LIFE CYCLE ASSESSMENT OF MAN-MADE CELLULOSE FIBRES

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The production of textile materials has undergone dramatic changes in the last century. Man-made cellulose fibres have played an important role for more than 70 years. Today, the man-made cellulose fibre industry is the worldwide second largest biorefinery (next to the paper industry). In the last few years, the interest in man-made cellulose fibres has grown as a consequence of increased environmental awareness and the depletion of fossil fuels. However, an environmental assessment of modern man-made cellulose fibres has not been conducted so far. The purpose of this study is to assess the environmental impact of man-made cellulose fibres. Five staple fibre products, i.e., 1) Lenzing Viscose Asia, 2) Lenzing Viscose Austria, 3) Lenzing Modal, 4) Tencel Austria, and 5) Tencel Austria 2012, are analysed by means of Life cycle assessment (LCA). The system boundary is cradle to factory gate. We compare the results with conventional cotton, novel bio-based fibres (PLA fibres), and fossil fuel-based fibres (PET and PP). The inventory data for the production of man-made cellulose fibres were provided by Lenzing AG. The inventory data for cotton, PET, PP, and PLA were obtained from literature sources. The environmental indicators analysed include resources and the impact categories covered by CML 2000 baseline method. The indicators for resources include non-renewable energy use (NREU), renewable energy use (REU), cumulative energy demand (CED), water use, and land use. The environmental impact indicators covered by the CML method are global warming potential (GWP) 100a, abiotic depletion, ozone layer depletion, human toxicity, fresh water aquatic ecotoxicity, terrestrial ecotoxicity, photochemical oxidation, acidification, and eutrophication. In addition, the system boundary of cradle to factory gate plus end-of-life waste management was analysed for NREU and GWP. Furthermore, sensitivity analyses have been carried out to understand the influence of various assumptions and allocation methods.

The LCA results show that Lenzing Viscose Austria and Lenzing Modal offer environmental benefits in all categories (except for land use and water use) compared to Lenzing Viscose Asia. Tencel Austria 2012, Lenzing Viscose Austria, Lenzing Modal, and Tencel Austria are the most favourable choices from an environmental point of view among all the fibres studied. These four man-made cellulose fibres offer important benefits for reducing NREU, GWP, toxicity impacts, water use, and land use. Lenzing Viscose Asia has higher impacts than the other man-made cellulose fibres with regard to NREU, GWP, abiotic depletion, photochemical oxidation, and acidification. Cotton is identified as the least preferred choice due to its high ecotoxicity impacts, eutrophication, water use, land use, and relatively low land use efficiencies.

The single-score analysis based on the mid-point results of this study is reported in [62].

Key words: man-made cellulose fibres; LCA, viscose, Tencel, Lyocell, Modal, environment, energy, GWP

Introduction

The production of textile materials has undergone dramatic changes in the last century. Prior to the industrial revolution in the 19th century, natural materials, e.g., cotton, animal furs and silk had been used for thousands of years. In the first decades of the 20th century, cotton accounted for more than 70% of all textile raw material production in the world [1]. The first commercial plant for viscose production was built in France in 1891 [2]. It was not until the 1930s that man-made cellulose fibres became one of the principal fibres on the world fibre market. Figure 1 shows the global production of man-made cellulose fibres in the past one hundred years. Before World War II, one of the most important motivations for developing man-made cellulose fibres was to replace cotton and to become self-sufficient with regard to textile material. After World War II the production of man-made cellulosics kept increasing, until in the 1960s synthetic fibres "swept" the whole textile market. In the meantime, water and air pollution caused by toxic compounds darkened the image of the man-made cellulosics [2]. After decades of fierce competition, man-made cellulose fibres are now primarily covering high-value applications. They have maintained their characteristic position in the world fibre market thanks to process improvement and new product development [2].

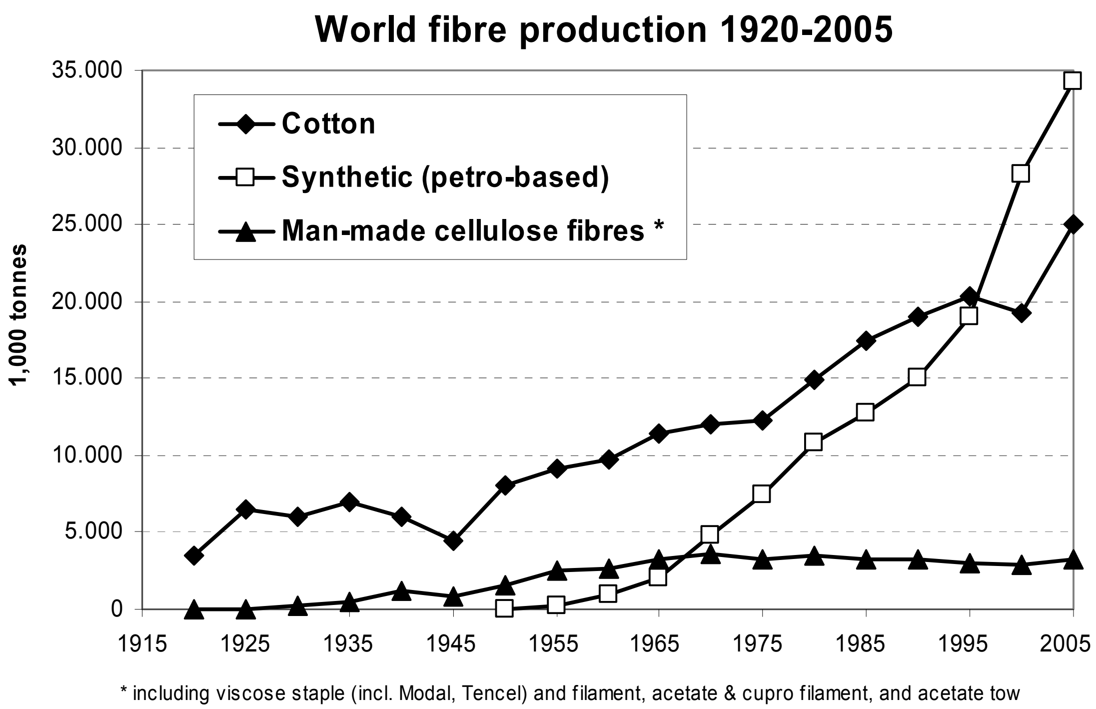

Figure 1. World fibre production 1920 – 2005 [1, 2, 3, 4, 5, 6].

Man-made cellulosics are synthetic polymers made from natural resources. Wood pulp and cotton linters are the common raw materials. At present, four methods are used to produce man-made cellulose fibres at an industrial scale:

- the viscose process is applied to produce Viscose and Modal fibres used for textiles and nonwovens (see Figure 2 for the different end-use applications);
- the Lyocell process is applied to produce Lyocell fibres (e.g., Tencel), which has similar applications as Viscose and Modal fibres;
- the cuprammonium process is applied to produce cuprammonium fibres (Cupro), e.g., for medical uses; and
- the acetate process is applied to produce cellulose acetate fibres mostly used for cigarette filters (acetate tow).

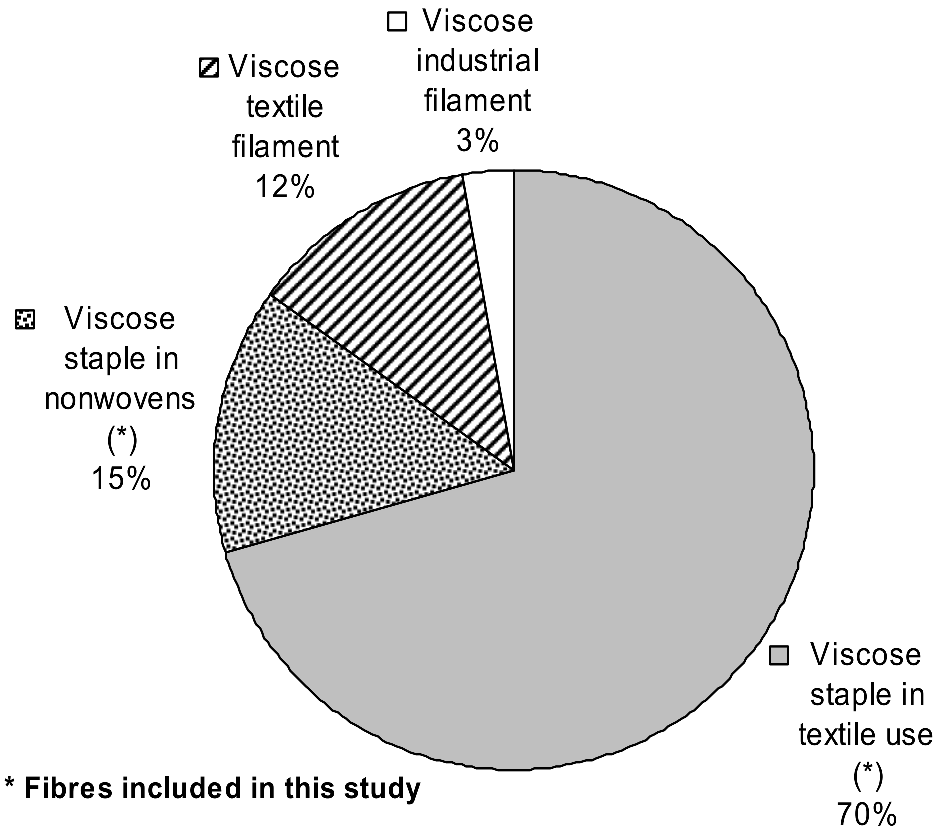

Figure 2. Viscose fibre consumption by end use in 2005, including Modal, excluding Tencel [3].

Viscose staple fibres are by far the most important man-made cellulose fibres. In 2002, the world-wide man-made cellulose fibre production was 2,800 kilo tonnes, of which staple fibres (including Viscose, Modal and Tencel) accounted for 62%, viscose filaments (including Modal) 13%, acetate tow 21%, and acetate & Cupro filaments 4% (see also Table 1) [7, 8]. The viscose process has set the standards for quality, variety, and price which other man-made cellulose fibres had to compete with [2]. Today, the world largest man-made cellulose fibre producer, Lenzing AG[1], has a global staple fibre production capacity of 570 kilo tonnes [9], which is about one fifth of the world's man-made cellulose fibre production (excluding acetate tow).

Lenzing produces cellulose fibres by the application of three generations of technologies: the conventional viscose process (Lenzing Viscose®), the modified viscose process – for high wet modulus fibres (Lenzing Modal®), and the Lyocell process (Tencel®)[2], which is a solvent based process that was commercialised in the early 1990s. All three generations of fibres are produced nowadays simultaneously in large quantity.

The purpose of this study is to assess the environmental impacts of man-made cellulose staple fibres. In the past, several studies have compared the energy consumption for the production of natural, man-made, and synthetic fibres [10, 11]. However, the data used in those studies are dated and the studies are incomplete by focussing only on the *energy requirements* for production. Moreover, all publicly available studies address viscose only in general terms and

[1] "Lenzing AG" represents the company name. "Lenzing" is also the name of the place in Austria, where the headquarter of Lenzing AG is located.
[2] Lenzing Viscose®, Lenzing Modal® and Tencel® are registered trade names by Lenzing AG.

do not distinguish between Viscose, Modal, and Tencel. In the past decades, strong efforts have been made to optimise the production process for Viscose and Modal fibres, reducing pollution and improving the material and energy efficiencies. The innovative Lyocell process does not use toxic compounds as reagents (e.g., CS_2) and it has the advantage of a substantially reduced total chemical use (e.g., NaOH). However, the environmental impacts of the various types of man-made cellulose fibres have not been assessed so far.

A further reason for preparing this study is that the production volume of man-made cellulose fibres is by far larger than all the other man-made bio-based polymers together (see Table 1). The man-made cellulose fibre industry operates the worldwide largest biorefineries (excluding paper) [12]. Bio-based materials have attracted much attention in the last few years due to concern about the environment, climate change, and the depletion of fossil fuels, which represents the main raw material of petrochemical synthetic fibres. Comparative environmental assessments between man-made cellulose fibres, natural cellulose fibres (e.g., cotton), and novel bio-based fibres (e.g., PLA) do not exist so far.

Table 1. Global production capacity of selected biomaterials (data for man-made cellulose fibres are for 2002, all other data are for 2003).

Type of biomaterial	Global capacity (kt)
Starch polymers	70-200 [13]
Polylactic acid (PLA)	140 [13]
Polytrimethylene terephthalate (PTT)	10 [13]
Man-made cellulose fibres	2,820 [5, 8]
- Viscose staple (incl. Modal and Tencel)	- 1,760 [5, 8]
- Viscose textile filament	- 300 [8]
- Viscose industrial filament	- 64 [8]
- Acetate & Cupro filament	- 100 [8]
- Acetate cigarette tow	- 600 [8]

Against this background, the research questions addressed by this report are:

1. What are the environmental impacts of the three types of man-made cellulose staple fibres, i.e., Viscose, Modal, and Tencel?
2. Which steps in the process chain contribute most to the overall environmental burden of man-made cellulose staple fibres?
3. What are the advantages and disadvantages of man-made cellulose fibres from an environmental point of view compared to cotton, PET, PP, and PLA fibres?

We applied the method of life cycle assessment (LCA) to assess the environmental impact of man-made cellulose fibres. LCA has been standardised by the International Standardisation Organisation (ISO) in the ISO 14040 series, namely:

- ISO 14040: 2006 - Principles and framework [14] and
- ISO 14044: 2006 – Requirements and guidelines [15].

This report intends to provide the information on the environmental profiles of man-made cellulose fibre for companies, governments, environmental scientists as well as general public.

Goal, functional unit, and system boundaries

The goal of this LCA is to assess the environmental impacts of three types of man-made cellulose fibres, namely, Viscose, Modal, and Tencel. The functional unit is defined as "*one metric tonne of staple fibres*". For all three types of cellulose fibres, the finished products are conditioned. Viscose and Modal fibres have a moisture content of 11%; Tencel fibre has a moisture content of 13%. Staple fibres are not end products, but are important semi-finished products which are ready to be converted to many textile end products.

The system boundary of this LCA is *cradle to factory gate*. A cradle to factory gate LCA study includes all steps from the extraction of raw materials and fuels, followed by all conversion steps until the product (staple fibres) is delivered at the factory gate. In one of the last parts of this study, the system boundary will be extended from cradle-to-factory gate to end-of-life waste incineration with energy recovery. The use phase of the fibre, e.g., the production of fabric and the usage of a garment, is excluded.

Table 2 introduces the product systems in this study. The detailed process description can be found in the part "Inventory analysis".

- **Lenzing Viscose Asia** is produced in Asia, using imported pulp based on eucalyptus wood which is produced from man-managed forest in the southern hemisphere. The fibre plant is representative for the state-of-the-art separate viscose fibre plant based on wood pulp in the world.
- **Lenzing Viscose Austria** is produced in Austria. The most important difference between Lenzing Viscose Asia and Lenzing Viscose Austria is the integration of pulp and fibre plants. The Austrian viscose fibre plant is integrated with a pulp mill, while pulp and fibre production are separate in the case of Viscose Asia; in this sense, Lenzing Viscose Austria represents the best available technology (BAT) of the current global viscose fibre production.
- **Lenzing Modal** is also produced at the integrated site in Lenzing, Austria. Both, Lenzing Viscose Austria and Lenzing Modal use wood from managed forest in Europe. In the integrated pulp/fibre plant, process energy is supplied by internal biomass (e.g., bark and thick liquor from the pulp production), external (purchased) biomass, municipal solid waste incineration (MSWI) with external municipal waste, and a very small amount of fossil fuels.
- **Tencel Austria** is produced based on the Lyocell process in Heiligenkreuz in Austria. Both, market pulp and pulp from the Lenzing pulp mill are used. The process energy for the current Austrian Tencel production is supplied by natural gas (70%) and external biomass (30%).
- In addition, we include a future Tencel fibre in the comparison, namely **Tencel Austria 2012**. As planned by Lenzing, in 2012 the energy supply of the Tencel fibre production will be entirely based on energy recovered from municipal solid waste incineration (MSWI).

Table 2. Product systems included in this study: types and geographic scope of man-made cellulose fibres in this study

Fibre Name in this study	Fibre[a]	Wood source	Pulp source	Fibre plant	Process energy
Lenzing Viscose Asia	Viscose	Eucalyptus	Market pulp	Asia	Local electricity, coal, gas, oil
Lenzing Viscose Austria	Viscose	European Beech	Lenzing pulp, integrated production, Austria		Biomass, recovered energy from MSWI
Lenzing Modal	Modal				
Tencel Austria	Lyocell	Eucalyptus and Beech	Lenzing pulp and Market pulp	Austria	70% gas 30% biomass
Tencel Austria 2012	Lyocell				100% recovered energy from MSWI

[a] Fibre designation according to ISO/TC 38.

Furthermore, the LCA result of man-made cellulose fibres is compared with PET, PP, PLA, and cotton. We defined the functional unit as “one metric tonne of staple fibre”. However, the properties of fibres studied are not identical and therefore the end applications of these fibres may not be exactly the same. Ideally, the comparison should hence be made for relevant end products. This seems hardly possible, because the extremely large number of end products involving different types of dyeing, spinning, and other steps in the textile value chain next to differences in washing during the use phase make a generalized approach impossible. It is therefore recommended to take into account the specific properties of fibres when using this LCA study for decision making.

Some physical properties of the studied fibres are listed in Table 3. An additional and less important remark on the functional unit is that natural fibres such as cotton usually have some impurities in the staple fibre product (e.g., dust and ginning residues), whereas man-made fibres, both bio-based and petroleum based, are produced from chemical processes and usually have very high purity. In general, man-made fibres therefore do not need purification before further textile processing.

Table 3. Selected mechanical, thermal and water retention properties of staple fibres.

Fibre name	Trade name	Density (g/cm^3)	Tenacity [a] (wet) (cN/tex)	Tenacity [a] (dry) (cN/tex)	Water retention (%)	Melting point (^oC)
Cotton		1.5-1.54 [16]	26-40 [17]	24-36	38-45 [7]	~400 [16]
Viscose	Lenzing Viscose	1.52-1.54[16]	10-13 [17]	24-26	90-100 [7]	n/a
Modal	Lenzing Modal	1.52-1.54 [16]	19-21 [17]	34-36	60-65 [7]	n/a
Lyocell	Tencel	1.50 [16]	34-36 [17]	40-42	60-70 [7]	n/a [b]
PET [16]	Dacron	1.36-1.41	30-55	28-55	3-5	250-260
PP [16]	Herculon	0.9-0.92	25-60	25-60	0	160-175
PLA [18]	Ingeo	1.25	n/a [b]	32-36	n/a [b]	170

[a] Tenacity is expressed in relative to the fineness (1 tex = 1 gram per 1000 metres). Figures for tenacity are based on both, fibre fineness (tex) and cross-sectional area of the sample. [b] n/a = data not available or not applicable

Life cycle inventory analysis

From trees to fibres

Wood production

Wood is the raw material of Lenzing man-made cellulose fibres. Lenzing Viscose Austria, Lenzing Modal and part of Tencel Austria are produced from the Lenzing pulp, which originates from beech wood. Half of the beech wood comes from Austria and most of the other half is from other European countries. The wood is transported by rail or truck to the pulp production site in Lenzing. The market pulp used for Lenzing Viscose Asia and Tencel Austria is based on eucalyptus wood produced in the southern hemisphere. The market pulp is transported by transoceanic ship to the fibre production sites in Asia and Europe.

The European beech production data were obtained from Ecoinvent (version 1.3) [19]. According to Ecoinvent, the average density of beech wood is assumed 650 kg/m^3 (dry mass and dry volume basis); the average yield of European beech wood is 3.40 oven-dried tonnes (odt) per hectare per year (including bark); the carbon content is approximately 49% [19]. The European beech is neither fertilised nor irrigated and is machine-harvested.

Data used to analyse the production of eucalyptus wood are given in Table 4. Small amounts of nitrogen and phosphate fertilizers are applied to the eucalyptus plantations but it is not irrigated. Since the amount of fertiliser use is relatively small, only the direct N_2O emissions are taken into account (see Table 4). Harvesting is mainly (80%) done by hand (private communication with the market pulp supplier). Wood is transported from the forest to the pulp mill by rail and road.

The beech forests and eucalyptus plantations have both existed for more than 20 years (private communication with Lenzing AG and the market pulp supplier). Thus, the GHG emissions from land transformation are considered negligible.[3]

Table 4. Key data on the eucalyptus wood production in tropical regions (odt = oven-dried tonne).

No.	Name of parameter	Value	Source	Note
1	Density	650 kg/m^3	Ecoinvent [19]	Dry mass, dry volume density for average hardwood.
2	Carbon content in wood	49.1%	Ecoinvent [19]	Assumed the same as average European hardwood
3	Bark content in wood	12% vol.	Ecoinvent [19]	Assumed the same as average European hardwood
4	CO_2 sequestered in 1 m^3 wood	1,319 kg CO_2	Calc. from 1-3	1 m^3 wood without debarking
5	Calorific value of eucalyptus wood	19.8 GJ/odt	Private communication with the market pulp supplier	
6	Yield of eucalyptus wood	12 odt/ha/yr	Private communication with the market pulp supplier	
7	Fertiliser use N fertiliser P fertiliser	 25 kg /ha/yr 17 kg/ha/yr	Private communication with the market pulp supplier	
8	Machinery use	1.2 kg diesel/m^3 (dry matter)	Literature data [22] and private communication with the market pulp supplier	
9	N_2O emissions from applying fertilisers	0.01 kg N_2O-N/kg N fertiliser	IPCC 2006 guidelines [20]	Direct emission from N fertiliser use

Pulp and fibre production

The pulp used to produce man-made cellulose fibres is so-called dissolving grade pulp. The difference between dissolving grade pulp and paper grade pulp can be described as follows:

[3] Both IPCC (2006) [20] and PAS 2050 [21] set as rule that only the direct land use change occurring “on or after 1 January 1990” should be included.

in paper grade pulp, lignin and resins are removed from wood and the pulp contains both cellulose and hemicellulose. In contrast, dissolving pulp is not only free of lignin and resins, but also large amounts of hemicellulose are removed, resulting in a very high content (90-94%) of alpha cellulose [9]. For dissolving pulp production, the acid sulfite or the kraft process is used.

Lenzing's dissolving pulp plant produces the by-products xylose, furfural and acetic acid; thick liquor and bio-sludge from waste water treatment plant (WWTP) are recovered and combusted in order to fuel both pulp and fibre production [7].

All plants producing "market pulp" (i.e., dissolving pulp for sale) are not integrated and they are located in different regions in the world. The plants producing market pulp are at various technology levels and can have very different energy efficiencies. The production of market pulp leads to much less by-products than the production of Lenzing pulp. For example, market pulp does not have the by-products of Lenzing pulp, i.e., xylose, furfural and acetic acid [9]. In this study, we assume average market pulp as the base case. Variations in the LCA results as a consequence of using different types and mixes of pulp are reported by uncertainty ranges.

