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Open-loop recycling: A LCA case study of PET bottle-to-fibre recycling

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ABSTRACT

This study assesses the environmental impact of polyethylene terephthalate (PET) bottle-to-fibre recycling using the methodology of life-cycle assessment (LCA). Four recycling cases, including mechanical recycling, semi-mechanical recycling, back-to-oligomer recycling and back-to-monomer recycling were analysed. Three allocation methods are applied for open-loop recycling, i.e. the “cut-off” approach, the “waste valuation” approach and the “system expansion” approach. Nine environmental impact indicators were analysed, i.e. non-renewable energy use (NREU), global warming potential (GWP), abiotic depletion, acidification, eutrophication, human toxicity, fresh water aquatic ecotoxicity, terrestrial ecotoxicity and photochemical oxidant formation. The LCA results are compared with virgin PET fibre and other commodity fibre products, i.e. cotton, viscose, PP (polypropylene) and PLA (polylactic acid). The LCA results show that recycled PET fibres offer important environmental benefits over virgin PET fibre. Depending on the allocation methods applied for open-loop-recycling, NREU savings of 40–85% and GWP savings of 25–75% can be achieved. Recycled PET fibres produced by mechanical recycling cause lower environmental impacts than virgin PET in at least eight out of a total of nine categories. Recycled fibres produced from chemical recycling allow to reduce impacts in six to seven out of a total of nine categories compared to virgin PET fibres. Note that while mechanical recycling has a better environmental profile than chemical recycling, chemically recycled fibres can be applied in a wider range of applications than mechanically recycled fibres.

1. Introduction

Polyethylene terephthalate (PET) bottles have experienced rapid growth since the 1970s when the technique of blow moulding was introduced (Glenz, 2007). Today, bottle grade PET is one of the most important packaging plastics. In 2007, the worldwide consumption of bottle grade PET was 15 million metric tonnes (10^6 metric tonnes or Mt) (Simon and Schnieders, 2009), representing 8% of the total demand of standard plastics.[1] Meanwhile, recycling of post-consumer PET bottles has become a well-established system with its own logistic chain including bottles collection, flake production and pellet production. In 2007, approximately 4.5 Mt of PET bottles were collected and recycled into 3.6 Mt of flakes worldwide (Thiele, 2009). Most of the recycled PET flakes were converted into fibres (Fig. 1). Recycled PET fibre accounted for approximately 8% of the world PET fibre production in 2007 (JCFA, 2008; Thiele, 2009).

In Europe, the amount of collected post-consumer PET bottle waste has increased from 0.2 Mt in 1998 to 1.26 Mt in 2008 (Petcore, 2008), representing an annual growth rate of approximately 19% (see Fig. 2). About 40% of all used PET bottles in Europe were collected for recycling in 2009 (PlasticsEurope, 2009a). It is expected that PET bottle waste collection in Europe will continue to increase by 10% p.a. in the near future (Glenz, 2007) (see Fig. 2).

The primary purpose of this study is to understand the environmental impacts of recycled PET fibre compared to virgin PET. Several studies reported the environmental impacts of PET recycling (Arena et al., 2003; Detzel et al., 2004; Song and Hyun, 1999). In these studies, PET recycling was seen as a post-consumer waste management option and was compared with other options such as landfilling and incineration. The goal of this study is not to analyse different waste management options, but to understand the environmental impact of making recycled PET fibres.

The second purpose of this study is to apply different allocation methods for this open-loop-recycling case. In LCA, there has been so far no standardised procedure for open-loop recycling. Several studies have discussed this methodological problem (Ekvall,

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[1] According to PlasticsEurope's definition, “Standard Plastics” refer to standard thermoplastics, including PE (polyethylene), PP (polypropylene), PVC (polyvinylchloride), PS (polystyrene), EPS (expanded polystyrene) and PET (bottle grade).

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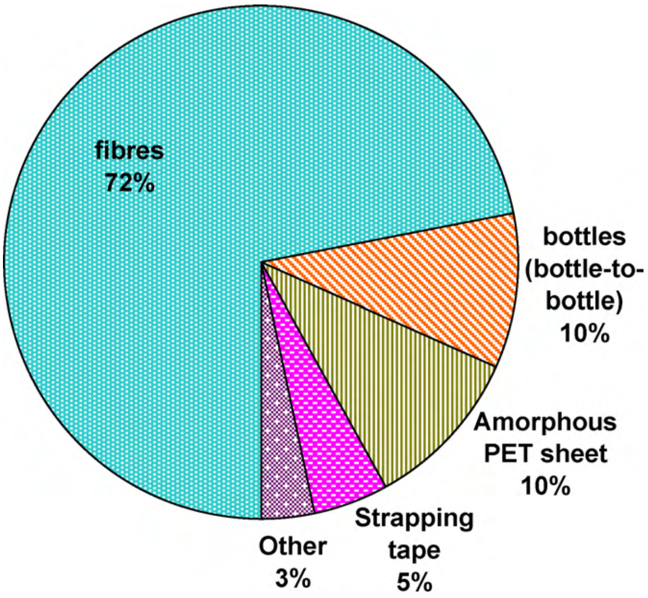

Fig. 1. Application of recycled PET flakes, worldwide 2007, based on data from Noone (2008).

