Fiber Recycling: Potential for Saving Energy and Resources

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EXECUTIVE SUMMARY

The annual production of fibers reached about 74 million t in 2007 and will further increase within the next years. With regard to the total amount of waste the fiber fraction is rather small. For the UK it has been reported that the portion of apparel and textiles in municipal solid waste ranges at approximately 4 to 5 %. However, since fiber manufacture and processing demands large amounts of energy and resources recycling processes are highly recommended. In order to get an idea about the ecological benefits, the environmental impact of different fiber recycling concepts has been considered based on data from the literature. LCA data considering different recycling routes are evaluated in terms of energy savings. Generally fiber production demands a large amount of energy. While for the production of 1 t amorphous PET grade 81 GJ are required, the manufacture of fibers is comparable to bottles and films and takes up additional 23 to 29 GJ. Also cotton, a renewable product, requires a lot of crop land, water for irrigation, fertilizers, pesticides, herbicides and fossil fuels. The production of 1 t baled cotton fibers demands 46 GJ of energy (range from 36 to 55), 5 730 m³ of water and emits 2.0 t CO_2 equivalents. However, fibers are only intermediates and are commonly further processed into apparel, home textiles or industrial products. The total energy requirement for the production of 250 pieces cotton T-shirts (correspond to 1 t) ranges between 188 and 325 GJ/t. Regarding the common praxis of waste incineration with energy recovery (considering a recovery rate of 60 %) only a small amount of energy originally required for all production processes can be recovered. The balance is even more unfavorable when considering the consumed energy for a final fiber product such as a T-shirt instead of raw fiber. It is, thus, obvious that incineration is a much better solution than landfilling but still means a large waste of energy.

Regarding apparel, which represents one of the most important fiber users, the reuse as second hand clothes represents the best solution. The energy required for collection and sorting ranges at about 6 GJ and is negligible compared to the effort for apparel production. Overall about 200 GJ of energy can be saved by the use end-of-life clothes as rewearables. However, only a certain portion of apparel can be used as second hand clothes and, thus, complementary recycling procedures are required.

Frequently fibrous residues, often called fluff, arise during several processes, such as tire grinding or processing shredder light fraction. However, it is already established that the fluff fraction can be converted into a marketable product to be used in the bitumen industry. Similar processes seem to be possible for other types of fibrous wastes such as apparel (the

fractions which cannot be used as rewearables). The energy consumption for processing fibrous waste (manly grinding) is much lower than the energy that can be saved a reuse of the waste derived fibers. Even if the reuse of recycled fibers is commonly only possible on a lower quality level ("downcycling") this prolongation of the life cycle can save energy since conventional fiber products can be substituted.

INTRODUCTION

This paper approaches the fiber market in regard of environmental impact caused by production and disposal. Different cradle to grave scenarios are compared revealing a large potential for saving energy and resources by avoiding landfill or incineration of fiber products.

The market offers a great variety of fiber types. Figure 1 gives an overview about the most important categories. Basically fibers are separated into natural and man-made fibers. Among natural fibers one distinguishes between crop and animal fibers. Man-made fibers are separated according to their chemical constitution whereas they may consist of organic or inorganic materials. Within organic man-made fibers it is distinguished between polymers from natural resources, mainly cellulose, and synthetic polymers originating from petroleum. In regard of this great variety it is clear that these fibers show quite different properties as well as totally different impacts for production and processing.