As mentioned above, two types of technologies for cellulose regeneration, i.e., the viscose process and the lyocell process are applied to produce three types of man-made cellulose fibres, namely Viscose, Modal and Tencel. The two processes are illustrated in Figure 3. The viscose process has been applied at industrial scale since the 1930s and nowadays the process is used for the production of both Viscose and Modal fibres. Modal fibres are manufactured by a modified viscose process with a higher degree of polymerisation and modified precipitating baths [2]. This leads to fibres with improved properties such as higher wet strength and being easy to wash.

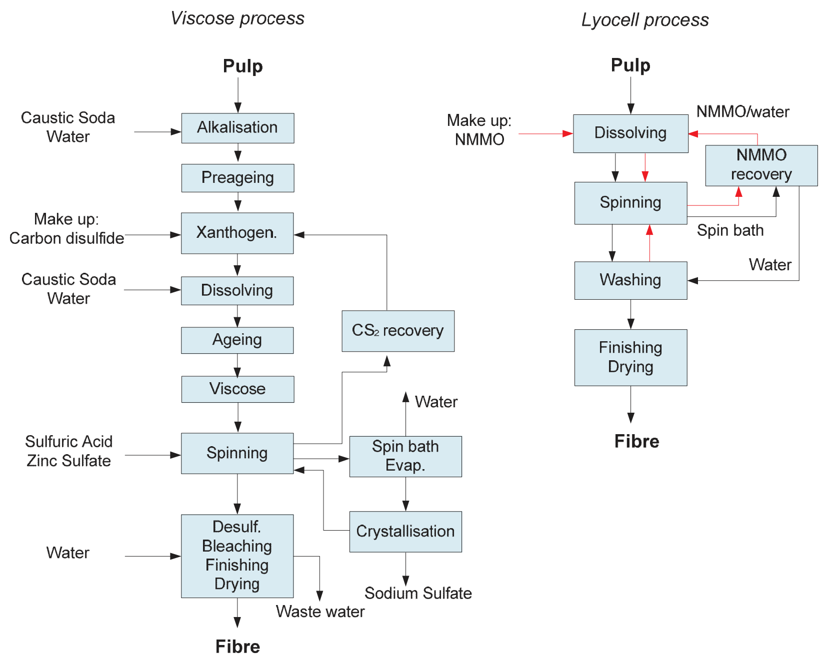

Figure 3. The Viscose process and the Lyocell process [17].

In the viscose process, pulp is first alkalised in caustic soda, then depolymerised and reacted with carbon disulfide (CS_2) to form cellulose xanthate, which is dissolved in caustic soda.

After filtration, degassing and ageing, the viscose solution is ready to be spun from a precipitation bath containing sulphuric acid, sodium sulphate, and zinc sulphate. Here, cellulose is regenerated in filament form. Classic spinnable xanthate solution contains 7 – 10 % cellulose, 5 – 7 % NaOH, 25 – 35 % CS_2 [2]. The solution is spun into regular Viscose fibres in an acid salt bath (80 g/l H_2SO_4, 150 – 300 g/l $NaSO_4$, 10 – 20 g/l $ZnSO_4$) at 45 – 55 °C [2].

In the Modal production process, the xanthate solution contains 6 – 8 % cellulose, 6.5 – 8.5 % NaOH, and 30-40 % CS_2; small amounts of modifier may also be added [2, 9]. Modal fibres are spun into filament in a slightly acid bath of low temperature and with a strong coagulating effect [2].

The viscose process requires large amount of caustic soda (0.5-0.8 kg NaOH per kg fibre) [23] and leads to sodium sulphate (Na_2SO_4) as by-product. Nowadays up to 70% of the CS_2 is directly recycled and reused. Most of the remaining 30% is converted into sulphuric acid which is also recycled to the process.

The lyocell process represents a complete technology innovation. Unlike the conventional viscose process, the lyocell process uses NMMO (N-methylmorpholine-N-oxide) to dissolve pulp and regenerate cellulose. The process has an almost completely closed solvent cycle (see Figure 3). This not only avoids the use of the highly toxic solvent CS_2, but also reduces number of the process steps and total chemical use.

Integrated production and separate production

Figure 4 and 5 show the two different production systems: *integrated* (for Lenzing Viscose Austria and Lenzing Modal) and *separate* production (for Lenzing Viscose Asia and Tencel). The main differences between integrated and separate production are:

- In the case of integrated production energy is recovered and also material use is optimised, while this is not the case for separate production.
- In the integrated production, only a small amount of fossil fuels is used. Bark, thick liquor and soda extraction liquor from the pulp production are used as energy sources for the pulp and fibre production. The remaining heat requirements (about 40% of the total heat requirements) are covered by externally purchased bark and a municipal solid waste incineration plant which is located next to the integrated plant. The integrated production (Lenzing Viscose Austria and Lenzing Modal) is self-sufficient in terms of electricity use, i.e., no electricity is required from the public grid.
- The Lenzing pulp, which is used for Lenzing Viscose Austria, Lenzing Modal, and partly Tencel, yields more by-products (e.g., xylose, acetic acid, furfural, and thick liquor[4]) than the market pulp.
- For average market pulp, a substantial amount of the process heat and power is provided from the combustion of thick liquor. Additional process energy is provided by fossil fuels. Small amounts of electricity are purchased from the local public grid.
- In the Lenzing Asian Viscose fibre plant, over 99% of the process heat and power originate from fossil fuels, which are mainly coal and oil; nearly half of the electricity is supplied from the regional grid.

[4] Most of the thick liquor is used to fuel the pulp and fibre production; a small amount is sold by Lenzing as a by-product.

- By integrated production, the transportation of pulp to the fibre plant is avoided, while the separate production of fibres requires the transportation of pulp.

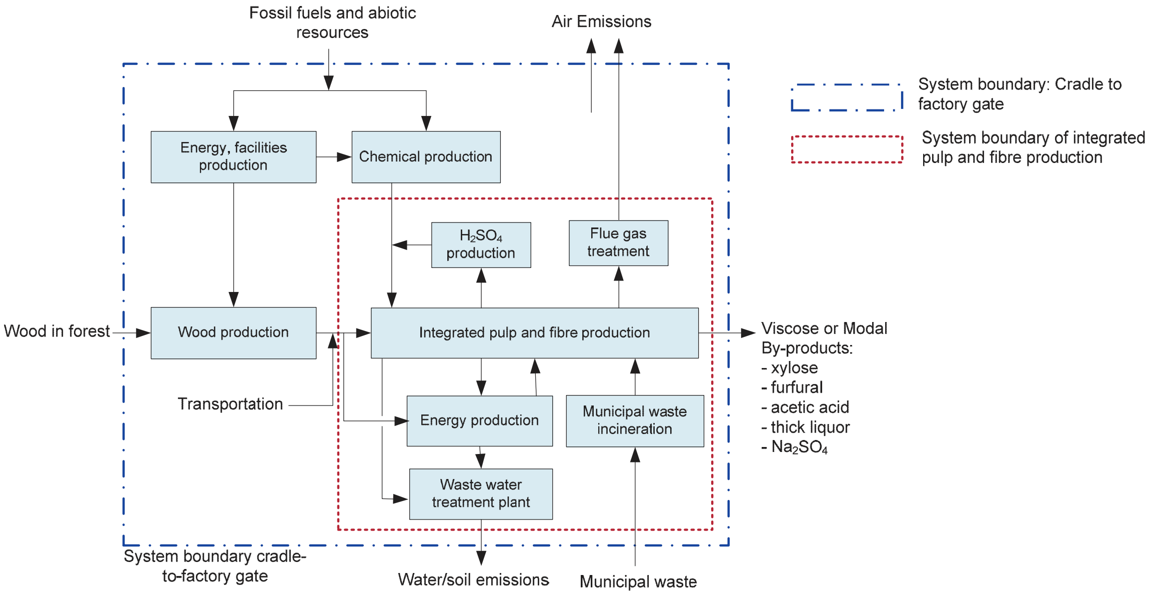

Figure 4. System description of man-made cellulose fibre: *integrated* pulp-fibre production.

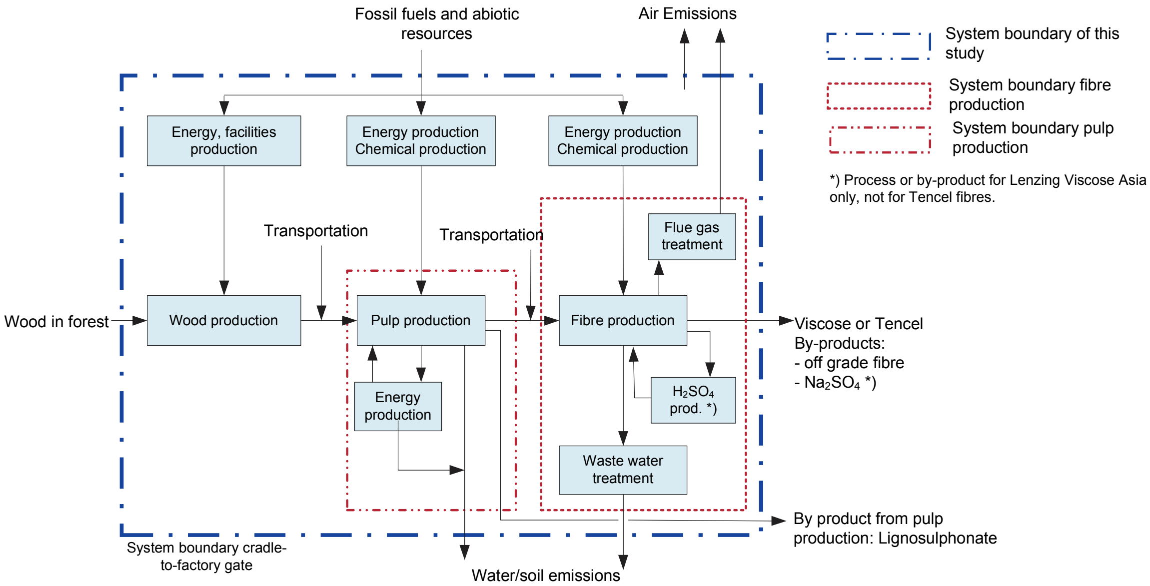

Figure 5. System description of man-made cellulose fibre: *separate* pulp-fibre production.

Data sources

The data used in the analytical work of the study can be categorised into two levels: site-specific data and region-specific data. Site-specific data are collected from the production sites, i.e., energy and material balances of the pulp and fibre production, and the distance and the means of transportation. Site-specific data were provided by Lenzing AG for the preparation of the LCI (life cycle inventory) of market pulp and Lenzing pulp, Lenzing Viscose Asia, Lenzing Viscose Austria, Lenzing Modal, Tencel Austria, and Tencel Austria 2012. Unless otherwise reported, the technology level assumed represents the mid 2000s.

Region-specific data refer to the country or the regional level. For example, the electricity used in the process studied was assumed to represent the average European electricity mix (for avoided grid power from MSWI) and the Indonesian electricity mix (for Lenzing Viscose Asia). To a large extent, power from the public grid is used for the production of NaOH. The data on the regional electricity mix and on efficiencies were obtained from the Ecoinvent database, statistics, and scientific reports. The data sources of this study are summarized in Table 5.

Table 5. Summary of data sources.

	Data source	**Notes**
Pulp production (Lenzing pulp, market pulp)	Lenzing AG	Site specific
Fibre production (Viscose, Modal, and Tencel)	Lenzing AG	Site specific
Public grid power	Ecoinvent database [24], IEA energy statistics [25, 26]	Country specific European electricity mix: 65% from the UCTE grid, 13% from the NORDEL grid, 9% from the CENTREL grid, 12% from the UK grid and 1% from the Irish grid.
Public grid heat	Ecoinvent database [27]	Grid heat from industrial gas boiler
Production of chemicals (e.g., caustic soda)	Ecoinvent database [28]	Region specific (Europe, Asia)
Production of fuels	Ecoinvent database [27, 29, 30]	Region specific (Europe)
Transportation	Ecoinvent database [31]	Including road, rail, barge and transoceanic transportation.
Municipal solid waste incineration	Ecoinvent database [32]	Average Switzerland
Energy recovery from MSWI (for post-consumer waste incineration)	Literature data and personal communication with experts [33, 34]	Average Western Europe
Cotton	Carbotech [35] for the US cotton; Ecoinvent [36] for the Chinese Cotton, see the impact assessment of the US cotton in Appendix I	Cradle to factory gate cotton fibre production including tillage, planting, fertiliser and pesticide use, harvesting, transportation, ginning and baling.
PET, PP polymer production	Boustead [37, 38]	Average Western Europe
PLA polymer production	Vink et al. [39]	Produced in the US
Energy requirement of PET, PP and PLA fibre spinning (from resin)	0.64 kWh electricity and 5 MJ heat (from fossil fuel) based on [40]	This energy data were cross-checked by several industrial experts.

Abbreviations:
UCTE stands for Union for the Co-ordination of Transmission of Electricity; countries included in UCTE are Austria, Bosnia and Herzegovina, Belgium, Switzerland, Germany, Spain, France, Greece, Croatia, Italy, Luxemburg, Macedonia, Netherlands, Portugal, Slovenia, and Serbia and Montenegro.
NORDEL stands for Nordic countries power association, including Denmark, Norway, Finland, and Sweden.
CENTREL stands for Central European power association, including Czech Republic, Hungary, Poland, and Slovakia.

In a few cases we had to make estimates because no inventory data was readily available. In particular this relates to the production of NMMO and ion exchange resin. For NMMO we assumed that the NREU and GWP 100a are 200 GJ/t and 16 t CO_2-eq/t, respectively. We aimed at making conservative assumptions resulting in rather too high than too low environmental impacts but uncertainties do remain (see also sensitivity analysis in the last section).

For the production of ion-exchange resin, the inventory data are available in Ecoinvent [41]. However, the information on ozone layer depleting emissions, especially chloroform emission, was outdated. A literature research did not yield useful information. We assumed that no ozone depleting substance was used in the ion-exchange resin production based on the agreement made by the Montréal Protocol in 1994. A detailed description of the assumptions made regarding the production of NMMO and a literature review on ion-exchange resin production can be found in Appendix II of this report.

Data sources for cotton, PET, PP, and PLA

The cradle to factory gate inventory data of conventional cotton fibre is based on a weighted average of US cotton and Chinese cotton. The cotton production in these two countries represented about 43% of world cotton production in the season 2004/2005 [42]. The LCA inventory data on cotton were provided by Carbotech AG [35] (for US Cotton, see Appendix I) and Ecoinvent [36] (for Chinese cotton). The allocation between cotton fibre and cotton seed is conducted based on mass and economic values. The allocation factor for cotton fibre is 0.85, and for cotton seed it is 0.15 [35].

Polyethylene terephthalate (PET) and polypropylene (PP) are petrochemical polymers. The life cycle inventory data for the production of amorphous PET and of PP resin were obtained from PlasticsEurope [37, 38], representing average Western European production in the 2000s.

Polylactic acid (PLA) is a bio-based polymer made from starch or sugar crops. The eco-profile data of PLA polymer originates from the peer-reviewed study of NatureWorks LLC [39]. In our comparison, two types of PLA polymer are included: PLA without wind (= PLA 5 in [39]) and PLA with wind (= PLA 6 in [39]). PLA with wind purchases wind energy (via renewable energy certificate) to offset process electricity.

Table 6. Comparison of cradle-to-factory gate NREU and GWP100a of PLA polymer [39, 43].

	NREU (GJ/t polymer)	GWP100a (kg CO_2 eq./t polymer)
PLA without wind (PLA 5)	50	2.0
PLA with wind (PLA 6)	27	0.3
Ingeo 2009	42	1.3

When this study was prepared, a new generation of PLA (Ingeo 2009) was announced by NatureWorks LLC. In this case the lactic acid production process is improved, wind energy is not used [43]. Compared to previous PLA without wind (PLA 5) and PLA with wind (PLA 6), the NREU and GWP of Ingeo 2009 are somewhere in-between (see Table 6).

When our study was finalised, the eco-profile of Ingeo 2009 was still under the third-party review. In this study, we used the peer-reviewed eco-profile data of PLA. Thus, both, PLA with and without wind are compared. Furthermore, only the impacts of energy and GWP are publicly available for PLA. For this reason, the comparison including PLA fibres is limited to these two impacts.

The life cycle inventory of PET, PP and PLA fibres consists of both polymer production and fibre spinning process. Based on the data from [40] we assumed that for the spinning process 0.64 kWh electricity and 5 MJ heat (from fossil fuel) are required per kg fibre.

Allocation principle

Allocation is needed where there are multiple products from one process. In this study, there are three types of allocation problems: allocation of by-products from pulp and fibre production, allocation of energy from waste, and other multi-output situations. We will now discuss the approaches chosen for each of them.

Allocation of by-products from pulp and fibre production

According to ISO allocation should, in principle, be avoided if possible [15]. This can be done by applying system expansion, i.e., by assuming that the co-product would otherwise need to be produced by standard technology. For example, for integrated Viscose fibre production, acetic acid is one of the by-products from the pulp mill. The standard route is to produce acetic acid from petrochemical ethylene. Therefore, credits are assigned to the integrated pulp and fibre production, representing the avoided petrochemical production of acetic acid. We therefore apply this allocation method for acetic acid and sodium sulphate (Na_2SO_4). The standard way to produce sodium sulphate is a mix of several technologies. According to Ecoinvent, worldwide about 60% of the sodium sulphate are of natural origin, 25% are produced as by-product and 15% are produced as main product (Mannheim process) [41]. Based on the assumption made by Ecoinvent, sodium sulphate which is produced as by-product is free of environmental burden [41]. The cradle to factory gate non-renewable energy use (NREU) of sodium sulphate is low (approximately 8.5 GJ/t).

However, there are also by-products for which Lenzing's production process represents the standard technology: xylose, furfural, and thick liquor are typical products from wood/pulp processing. It is therefore not possible to apply system expansion to avoid allocation in these cases. Instead, we apply economic allocation, i.e., we assign the total environmental impact to the various outputs based on the prices of these outputs (the higher the economic volume of a given by-product, the larger its environmental impact is). Apart from the wood-derived chemicals just mentioned, economic allocation is also applied for off-grade fibres (fibres with lower quality and sold at a discount). For these by-products, allocation based on calorific values could be applied instead of economic values, because xylose, furfural, and thick liquor (lignosulphonate) could all be combusted to generate process energy. Furthermore, all by-products can also be allocated based on economic values without applying the system expansion method. These two alternative methods (i.e., economic allocation and mass allocation) will be discussed in the last part of this study.

Allocation of heat from waste incineration plant

In the case of the integrated Viscose and Modal production, as well as for the future Tencel production (see Figure 4 and 5), part of the energy is supplied in the form of heat from a municipal solid waste incineration (MSWI) plant, operated with municipal solid waste (i.e., not with the solid waste from fibre production). The MSWI plant consumes a small amount of fossil fuels and it delivers two services: waste disposal service and energy production (recovered heat; see Figure 6). It is therefore necessary to determine how much of the environmental burden of the MSWI plant should be allocated to the waste disposal service and how much to the recovered heat which is used in fibre production. We now discuss three approaches, namely two allocation approaches and one method based on system expansion.

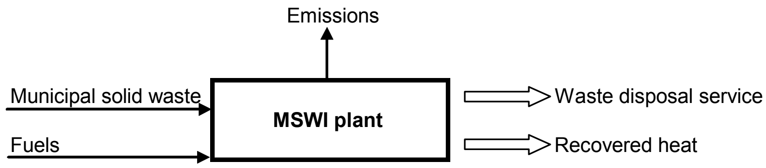

Figure 6. Inputs and outputs of a municipal solid waste incineration plant.

For the MSWI plant physical allocation based on energy, exergy or mass is not possible because the two services are not comparable in terms of energy, exergy, or mass content. Therefore, allocation based on economic values is applied. According to [9], the average cost (not including collection and transportation) for the disposal of one tonne of solid waste in a MSWI plant in Austria is 200 € (value for 2006). Assuming that the selling price of the recovered heat is the same as the price that is paid for the heat from fossil fuels[5], the income from selling the recovered heat is about 17.5% of the total income of a MSWI plant; 82.5% can hence be assigned to the waste disposal service of the MSWI plant. We use this allocation method as the baseline (default method) for later calculations (see Table 7).

Table 7. Allocation methods for heat from municipal solid waste incineration (MSWI).

Name	Method	Description
Baseline	Economic allocation	17.5% of environmental burden of MSWI plant is assigned to recovered heat
"Free heat"	Economic allocation	0% of environmental burden of MSWI plant is assigned to recovered heat
"Natural gas"	System expansion	Heat is supplied by a natural gas-fired boiler

However, the income composition of a MSWI plant differs among regions and countries. According to Ecoinvent [32], in Switzerland the revenue from energy recovered from waste incineration is only 5-10% of total revenue of a MSWI plant. Therefore Ecoinvent assigns no environmental burden to energy recovery from waste incineration, while the waste disposal service bears the entire environmental burden. In this study, we refer to Ecoinvent's approach as "free heat" case for quantifying the environmental impacts related to the supply of heat from a MSWI plant (Table 7).

On the other hand, one could also argue that using heat from waste incineration is a coincidental situation. If there were no MSWI plant close-by, the fibre production would most likely obtain the required heat from a natural gas-fired boiler. Therefore, we use this so-called system expansion approach as the third method for solving the allocation problem.

According to ISO guidelines [15], allocation should preferably be avoided by applying system expansion. However, in this case, among the three methods, system expansion results in the highest environmental impacts for heat from waste incineration. By using this method, the environmental benefits of using heat from waste are totally ignored. Therefore, we choose system expansion as our "natural gas" case, but not as our baseline (Table 7).

Other allocations

The allocation methods described in Table 7 are also used for other types of combustible solid wastes, which are generated during the pulp/fibre production process. They are then

[5] This is the situation in Switzerland according to Doka (2003, Ecoinvent report No.13) [32].

disposed off by a MSWI plant or a HWI (hazardous waste incineration) plant with energy recovery.

Caustic soda (NaOH), which is one of the most important input materials for the pulp, Viscose, and Modal production, is produced as one of the co-products by electrolysis of an aqueous solution of sodium chloride (the other co-products are chlorine and hydrogen). We use data from the study of PlasticsEurope [44], in which the allocation to chlorine, caustic soda, and hydrogen is carried out on a mass basis. Using this approach, about 52% of the environmental impacts of the electrolysis process are assigned to NaOH (46% are assigned to Cl_2 and 1.3% are assigned to H_2)[6].

