,51E-03	1,07E-01	-9,59E-01	1,01E-01	-3,90E-01
Eutrophication, terrestrial	mol N eq	1,94E+00	7,38E-05	1,66E-02	1,22E+00	-9,29E+00	1,23E+00	-4,68E+00
Ecotoxicity, freshwater	CTUe	3,00E+03	1,29E-01	1,39E+02	5,06E+02	-1,86E+04	1,64E+03	-5,09E+03
Land use	Pt	1,07E+03	3,31E-02	1,97E+01	3,54E+01	-2,54E+03	6,73E+02	-1,92E+03
Water use	m3 depriv.	4,90E+01	8,60E-01	-5,25E-01	3,58E+00	-5,01E+02	3,42E+01	-9,93E+01
Resource use, fossils	MJ	4,38E+03	1,17E-01	1,25E+01	9,10E+01	-2,16E+04	5,07E+03	-1,43E+04
Resource use, minerals and metals	kg Sb eq	2,91E-04	1,03E-08	1,16E-06	1,61E-05	-2,76E-03	5,23E-05	-1,63E-04

Table 40 : Absolute values for characterized environmental profile of mechanical recycling of polyester – best case scenario for avoided materials

Impact category	Unit	Electricity	Water	Treatment of metals	Incineration of polyester	Avoided virgin production of polyester fibre	Avoided waste treatment - incineration with energy recovery	Avoided heat and electricity production	Avoided virgin materials for non-woven
Climate change	kg CO2 eq	2,14E+02	6,90E-03	6,91E-01	8,98E+01	-2,38E+03	-1,74E+03	-3,32E+01	-4,46E+02
Ozone depletion	kg CFC11 eq	1,80E-05	6,07E-10	1,59E-07	6,76E-08	-1,31E-04	1,14E-04	-3,77E-06	-1,64E-05
Ionising radiation	kBq U-235 eq	3,83E+01	8,10E-04	4,63E-02	1,12E-02	-7,10E+01	9,93E+01	-3,25E+00	-9,91E+00
Photochemical ozone formation	kg NMVOC eq	4,91E-01	2,32E-05	5,18E-03	1,40E-02	-1,04E+01	1,23E+00	-5,42E-02	-1,36E+00
Particulate matter	disease inc.	3,25E-06	3,36E-10	1,55E-07	8,01E-08	-9,09E-05	6,14E-06	-2,80E-07	-1,42E-05
Human toxicity, non-cancer	CTUh	2,64E-06	4,19E-10	2,12E-08	8,43E-08	-2,49E-05	2,92E-06	-1,79E-07	-3,93E-06

Human toxicity, cancer	CTUh	7,75E-08	1,87E-11	1,29E-09	1,08E-08	-1,08E-06	-1,59E-07	-5,64E-09	-1,68E-07
Acidification	mol H+ eq	1,24E+00	4,00E-05	4,55E-03	1,01E-02	-1,05E+01	3,09E+00	-1,11E-01	-1,72E+00
Eutrophication, freshwater	kg P eq	2,26E-02	5,48E-07	1,17E-05	8,81E-06	-1,09E-01	5,68E-02	-1,86E-03	-9,87E-03
Eutrophication, marine	kg N eq	1,57E-01	6,35E-06	1,51E-03	4,60E-03	-2,11E+00	3,71E-01	-1,67E-02	-3,04E-01
Eutrophication, terrestrial	mol N eq	1,94E+00	7,38E-05	1,66E-02	5,24E-02	-2,04E+01	4,54E+00	-2,00E-01	-3,31E+00
Ecotoxicity, freshwater	CTUe	3,00E+03	1,29E-01	1,39E+02	2,17E+01	-4,09E+04	6,02E+03	-2,18E+02	-4,60E+03
Land use	Pt	1,07E+03	3,31E-02	1,97E+01	1,52E+00	-5,59E+03	2,48E+03	-8,23E+01	-7,45E+02
Water use	m3 depriv.	4,90E+01	8,60E-01	-5,25E-01	1,53E-01	-1,10E+03	1,26E+02	-4,25E+00	-2,52E+02
Resource use, fossils	MJ	4,38E+03	1,17E-01	1,25E+01	3,90E+00	-4,74E+04	1,86E+04	-6,12E+02	-1,29E+04
Resource use, minerals and metals	kg Sb eq	2,91E-04	1,03E-08	1,16E-06	6,90E-07	-6,07E-03	1,93E-04	-6,97E-06	-3,25E-02

A.4.6 Results life cycle assessment mechanical recycling polyamide

Figure 59 shows the environmental profile of the mechanical recycling of 1 tonne of polyamide, using the worst case situation for the avoided materials. Figure 60 shows the results for the best case scenario with regard to the avoided products. Table 41 and Table 42 provide the absolute values per tonne of treated polyamide.