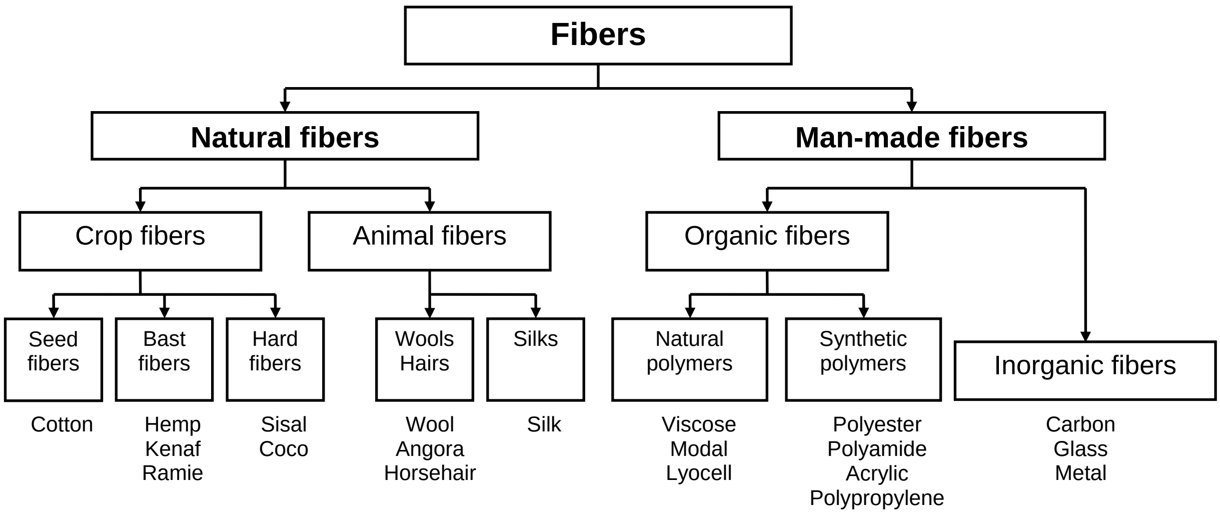

Figure 1. Categorization of the most important fibers (BISFA, 2000; DIN 60001)

With regard to the total amount of waste the fiber fraction is rather small. For the UK it has been reported that the portion of apparel and textiles in municipal solid waste ranges at approximately 4 to 5 % (Woolridge, 2006). The annual production of fibers reached about 73.7 million t in 2007 (CIRFS, 2008) and will further increase within the next years. It can be assumed that, with a certain time delay, a comparable amount of fibers will end up in waste.

Figure 2 shows the annual production rates for synthetics, cotton, cellulosics and wool back to the year 1900. Wool and cellulosic fibers have been of importance until the late 1960ies but had then been marginalized since the production of man-made fibers from synthetic polymers significantly increased. Cotton, which is the only relevant natural fiber today, was the most important fiber for decades and it was only in the 1990ies when the production of synthetic fibers overran cotton. Today the production of synthetics exceeds cotton by approximately 30 %. The right chart in Figure 2 summarizes all fiber categories indicating the present production of more almost 75 million t. It can be assumed that fiber production will further grow within the next years based on two main reasons. On the one hand, fiber consumption is closely related to prosperity and many countries, such as China, will increase their per capita consumption towards EU and USA levels. On the other hand, population growth is still going on and every human being needs a minimum of fibers for clothing. The extrapolation indicates that in 2015 world fiber production might reach 120 million t.

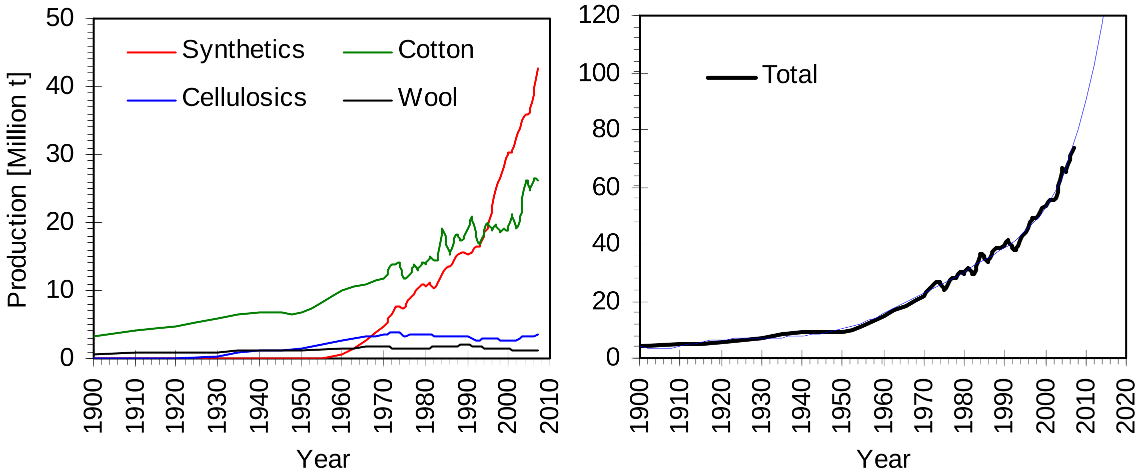

Figure 2. Annual production of synthetics, cotton, cellulosics and wool from 1900 to 2008 (left chart) and total fiber production (right chart) including the trend (CIRFS, 2008)

Although quite reliable data are available for fiber production it is difficult to quantify the respective uses exactly. However, it is clear that the most important markets are apparel, home furnishing and industrial uses. Furthermore, it is evident that fibers are used for a great variety of applications and, thus, they can be found in a great spectrum of waste.