Environmental impact indicators

In the Life Cycle Impact Assessment, the life cycle inventory data, which represents the various types of emissions and the raw material requirements, are converted into environmental impact categories, such as the contribution to global warming or acidification. These results for the various environmental impact categories are generally referred to as LCA mid-point results. In this study, we include two types of environmental indicators: 1) resources, i.e., non-renewable energy use (NREU), renewable energy use (REU), cumulative energy demand (CED), water use and land use, and 2) environmental impact categories, i.e., global warming potential (GWP) 100 years [46], and the categories according to the CML 2 baseline 2000 method[7] [47] (i.e., abiotic depletion, ozone layer depletion, human toxicity, fresh water aquatic ecotoxicity, terrestrial ecotoxicity, photochemical oxidant formation, acidification, and eutrophication). As an optional step, normalisation is included in this study based on the CML normalisation values for world 2000 [48].

Method applied to calculate energy use, land use, and water use

Energy use

Cumulative energy demand (CED) represents cradle to factory gate primary energy. Two categories of energy can be distinguished: non-renewable energy use (NREU) and renewable energy use (REU). NREU is the total of fossil fuel and nuclear energy; REU consists primarily of biomass, solar, hydro, and wind energy. In this report we define cumulative energy demand (CED) as the total of NREU and REU.

Land use

The indicator of land use in this study refers to the land use for biomass production (i.e., agriculture and forest). The land occupation of infrastructure (e.g., land use of a pulp mill or a cotton spinning factory), land transformation (e.g., the agriculture land that is transferred from forest land) and land for transportation are not taken into account. In the result section, land use is expressed in the unit “hectares per year per tonne”.

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[6] Allocation based on economic values of caustic soda, chlorine, and hydrogen is not practical because the market dynamics of all three co-products develop very differently; for this reason the market prices of all three co-products are not linked and the price ratios vary strongly. [45].

[7] CML: Centrum voor Milieuwetenschappen Leiden (Institute of Environmental Science), Leiden University, the Netherlands

Water use

The water use is expressed as the sum of original natural fresh water consumption. Natural water includes river water, lake water, and ground water; the total of the former two types is also called surface water. Sea water is excluded in this study. Four categories of water use during the production are taken into account, namely, process water, cooling water, irrigation surface water, and irrigation ground water. Rain water is not taken into account because the use of rain water does not cause environmental problems. The choice of the four categories of water is based on the understanding that they may have very different impacts on the environment. For example, process water is usually quality-controlled water, e.g., deionised water, softened water, decarbonised water, or tap water. Energy and materials input are required to produce process water (see Table 8 for natural water requirements for process water production). In contrast, cooling water is usually river water and does not require much energy to be produced or transported. One kg cooling water requires one kg natural water input. The impact of the heat released to the environment is not taken into account.

Table 8. Average natural water requirement for process water production in Europe [45].

1 kg processed water	Requires natural fresh water
Deionised water	1.24 kg
Softened water	1.08 kg
Decarbonised water	1.03 kg
Tap water	1.13 kg

Irrigation water and process/cooling water also differ in important features. Irrigation water can have strong direct impact on local hydrological systems (e.g., depletion of local available surface or ground water), whereas cooling/process water usually does not. Furthermore, using surface water and ground water for irrigation also has different impacts depending on the local situation such as salination of the soils [49]. So far no aggregation methods have been developed in order to assess total environmental impact of water consumption. Therefore, we report the four types of water consumption separately in this study as an inventory result.

CML baseline 2000 environmental impact indicators

Global Warming Potential

The characterisation model as developed by the Intergovernmental Panel on Climate Change (IPCC) has been selected to determine global warming potentials (GWP). GWP is a measure for the greenhouse effect of a given gas. It is expressed on a relative scale comparing the chosen greenhouse gas (GHG) to the same mass of CO_2 (whose GWP is by definition 1). GWP is based on a number of factors, including the radiative forcing of each greenhouse gas relative to that of CO_2, as well as the decay rate of each gas (the amount removed from the atmosphere over a given number of years) relative to CO_2 [46]. A GWP is calculated over a specific time interval. In this study, the results for the GWP refer to a time horizon of 100 years (GWP100), which is the most common metric.

The calculation of cradle-to-factory gate greenhouse gas (GHG) emissions is illustrated in Figure 7. The release of GHG emissions can be calculated from the total CO_2 emitted (biogenic CO_2 + fossil CO_2, i.e., C_2 + C_3) minus the CO_2 sequestered in the harvested biomass (C_0). This method can be applied when the available data for the biogenic CO_2 emissions are accurate. However, in this study we found it difficult to close the balance for the bio-based carbon, leading to inaccurate emission calculations. This was especially the case for the market pulp. Alternatively, GHG emissions can also be calculated simply by deducting the bio-based carbon embedded in the product (as CO_2, C_4) from the fossil CO_2 emissions (C_3). Since it is easier to acquire relatively accurate values for the flows C_3 and C_4, we chose the second approach in this study for the calculation of cradle to factory gate GHG emissions.

When calculating the greenhouse gas (GHG) emissions for the system cradle to *grave*, the bio-based carbon embedded in the product (C_4) is released again. In *net* terms, the cycle of bio-based carbon is then closed.

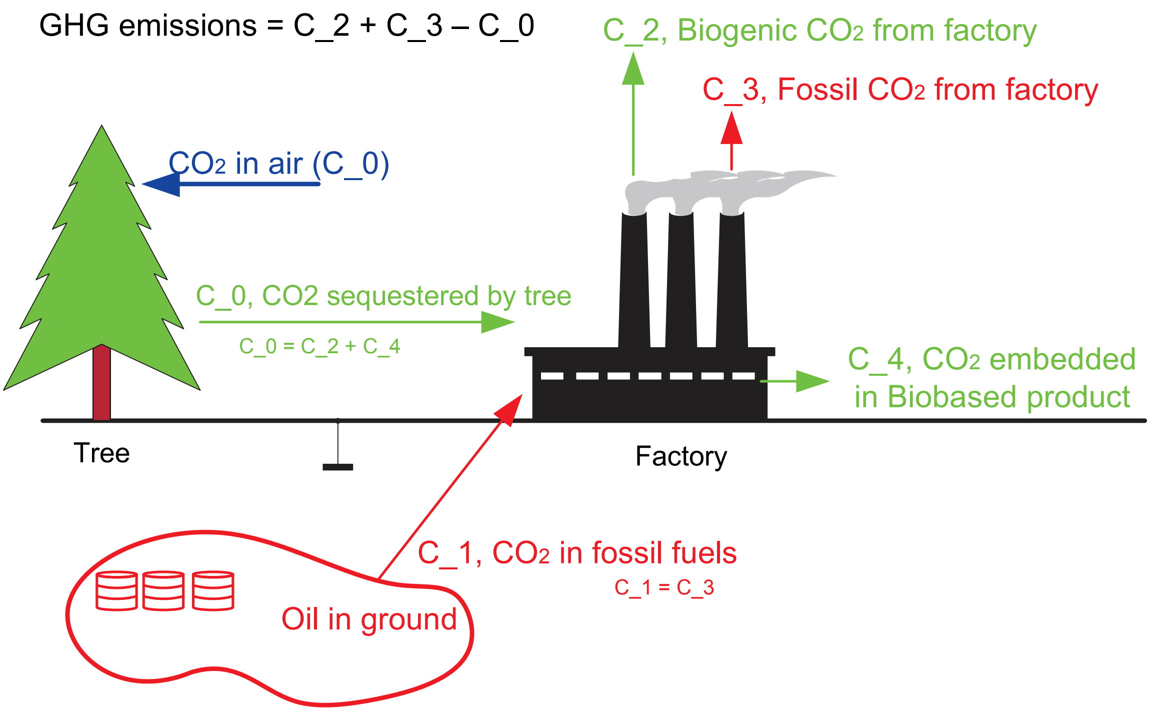


Figure 7. Cradle-to-factory gate GHG emissions of bio-based products.

Other CML baseline indicators

In this study the following impact categories are selected from the CML 2 baseline 2000 method [47]: abiotic depletion, ozone layer depletion, human toxicity, fresh water aquatic ecotoxicity, terrestrial ecotoxicity, photochemical oxidant formation, acidification and eutrophication.

<u>Depletion of abiotic resources</u>

Depletion of abiotic resources is an indicator for the depletion of non-renewable natural resources such as the use of minerals (such as ores) and fossil fuels. It indicates the ratio of the extraction of resources relative to the ultimate reserve of the resource. In order to account for different types of abiotic resources, the ratios are normalized relative to antimony (kg Sb equivalents) and then added up [47].

<u>Stratospheric Ozone depletion</u>

Depletion of the ozone layer leads to an increase in the amount of UV light reaching the earth's surface, which in turn may lead to human diseases (e.g., skin cancer) and may influence ecosystems. The characterisation model was developed by the World Meteorological Organisation (WMO) and defines the ozone depletion potential of different gases (kg CFC-11 equivalent/ kg emission) [47].

Acidification

This impact category defines the potential deposition of acid emissions into the air, onto the soil, and into the water (kg SO_2 equivalent/ kg emission). The main acidifying compounds are SO_2, NO_x, and ammonia.

Eutrophication

Eutrophication defines the effects of nitrification, which is the addition of mineral nutrients to the soil or water. Eutrophication increases biomass production. It is determined for each eutrophication substance as kg PO_4^{3-} equivalent/ kg emission [47]. The aggregated sum represents the total effect.

Human toxicity, fresh water aquatic ecotoxicity, and terrestrial ecotoxicity

For toxicity impacts, characterisation factors are calculated to describe the fate, exposure, and effects of toxic substances for an infinite time horizon. For each toxic substance, toxicity potentials are expressed as 1,4-dichlorobenzene equivalents/ kg emission [47].

In the last few years, several studies have expressed doubts about the quality of toxicity calculations in LCA tools, caused by the lack of reliable toxicity assessment models and the limited data availability [50, 51, 52]. The methodology and empirical basis of toxicity models is being improved at this moment [53].

Marine aquatic ecotoxicity is excluded from the aggregated environmental assessment of this study. Apart from above mentioned uncertainties of toxicity assessment in general, Heijungs *et al*. [52] pointed out a dominant effect from marine aquatic ecotoxicity over all other environmental impacts due to the high uncertainties of the environmental impact from non-ferro metals in the CML method. The currently used model for aquatic ecotoxicity limits the accuracy of the production of the market pulp. Therefore, we do not report marine aquatic ecotoxicity impacts.

Normalisation

Normalisation is an optional step in an LCA according to ISO 14042. This step allows determining the relative contribution of the product system to the impact categories at a national, regional or global level. To this end, the results per impact category are divided by the respective values for a given area (e.g., Europe or world). The normalised results do not imply a certain weighting between impact categories, they merely give an indication to which extent the studied product system contributes to the total environmental loads of a region during a year. In this study we chose the CML normalisation values, which are based on the total emissions in World 2000 (see also Table 9) [48]. The normalised results are obtained by dividing the mid-point results by the normalisation factors.

Table 9. CML normalisation factors, global impact per year, World 2000 [48].

Environmental themes	Normalisation factors
Global warming (kg CO_2 eq./yr)	4.18×10^{13}
Abiotic depletion (kg Sb eq./yr)	1.83×10^{11}
Ozone layer depletion (kg CFC-11 eq./yr)	2.30×10^{8}
Human toxicity (kg 1,4 DB eq./yr)	3.82×10^{13}
Fresh water ecotoxicity (kg 1,4 DB eq./yr)	3.48×10^{12}
Terrestrial ecotoxicity (kg 1,4 DB eq./yr)	1.09×10^{11}
Photochemical oxidation (kg C_2H_4 eq./yr)	5.44×10^{10}
Acidification (kg SO_2 eq./yr)	2.39×10^{11}
Eutrophication (kg PO_4^{3-} eq./yr)	1.58×10^{11}

Results

Resources: Energy use, land use, and water use

Energy use

Figure 8 shows the cradle-to-factory gate energy use for the studied man-made cellulose fibres. Cumulative energy demand (CED) is the sum of non-renewable energy use (NREU) and renewable energy use (REU). The CED of the studied man-made cellulose fibres is 65-106 GJ/t. As explained in the section "*Allocation principle"*, we chose as default the allocation method on a case-by-case basis, i.e., we combine different types of allocation methods for by-products. The large uncertainty ranges for Lenzing Viscose Asia and Tencel Austria originates from market pulp of various origins. The uncertainty ranges for Lenzing Viscose Austria and Lenzing Modal result from two alternative allocation methods applied for the energy recovered from MSWI (see section "*Allocation principle"*); the lower ranges represent the results based on the "free heat" case and the higher ranges show the results based on the "natural gas" case. The results for Tencel Austria 2012 are subject to relatively large uncertainties, due to the use of market pulp and as a consequence of the allocation methods applied for the energy obtained from external MSWI.

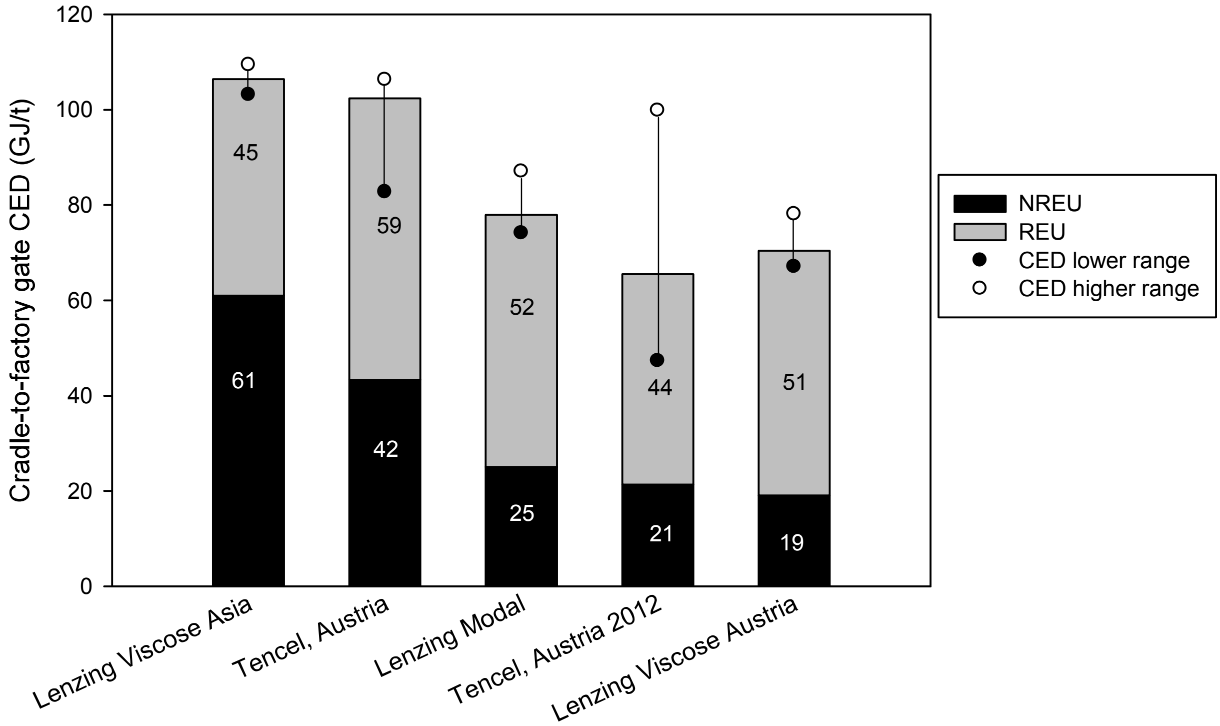


Figure 8. Cradle-to-factory gate NREU, REU, and total energy use for one tonne of man-made cellulose fibres (default method for by-products allocation).

According to Figure 8, Lenzing Viscose Asia requires three times as much NREU as Lenzing Viscose Austria and Lenzing Modal. The particularly large NREU result for Lenzing Viscose Asia is primarily related to the relatively inefficient coal-based heat and power production in Asia. Next to fossil fuel use in fibre production, the production of chemicals (including caustic soda) is a very important contributor to the NREU of Lenzing Viscose Asia (see Figure 9).

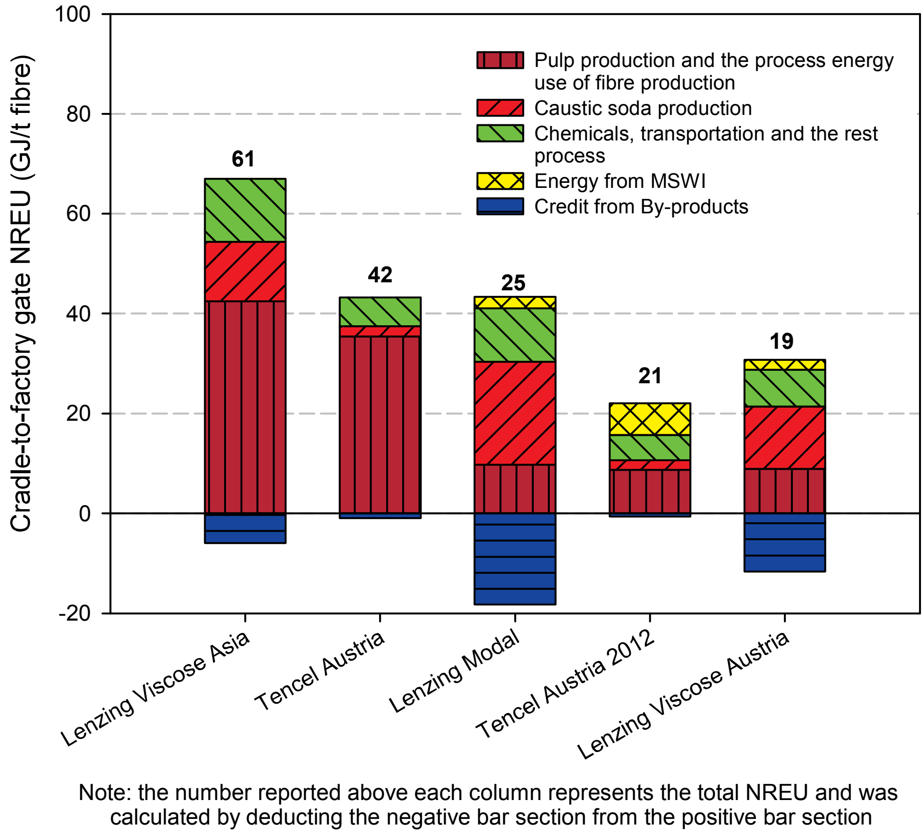


Figure 9. Contribution analysis for cradle-to-factory gate NREU, one tonne of man-made cellulose fibres (default allocation method for by-products).

Unlike for Lenzing Viscose Asia, process energy from fossil fuels does not play such an important role for Lenzing Viscose Austria and Lenzing Modal. The use of renewable energy and process integration are both important reasons for the low fossil fuel requirement of the two fibres. The NREU of caustic soda is the most important contributor, accounting for more than half of the total NREU (Figure 9). Caustic soda is used in both pulping process and fibre production process. Other important processes for Lenzing Viscose Austria and Lenzing Modal are the production of chemicals such as sulphur, CS_2 and NaOCl.

Compared to the viscose process, in the lyocell process the chemical consumption is considerably lower (Figure 9) and therefore also the energy requirement is lower. Process energy from natural gas is currently the biggest contributor to the NREU for the Tencel fibre production; it accounts for more than 70% of the total NREU (Figure 9). The NREU of Tencel Austria 2012 will decrease by 50% (from 42 GJ/t to 21 GJ/t) when process energy is entirely supplied by energy recovered from MSWI.

By-products from Lenzing Viscose Austria and Lenzing Modal (see the negative values in Figure 9) significantly reduce the total NREU of the two fibres, largely due to the avoided impacts from Na_2SO_4 and acetic acid. The credits assigned to sodium sulphate originates from the large quantity, although the NREU per unit is low (approx. 8.5 GJ NREU /t, see section "*Allocation of by-products from pulp and fibre production*"). The production volume of acetic acid is much smaller than sodium sulphate. However, petrochemical ethylene-derived acetic acid is an energy intensive product (approx. 54 GJ NREU/t). Thus, acetic acid has similar credits as sodium sulphate. Since the co-production of acetic acid and Na_2SO_4

reduce the final results for NREU based on the system expansion approach, a sensitivity analysis of allocation methods is discussed at the end of this paper.

By-products of off-grade fibres and lignosulphonate from Lenzing Viscose Asia have a relatively limited contribution due to the high energy consumption of Viscose fibre produced in Asia. Furthermore, for both, current Tencel and future Tencel fibres, acetic acid is the most important by-product of Lenzing pulp.

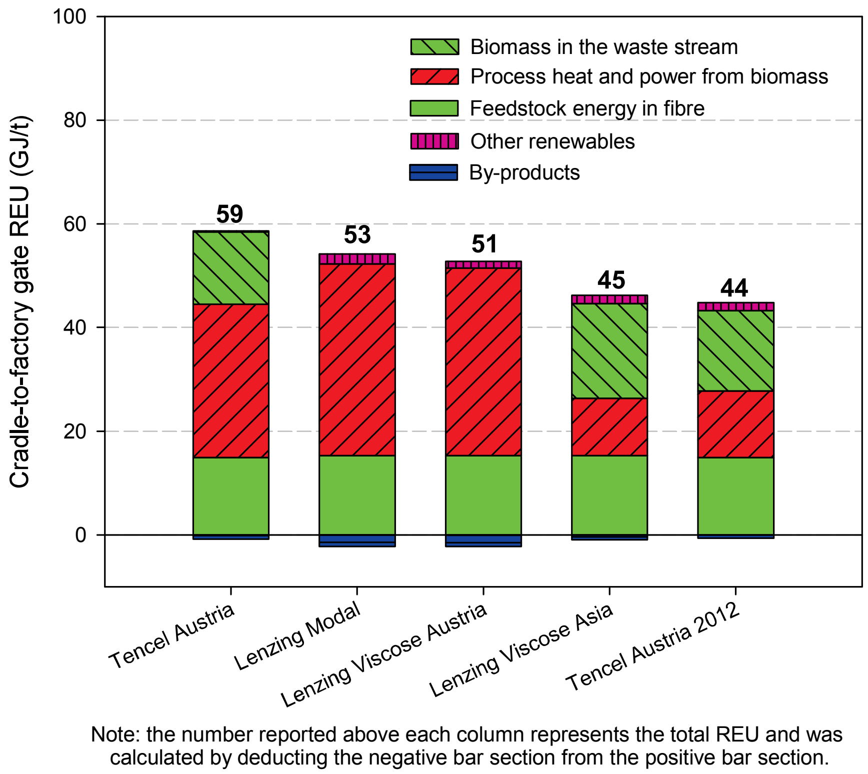


Figure 10. Contribution analysis for cradle-to-factory gate REU, one tonne of man-made cellulose fibres (default allocation method for by-products).