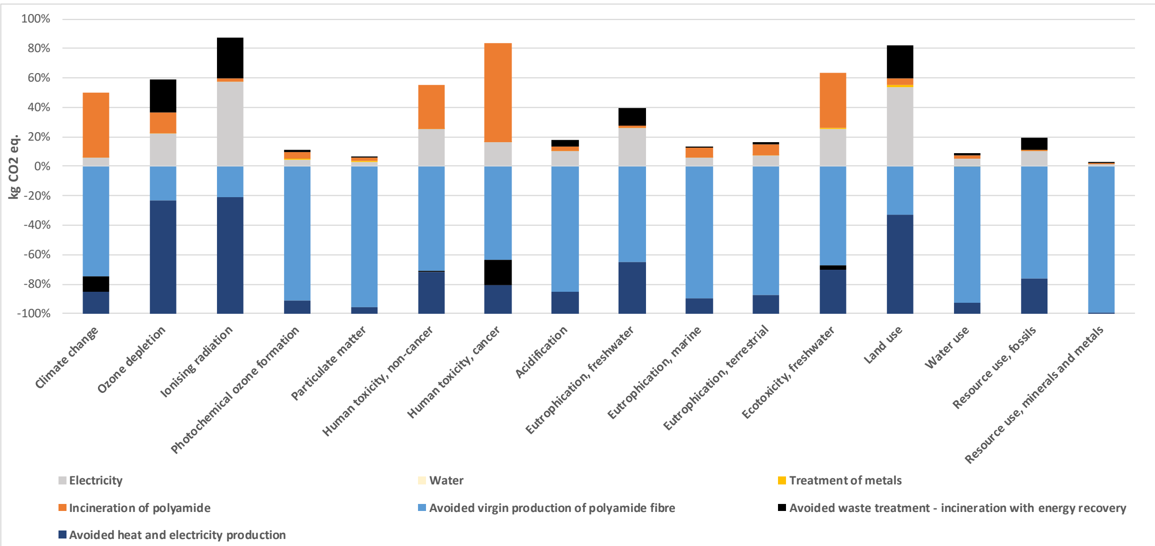

Figure 59 : Characterised environmental profile for the mechanical recycling of polyamide – worst case scenario for the avoided material

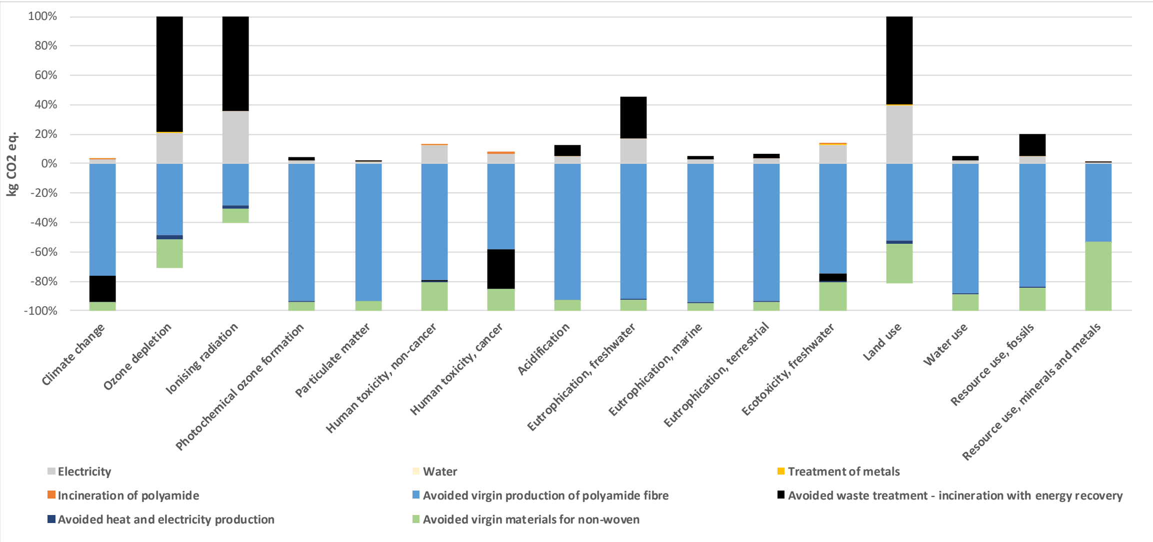

Figure 60 : Characterised environmental profile for the mechanical recycling of polyamide– best case scenario for the avoided material

Table 41 : Absolute values for characterized environmental profile of mechanical recycling of polyamide – worst case scenario for avoided materials