PRODUCTION

It seems quite obvious that fiber production demands more energy than the pure manufacture of a polymer. Figure 3 compares the energy required for Polyester and Polypropylene production and the surplus demand to produce bottles, films or fibers. The additional energy requirement is about 20 to 30 %. From this it is clear that fibers, even they consist of synthetic polymers, must not be compared to bulk material

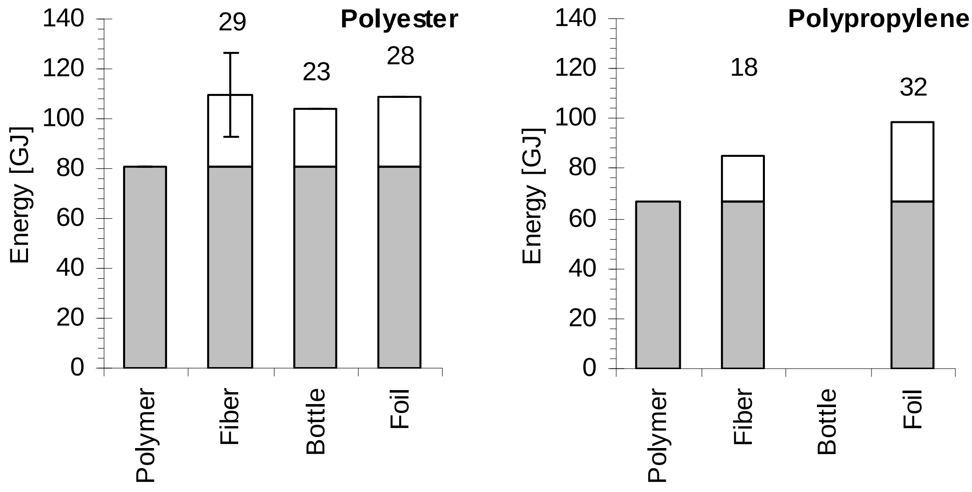

Figure 3. Energy demand for production of polymers (PET and PP) and the surplus demand for production of bottles, foils and fibers (Boustead, 2005; Woolridge, 2006; Patel, 2008)

A proper tool for evaluating the consumption of energy and resources of a product or a process is life cycle assessment (LCA) also known as life cycle analysis, ecobalance, or cradle-to-grave analysis. Based on LCA data different recycling routes are evaluated in terms of energy savings. A general problem of LCA is the definition of the system boundaries. Especially for fibers which can be used for several applications it seems the best solution to define a so-called cradle to factory gate system. Thus, the influence of various uses is excluded and different fibers can be compared to each other.

Figure 4 compares the energy consumption (non-renewable and renewable) and the emissions of green house gases for Lyocell (CLY, production in Austria), Viscose (CV, production in Austria and China), Polypropylene (PP, production in Western Europe), Polyethylene (PET, production in Western Europe) and cotton (CO, cultivation in USA and China). Although cotton is a renewable fiber it cannot be considered as sustainable. Due to a high employment of agricultural chemicals and fertilizers the demand for non-renewable energy and, thus, greenhouse gas emissions are fairly high. It is estimated that the cultivation of cotton uses about 2.4 % of all available crop land but requires up to 18 % of worldwide pesticide production (Paulitsch, 2004). Another drawback of cotton is its enormous demand of water necessary for irrigation. At an average 5,730 m³/t are reported (Patel, 2008) which is much higher as necessary for man-made fibers (76 to 445 m³/t, Patel, 2008). However, in particular cases insufficient irrigation system might result in a water consumption up to 27,000 m³/t (Paulitsch, 2004).