Figure 10 shows the process contribution of the REU for the five fibre products. For cellulose fibres, the most important source of renewable energy is wood. Part of the wood is converted into the final product (fibre) (shown in the Figure as "feedstock energy in fibre"). The rest of the wood which cannot be converted into fibre is mainly embodied in bark, thick liquor, and soda extraction liquor, which are either combusted for energy and thus shown as part of the "process heat and power from biomass", or are converted into by-products, or are disposed of in the production waste stream. Moreover, Lenzing Viscose Austria, Lenzing Modal, Tencel Austria, and Tencel Austria 2012 use external biomass (barks or wood chips) as additional fuel for the production. In Figure 10, "Other renewables" refer to the waste combusted in the MSWI plant on site and to the renewables used in the secondary chain for the generation of electricity (e.g., hydropower, wind power, and solar power). For all five fibres, by-products have a minimal impact on the overall REU, although for Lenzing Viscose Austria and Lenzing Modal, about 10% of the wood is converted into by-products.

Land use

In this study only the land use related to biomass production is discussed. The land use is estimated based on the yields of wood production. Allocation between fibres and by-products are performed based on economic values (see section "*Allocation principle*"). For Lenzing Viscose Austria and Lenzing Modal, also partly for Tencel Austria and Tencel Austria 2012, the wood originates from plantation (primarily beech) in Europe. According to Ecoinvent, the average yield of hardwood and softwood from man-managed forest in Europe is about 3.4 odt/ha/year[8] [19]. The eucalyptus wood is produced from plantation in the southern hemisphere and the average yield is 12 odt/ha/year.

The forest land use for the five man-made fibres is shown in Figure 11. The uncertainty range shows the land use assuming different sources of pulp (various sources of market pulp and/or Lenzing pulp). In general, more land is required for the types of fibres which are made from European wood because of the low forestry (biomass) yields in Europe compared to warmer world regions.

Tencel Austria requires slightly more land use than Tencel Austria 2012. The difference is caused by the additional land use required for the biomass which is converted to process energy in the case of Tencel Austria 2012.

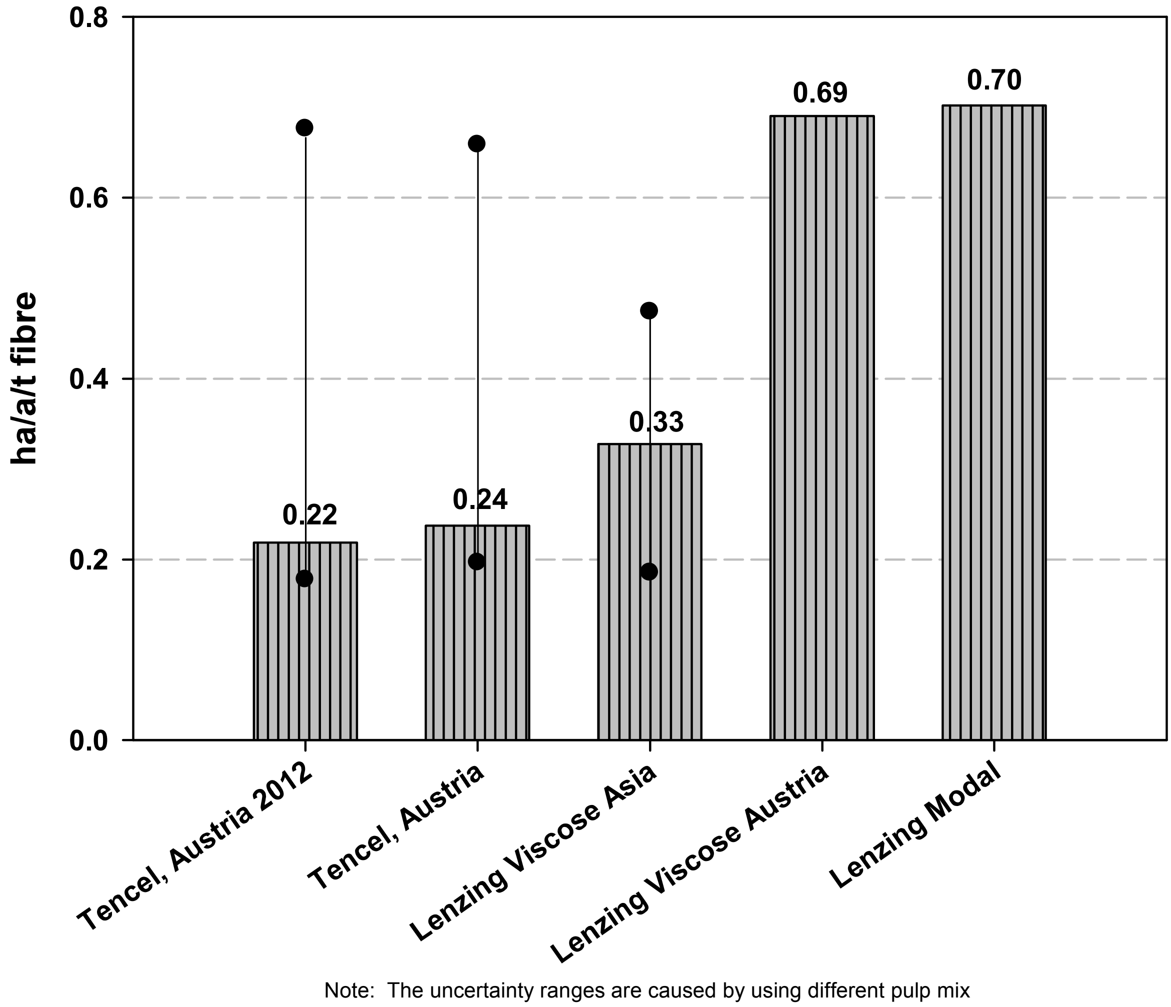


Figure 11. Forest land for the production of man-made cellulose fibres (economic allocation for by-products).

[8] The yields of European natural hardwood and softwood are 784 m^3/ha and 1,340 m^3/ha, respectively; the period of time from planting trees to harvesting for softwood and hardwood are 150 years and 120 years, respectively [19]. These figures exclude the land use for forest roads. The densities of hardwood and softwood are 650 kg/m^3 and 450 kg/m^3, respectively (based on dry mass and dry volume) [19].

Water use

The water use for cellulose fibre production is dominated by cooling water use. Cooling water accounts for about 90-95% of total water consumption. The remaining 5-10% is process water which is softened water, deionised water, decarbonised water, or tap water. No irrigation is needed for man-managed forests in Europe and neither for eucalyptus plantations. As already mentioned before, natural rainfall is not taken into account. Table 10 shows the overall water use of the five cellulose fibres, allocation between fibres and by-products was performed based on economic values.

Table 10. Cradle-to-factory gate water use to produce one tonne man-made cellulose fibre (default allocation method for by-products).

	Process water (m^3)	**Cooling water (m^3)**
Lenzing Viscose Asia	11	308
Lenzing Viscose Austria	42	403
Lenzing Modal	43	429
Tencel Austria	20	243
Tencel Austria 2012	20	243

Environmental impact assessment

Global warming potential (GWP) 100 years

Figure 12 shows the cradle-to-factory gate GWP of the five man-made cellulose fibre products. The cradle-to-factory gate GWP is calculated by subtracting the embedded biogenic CO_2 from the fossil CO_2 emissions. As Figure 12 shows, all five fibres have a similar amount of embedded carbon (the negative part in graph a); the slight difference is caused by the different moisture contents of final products[9]. The overall GWP (part b) is largely determined by the fossil CO_2 emissions, which are highest for Lenzing Viscose Asia and lowest for Lenzing Viscose Austria.

A breakdown of GWP by processes (Figure 13) shows that, for Lenzing Viscose Asia the (market) pulp production and the process heat and the power from fossil fuels in the fibre production account for more than three quarters of its total fossil carbon emissions; the production of caustic soda and other chemicals are also important processes. The process energy use of Lenzing Viscose Asia is based on a coal- and oil-based system with an emission factor of 87 kg fossil CO_2 eq./GJ NREU.

Figure 13 also shows that Lenzing Viscose Austria has a negative cradle-to-factory GWP and Lenzing Modal has a nearly zero GWP. The low GWP of both fibres is a result of both, low fossil CO_2 emissions during production process and significant credits from by-products and biogenic carbon embedded in the product. For both fibres, the most important fossil CO_2 emissions are from the production of caustic soda, which accounts for more than half of the total fossil CO_2 emissions. Moreover, both fibres are produced based on natural gas-fuelled energy systems with a relatively low emission factor of about 60 kg fossil CO_2 eq./GJ NREU. In addition, for both fibres, credits from by-products represent about at least one-third of their fossil CO_2 emissions; credits from embedded carbon represent 85% and 60% of the fossil CO_2 emissions of Lenzing Viscose Asia and Lenzing Modal, respectively.

[9] Viscose and Modal fibres have a moisture content of 11%; Tencel fibres have a moisture content of 13%.

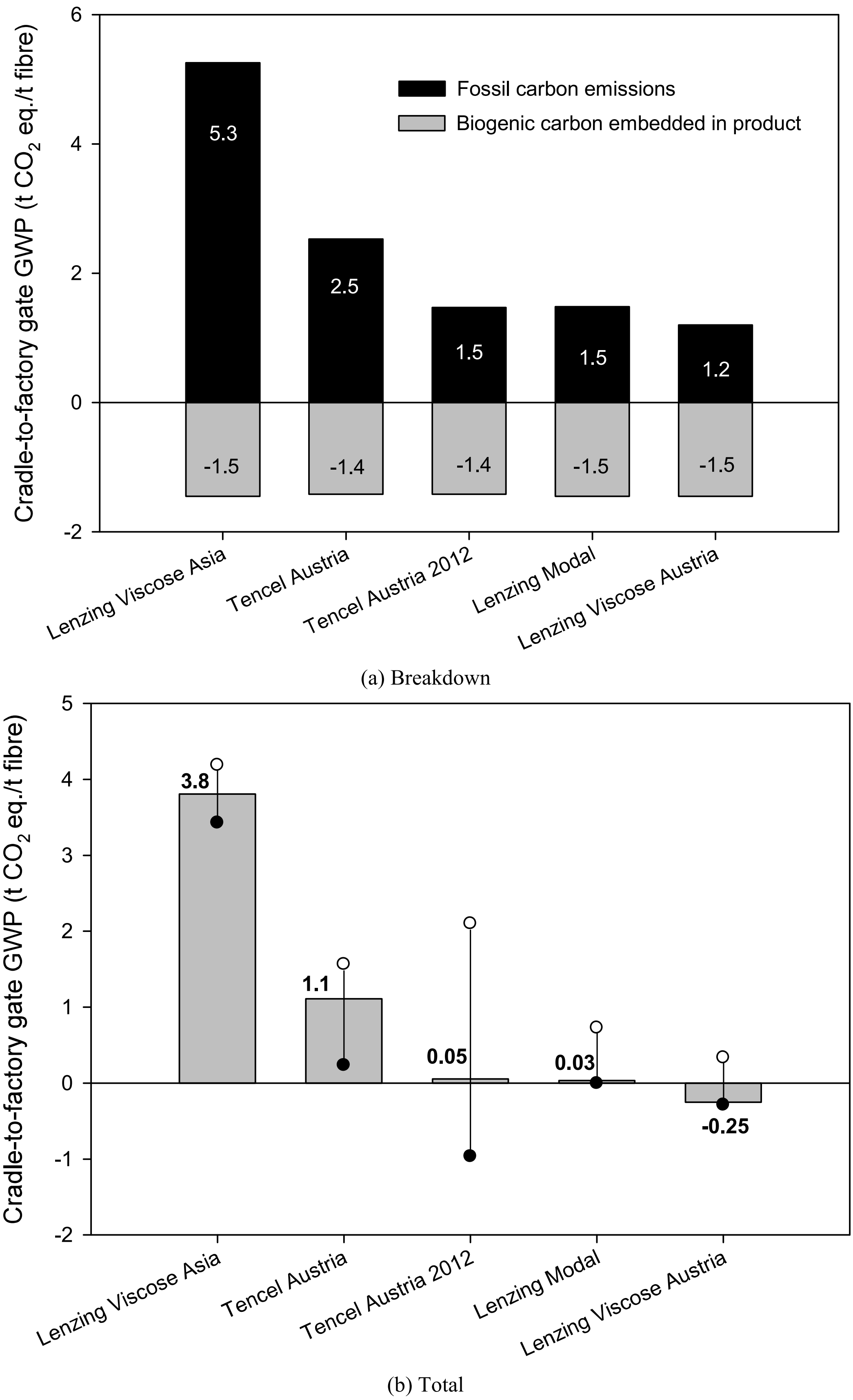


Figure 12. Cradle-to-factory gate GWP 100a of one tonne man-made cellulose fibres: (a) breakdown; (b) total GWP with uncertainties (default allocation method for by-products).

For Tencel Austria, more than half of the fossil carbon emissions originate from the natural gas consumed to provide the required process heat. The GWP of Tencel Austria 2012 is reduced by nearly 90% compared to Tencel Austria, because energy from natural gas is replaced by energy recovered from MSWI. The results for Tencel Austria 2012 are subject to relatively large uncertainties, due to the use of market pulp and as a consequence of the allocation methods applied for the energy obtained from external MSWI.

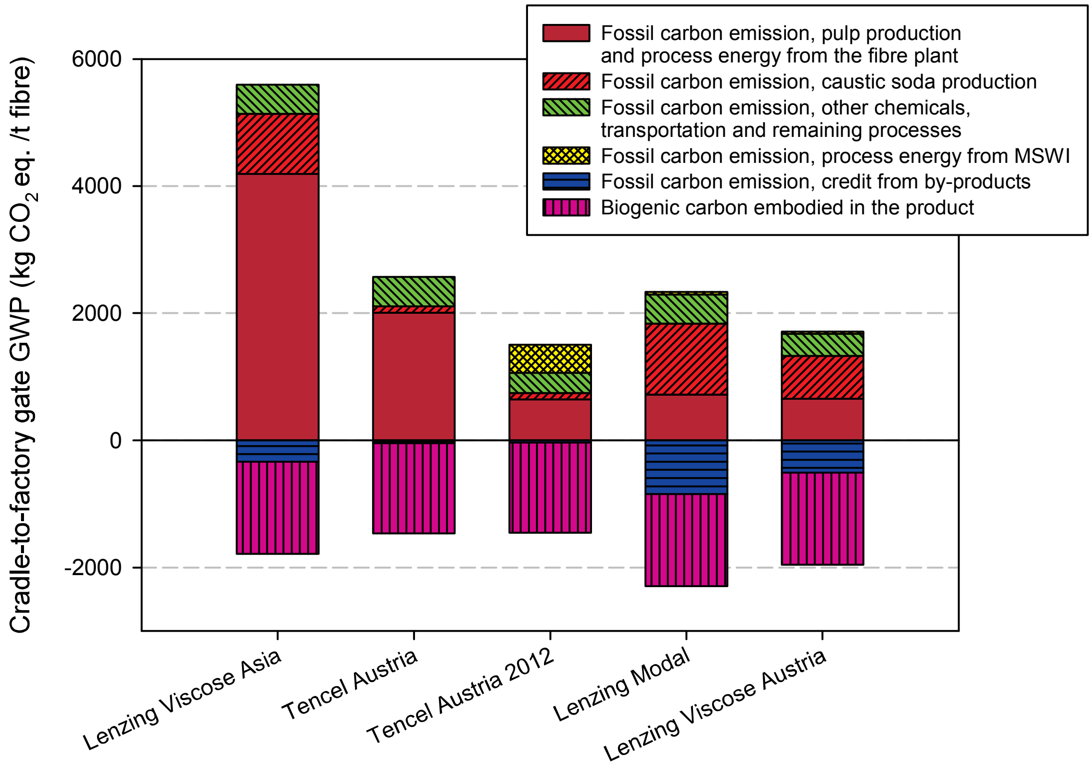


Figure 13. Process contribution of cradle-to-factory gate GWP of one tonne man-made cellulose fibres (default allocation method for by-products).

Table 11. Cradle-to-factory gate environmental impact assessment for one tonne of staple fibre, CML 2 baseline 2000 (default allocation method for by-products).

	Lenzing Viscose Asia	Lenzing Viscose Austria	Lenzing Modal	Tencel Austria	Tencel Austria 2012
Abiotic depletion (kg Sb eq./t)	40	14	18	20	7
Ozone layer depletion ($x10^{-3}$ kg CFC11eq./t)	0.28	0.03	0.04	0.11	0.07
Human toxicity (kg 1,4 DB eq./t)	1490	630	770	470	660
Fresh water aquatic ecotoxicity (kg 1,4 DB eq./t)	160	74	93	85	75
Terrestrial ecotoxicity (kg 1,4 DB eq./t)	16	11	16	5	5
Photochemical oxidant formation (kg C_2H_4 eq./t)	1.8	0.5	0.5	0.6	0.4
Acidification (kg SO_2 eq./t)	45	14	15	17	13
Eutrophication (kg PO_4^{3-} eq./t)	2.3	1.2	1.3	1.8	1.9

Other CML baseline indicators

Table 11 shows the results by environmental impact category based on the CML 2 baseline method. Lenzing Viscose Asia has the highest impact in seven out of eight impact categories. Tencel Austria 2012 has the lowest impact in four out of eight categories and Lenzing Viscose Austria has the lowest impact in three out of eight categories. Tencel Austria 2012 and Lenzing Viscose Austria show the best environmental profiles among all man-made cellulose fibres. In this section each impact category will be discussed in detail.

Abiotic depletion

Abiotic depletion refers to the environmental impacts from using non-renewable energy and material resources, for example, copper, oil, gas, and coal. The indicator takes antimony (Sb) as the reference material [47]. Other minerals or energy sources are converted into kg Sb equivalents and aggregated to one indicator. For example, 1 kg copper is equivalent to 0.00194 kg Sb; 1 kg natural gas is equivalent to 0.025 kg Sb; and 1 kg hard coal is equivalent to 0.0134 kg Sb (CML characterisation factor version 2.03) [54].

Lenzing Viscose Asia has the highest abiotic depletion impact. Coal, market pulp, and caustic soda account for nearly 60% of the abiotic depletion impact of Lenzing Viscose Asia. Fuel oil, CS_2 production, sulphur production, and external electricity account for approximately 40% of the impact. More generally, for the fibres based on the viscose process, caustic soda, CS_2 and sulphur production are the important factors next to energy use. For fibres based on the lyocell process (i.e., Tencel) the process energy (e.g., natural gas) and the market pulp are the most important factors, while the consumption of chemicals plays a less important role.

Ozone layer depletion

Ozone layer depletion is caused by the substances which deplete the stratospheric ozone layers of the earth. The depletion of the ozone layer leads to an increase in the amount of UV light reaching the earth's surface, which in turn may lead to human diseases (e.g., skin cancer) and influence ecosystems. The World Meteorological Organisation (WMO) developed a model to define the ozone depletion potential (ODP) of different gasses, using CFC-11 (trichlorofluoromethane) as the reference substance. The ODP is expressed in terms of kg CFC-11 equivalent/ kg emission. For example, Halon 1301 (bromotrifluoroethane) has an ODP of 12 kg CFC-11 eq./kg [54].

The ozone layer depletion impacts of the fibres included in this study are mainly caused by emissions of Halon 1301 and Halon 1211 which are released during crude oil production according to the Ecoinvent database[10] [29]. As laid down in the Montreal Protocol the production of Halon has been banned in developed nations since 1994 [55]. For the developing nations, the production of ozone layer depletion substances will be phased out in 2010 [55]. However, due to existing stocks, developed nations "have enough Halon 1301……to last some 25 years" [56]. This indicates that although the production of ozone layer depleting substances are being phased out gradually, the current status of the production and consumption of Halon still makes ozone layer depletion an important environmental issue within the following decades.

In crude oil production, especially in the Middle East, Russia, and Africa, Halon 1301 is used in fire extinguishing systems [29]. Therefore, processes which require oil as input have a

[10] As explained in section 3.2, the originally identified ozone depleting impact related to the production of the ion exchange resin was found to be irrelevant for the lyocell process.

relatively high ozone layer depletion impact. For example, in the case of Lenzing Viscose Asia, approximately 65% of the ozone layer depletion problem is caused by fuel oil production and caustic soda production, where oil is one of the fuels for generating grid electricity. Nearly 30% of the ozone layer depletion is caused by the grid electricity (partly fuelled by oil) and the market pulp production (mainly from caustic soda production, which requires a large amount of electricity).

Human toxicity, fresh water aquatic ecotoxicity, and terrestrial ecotoxicity

As for all other environmental impact categories, toxicity impacts are caused by the relevant ***emissions*** of processes: only the toxic compounds ***released*** to the environment cause problems, not the toxic compounds that are *not* released to the environment (e.g., toxic compounds that remain in the encapsulated production facility). All the toxicity impacts are quantified using 1,4-dichlorobenzene equivalent (1,4-DB eq.) as the indicator [47]. For example, the characterisation factors of human toxicity of copper emitted to air, water (as ion), and soil are 4300 kg, 1.34 kg, and 1.25 kg 1,4-DB eq., respectively (CML characterisation factor version 2.03) [54].

For viscose fibres, the important contributors to human toxicity are the production of caustic soda, of market pulp, of CS_2, and of sulphur plus the external electricity use and CS_2 emissions. For Tencel fibres, these inputs and outputs cause little or no impacts, except for the production of market pulp. Tencel Austria 2012 has slightly higher human toxicity than Tencel Austria because of the emissions from the waste incineration plant, where energy is recovered and provided to the production of Tencel Austria 2012.

Concerning the fresh water aquatic ecotoxicity and terrestrial ecotoxicity, the most important contributors for all the fibres are the production of market pulp and of caustic soda. Fresh water and terrestrial ecotoxicity of Lenzing pulp originates mainly from the production of chemicals such as magnesium oxide, caustic soda, and hydrogen peroxide. For market pulp, chemicals (e.g., caustic soda and chlorine dioxide) are the most important factors.

For all cellulose fibres studied, the credits related to by-products, especially Na_2SO_4 and acetic acid, significantly contribute to lower human toxicity impacts and fresh water aquatic ecotoxicity. Terrestrial ecotoxicity is not strongly influenced by the by-products.

Photochemical oxidant formation

Photochemical oxidants form smog. The CML method uses the photochemical oxidant formation of 1 kg ethylene (C_2H_4) as reference. For example, 1 kg methane and 1 kg SO_2 have photochemical oxidant formation factors of 0.006 and 0.048 kg ethylene equivalents, respectively (CML characterisation factor version 2.03) [54].