Impact category	Unit	Electricity	Water	Treatment of metals	Incineration of polyamide	Avoided virgin production of polyamide fibre	Avoided waste treatment - incineration with energy recovery	Avoided heat and electricity production
Climate change	kg CO2 eq	2,14E+02	6,90E-03	6,91E-01	1,64E+03	-2,77E+03	-3,94E+02	-5,41E+02
Ozone depletion	kg CFC11 eq	1,80E-05	6,07E-10	1,59E-07	1,12E-05	-1,87E-05	1,80E-05	-6,16E-05
Ionising radiation	kBq U-235 eq	3,83E+01	8,10E-04	4,63E-02	1,18E+00	-1,39E+01	1,84E+01	-5,28E+01
Photochemical ozone formation	kg NMVOC eq	4,91E-01	2,32E-05	5,18E-03	4,87E-01	-9,43E+00	1,41E-01	-8,83E-01
Particulate matter	disease inc.	3,25E-06	3,36E-10	1,55E-07	2,84E-06	-9,62E-05	6,15E-07	-4,56E-06
Human toxicity, non-cancer	CTUh	2,64E-06	4,19E-10	2,12E-08	3,11E-06	-7,42E-06	-7,00E-08	-2,92E-06
Human toxicity, cancer	CTUh	7,75E-08	1,87E-11	1,29E-09	3,25E-07	-3,07E-07	-8,34E-08	-9,18E-08
Acidification	mol H+ eq	1,24E+00	4,00E-05	4,55E-03	4,24E-01	-1,04E+01	4,93E-01	-1,80E+00
Eutrophication, freshwater	kg P eq	2,26E-02	5,48E-07	1,17E-05	1,11E-03	-5,62E-02	1,04E-02	-3,02E-02
Eutrophication, marine	kg N eq	1,57E-01	6,35E-06	1,51E-03	1,77E-01	-2,43E+00	3,40E-02	-2,72E-01
Eutrophication, terrestrial	mol N eq	1,94E+00	7,38E-05	1,66E-02	1,91E+00	-2,32E+01	4,82E-01	-3,26E+00
Ecotoxicity, freshwater	CTUe	3,00E+03	1,29E-01	1,39E+02	4,46E+03	-8,09E+03	-3,27E+02	-3,54E+03
Land use	Pt	1,07E+03	3,31E-02	1,97E+01	9,90E+01	-6,48E+02	4,42E+02	-1,34E+03
Water use	m3 depriv.	4,90E+01	8,60E-01	-5,25E-01	1,96E+01	-8,89E+02	1,77E+01	-6,91E+01
Resource use, fossils	MJ	4,38E+03	1,17E-01	1,25E+01	3,17E+02	-3,21E+04	3,45E+03	-9,97E+03
Resource use, minerals and metals	kg Sb eq	2,91E-04	1,03E-08	1,16E-06	8,19E-05	-1,66E-02	1,12E-05	-1,13E-04

Table 42 : Absolute values for characterized environmental profile of mechanical recycling of polyamide – best case scenario for avoided materials

Impact category	Unit	Electricity	Water	Treatment of metals	Incineration of polyamide	Avoided virgin production of polyamide fibre	Avoided waste treatment - incineration with energy recovery	Avoided heat and electricity production	Avoided virgin materials for non-woven
Climate change	kg CO2 eq	2,14E+02	6,90E-03	6,91E-01	7,04E+01	-6,09E+03	-1,45E+03	-2,32E+01	-4,46E+02
Ozone depletion	kg CFC11 eq	1,80E-05	6,07E-10	1,59E-07	4,80E-07	-4,11E-05	6,62E-05	-2,64E-06	-1,64E-05
Ionising radiation	kBq U-235 eq	3,83E+01	8,10E-04	4,63E-02	5,07E-02	-3,05E+01	6,78E+01	-2,26E+00	-9,91E+00
Photochemical ozone formation	kg NMVOC eq	4,91E-01	2,32E-05	5,18E-03	2,09E-02	-2,07E+01	5,21E-01	-3,78E-02	-1,36E+00
Particulate matter	disease inc.	3,25E-06	3,36E-10	1,55E-07	1,22E-07	-2,12E-04	2,26E-06	-1,95E-07	-1,42E-05