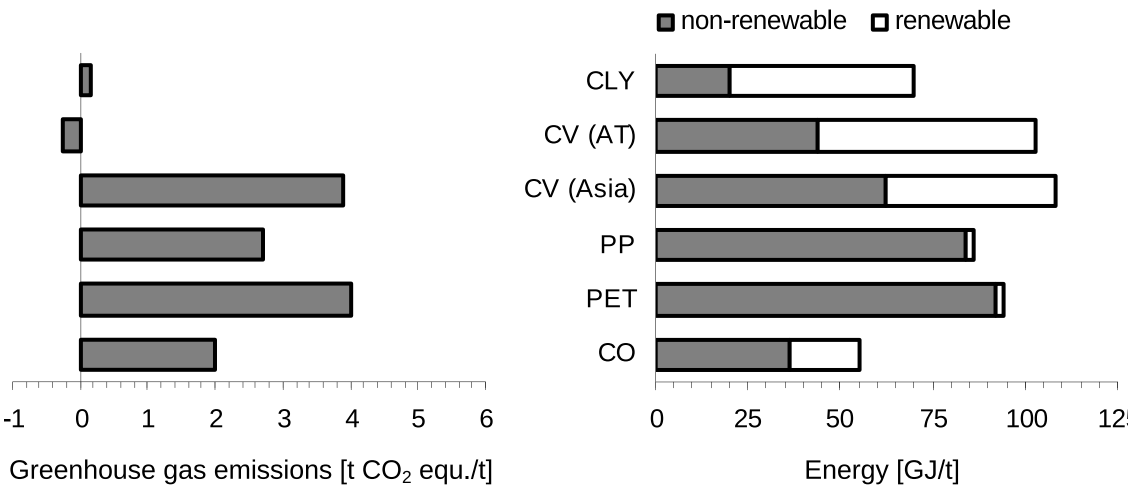

Figure 4. Data from LCA considering cradle to factory gate for some fibers (Patel, 2008); material code according to DIN, 1999; BISFA, 2000)

Regarding cellulosics (CLY and CV) it is obvious that the location of the production plant significantly influences energy demand and greenhouse gas emissions. Depending on the efficiency of the plant as well as the locally available energy mix, the environmental impact of cellulosic man-made fibers might even undercut cotton. In terms of consumption of non-renewable energy, man-made fibers (PP and PET) exhibit the highest value. However, it is striking that the emissions of green house gases at the Viscose production site in China are about the same as for PET. It is caused by the fact that coal is used as energy source.

From these data it is clear that fiber production exhibits a significant impact on the environment and, thus, recycling processes are recommended. This is also valid for renewable fibers (cotton).

Apparel

Fibers are only intermediates and are commonly further processed into apparel, home textiles or industrial products. As an example the consumption of energy for all production steps necessary to bring a T-shirt (100 % cotton) to the retailer is shown in Table 1. The total energy requirement ranges between 188 and 325 GJ/t (average: 257 GJ/t). Considering the manufacture of virgin cotton, which is assumed with 55 GJ/t, it is clear that the saving potentials for apparel are much higher than for fibers.

Table 1 Energy demand for the production of 1 t T-shirts (approximately 4,000 pieces).

Process	Energy demand [GJ]			Process
Reference	Woolridge, 2006		Allwood, 2006	Reference
Crop cultivation	55	} 173	64	Material; i.e. cultivation and yarn production
Preparation/blending	29			
Spinning	89			
Knitting	32	} 68	96	Production; i.e. complete textile process chain
Dying / finishing	27			
Making up	9			
Packing/transport/sale	84		28	Transport
Total	325		188	Total

RECYCLING

Scenarios

Figure 5 shows a cradle to grave chart indicating three cases for recycling end-of-life fiber products.

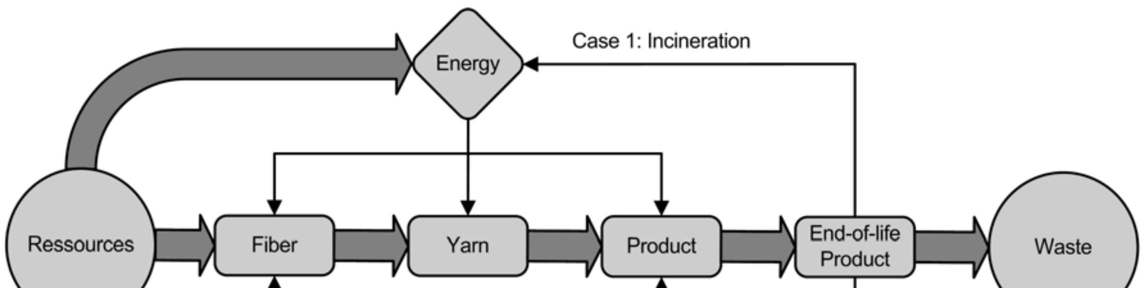

Figure 5. Cradle to grave chart for fibers indicating three cases for recycling

Case 1 (incineration)

As sketched in Figure 5 the recycling route of case 1 represents the common praxis of waste incineration with energy recovery. The reclaimable energy (considering a recovery rate of 60 %) is, however, much lower than the energy needed for fiber production as demonstrated in Figure 6. The portion of energy recovery ranges between 15 and 47 %. The highest value is a runaway based on Viscose fiber produced in Austria (energy supply by waste incinerator). However, the balance is significantly more unfavorable when considering the consumed energy for a final fiber product such as a T-shirt (compare with data given in Table 1). Due to the high energy demand of the textile processing chain incineration can only recover 4 % of energy already consumed. Incineration is a much better solution than landfilling but it is obvious that it still means a large waste of energy. In order to improve the overall balance of fiber LCA recycling processes are the better choice.