For man-made cellulose fibres the most important factor for photochemical oxidant formation are the SO_2 emissions. These mainly originate from two sources: the emissions from the production of SO_2 (SO_2 is used as a process input in both, Lenzing pulp and market pulp production) and the SO_2 emissions from energy production. For Lenzing Viscose Austria, Lenzing Modal, Tencel Austria, and Tencel Austria 2012, the production of SO_2 in pulp production is the most important source of emissions. Lenzing Viscose Asia has the highest photochemical oxidant formation due to high SO_2 emissions from the energy production in the fibre plant – the SO_2 emissions from Lenzing Viscose Asia are about 10 times higher than those from Lenzing Viscose Austria.

Acidification

Acidification is expressed in kg SO_2 equivalent. For man-made cellulose fibres the SO_2 emissions are the most important acidifying compound. Lenzing Viscose Asia has the highest acidification impact due to the high SO_2 emissions in the fibre production; the emissions account for about 50% of the total acidification impact. Market pulp, NaOH, external electricity, CS_2, and sulphur are important factors for the acidification impact of Lenzing Viscose Asia.

For Lenzing Viscose Austria and Lenzing Modal the SO_2 emissions from the fibre plant are 10 times less than those of Lenzing Viscose Asia. For Tencel fibres, there are no SO_2 emissions from the energy production in the fibre plant. The acidification impacts of Lenzing Viscose Austria, Lenzing Modal, Tencel Austria, and Tencel Austria 2012 mainly originate from the SO_2 emissions from the SO_2 production in the Lenzing pulp mill.

Eutrophication

Eutrophication is quantified in terms of kg PO_4^{3-} equivalent. It is an indicator expressing the release of to many nutrients to the environment. Lenzing Viscose Asia has a high eutrophication impact when compared to other man-made cellulose fibres. Tencel Austria and Tencel Austria 2012 score second and third with regard to eutrophication impact. For these three man-made cellulose fibres, important sources of eutrophying compounds are the NO_x emissions from market pulp production and fibre production, the production of caustic soda (used in both market pulp and fibre production), external electricity (for Lenzing Viscose Asia only), chemical inputs for the waste water treatment plant (e.g., triplesuperphosphate and phosphoric acid) and the COD emissions to water.

Lenzing Viscose Austria and Lenzing Modal have relatively low eutrophication impacts compared to the other three man-made cellulose fibres. For these two fibres, Lenzing pulp production, caustic soda production, and NO_x emissions are the most important factors, accounting for approximately 80% of the impact. For Lenzing Viscose Asia, the most important factors are market pulp production (30%) and caustic soda production (20%); for Tencel Austria, the market pulp contributes 40% of the impact; for Tencel Austria 2012, market pulp and energy recovered from MSWI account for more than 70% of the impact.

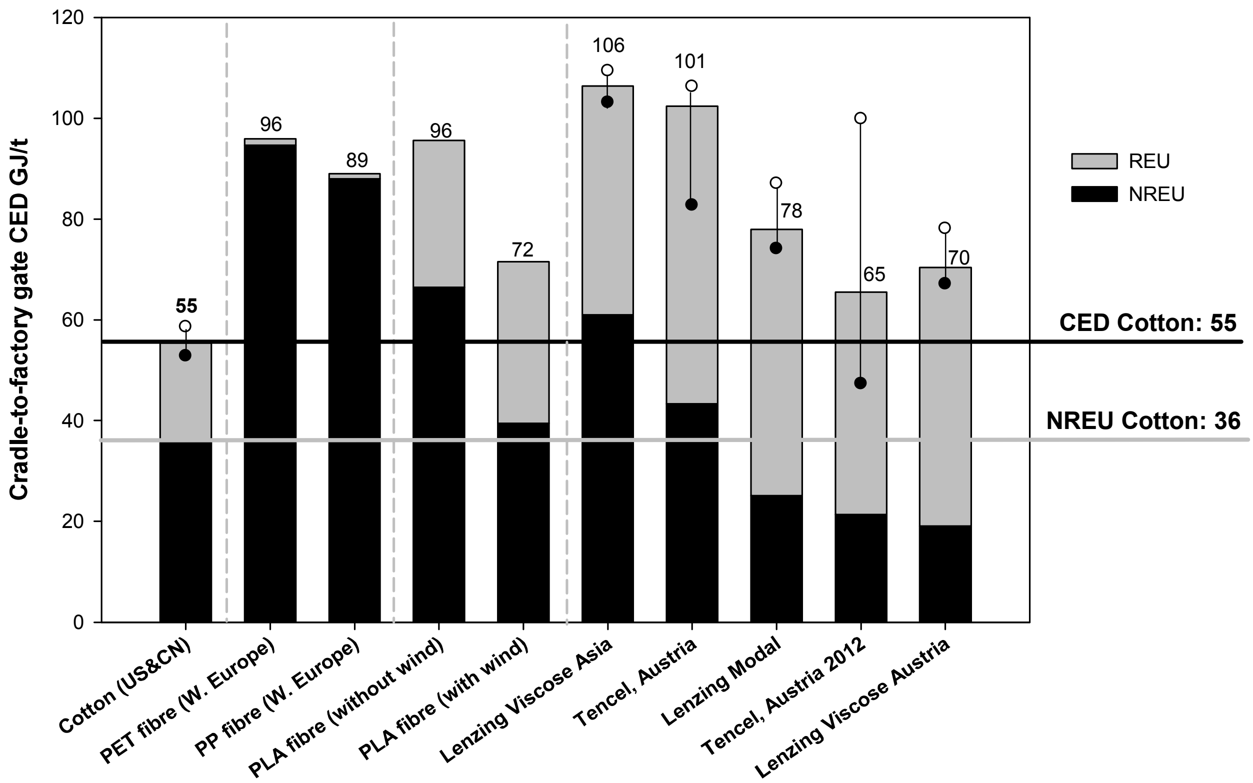
Comparisons with cotton, PLA, PET, and PP

In this section we compare man-made cellulose fibres with other commodities or novel fibres, i.e., conventional cotton, PET and PP fibres and PLA. In this section, we take cotton as the benchmark for comparison; because in terms of market volume cotton is by far the most important natural cellulose fibre in terms of market volume (see Figure 1).

Energy use, land use, and water use

Figure 14 shows the cradle-to-factory gate comparison of the energy profiles for all fibres that are considered in this comparison. The NREU of all cellulose fibres are lower than those of the synthetic fibres (PET and PP) and the PLA fibres produced without wind energy. Both, Tencel Austria and PLA fibre with wind have a slightly higher NREU than cotton but they are at rather comparable level. Lenzing Viscose Austria has the lowest NREU and the PET fibre has the highest NREU amongst all the fibres studied. Cotton is not an energy-intensive product. Lenzing Viscose Asia has a 70% higher NREU than cotton. Lenzing Modal, Tencel Austria 2012, and Lenzing Viscose Austria has 30%, 40%, and 50% respectively lower NREU than cotton.

In terms of cumulative energy demand (CED), cotton becomes the most favourable choice, followed by Tencel Austria 2012. However, this refers to the default calculations, where the entire heat demand is covered by a municipal waste incineration plant; a different allocation for the source of the heat used, as well as a different mix of market versus Lenzing pulp may change the ranking (see the uncertainty ranges in Figure 14). Man-made bio-based fibres, including both cellulose fibres and PLA fibres, require relatively large REU compared to cotton, PET and PP. This is caused not only by the feedstock energy requirements, but also by the large amount of biomass energy used in the production.



The numbers above each column represent CED. The uncertainty ranges represent the uncertainty of CED. For man-made cellulose fibres, the uncertainty ranges are caused by using different pulp mix and different allocation methods; for cotton, the lower value represents Chinese cotton and the higher value is for US cotton.

Figure 14. Comparing one tonne staple fibre, cradle-to-factory gate, NREU, REU, and CED (default allocation method for by-products).

The comparison of land use for the production of bio-based fibres is summarised in Figure 15. The values were calculated directly from the biomass yields. Allocations for staple fibres are conducted based on mass and economic values. It should be noted that the land use for wood plantations in Europe and in the southern hemisphere and for agricultural land are reported in the same chart, even though the environmental impact of land use is different depending on types of land, local climate and local ecosystem. In this study we limit ourselves to the inventory data (quantity). We do not assess the overall environmental/ecological impact of land use because suitable aggregation methods are still missing. Applying simple addition of the various types of land, we find that the average US and CN cotton fibres require about 20% more land than Lenzing Viscose Austria and Lenzing Modal, 150% more land than Lenzing Viscose Asia and 200 to 300% more land than Tencel Austria, Tencel Austria 2012, and PLA fibres (for both with and without wind). The world average cotton requires 60% more land than Lenzing Viscose Austria and Lenzing Modal, 230% more than Lenzing

Viscose Asia, and 300 to 500% more than Tencel Austria, Tencel Austria 2012, and PLA fibres.

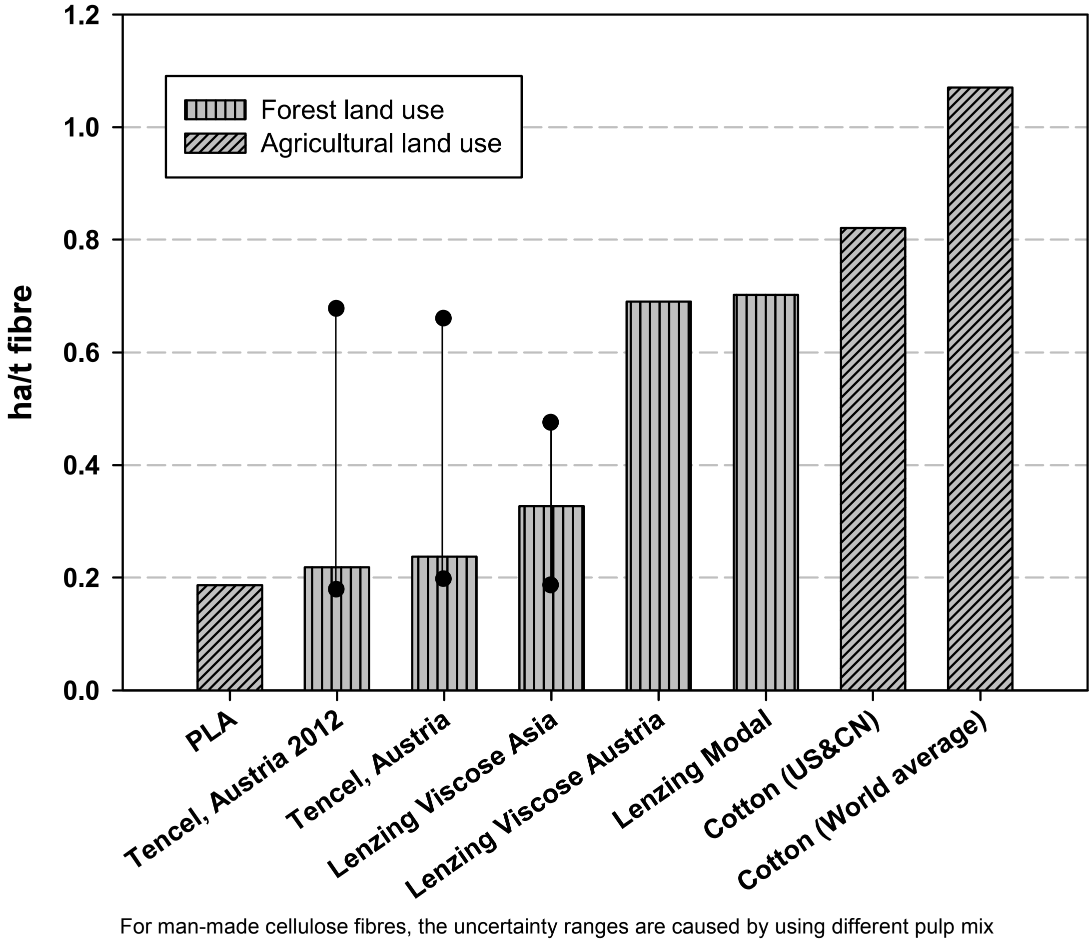


Figure 15. Land use for one tonne of staple fibres (default method).

Table 12 shows the comparison of water use for one tonne of staple fibres. For process water, we used the conversion efficiencies shown in Table 8 to calculate the equivalent amount of natural water. If we exclude cooling water, the water consumption for cotton fibre production is more than 100-500 times greater than for man-made cellulose fibres. If we include cooling water, cotton still requires about 10-20 times more water than man-made cellulose fibres. Almost all (>99%) water used by cotton is for irrigation. For the average Chinese and US cotton, about 70% of the irrigation water originates from ground water and 30% originates from surface water. It should be noted that the environmental impacts of various forms of water are rather different. For example, cooling water does not cause local fresh water resource depletion but irrigation water may do. Moreover, irrigation with ground water and with surface water (and also irrigation efficiency) may have different impacts depending on the local hydrological conditions. A further point is that irrigation may cause environmental impacts such as soil salination and water shortage downstream the river [49]. The data shown in Table 12 should hence be interpreted as inventory data instead of being considered as environmental impact.

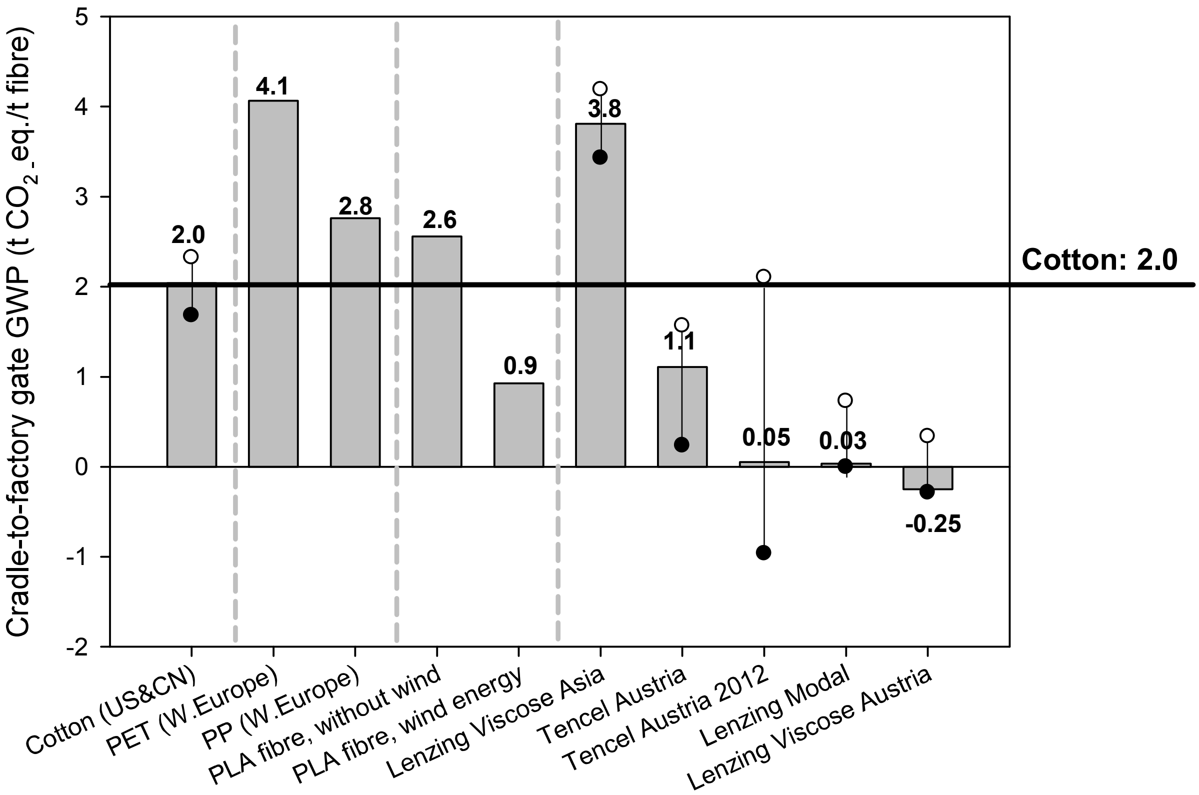
Table 12. Water use for one tonne of staple fibres, based on natural water origin (m^3 per tonne fibre; default method).

Type	Name	Process water	Cooling water	Irrigation water
Petrochemical fibres	PP (W.Europe)	<2	74	-
	PET (W.Europe)	<5	125	-
Man-made cellulose fibres	Lenzing Viscose Asia	11	308	-
	Tencel Austria 2012	20	243	-
	Tencel Austria	20	243	-
	Lenzing Viscose Austria	42	403	-
	Lenzing Modal	43	429	-
Cotton	Cotton (US&CN)	<5	37	5690 (4300-6860) [a]

[a] The lower range is the average US cotton and the higher range is the average Chinese cotton.

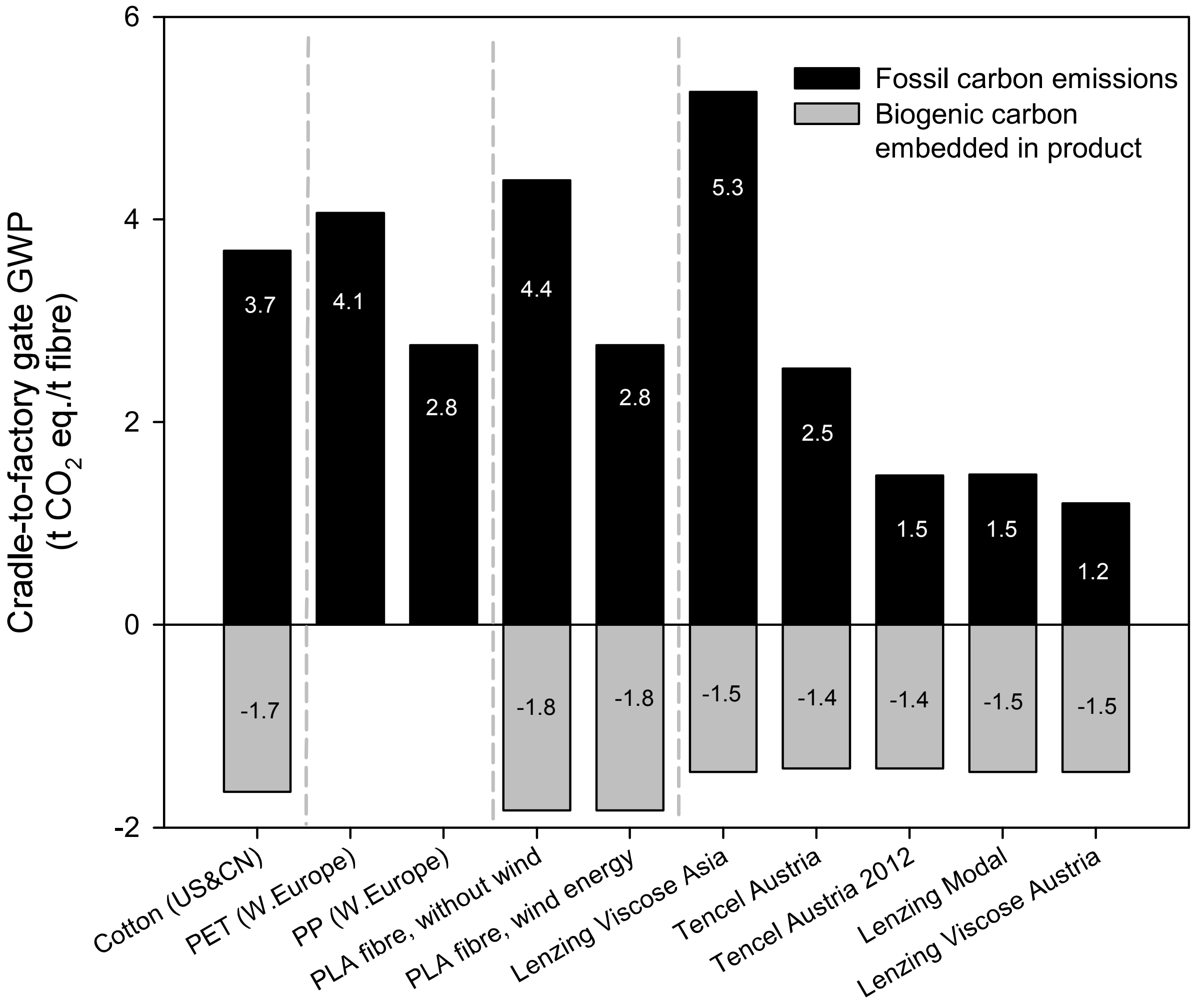
Comparing the environmental impact - Global Warming Potential 100 years

Figure 16 shows the comparison of cradle-to-factory gate GWP: graph (a) shows the total of GWP and graph (b) shows the breakdown into the impact of released fossil CO_2 and embodied biogenic CO_2. From graph (a) it can be seen that from cradle to factory gate, 1) all man-made cellulose fibres have lower GWP than PET fibres; 2) all man-made cellulose fibres except for Lenzing Viscose Asia have lower GWP than PET, PP, PLA without wind and cotton; 3) Lenzing Modal and Tencel Austria 2012 have nearly zero carbon emissions; and 4) Lenzing Viscose Austria has a negative GWP, which means that it sequestrates more carbon in the product than it emits.



- For man-made cellulose fibres, the uncertainty ranges are caused by using different pulp mix and different allocation methods.
- For cotton, the lower value represents U.S. cotton and the higher value is Chinese cotton (contrary to the NREU of cotton).

(a) Total



(b) Breakdown

Figure 16. Comparing the cradle-to-factory gate GWP for one tonne of staple fibres: (a) summary; (b) breakdown into the impact of released fossil CO_2 and embodied biogenic CO_2 (default allocation method for by-products).

A breakdown of the GWP (Figure 16, b) shows that the fossil carbon emission is the most influential factor. As described in the methodology above, GWP is calculated based on the fossil carbon emissions and the biogenic carbon embedded in the product. Lenzing Viscose Austria, Lenzing Modal, and Tencel Austria 2012 have much lower GWP than all other fibres because the fossil carbon emissions are much lower. Tencel Austria is comparable with PLA with wind energy and both of them have lower GWP than PET and Lenzing Viscose Asia. PET and Lenzing Viscose Asia have the highest GWP due to the high fossil CO_2 emissions. Cotton, PP, and PLA without wind have an intermediate position.

Comparing environmental impact based on other CML baseline categories

Table 13 shows the results based on the CML baseline method. All man-made cellulose fibres except for Lenzing Viscose Asia cause lower environmental impacts than cotton and PET in seven out of eight categories. Lenzing Modal and Tencel Austria are comparable with cotton in terms of abiotic depletion. Lenzing Viscose Asia is a less preferable choice compared to cotton in terms of abiotic depletion, ozone layer depletion, photochemical oxidation and acidification. The breakdown of the overall impacts of Lenzing Viscose Asia was described in section "Environmental impact assessment".

Table 13. Comparing the environmental impact of the production of one tonne of staple fibres, cradle-to-factory gate, characterisation results based on CML 2 baseline 2000 (default method).