Human toxicity, non-cancer	CTUh	2,64E-06	4,19E-10	2,12E-08	1,33E-07	-1,63E-05	-2,58E-07	-1,25E-07	-3,93E-06
Human toxicity, cancer	CTUh	7,75E-08	1,87E-11	1,29E-09	1,39E-08	-6,76E-07	-3,07E-07	-3,93E-09	-1,68E-07
Acidification	mol H+ eq	1,24E+00	4,00E-05	4,55E-03	1,82E-02	-2,28E+01	1,81E+00	-7,73E-02	-1,72E+00
Eutrophication, freshwater	kg P eq	2,26E-02	5,48E-07	1,17E-05	4,78E-05	-1,24E-01	3,83E-02	-1,30E-03	-9,87E-03
Eutrophication, marine	kg N eq	1,57E-01	6,35E-06	1,51E-03	7,57E-03	-5,35E+00	1,25E-01	-1,16E-02	-3,04E-01
Eutrophication, terrestrial	mol N eq	1,94E+00	7,38E-05	1,66E-02	8,19E-02	-5,10E+01	1,78E+00	-1,40E-01	-3,31E+00
Ecotoxicity, freshwater	CTUe	3,00E+03	1,29E-01	1,39E+02	1,91E+02	-1,78E+04	-1,20E+03	-1,52E+02	-4,60E+03
Land use	Pt	1,07E+03	3,31E-02	1,97E+01	4,24E+00	-1,43E+03	1,63E+03	-5,73E+01	-7,45E+02
Water use	m3 depriv.	4,90E+01	8,60E-01	-5,25E-01	8,40E-01	-1,96E+03	6,51E+01	-2,96E+00	-2,52E+02
Resource use, fossils	MJ	4,38E+03	1,17E-01	1,25E+01	1,36E+01	-7,06E+04	1,27E+04	-4,27E+02	-1,29E+04
Resource use, minerals and metals	kg Sb eq	2,91E-04	1,03E-08	1,16E-06	3,51E-06	-3,66E-02	4,13E-05	-4,86E-06	-3,25E-02

B Annex 2: Expert interview questionnaire – guiding questions

1) **Establishing a consistent feedstock stream for textile recycling**: In order to enable large-scale recycling of textiles, a regular inflow of sufficient amounts of textile waste in good quality is needed.
   a) How can EU policy help to avoid competition between different textile collection pathways (i.e. collection for re-use vs. collection for recycling)?
   b) In order to foster circularity of textile products, should the EU take action to keep textile wastes inside the EU? If so, how?

2) **Improving information flows along the value chain:** Transparency of used materials and chemicals for the production of textiles is largely lacking and hampers recycling.
   a) In order to enhance recycling of textiles, which kind of information is required along the value chain? Where do the major information gaps currently lie?
   b) Which aspects does EU level policy need to consider when introducing an obligatory digital product passport for textiles? (What is important to make it an effective instrument?)
   c) How can EU policy better support and promote safe alternatives to harmful chemicals in the textile industry?

3) **Promoting recyclability of textiles:** Even if collected separately, textile waste often cannot be easily recycled due to its contents (problematic chemicals, blends, low quality, etc.).
   a) In your view, what should **minimum design requirements** for recyclability encompass?
      - How can such minimum design requirements be enforced? (Ecodesign Directive);
   b) What can be done at EU policy level to accelerate the phase-out of hazardous chemicals in the textile value chain?
   c) How can EU policy ensure that when introducing EPR schemes for textiles, these have an effect on the design and improve the recyclability of textile products?

4) **Clarifying end-of-waste-status:** Currently, an unclear definition of waste and varied interpretations of end-of-waste criteria for recycled textiles hamper the sourcing and recycling of used textiles. In particular, different interpretations between Member States present a bottleneck for intra-EU shipments of used textiles destined for recycling.
   a) Do we need harmonised standards to improve this situation? Should these standards be used in/referred to in EU legislation?
   b) Are end-of-waste criteria sufficient to exempt recycled textile fibres from waste status? How should end-of-waste criteria be formulated to ease textile fibre recycling?
   c) Which EU legislation(s) create compliance issues for companies related to the shipment of textile waste?
   d) What could be done at EU policy level to improve this situation?

5) **Stimulating demand:** A lack of demand for recycled textiles slows down investments and innovation in textile fibre recycling. In addition, recycled fibres have to compete with cheaper virgin fibres on the EU market.
   a) In order to introduce a mandatory recycled content for specific textile products, which open questions need to be clarified in your view? Which materials or product groups are most suitable for introducing mandatory recycled content?
   b) In your view, what should minimum design requirements for recyclability encompass?

6) **Incentivizing investments:** Investments into recycling capacities, infrastructure, technological innovation and circular business models are needed in order to enable large-scale textile fibre recycling in Europe.
   a) How can EU funding programmes be used to reduce the economic risks and insecurity for companies that consider investing into recycling capacities?
   b) What is important when considering the introduction of mandatory extended producer responsibility schemes for textiles?
   c) What effects would you expect from regulating the destruction of unsold or returned textiles on the EU market?

Wrap-up question:

Are there further solutions or gaps in the legislation that EU policy should address in order to facilitate textile fibre recycling?

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