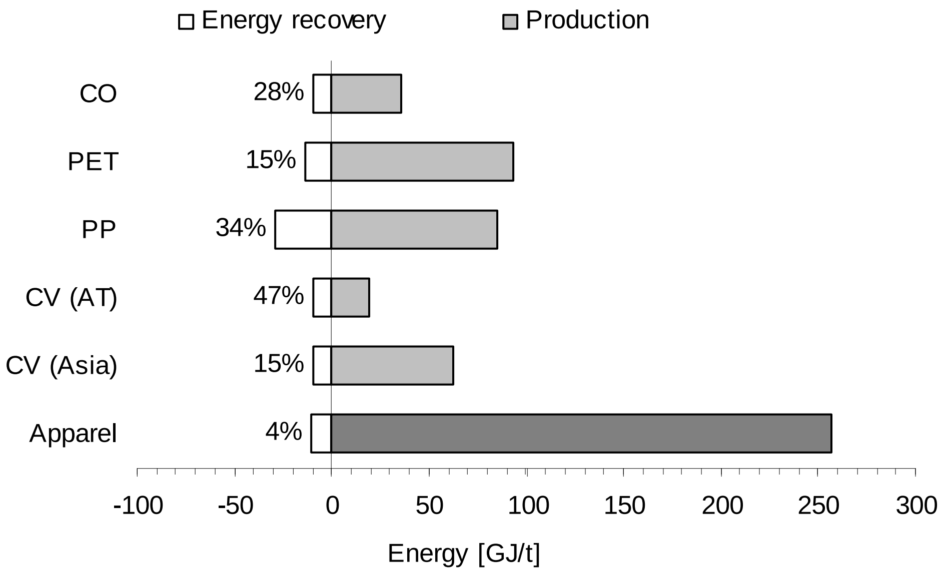

Figure 6. Consumption of non-renewable energy for fiber production compared to energy recovery by waste incineration; the percentages indicate the portion of reclaimable energy (Patel, 2008; Koslowski, 2000).

Case 2 (apparel collection)

An example for a recycling schedule according to case 2, as sketched in Figure 5, represents second-hand clothes. I many EU countries end-of-life apparel is collected by a separately from other types of waste and subsequently fractionated into different fractions. The fraction to be most economic contains rewearables which can be directly used for second-hand clothes. Unfortunately, the sorting of end-of-life clothes is labor intensive and, thus, the number of sorting plants in Europe is decreasing.

The energy required for collection and sorting ranges at about 6 GJ (Allwood, 2006) and is negligible compared to the effort for apparel production. As summarized in Table 2, overall 182 and 229 GJ of energy can be saved by the reuse of T-shirts and blouses, respectively. Similar or even larger saving potentials exist for apparel of synthetic fibers.

Table 2 Energy demand for the production of 1 t apparel compared to the consumption for collection and sorting (Allwood, 2006)

		T-shirt	Blouse
Material		100 % Cotton (CO)	100 % Viscose (CV)
Approx. pieces	[-]	4,000	5,000
Total energy for production	[GJ]	188	235
Energy for collection and sorting	[GJ]	6	6
Savings	[GJ]	182	229

Case 3 (recycling)

A showcase for case 3 is the recycling of fibers from end-of-life tires. The collected tires are cut and ground resulting in the fractions rubber, steel and fluff. The fluff fraction contains fibers commingled with rubber powder and minor amounts of rubber. Commonly the fluff fraction is incinerated causing high disposal costs. However, it is already established that this fluff fraction can be converted into a marketable product to be used in the bitumen industry (Bartl, 2005).