	Cotton	PET	PP	Lenzing Viscose Asia	Lenzing Viscose Austria	Lenzing Modal	Tencel Austria	Tencel Austria 2012
Abiotic depletion (kg Sb eq./t)	17	45	42	40	14	18	20	7
Ozone layer depletion ($x10^{-3}$ kg CFC11eq./t)	0.20	0.07	0.07	0.28	0.03	0.04	0.11	0.07
Human toxicity (kg 1,4DB eq./t)	1700	4,393	369	1490	630	770	470	660
Fresh water aquatic ecotoxicity (kg 1,4DB eq./t)	17310	58	53	160	74	93	85	75
Terrestrial ecotoxicity (kg 1,4DB eq./t)	1568	12	12	16	11	16	5.0	4.6
Photochemical oxidant formation (kg C_2H_4 eq./t)	0.7	1.0	0.6	1.8	0.5	0.5	0.6	0.4
Acidification (kg SO_2 eq./t)	41	21	11	45	14	15	17	13
Eutrophication (kg PO_4^{3-} eq./t)	22	1.2	1.0	2.3	1.2	1.3	1.8	1.9

For the toxicity impacts of cotton (i.e., human toxicity, freshwater aquatic ecotoxicity and terrestrial ecotoxicity), we only take the impacts from the US cotton into account. The reason is that the Chinese cotton uses very different pesticides and fertilisers and many of them cannot be assessed with the CML methods, which would cause an underestimation of the impacts. We therefore decide to use the toxicity impact of the US cotton as a proxy for the toxicity impacts of cotton. However, this approach most probably still underestimates the toxicity impacts, because the US cotton farming has to comply with more legal requirements on the fertiliser and pesticide use than most other conventional cotton cultivations in the rest of the world.

Compared to man-made cellulose fibres, cotton has relatively higher impacts on fresh water ecotoxicity, terrestrial ecotoxicity, and eutrophication mainly due to pesticides use and fertiliser use in the cultivation phase. More than 80% of the freshwater aquatic ecotoxicity and more than 90% of the terrestrial ecotoxicity of cotton are caused by the release of one type of insecticide, namely aldicarb, to the soil. According to a USDA's survey, on average about 0.67 lb of aldicarb per acre (approx. 0.75 kg/ha) was applied to about 19% of the cotton fields in the US in 2005 [57]. Therefore in our calculation we take account of 0.75*19% = 0.14 kg aldicarb per hectare for the cotton production in the US.

PET and PP fibres cause a relatively high abiotic depletion impact because of the depletion of non-renewable energy. PET fibre has a high impact on human toxicity (Table 13). More than 90% of the impact is caused by the air emission of PAH (polycyclic aromatic hydrocarbons) during amorphous PET production [58].

Comparison of normalised results

Normalisation is an optional LCA step to show to what extent an impact category has a significant contribution to the overall environmental problem in a country or in a region. Normalisation serves two purposes [59]. First, impact categories that have very small contribution compared to other categories can be left out in the interpretation. Therefore the number of environmental issues that need to be considered can be reduced. Second, the normalised results allow to rank the options in terms of the generated environmental problems (compared to the total environmental loads in a specific region over a specific time).

Figure 17 shows the comparison of the normalised results (based on normalisation values for World 2000 [48]. The normalised environmental impacts of ozone layer depletion and photochemical oxidation are nearly invisible. Thus these two categories do not need to be considered in the interpretation. Furthermore, all man-made cellulose fibres studied cause comparatively insignificant impacts to human toxicity, fresh water aquatic ecotoxicity and eutrophication. On the other hand, the normalised results show that for Lenzing Viscose Asia, global warming, abiotic depletion, and acidification are the relatively important environmental issues. For Lenzing Modal and Tencel Austria, the relatively important environmental issues are abiotic depletion and acidification. None of the impact categories of Lenzing Viscose Austria and Tencel Austria represent a significant contribution.

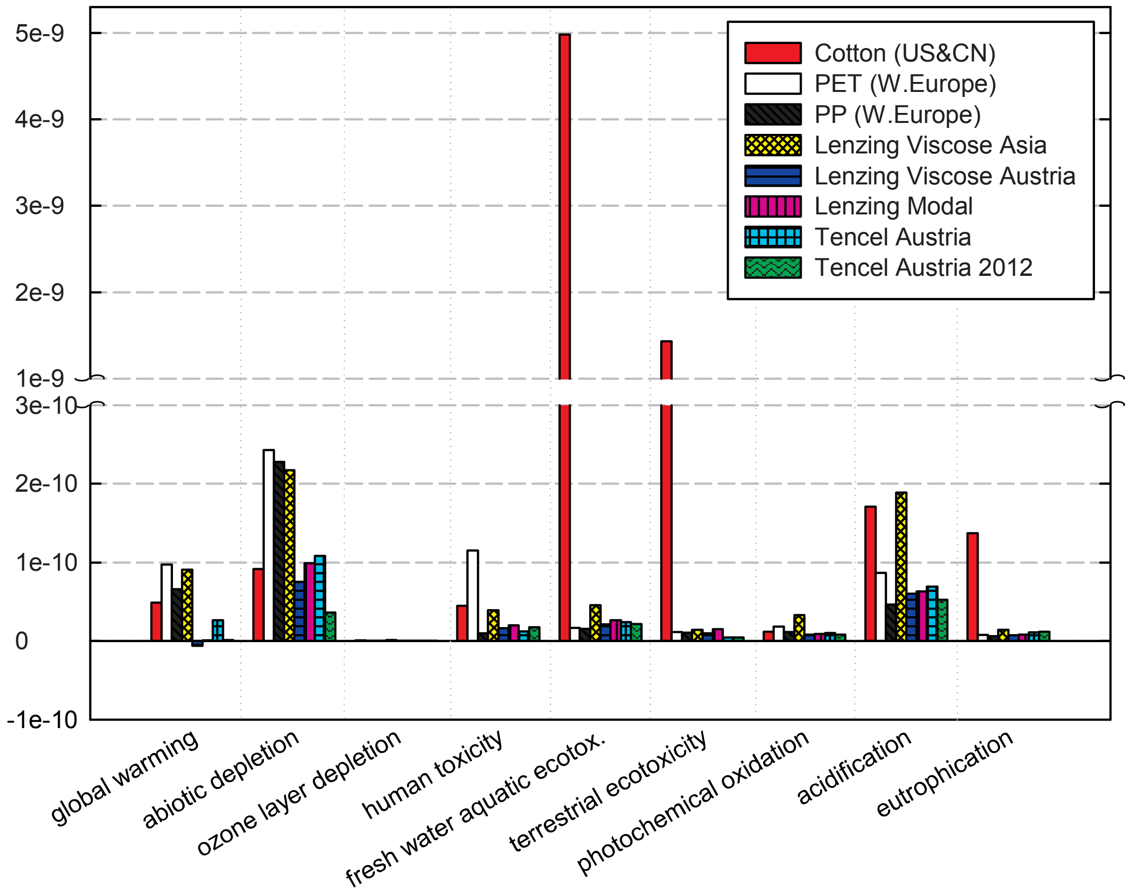


Figure 17. Comparing cradle-to-factory gate environmental impact, one tonne staple fibre, CML 2 baseline 2000 method, Normalisation to World 2000 (default allocation method for by-products).

For cotton, ecotoxicity (fresh water and terrestrial) represents an extremely important issue; cotton fibres also have high contributions to acidification and eutrophication problems. The environmental problems of PET and PP are mainly focused on global warming, abiotic depletion, and acidification.

When interpreting this data, it is important to consider the limitations of the normalisation step. For example, a low normalized value, e.g., for human toxicity, does not necessarily mean that no further action needs to be taken for this environmental impact because the status quo of toxic emissions (representing the denominator) may actually be unacceptably high. Or, to take a different example, using normalisation values for a country with very high GHG emissions would give the impression that no action is required for the product studied, while one could argue that exactly the opposite is true and that all available measures should be taken to abate GHG emissions.

Discussion

Sensitivity analysis for fertiliser use in eucalyptus production

In Table 4 we showed key data on eucalyptus wood production. The given data on fertiliser use and machinery use are assumptions based on expert estimates. These assumptions could differ for eucalyptus grown in another world region and/or by another producer. In this section, we check the sensitivity of these assumptions in relation to the cradle-to-factory gate NREU, GWP 100 and eutrophication of fibres that are partly produced from the eucalyptus pulp, for example, Lenzing Viscose Asia and Tencel Austria.

Table 14 shows the sensitivity of fertiliser use and machinery use. As the fertiliser use (11-126 kg/ha/yr) and machinery use (0.3-3.6 kg diesel/ha) change between -75% and +300%, while all other parameters of the inventory analysis remain unchanged, the changes of the NREU, GWP and eutrophication of Lenzing Viscose Asia and Tencel Austria are less than ±5%. Therefore, we conclude that the NREU, GWP and eutrophication of Lenzing Viscose Asia and Tencel Austria are not sensitive to the fertiliser and machinery use in the eucalyptus wood production. This is also a consequence of the fact that eucalyptus wood production represents a very small contribution (<2%) to the total NREU, fossil CO_2 emissions and eutrophication impacts.

Sensitivity analysis for NMMO

The assumptions for the NREU of NMMO (200 GJ/t) were discussed above. Here, we examine the sensitivity of these assumptions by varying the value between 50 and 350 GJ/t. The results for Tencel Austria are shown in Table 15. The NREU does not change significantly (less or about ±3%), while the GWP of Tencel Austria is slightly sensitive to the energy requirement of NMMO (< ±10 %).

Table 14. Sensitivity of NREU and GWP of Lenzing Viscose Asia to changes in fertiliser and machinery use in eucalyptus wood production (default allocation method for by-products).

Fertiliser use[a] (kg/ha/yr)	Machinery use (kg diesel /ha)	Changes in fertiliser and machinery use	Changes in NREU		Changes in GWP		Changes in Eutrophication	
			Lenzing Viscose Asia	Tencel Austria	Lenzing Viscose Asia	Tencel Austria	Lenzing Viscose Asia	Tencel Austria
11	0.3	-75%	-0.4%	-0.4%	-0.6%	-1.7%	-0.5%	-0.6%
21	0.6	-50%	-0.2%	-0.3%	-0.4%	-1.1%	-0.3%	-0.4%
42[b]	*1.2*[b]	*0*	*0*	*0*	*0*	*0*	*0*	*0*
63	1.8	+50%	0.2%	0.3%	0.4%	1.1%	0.3%	0.4%
74	2.1	+75%	0.4%	0.4%	0.6%	1.7%	0.5%	0.6%
84	2.4	+200%	0.5%	0.6%	0.8%	2.3%	0.7%	0.8%
126	3.6	+300%	1.0%	1.2%	1.5%	4.5%	1.4%	1.5%

[a] Fertiliser use is shown as the total of N and P fertilisers.
[b] This is the default assumption, see Table 4.

Table 15. Sensitivity of the NREU and GWP of Tencel Austria to changes in the NREU of NMMO (default allocation method for by-products).

NREU of NMMO (GJ/t)	Changes, NREU of NMMO	Changes, Tencel Austria	
		NREU	GWP
50	-75%	-3%	-9%
100	-50%	-2%	-6%
150	-25%	-1%	-3%
200	*0*	*0*	*0*
250	+25%	+1%	+3%
300	+50%	+2%	+6%
350	+75%	+3%	+9%

Sensitivity analysis of allocation methods applied for by-products

Above we explained the allocation method applied for the by-products from the integrated pulp and fibre production, namely system expansion in combination with allocation based on economic values. Alternatively, we can also carry out the approach of system expansion in combination with allocation based on calorific values, because by-products such as thick liquor, xylose, and furfural (for which the system expansion method cannot be applied) can also be considered as fuel. Furthermore, based on the system expansion approach, the by-products Na_2SO_4 and acetic acid substantially reduce the environmental impact of the cellulose fibres produced from Lenzing pulp (see section *Results*). Since all by-products have economic values, it is also possible to perform economic allocation, thereby avoiding system expansion. In this section, we will compare the results based on these two alternative methods.

Alternative method 1: system expansion in combination with allocation based on calorific values

Like the default allocation approach, this approach contains two steps. First, credits are given for avoided acetic acid and sodium sulphate; then, the remaining environmental burden is allocated based on the calorific values of the main products (i.e., Viscose fibre and Modal fibre) and the by-products (i.e., xylose, furfural, thick liquor and off grade fibres). For the Tencel fibres (i.e., Tencel Austria and Tencel Austria 2012) and for Lenzing Viscose Asia, no system expansion is required (no acetic acid and sodium sulphate as by-products). The default allocation method for allocating the remaining environmental burden is based on economic values of lignosulphonate and off grade fibres. In this alternative approach, this latter allocation is carried out based on calorific values of the by-products.

This approach results in slightly higher allocation factors for by-products compared to the default method. Consequently, the environmental impact of the fibres decreases slightly. This effect is found for all environmental impacts, i.e., NREU, REU and the eight CML environmental impact indicators. The LCA results based on this alternative allocation method can be found in Appendix III. For Lenzing Viscose Asia, Tencel Austria and Tencel Austria 2012, the environmental impacts based on calorific-value allocation decrease insignificantly (<1%). For Lenzing Viscose Austria and Lenzing Modal, the environmental impacts decrease by about 8-9%.

Figure 18 shows an analysis of the NREU of Lenzing Viscose Austria based on different allocation methods. The credits given to acetic acid and Na_2SO_4 are identical for both the default method and this alternative method (method 1). The small difference is caused by the increase of the allocation factor of other by-products (xylose, furfural and thick liquor). The overall results of the comparison with cotton, PET and PP do not change by this alternative allocation method.

Alternative method 2: allocation based on economic values (no system expansion applied)

In the second alternative approach, no system expansion is applied, i.e., acetic acid and sodium sulphate do not gain any credits for the fibres. The environmental burden is allocated based on economic values. As a consequence, the environmental impact of the main product (fibres) increases because the environmental burden assigned to acetic acid and sodium sulphate is much smaller than the avoided environmental burden from the production of acetic acid and sodium sulphate (see Figure 18).

For Tencel Austria and Tencel Austria 2012, the changes of the LCA results (e.g., NREU, REU, CED and the CML indicators) are negligible (< ±3%). For Lenzing Viscose Asia, the changes are also insignificant (0.1-9%). Lenzing Viscose Asia yields a similar amount of sodium sulphate as Lenzing Viscose Austria. However, due to the higher process energy use the credit given to sodium sulphate is relatively small, accounting for only 8% of the total NREU (as opposed to 35% in the case of Lenzing Viscose Austria; see Figure 9). Therefore, for Tencel Austria, Tencel Austria 2012 and Lenzing Viscose Asia, the influence of this alternative method (method 2) is minor. The ranking among these three fibres and cotton, PET and PP does not change.

However, for Lenzing Viscose Austria and Lenzing Modal, the LCA results change significantly. The impacts are higher by approximately 15-60% for NREU, abiotic depletion, human toxicity, fresh water aquatic ecotoxicity, photochemical oxidant formation, and acidification. GWP 100a increases from -250 kg CO_2 eq. and 33 kg CO_2 eq. to 94 kg CO2 eq., and 650 kg CO2 eq., for Lenzing Viscose Austria and Lenzing Modal, respectively. Ozone layer depletion increases by 140-170%, making it the most sensitive impact category to allocation method. CED, terrestrial ecotoxicity, and eutrophication are slightly higher (by approx. 4-15%). REU decreases slightly (by -6%). Appendix III shows the result of the analysis.

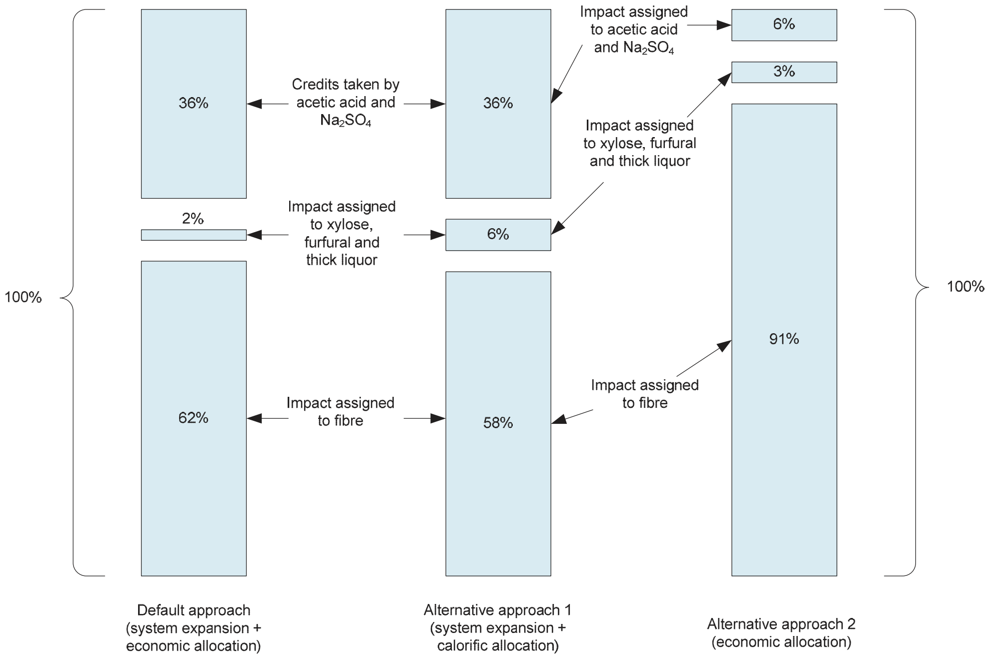


Figure 18. Comparison of the allocation of NREU of Lenzing Viscose Austria based on the default method and two alternative methods.

Compared to the default method, the impact assigned to acetic acid and sodium sulphate is substantially lower based on this alternative allocation method. For example, for the NREU of Lenzing Viscose Austria, the impact assigned to these two by-products is reduced from 36% to 6% (Figure 18), resulting in a large allocation factor (91%) assigned to the main product – fibre.

Although this allocation method increases the environmental impacts of Lenzing Viscose Austria and Lenzing Modal, the ranking relative to cotton, PET and PP does not change substantially (see Appendix III). Lenzing Viscose Austria and Lenzing Modal still have lower impact in the majority of the categories than cotton, PET and PP. The exception is that the NREU of Lenzing Modal becomes slightly higher than cotton (39 GJ/t vs. 36 GJ/t) and the photochemical oxidant formation of both Lenzing Viscose Austria and Lenzing Modal is comparable with that of cotton, PET and PP.

Discussion on environmental impact assessment methods

CML 2 baseline 2000 method

The CML method has ten environmental impact categories. In this study, we reported nine of them. The one that we excluded is marine aquatic ecotoxicity because of the data uncertainties in the characterisation factors [52]. When using the LCA results from this study, readers are recommended to treat the toxicity impacts with caution.

A further limitation of the CML method is that some substances that are known to be problematic cannot be assessed. For example, the level of AOX emission is a standard indicator for the pollution level of wastewater, but it is not taken into account by the CML method in any of its environmental impact categories.

Environmental impact of land use and water use

As described above, the results of land use in this study only refer to the land use for biomass production. Other forms of land use, such as the land use of a pulp mill or a PET production facility, are negligible compared to the land use of biomass production. We report the direct agricultural/forestry land use based on biomass yields and these land use data are then compared in the context of energy and GHG savings. However, one should be aware that land use is a very regional indicator. Cross-region comparisons of land use shows high uncertainties because the real biomass yields are a function of various local conditions, such as climate, soil type, land use transformation, and the fragility or stability of the local ecosystem. It is beyond the scope of this study to look into these factors. Amongst all the available impact assessment methods, Eco-indicator 99 provides land use as one of the mid-point indicators. However, in Eco-indicator 99 all forms of land use are assumed to occur within Europe (therefore the environmental impact is also assumed to occur in Europe[11]) [60]. In our study, only the forest land use occurs in Europe (for Lenzing Viscose Austria and Lenzing Modal, partly for Tencel Austria and Tencel Austria 2012); the other type of forest land use (for eucalyptus wood) is located in the southern hemisphere; and some part of cotton is produced in different climate zones in China and in the US. So far, there are no generally accepted methods for aggregating different forms of land use.

[11] According to the methodology description of Eco-indicator 99 [60], the environmental impact (damage) of land use is expressed in Potential Disappeared Fraction (PDF) of species; the species numbers are determined by observations (counting), not by models. This is why this method is very regional-based and why we do not use the European data to estimate data from other regions such as Asia and the US.

In section *Results* we reported our inventory analysis on water use (by natural origin) for each type of fibre. Water use causes different types and different levels of environmental impacts depending on the regional hydrological system and ecological system. Climate (precipitation) fragility of local hydro-ecosystem and the efficiency of irrigation can all be important factors when assessing the environmental impact of water use. To our knowledge, there is no mature method for the aggregated assessment of different types of water use.

Further analysis: cradle-to-factory gate plus waste incineration

The system boundary of this LCA is "cradle to factory gate". After leaving the factory gate, fibres are used to produce various textile or nonwoven end products. The end products are then consumed and disposed of. In the waste stage, the used products may be incinerated, recycled or landfilled (direct landfilling is prohibited in several European countries).

In this section, we will calculate the *Net* NREU and *Net* GWP of the fibre products. The Net NREU is defined as the total gross NREU for production minus the energy recovered from waste incineration, i.e., the system boundary includes the cradle-to-factory gate stage and the waste management stage. The production and consumption of the end-products are excluded (Figure 19) because the extremely large number of end products involving different types of dyeing, spinning and other steps in the textile value chain next to differences in washing during the use phase make a generalized approach impossible.

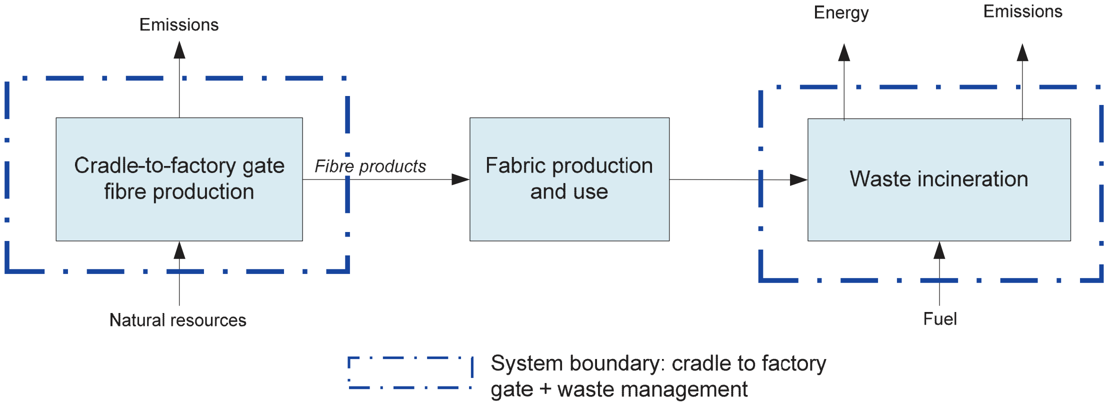


Figure 19. System boundary: cradle-to-factory gate plus waste incineration with energy recovery.

It is assumed that the fibres are incinerated in a MSWI plant with cogeneration of electricity and heat. The recovered energy replaces grid electricity and conventionally raised heat. This means that the fossil fuels, that would have otherwise been used to generate grid electricity and heat, are avoided. Incineration with a recovery rate of 60%[12] (in primary energy terms) has been estimated to represent the average level in Europe.

For bio-based products such as man-made cellulose fibres, the biogenic carbon embedded in the product has been deducted from the total GHG emissions in the cradle-to-factory gate analysis. However, in the waste incineration stage the embedded carbon is released again into

[12] The "60%" can be explained as follows: the efficiencies of electricity and heat are 10.6% and 22.3% in an average MSWI (municipal solid waste incineration) plant in Europe according to [33, 34]. This means that 1 GJ waste yields 0.106 GJ_e (electricity) and 0.223 GJ_{th} (heat). These amounts of electricity and heat would be otherwise produced conventionally with an electricity efficiency of 30% and a heat efficiency of 85% (cradle to factory gate efficiency of average EU electricity mix). Thus, 0.106 GJ_e electricity replaces 0.106/30% = 0.35 GJ_p primary fossil fuels and 0.223 GJ_{th} heat replaces 0.223/85% = 0.26 GJ_p primary fossil fuels. The total primary fossil fuel that can be avoided is 0.35 GJ_p + 0.26 GJ_p = 0.61GJ_p – this is about 60% of the energy content of the waste.

the air. This amount of GHG emissions should be added to the total GHG emissions in a cradle-to-grave analysis. Furthermore, when there is *energy recovery* in the waste incineration stage, the electricity and heat recovered from the calorific value of the waste avoids the use of fossil fuels combustion. Here, we assume that the avoided fossil fuel is natural gas. The emission factor of natural gas is 56 kg CO_2 eq/GJ [61]. Therefore, 1 GJ of primary fuel (natural gas, net heating value) saved also avoids 56 kg CO_2 eq. of GHG emissions. The *Net* GWP is computed as cradle-to-factory gate GHG emissions plus the biogenic emissions from waste incineration minus the saved CO_2 emissions from the energy recovery (56 kg CO_2 eq./GJ at 100% recovery rate, and 34 kg CO_2 eq./GJ at 60% recovery rate).

To summarise, the Net NREU and the Net GWP are calculated based on the following equations:

Net NREU **=** $NREU_{CF} - NREU_{avoided}$
Net GWP **=** $GWP_{CF} + (GWP_{incin.} - GWP_{avoided})$

where
$NREU_{CF}$ stands for cradle-to-factory gate NREU;
$NREU_{avoided}$ is the NREU avoided by the recovered energy, which is 60% of the gross heating value of the fibre incinerated (see text above);
GWP_{CF} stands for cradle-to-factory gate GWP;
$GWP_{incin.}$ is the GHG emitted from the incineration of the fibre product; it is equal to the embodied carbon (as CO_2 equivalent) in the product; and
$GWP_{avoided}$ is the avoided GWP from recovered energy, which is 34 kg CO_2 eq. per GJ recovered energy (in primary energy term, see text above).

Net NREU

Table 16 shows the comparison of man-made cellulose fibres with other polymers in terms of Net NREU. All studied man-made cellulose fibres have a lower Net NREU than PP and PET. This is remarkable because man-made cellulose fibres have a lower calorific value than petrochemical polymers and hence receive a lower credit from energy recovery in the waste management stage. Lenzing Viscose Austria, Tencel Austria 2012, and Lenzing Modal have a substantially lower (40-60%) Net NREU value compared to cotton. The Net NREU of Tencel Austria is somewhat higher than those of cotton and PLA with wind. The Net NREU of Lenzing Viscose Asia is very similar to PLA without wind but it is twice as high as cotton.

Net GWP

The results for Net GWP are presented in Table 17. Tencel Austria 2012, Lenzing Modal, and Lenzing Viscose Austria have a Net GWP of around or less than 1 t CO_2 eq. per t fibre, which is half of the Net GWP of Tencel Austria and PLA with wind, 1/3 of that of cotton, 1/4 of those of PP and PLA without wind and 1/5 of those of PET and Lenzing Viscose Asia. The Net GWP of Lenzing Viscose Asia is similar to PET and PP but it is clearly higher compared to cotton and PLA fibres.

Table 16. Comparison of Net NREU (GJ/t fibre) of man-made cellulose fibres, cotton, PET and PP (including cradle-to-factory gate plus waste incineration with energy recovery, excluding fabric production and use phase; default allocation method for by-products).

	Cradle-to-factory gate NREU ($NREU_{CF}$)	NREU of waste incineration with energy recovery (recovery rate =60%) ($NREU_{avoided}$)	Net NREU	
Cotton (US&CN)	36	-10	**26**	(23~30)
PET (W. Europe)	95	-14	**81**	
PP (W. Europe)	88	-29	**59**	
PLA (without wind)	66	-11	**55**	
PLA (with wind)	39	-11	**28**	
Lenzing Viscose Asia	61	-9	**52**	(48~56)
Tencel Austria	42	-9	**33**	(19~39)
Lenzing Modal	25	-9	**16**	(14~26)
Tencel 2012	21	-9	**12**	(-3~49)
Lenzing Viscose Austria	19	-9	**10**	(8~19)

Note: For man-made cellulose fibres, the uncertainty ranges are caused by using different pulp mix and different allocation methods. For cotton, the lower value represents Chinese cotton and the higher value is U.S. cotton.

Table 17. Comparison of Net GWP 100a (t CO_2 equivalent/t fibre) of man-made cellulose fibres, cotton, PET and PP (including cradle-to-factory gate plus waste incineration with energy recovery, excluding fabric production and use phase; default allocation method for by-products).

	Cradle-to-factory gate GWP (GWP_{CF})	GWP of waste incineration with energy recovery (recovery rate = 60%) ($GWP_{incin.}$- $GWP_{avoided}$)	Net GWP	
Cotton (US&CN)	2.04	1.10	**3.13**	(2.78~3.42)
PET (W.Europe)	4.06	1.50	**5.56**	
PP (W.Europe)	2.76	1.49	**4.25**	
PLA (without wind)	2.56	1.19	**3.75**	
PLA (with wind)	0.93	1.19	**2.12**	
Lenzing Viscose Asia	3.81	0.94	**4.74**	(4.36~5.12)
Tencel Austria	1.11	0.92	**2.03**	(1.15~2.48)
Lenzing Modal	0.03	0.94	**0.97**	(0.93~1.66)
Tencel 2012	0.05	0.92	**0.97**	(-0.05~3.24)
Lenzing Viscose Austria	-0.25	0.94	**0.69**	(0.65~1.27)

Note: For man-made cellulose fibres, the uncertainty ranges are caused by using different pulp mix and different allocation methods. For cotton, the lower value represents US cotton and the higher is Chinese cotton

Land use efficiencies

In addition to land use, we calculate the indicator "land use efficiencies" by comparing the production of bio-based fibres (with substantial land use for biomass production) with the production of PET fibres (with negligible land use): the NREU savings and GHG emission reduction (determined by comparison of the bio-based fibres with PET) are divided by the land use for biomass production in order to assess how efficiently the land is used for the purposes of energy saving and climate protection. The following formulas are used in our calculation. The higher the land use efficiency number is, the more NREU or GHG emissions are saved per hectare land.

$$LanduseEfficiency_{NREU} = \frac{NREU_{PET} - NREU_i}{Landuse_i}$$

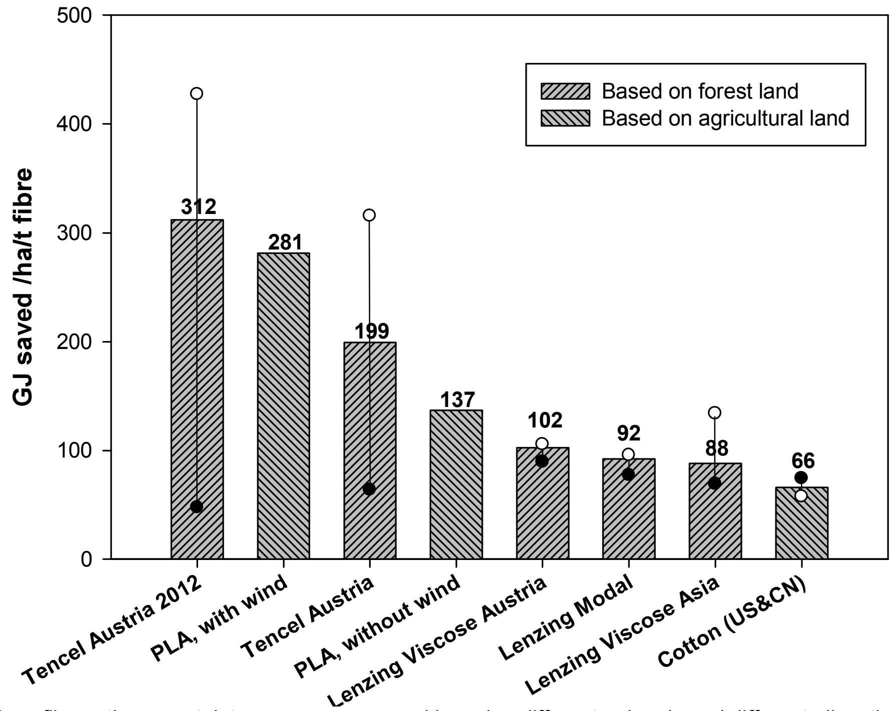
$$LanduseEfficiency_{GHG} = \frac{GHG_{PET} - GHG_i}{Landuse_i}$$

(*i* refers to the type of fibre in comparison)

For man-made cellulose fibres, large amount of biomass is used for process energy. This raises the question how efficiently the land is used in terms of Net NREU savings and Net GWP reduction. Figure 20 and Figure 21 illustrate the results for such a comparison.

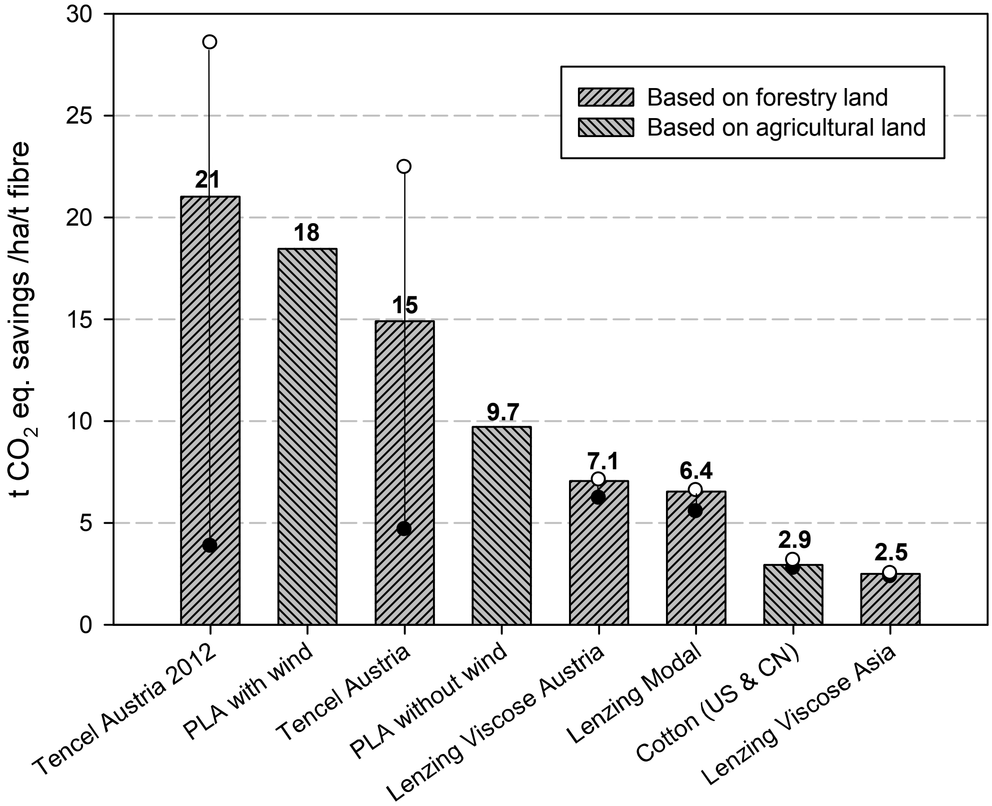
Figure 20 shows that per hectare of land, all the bio-based fibres studied offer energy savings compared to PET. Man-made cellulose fibres in general offer 90-310 GJ NREU savings per tonne fibre, which is 1.5-5 times higher than cotton. PLA fibres, both with or without the wind credit, also have relatively high energy savings per hectare agriculture land use (140-280 GJ/ha/t fibre).

Figure 21 shows the land use efficiency in relation to Net GWP reduction. Again, all the bio-based fibres in this study offer GHG emission savings per hectare land use compared to PET. Tencel Austria 2012, PLA with wind and Tencel Austria fibres offer the highest GHG emissions savings, they can save about 15-21 t CO_2 eq. GHG emissions per hectare land compared to PET fibre. PLA without wind, Lenzing Viscose Austria and Lenzing Modal offer 6-10 t CO_2 equivalent savings per hectare land savings. Man-made cellulose fibres and PLA fibres, except for Lenzing Viscose Asia, can offer 2-7 times more GHG emissions savings than cotton (take PET fibres as the reference). Lenzing Viscose Asia saves slightly less carbon emissions than cotton. It must again be emphasized that the different types of land use (forest and agriculture) are actually not comparable.



Man-made cellulose fibres: the uncertainty ranges are caused by using different pulp mix and different allocation methods
Cotton: the lower value represents US cotton and the higher is the Chinese cotton.

Figure 20. Land use efficiency for Net NREU savings, one tonne staple fibres (economic allocation for by-products).



Man-made cellulose fibres: the uncertainty ranges are caused by using different pulp mix and different allocation methods
Cotton: the lower value represents Chinese cotton and the higher is US cotton (in contrary to Net NREU savings in Figure 20)

Figure 21. Land use efficiency for Net GWP reduction, one tonne staple fibre (economical allocation for by-products).

Alternative allocation methods for energy recovered from post-consumer MSWI

For end-of-life waste management (i.e., MSWI with energy recovery), we applied the system expansion method, i.e., the recovered energy avoids the production of grid electricity and heat. This approach follows the ISO principle that allocation should be avoided, wherever possible [14]. However, we applied a somewhat different method for the process heat obtained from MSWI (see "Lenzing Viscose Austria, Lenzing Modal, and Tencel Austria 2012" in Table 2). Here, the system expansion approach is not completely justified because it does not allow distinguishing between the heat from MSWI and the heat from natural gas. Therefore, we consider economic allocation to be a suitable choice.

One may argue that adopting different approaches leads to inconsistency in this analysis. To a certain extent, this is true. However, one may also argue that the applied methods strictly follow the ISO guideline, i.e., to first avoid allocation, if possible; and if it is not possible to avoid allocation, physical allocation is applied [14]. Different solutions therefore are required for the end-of-life management of fibres on the one hand and for the MSWI plant producing steam used for fibre production on the other.

The influence of alternative allocation methods on the LCA results can be understood by conducting a sensitivity analysis. In the case of process heat from MSWI, the alternative allocation methods (i.e., zero allocation and system expansion) have been implemented in the LCA analysis. In the case of post-consumer waste incineration of fibres in a MSWI with energy recovery, two alternative allocation methods can be applied:

i) Zero allocation for recovered energy and 100% allocation for fibre waste, i.e., the “free heat” case in Table 7. This method can also be seen as MSWI without energy recovery.
ii) Economic allocation where 82.5% of the environmental burden is allocated to the post-consumer waste and 17.5% of the burden is assigned to the recovered energy (i.e., the “baseline” case in Table 7).

Table 18. Sensitivity of alternative allocation methods to Net NREU for MSWI fibre waste with energy recovery.

	Net NREU (GJ/t)		
	Default method (system expansion)	Alternative i) (“free heat”)	Alternative ii) (economic allocation)
Allocation factor for fibre waste	n/a	100%	87.5%
Cotton (US&CN)	26	36 (+38%)	36 (+38%)
PET (W.Europe)	81	95 (+17%)	95 (+17%)
PP (W.Europe)	59	88 (+50%)	88 (+50%)
PLA (without wind)	55	66 (+21%)	66 (+21%)
PLA (with wind)	28	39 (+41%)	39 (+41%)
Lenzing Viscose Asia	52	61 (+18%)	61 (+18%)
Tencel Austria	33	42 (+27%)	42 (+27%)
Lenzing Modal	16	25 (+58%)	25 (+58%)
Tencel 2012	12	21 (+72%)	21 (+72%)
Lenzing Viscose Austria	10	19 (+93%)	19 (+93%)

Note: percentages in brackets show the changes compared to the default case. n/a stands for not applicable.

Table 19. Sensitivity of alternative allocation methods to Net GWP for MSWI fibre waste with energy recovery.

	Net GWP (t CO_2 eq./t)		
	Default method (system expansion)	Alternative i) (“free heat”)	Alternative ii) (economic allocation)
Allocation factor for fibre waste	n/a	100%	87.5%
Cotton (US&CN)	3.13	3.69 (+18%)	3.40 (+8%)
PET (W.Europe)	5.56	6.35 (+14%)	5.95 (+7%)
PP (W.Europe)	4.25	5.90 (+40%)	5.35 (+26%)
PLA (without wind)	3.75	4.39 (+17%)	4.07 (+8%)
PLA (with wind)	2.12	2.76 (+30%)	2.44 (+15%)
Lenzing Viscose Asia	4.74	5.26 (+11%)	5.00 (+6%)
Tencel Austria	2.03	2.53 (+25%)	2.28 (+13%)
Lenzing Modal	0.97	1.48 (+53%)	1.23 (+27%)
Tencel 2012	0.97	1.47 (+52%)	1.22 (+26%)
Lenzing Viscose Austria	0.69	1.20 (+75%)	0.95 (+38%)

Note: percentages in brackets show the changes compared to the default case. n/a stands for not applicable.

We applied these two alternative methods for all fibres studied, i.e., cotton, PLA, PET, PP, and Lenzing man-made cellulose fibres for Net NREU and Net GWP. The results are shown in Table 18 and Table 19.

Table 18 shows the influence of different allocation methods on Net NREU. The last two columns in the table show that the Net NREU based on both alternative allocation methods are the same, because there are basically no extra energy requirements (as the environmental burden) to allocate: The extra energy requirements to incinerate one tonne fibre waste are negligible compared to the calorific value of fibre. Thus, the Net NREU is the same as the

cradle-to-factory gate NREU. From the table it can be seen that for all fibres studied, the Net NREU change substantially (increase by 17-93%) compared to the default method. The increase is substantial especially for fibres with high heating values (e.g., PP) or fibres with low cradle-to-factory gate NREU (e.g., PLA with wind and Lenzing Viscose Austria). Nonetheless, the ranking of fibres for Net NREU does not change compared to the ranking based on the default method.
Table 19 shows the results of the sensitivity analysis of applying the two alternative allocation methods for Net GWP. Based on the first alternative method ("Alternative i"), the Net GWP increases substantially compared to the default method, especially for fibres with high heating values (e.g., PP) and bio-based fibres whose Net GWPs are dominated by embodied carbon (e.g., PLA with wind and Lenzing Viscose Austria). The Net GWP based on "Alternative ii" increases less substantially compared to the results based on "Alternative i". For cotton, PET, PLA without wind and Lenzing Viscose Asia, the increase of the Net GWP is not substantial (<10%). Additionally, the ranking of fibres changes slightly. PP moves from the third highest to the second highest among all studied fibres.

Conclusions

We conducted a comparative LCA to assess the environmental impacts of three types of man-made cellulose fibre (Viscose, Modal and Tencel). The LCA results are compared with conventional cotton (as benchmark), novel bio-based fibre (i.e., PLA), and synthetic fibres (i.e., PET and PP). The environmental indicators we assessed include both resources and impact indicators. Resources include primary energy requirements (NREU/REU/CED), water use and land use. Environmental impact indicators include nine categories from the CML baseline method, namely GWP100a, abiotic depletion, ozone layer depletion, human toxicity, fresh water aquatic ecotoxicity, terrestrial ecotoxicity, photochemical oxidant formation, acidification and eutrophication. The functional unit is one tonne of staple fibre. The analysis was first carried out for the system cradle-to-factory gate. Waste incineration with energy recovery was then added in order to obtain a more complete overview of the energy and GWP profiles of the studied fibres. A summary of the LCA results is shown in Table 20. The following conclusions can be drawn from this study:

1. The integrated fibre-pulp production (i.e., Lenzing Viscose Austria and Lenzing Modal) leads to much lower environmental impacts than the separate production of pulp and fibres (i.e., Lenzing Viscose Asia). The environmental benefits of Lenzing Viscose Austria and Lenzing Modal are largely attributed to low fossil energy requirements in the pulp and fibre production. This is a result of both process integration and the use of renewable energy. Furthermore, Lenzing Viscose Austria and Lenzing Modal cause much lower process emissions (e.g., SO_2 and NO_x) than Lenzing Viscose Asia, leading to lower impacts on human toxicity, photochemical oxidant formation, acidification and eutrophication.
2. Tencel Austria 2012 has a better environmental profile than Tencel Austria for nearly all indicators (except for ozone layer depletion, human toxicity and eutrophication). For abiotic depletion, terrestrial ecotoxicity, photochemical oxidant formation and acidification, Tencel Austria 2012 causes even lower impact than the fibres produced in integrated plants. The environmental benefits are the result of low energy consumption, low chemical use, low CO_2 emissions, low SO_2 emissions and low water consumption. A further important reason is the supply of process heat from municipal solid waste

incineration; however with the chosen allocation method strongly influencing the outcome.

3. Lenzing Viscose Asia is less favourable than the other man-made cellulose fibres studied. The major environmental problems are global warming potential, abiotic depletion, photochemical oxidation, and acidification. Compared to Lenzing Viscose Austria, the higher impact of Lenzing Viscose Asia is primarily attributable to process fuels (most of which are of fossil origin), process electricity supplied from the public grid, the use of market pulp and local sourcing of chemicals while the emissions from the viscose process are a comparatively small contributor to the overall impact.