Similar processes seem to be possible for other types of fibrous wastes. Table 3 shows some possible sources of waste that could serve as feedstock for deriving fibers. Whether a recycling is technologically and economically viable or not, depends on several parameters such as fiber content, fluctuation of fiber portion, processability or existence of problematic by-products. The processing details have to be adapted to the specific situation and waste properties. The aim of the recycling process is to gain a product composed of short fibers so that entangling is largely prevented and a sufficient flowability is guaranteed.

Table 3 Potential sources for deriving fibers from waste

End-of-life product	Remark
Apparel residues (not adequate for rewearables)	Contain undesired components (e.g.: zips, metallic parts); varying fiber materials;
Fluff from tire recycling	Contain Viscose, Polyester and Polyamide commingled with rubber; successfully used in Bitumen industry
Fluff from shredder light fraction	Arises in the course of vehicle recycling; relatively low fiber content; complex mixture of different;
Carpets	Contains predominately polypropylene and polyamide fibers; foam (styrene butadiene styrene) and inorganic materials as by-products;
Production residues	Arise during fiber processing (e.g.: spinning, weaving); relatively clean and constant composition; contain commonly no by-products

The proper processing of fibrous waste into a well defined product is an inevitable but not a sufficient condition for an economically feasible recycling. It is also necessary to find applications in which the recycling material can substitute more or less expensive state-of-the-art products. It is well known that short fibers can significantly increase viscosity of liquids and change their flow behavior from Newtonian to thixotropic (Nawab, 1958; Ganani, 1985). Liquid or pasty products have to fulfill certain requirements in regard to viscosity and thus suitable additives are frequently used. Among a variety of additives also fibrous products are well established and could be substituted by fibers derived from end-of-life apparel (Bartl, 2006). Table 4 shows several examples of materials that already contain fibers (mostly from virgin materials) or additives to influence viscosity (frequently expensive polymers).

Table 4 Products containing fibers or additives to influence viscosity

Product	Typical additives
Adhesives	Pyrogenic and precipitated silica, spar or in special cases fibers and metal powders
Paints and Coatings	Additives are used for rheology control: silicates, chelates, cellulose ethers and synthetic polymers
Dry mortars	thickening and water retaining agents
Bitumen	long fibers for reinforcement short fibers (e.g., Arbocel® or Lignocel®) influence drying behavior
Cement and concrete	Polymers, carbon and glass fibers tire derived fibers can be used as favorably concrete additive (Li, 2004)

It is clear that deriving fibers from waste leads to an application on a lower quality level. Strictly speaking it is not recycling but downcycling. However, this prolongation of the life cycle can save energy since conventional fiber products can be substituted. Table 4 compares the energy demand for producing fibers with the effort of collection and grinding. The energy savings are much lower than compared to a reuse of a fiber product (second-hand clothing) but still significantly higher than compared with incineration.

Table 5 Energy demand for the production of 1 t fibers compared to the consumption for collection and grinding (Allwood, 2006; Patel, 2008)

		CV (EU)	CV (Asia)	PET	CO
Total energy for production	[GJ]	19	62	93	36
Energy for collection and grinding	[GJ]	8	8	8	8
Savings	[GJ]	11	54	85	28

CONCLUSIONS AND OUTLOOOK

Fiber production requires large amounts of energy and resources so that a reuse is highly recommended from an ecological point of view. Thermal recycling, which can recover the caloric value to a certain extent, is the most nearby alternative to landfill but shows several disadvantages. Prices for incineration are quite high and the portion of reclaimable energy is fairly low compared to the total consumption during the manufacturing process.

Apparel collection and utilization as rewearables is an excellent example for product reuse. Second hand clothes can save significant amounts of energy and are, thus, ecologically sound but also show economic as well as social benefits. However, this favorable method requires clean and proper clothes and is not applicable for dirty and torn apparel or other sources of fibers.

It is, thus, recommended to develop another process that can handle various types of fiber containing waste. Usually, the processing schedule contains several steps most likely including comminution, separation of non-fibrous components and tailoring (i.e. production of fibers exhibiting a predetermined length). In the case of fluff, originating from tire recycling, a processing scheme has already been introduced at an industrial scale including a successful marketing of the reclaimed fibers in the bitumen industry. Principally, this method is applicable to other types of fiber containing wastes but needs to be adapted to the specific requirements.

It is obvious that recycling processes for fibers can significantly reduce the consumption of energy and resources. Several recycling processes for fibers are already well established but there still exists a large potential for further improvements. LCA data demonstrate that it is worth to develop adequate recycling processes for fibers since considerable amounts of resources can be saved. Parallel to these ecological benefits a large economic potential is obvious.

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