4. Based on the results shown in Table 20 for the system boundary cradle-to-factory gate we conclude that Lenzing Viscose Austria, Lenzing Modal, Tencel Austria, and Tencel Austria 2012 have better environmental profiles than PET and cotton. Lenzing Viscose Asia is comparable with cotton and less preferable than PET, PP, and PLA with and without wind. Among the man-made cellulose fibres, the difference in environmental impact is quite substantial (e.g., differing by a factor of three for Net NREU without Lenzing Viscose Asia and by a factor of five including Lenzing Viscose Asia).
   - Lenzing Viscose Austria has a lower environmental impact than cotton (in 12 out of 13 categories), PET (in 10 out of 12 categories), PP (in 7 out of 12) and PLA with and without wind (in 3 out of 4). It has the lowest impact on NREU, GWP100a, and ozone layer depletion.
   - Lenzing Modal has a lower environmental impact than cotton (in 11 out of 13 categories), PET (in 10 out of 12) and PLA without wind (in 3 out of 4); it is comparable with PP and PLA with wind.
   - Lenzing Viscose Asia has higher impacts than cotton for seven out of 12 impact categories among them for NREU and GWP and is less favourable than PET (only better for four out of 12), PP (better for four out of 12) and PLA with and without wind (better for zero out of four).
   - Tencel Austria has a lower environmental impact than cotton (in 10 out of 13 categories) and PET (in 8 out of 12); it is comparable with PLA without wind; and it is less favourable than PP (only better in 4 out of 12 categories).
   - Tencel Austria 2012 is a better choice compared to cotton (11 out of 13), PET (7 out of 12) and PLA with and without wind (3 out of 4). It has the lowest impact on abiotic depletion, terrestrial ecotoxicity and photochemical oxidant formation.
   - Cotton, the most important natural cellulose fibre in the market, is not an energy-intensive product; it has the lowest CED. However, cotton is has the highest impact among all fibres studied in 5 out of 13 categories i.e., land use, water use, fresh water aquatic ecotoxicity, terrestrial ecotoxicity and eutrophication. The cultivation of cotton causes the largest part of the environmental impacts. Pesticides use is responsible for the high ecotoxicities and fertiliser use is the main cause of eutrophication.

5. Based on the normalised results (to World 2000), we conclude that the fresh water aquatic ecotoxicity and terrestrial ecotoxicity of cotton is very high; all man-made cellulose fibres studied cause comparatively insignificant impacts to human toxicity, fresh water aquatic ecotoxicity and eutrophication; and all man-made cellulose fibres, PET, PP and cotton have minor contribution to ozone layer depletion and photochemical oxidant formation.

6. The main findings for the system cradle to factory gate plus waste incineration with energy recovery (60% energy recovery rate):
   - All Lenzing man-made cellulose fibres studied are better than PET, PP, and PLA without wind in terms of Net NREU. Cotton requires relatively little energy; the Net NREU of cotton is lower than in the case of PET, PP, PLA (both with and without wind), Lenzing Viscose Asia and Tencel Austria. Only three fibres studied have a lower Net NREU than cotton, namely, Lenzing Viscose Austria, Lenzing Modal, and Tencel Austria 2012.
   - All the Lenzing man-made cellulose fibres studied except for Lenzing Viscose Asia have a lower Net GWP than PET, PP, cotton and PLA (both with and without wind). Lenzing Viscose Asia's Net GWP is slightly higher than PP's and is lower than PET's.
   - Lenzing man-made cellulose fibres can offer 1.3-5 times more Net NREU savings per hectare land use compared to cotton. Except for Lenzing Viscose Asia, man-made cellulose fibres offer 2-7 times more Net GWP reductions per hectare land use compared to cotton. Lenzing Viscose Asia's net GHG reduction per hectare of land is comparable with cotton's (taking PET as reference).
   - For end-of-life MSWI with energy recovery, applying different allocation methods (allocation factors: 0% and 87.5% to fibre waste) instead of system expansion significantly increases the Net NREU (by 20-90%) and Net GWP (by 6-75%) for all fibres. However, the ranking of Net NREU among all fibres does not change; the ranking of Net GWP shows a minor change (Lenzing Viscose Asia moves from the second highest to the third highest based on economic allocation).

The main caveats of this study are

- Since the functional unit of this study is "*one tonne staple fibres*", it does not refer to final textile products. The latter would be the preferred choice because textile products represent the final purpose. The choice of final textile products as functional unit could lead to other conclusions because different amounts of fibres may be required to ensure the same functionality and due to differences in processing. A comparison for final textile products would be a challenging task because of the large number and types of textile products and because a suitable way for accounting for the different fibre properties in the use phase (e.g., differences in comfort level as a consequence of differences in water absorption) would need to be found.
- The data gaps in the inventory analysis are relatively small and, in most cases, the sensitivity of the final results is limited.
- To deal with the allocation of by-products (especially relevant for pulp production), the system expansion method was applied as default, wherever possible. This approach is in line with the ISO rules for LCA. However, it leads to relatively large credits especially for sodium sulphate and acetic acid. Since both by-products have relatively low economic values (price), economic allocation leads to less favourable results compared to the default method. However, the ranking of all fibres studied does not change based on both allocation methods. The only exception is the NREU of Lenzing Modal, which is slightly higher than that of cotton based on economic allocation (see Appendix III). For the by-products xylose, furfural and thick liquor, the default approach is economic allocation. Alternatively, allocation based on calorific value can be a plausible choice; the results do not differ very substantially from the default method for the cases applied in this study. To deal with the allocation of post-consumer waste incineration with energy recovery, system expansion was applied as the default method. Alternatively, economic allocation and cut-off rules were be applied. Both alternative methods lead to higher Net NREU and

Net GWP for all fibres when compared to the default method. However, the ranking of all fibres studied does not change, except that the Net GWP of PP fibre is higher than that of Lenzing Viscose Asia based on both alternative methods.

- State-of-the-art LCA methodologies were applied in this study in order to assess the environmental impacts. However, the quality of toxicity calculations in LCA tools is currently still doubtful and research is underway to improve the methodologies and to make the databases more complete.
- Only environmental impact categories that are generally considered in LCA studies have been taken into account. For example, an environmental impact category which was not considered is the impacts on biodiversity. Land use and water use have been exclusively reported as inventory results, i.e., different types of land (and of water) were not differentiated due to the lack of suitable methods. The risk of explosion has neither been taken into account.

Table 20. Summary of the LCA results, rankings of the environmental profiles for cradle-to-factory gate for one tonne staple fibre.

- Ranking scale 1-10 for NREU, CED and GWP100a. 1 - the lowest impact; 10 - the highest impact
- Ranking scale 1-9 for land use and water use. 1 - the lowest impact; 9 - the highest impact
- Ranking scale1-8 for abiotic depletion, ozone layer depletion, human toxicity, fresh water aquatic ecotoxicity, terrestrial ecotoxicity, photochemical oxidant formation, acidification and eutrophication. 1 - the lowest impact; 8 - the highest impact

	Resources				Environmental impact indicators								
	NREU	CED	Land use a	Water use b	GWP 100a	Abiotic depletion	Ozone layer depletion	Human toxicity	Fresh water aqua. ecotoxicity	Terrestrial ecotoxicity	Photo-chemical oxidant formation	Acidifi-cation	Eutrophi-cation
Lenzing Viscose Austria	1	3	6	6	1	2	1	3	3	3	2	3	2
Lenzing Modal	3	5	7	7	2	4	2	5	6	6	2	4	4
Lenzing Viscose Asia	7	10	5	3	9	6	7	6	7	6	8	8	7
Tencel Austria	6	9	4	4	5	5	5	2	5	2	4	5	5
Tencel Austria 2012	2	2	3	4	3	1	8	4	4	1	1	2	6
PET (W. Europe)	10	7	N/A	1	10	8	3	8	2	4	7	6	2
PP (W. Europe)	9	6		1	8	7	3	1	1	4	4	1	1
PLA (without wind)	8	7	1	N/A	7	N/A							
PLA (with wind)	5	4	1		4								
Cotton (US & CN)	4	1	8	8	6	3	6	7	8	8	6	7	8

[a] The land use of man-made cellulose fibres is forest land; the land use of PLA and cotton is agricultural land.
[b] Water use includes process water and irrigation water. Cooling water is excluded.

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Appendices

Appendix I. Impact analysis of the US cotton

In this study, the inventory analysis of conventional cotton produced in the US is provided by Carbotech (Dinkel and Stettler, 2008). Table A-1 shows the non-renewable energy use (NREU) for the production of 1 t US cotton by type of activity. In addition, we calculated the NREU based on the inventory data published by Cotton Inc. (Cotton Inc., 2009) and from the latest Ecoinvent database (version 2.0) (Nemecek and Kägi, 2007). Table A-1 shows that Carbotech's data leads to relatively higher NREU of cotton, compared to Cotton Inc and Ecoinvent's data. The major differences originate from the energy use of irrigation, harvesting, transportation and ginning.

Table A-1. Comparison of cradle-to-factory gate NREU of 1 t cotton fibre produced in the US.

	Carbotech (MJ/kg fibre) Used in this report	Cotton Inc. (2009) (MJ/kg fibre)	Ecoinvent 2.0 (MJ/kg fibre) "Cotton fibres at farm, US"
Tillage	2.86 [a]	1.63 [b]	4.88 [c]
Irrigation	8.07	5.49	0.01
N-fertilizer	4.65	5.81	5.27
P-fertilizer	2.63	0.25	1.45
K-fertilizer	0.66	0.30	0.94
Total chemical use (excluding fertilizers)	1.04	1.72	1.04
$CaCO_3$	0	0.44	0
Fertilizing by broadcasting	1.05	0.61	1.34
Other chemical applications	0.86	0.77	2.79
Combine harvesting and baling	7.04	1.21	4.40
Transportation	1.38	0.12	0.07
Ginning	6.50	1.68	0.002
Other [d]	0.04	0	0.06
Total NREU	**36.8**	**20.0**	**22.3**

[a] Including ploughing, harrowing, hoeing, currying and sowing.
[b] Including tillage, disk, cultivate, plant and planting seed.
[c] Including mulching, sowing, cultivating chiselling, harrowing by rotary harrow.
[d] Including e.g., packaging.

The environmental impact of 1 t US cotton is shown in Table A-2. Two data sources are compared: the Carbotech data and the Ecoinvent data. Cotton has a very high ecotoxicity impact compared to other fibres due to pesticides and insecticides use. The high ecotoxicity impact of cotton is also observed from the impact assessment based on the Ecoinvent data (see Table A-2). For Carbotech's analysis, the chemical use for cotton is obtained from USDA's publication on agriculture chemical usage (USDA, 2006). We consider this data source of chemical use for cotton a reliable source.

Furthermore, from Table A-2 it can be seen that except for GWP100a and abiotic depletion, Carbotech and Ecoinvent lead to very similar impact assessment results for the US cotton. The differences of GWP and abiotic depletion are caused by different energy data used (see Table A-1). Furthermore, the direct N_2O emissions and the indirect leaching of nitrates (to air, water and soil), which originate from the fertilizer use, have been modelled by Carbotech.

Table A-2. Environmental impact of cradle-to-factory gate for one tonne of US cotton fibre based on Carbotech and Ecoinvent (version 2.0), CML baseline 2000.

Environmental impact categories	Based on Carbotech data Used in this report	Based on Ecoinvent 2.0 "Cotton fibres at farm, US"
GWP100a (kg CO_2 eq)	1680	831
Abiotic depletion (kg Sb eq.)	18	10
Ozone layer depletion (kg CFC11 eq.)	0.0002	0.0002
Human toxicity (kg 1,4-DB eq.)	1700	1464
Fresh water aquatic ecotoxicity (kg 1,4-DB eq.)	17310	17294
Terrestrial ecotoxicity (kg 1,4-DB eq.)	1568	1582
Photochemical oxidant formation (kg C_2H_4 eq.)	0.64	0.35
Acidification (kg SO_2 eq.)	28	22
Eutrophication (kg PO_4^{3-} eq.)	21	20

Literature used in this Appendix

Cotton Inc. (2009) Summary of Life Cycle Inventory Data for Cotton. Field to bale, version 1.1, 2 July 2009

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Appendix II. Assumptions for NMMO production and Ion exchange resins

NMMO production

N-methylmorpholine-N-oxide (NMMO) is derived from petrochemical feedstocks. It is industrially produced by oxidation of NMM (N-methylmorpholine). This oxidation step requires about 7 GJ NREU/t (including 7% electricity and 93% of steam (Private communication with a NMMO producer).

NMM is a morpholine derivative and it can be obtained by two methods: reacting morpholine with formaldehyde; or through the alkylation of morpholine with methanol under pressure and in presence of hydrogen at 10 bar (Merker, 1997). Industrial morpholine is either produced by amination and hydrogenation of diethylene glycol, or by cyclisation of diethanolamine (Merker, 1997; IPCS, 1997). Assuming that the process energy requirement is 30% of the NREU of the feedstock materials, it can be roughly estimated that the cradle-to-factory gate NREU of NMMO falls into the range between 75 GJ/t and 170 GJ/t [13] depending on which process route is selected.

In order to avoid the underestimation of the environmental impacts we set the cradle to factory gate NREU of NMMO to 200 GJ/t. This is nearly 1.5 times as much as the NREU of the most energy-intensive oil products [14]. The cradle-to-factory gate GHG emission of NMMO is assumed to be 80 kg CO_2 eq./GJ, which is the upper bound of emission factors for combusting liquid oil products (70-80 kg CO_2/GJ_{HHV}) (IEA, 1997). On this basis we estimate the global warming impact of the production of NMMO at 16 t CO_2-eq./t. We proceeded in a comparable manner for all other environmental impacts.

Ion Exchange resins

It is not straightforward to make an environmental assessment of the ion exchange resin, which is used the Tencel production process. We conducted our first calculations using Ecoinvent data on the production of anionic resins (Althaus et al., 2004; Frischknecht, 1999). According to this dataset the production process requires chloroform (trichloromethane), which is an ozone depleting compound. During chloroform production 0.1% of tetrachloromethane (carbon tetrachloride, CFC-10) is released (Frischknecht, 1999). We used this data and calculated the resulting environmental impacts per tonne of Tencel fibre. After normalization of the results the ozone depletion impact of Tencel fibres was found to be three times larger compared to cotton and 20 times larger than Lenzing Viscose Austria. Since the phase-out of ozone depleting compounds was agreed upon in the Montreal Protocol for the developed countries since 1994 [55], the question arises whether the dataset for the production of the ion exchange resin may not be up to date or at least irrelevant for Lenzing. We therefore contacted Lenzing's ion resin supplier who kindly provided the patent of the process applied (this information was provided under a secrecy agreement). The main features of the process are:

- The reacting compound used is a chlorinated hydrocarbon that is not subject to the Montreal Protocol. Moreover, we could not find any information according to which the compound used has an ozone depleting potential.

[13] The NREU of formaldehyde is 45 GJ/t and the NREU of diethylene glycol is 34 GJ/t (IPPC, 2002). The NREU of methanol is 38 GJ/t and the NREU of diethanolamine is 95 GJ/t (Althaus et al., 2004).

[14] For example, Nylon is one of the most energy intensive chemical products. Nylon's cradle-to-factory gate NREU is 134 GJ/t (Boustead, 2005).

- During the process, traces of the chlorinated hydrocarbon are converted to another chlorinated hydrocarbon which is highly toxic. The entire process is therefore encapsulated.
- The modified resin is washed in methanol, leading to a stable final product; in other words, the final product does not release any ozone depleting compounds. The methanol is regenerated and a certain amount of it is discharged and incinerated in order to avoid the accumulation of residual compounds in the process.

According to Ecoinvent the production of 1 kg of ion exchange resins leads to emissions of approximately 2.35 x 10^{-4} kg tetrachloromethane (CFC-10) (Althaus et al., 2004). Toxic release data were not provided to us by Lenzing's ion exchange resin supplier. Moreover, the Ecoinvent database does not contain toxicity data for the compounds used by the ion exchange resin producer. Given the incomplete information we were forced to make the following simplifying assumptions in order to quantify the environmental impacts related to the production of the ion exchange resin used by Lenzing:

- Due to the use of compounds which are not classified as ozone depleting and given the encapsulation of the plant, we set the ozone depleting potential to zero.
- We make the assumption that similarly strict regulatory requirements apply for toxic emissions from Lenzing's ion exchange resin supplier as from the process included in Ecoinvent. We therefore use the toxicity impacts reported by Ecoinvent as proxy for the impacts of Lenzing's resin supplier. We proceed likewise for the other environmental impact categories.

Literature used in this Appendix:

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Appendix III. Comparison of LCA results based on different allocation methods for by-products

	NREU (GJ/t)	REU (GJ/t)	CED (GJ/t)	GHG total (kg CO_2 eq./t)	Abiotic depletion (kg Sb eq./t)	Ozone layer depletion (kg CFC11 eq./t)	Human toxicity (kg 1,4-DB eq./t)	Fresh-water aquatic ecotox. (kg 1,4-DB eq./t)	Terrestrial eco-toxicity (kg 1,4-DB eq.t)	Photo-chemical oxidant formation (kg C_2H4 eq./t)	Acidification (kg SO_2 eq./t)	Eutrophication (kg PO_4^{3-} eq./t)
Default method: system expansion + economic allocation												
Lenzing Viscose Austria	19	51	70	-250	14	3.0×10^{-5}	630	74	11	0.5	14	1.2
Lenzing Modal	25	53	78	34	18	3.7×10^{-5}	766	93	16	0.5	15	1.3
Lenzing Viscose Asia	61	45	106	3810	40	$2.8 \text{ X } 10^{-4}$	1490	160	16	1.8	45	2.3
Tencel Austria	42	59	101	1110	20	1.1×10^{-4}	470	85	5	0.6	17	1.8
Tencel Austria 2012	21	44	65	53	7	7.2×10^{-5}	663	75	5	0.4	13	1.9
Alternative method 1: System expansion + Calorific allocation												
Lenzing Viscose Austria	18	47	65	-345	13	2.8×10^{-5}	580	68	10	0.4	13	1.1
Lenzing Modal	23	48	71	-90	17	3.4×10^{-5}	700	85	15	0.4	14	1.2
Lenzing Viscose Asia	61	45	106	3800	40	2.8×10^{-4}	1490	159	16	1.8	45	2.3
Tencel Austria	42	59	101	1090	20	1.1×10^{-4}	470	83	5	0.6	16	1.8
Tencel Austria 2012	21	44	65	43	7	7.2×10^{-5}	658	74	5	0.4	12	1.9
Alternative method 2: Economic allocation, without applying system expansion												
Lenzing Viscose Austria	28	48	76	95	17	7.2×10^{-5}	750	100	12	0.6	17	1.2
Lenzing Modal	39	50	89	650	23	$1.0 \text{ X } 10^{-4}$	990	140	18	0.8	19	1.4
Lenzing Viscose Asia	64	44	108	3910	41	$3.0 \text{ X } 10^{-4}$	1550	170	16	1.8	46	2.3
Tencel Austria	43	59	102	1115	20	1.1×10^{-4}	475	84	5	0.6	17	1.8
Tencel Austria 2012	22	44	66	58	7	7.4×10^{-5}	664	75	5	0.5	13	1.9
For comparison												
Cotton (US&CN)	36	19	55	2040	17	2.0×10^{-4}	1700	17310	1568	0.7	41	22
PET (W.Europe)	95	1	96	4063	45	7.0×10^{-5}	4393	58	12	1.0	21	1.2
PP (W. Europe)	88	1	89	2760	42	7.0×10^{-5}	370	53	12	0.6	11	1.0
PLA w/o wind (US, PLA 5)	66	29	96	2560	Not Available							
PLA with wind (US, PLA 6)	39	32	72	930								

List of abbreviations

1,4-DB	1,4-dichlorobenzene
AOX	adsorbable organic halogen compounds
BAT	best available technology
BOD	biochemical oxygen demand
CED	cumulative energy demand
CFC	chlorofluorocarbon
Cl_2	chlorine
CML	Centrum voor Milieuwetenschappen Leiden (Institute of Environmental Science, Leiden University, the Netherlands)
COD	chemical oxygen demand
CO_2	carbon dioxide
CS_2	carbon disulfide
GHG	greenhouse gas
GJ	gigajoule
GWP	global warming potential
H_2	hydrogen
ha	hectare
HWI	hazardous waste incineration
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standardization Organisation
LCA	life cycle assessment
LCI	life cycle inventory
MSWI	municipal solid waste incineration
Na_2SO_4	sodium sulphate
NaOCl	sodium hypochlorite
NaOH	sodium hydroxide
NMM	nitro-methylmorpholine
NMMO	nitro-methylmorpholine-nitro oxide
NO_x	nitrogen oxides
NREU	non-renewable energy use
ODP	ozone depletion potential
odt	oven dried tonne
PDF	potential disappeared fraction
PET	polyethylene terephthalate
PLA	polylactic acid
PO_4^{3-}	orthophosphate ion
PP	polypropylene
PTT	polytrimethylene terephthalate
REU	renewable energy use
Sb	antimony
SO_2	sulfur dioxide
TOC	total organic carbon
UV	ultraviolet
WMO	World Metrological Organisation

Critical Review Statement

The study "Life Cycle assessment of man-made cellulose fibres" has been peer-reviewed by the following LCA experts:

- Professor Adisa Azapagic, The University of Manchester, UK;
- Jürgen Giegrich, Institute for Energy and Environmental Research (IFEU), Heidelberg, Germany; and
- Professor David Shonnard, Michigan Technological University, Houghton, MI, USA.

The critical review was commissioned by Lenzing AG, who also commissioned the LCA study. All reviewers are independent of the authors of the LCA study and Lenzing AG.
The critical-review process involved the following steps and activities:

- a review of the draft study report and the results, followed by a draft critical-review reports by each reviewer, in which a number of specific recommendations for improvements to the study were made;
- a review of the subsequent final study report, in which the authors of the study addressed all the points as suggested in the draft critical review; and
- the final critical review report (this review statement).

The aim of the review was to ensure that:

- the methods used to carry out the LCA are consistent with the ISO 14040:2006 and 14044:2006 standards;
- the methods used to carry out the LCA are scientifically and technically valid given the goal of the study;
- the data used are appropriate and reasonable in relation to the goal of the study,
- the interpretations reflect the limitations identified and the goal of the study, and
- the study report is transparent and consistent.

Although the data were available for inspection, the critical review did not involve a review of the data used in the study so that all the findings of the review presented here are based solely on the draft and final reports and the discussions with the authors of the study and Lenzing AG.

Conclusion of the peer review:

- The study follows the guidance of and is compliant with the international standards for Life Cycle Assessment (ISO 14040:2006 and 14044:2006).

NB: This critical review statement refers only to the report titled "Life Cycle assessment of man-made cellulose fibres" and does not cover the accompanying study "Single-score analysis of man-made cellulose fibres".

Adisa Azapagic   Jürgen Giegrich   David Shonnard

March 2010