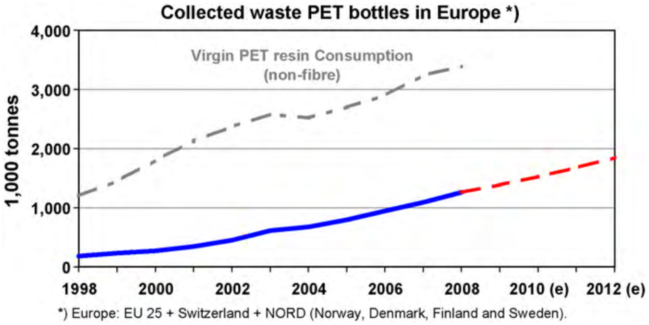

Fig. 2. Collected post-consumer waste PET bottles in Europe over the last 10 years based on data from Forum-PET (2009) and Petcore (2009b) and the estimate for the near future based on 10% p.a. growth rate (Glenz, 2007). Virgin PET consumption data were obtained from (Glenz, 2004; PlasticsEurope, 2009a).

2000; Ekvall and Tillman, 1997; Klöpffer, 1996; Werner and Richter, 2000). A common practice is to follow the “cut-off” principle which distinguishes the first life (virgin product) and the second life (recycled product) as separate systems; the post-consumer waste from the first life does not bear any environmental burden when it is used as the feedstock in the second life. The cut-off rule has been widely applied for recycled or recovered products. For example in the Ecoinvent database, heat recovered from waste incineration is considered free of environmental impact (Frischknecht et al., 2007a). Another example is the EU Directive 2009/28/EC, in which crude glycerol is treated as waste and is considered to be free of greenhouse gas emissions (EU Directive, 2009). The cut-off method is considered simple and easy to apply, because no data of the first life is needed.

In this study, we started the analysis with the “cut-off” approach. Two alternative methods were introduced in order to further develop the methodology for open-loop recycling. The first alternative method is the “waste valuation” method, which follows the principle of economic allocation. The second alternative method is the “system expansion” method, in which the entire system (cradle-to-grave) is analysed.

Four PET recycling cases are investigated in this study, including mechanical recycling, semi-mechanical recycling, back-to-oligomer recycling and back-to-monomer recycling. For each of the first three types of recycling technologies, the respective process data for the year 2008 were provided by three companies. Due to confidentiality issues, no plant data were available for back-to-monomer recycling. Therefore, the analysis was performed based on publicly available information. Virgin PET fibre produced in Western Europe was taken as the reference system. In addition, the LCA result was compared with commodity fibres, i.e. cotton, viscose and polypropylene (PP) as well as novel bio-based fibres, i.e. man-made cellulose fibres (Viscose and Tencel) and polylactic acid (PLA) fibres.

2. Methodology

LCA has been standardised by the ISO 14040 series, namely:

- ISO 14040: 2006 – Principles and framework (ISO, 2006a); and
- ISO 14044: 2006 – Requirements and guidelines (ISO, 2006b).

Table 1
Product systems in this study, comparing type of fibre, property and application.

	Recycling case 1	Recycling case 2	Recycling case 3	Recycling case 4	Reference
Technology	Mechanical	Semi-Mechanical	Chemical, back-to-BHET recycling	Chemical, back-to-DMT recycling	Single-use Virgin PET
Current technology level	Large scale production	Large scale production	Small scale production	Small scale or pilot scale production	Large scale production
Inventory data	Wellman International Ltd. (Wellman)	Long John Group (LJG)	Far Eastern New Century Co. (FENC)	Literature data[a]	Literature data[b]
Geographic scope	Western Europe	Taiwan	Taiwan	Western Europe	Western Europe
Type of fibre studied	Staple	Filament (POY)	Filament (POY)	Filament (POY)	Staple and filament (POY)
Property	High to medium denier Staple No-microfibre	High to medium denier Staple and filament Limited microfibre	Medium to low denier Mainly filament Microfibre	Medium to low denier Mainly filament Microfibre	Full denier range Staple and filament Microfibre
Application	Non-woven Technical end use	Footwear Technical textile Bags	Apparel Soft hand feel Moisture management Limited colours available	Performance apparel Soft hand feel Moisture management All colours available	Non-woven Apparel Performance apparel Moisture management All colours available

Abbreviations: BHET: bis-hydroxylethylene terephthalate; DMT: dimethyl terephthalate; POY: partially oriented yarn.

[a] See data sources in Sections 2.2 and 3.3.2.

[b] See data sources in Section 2.2.

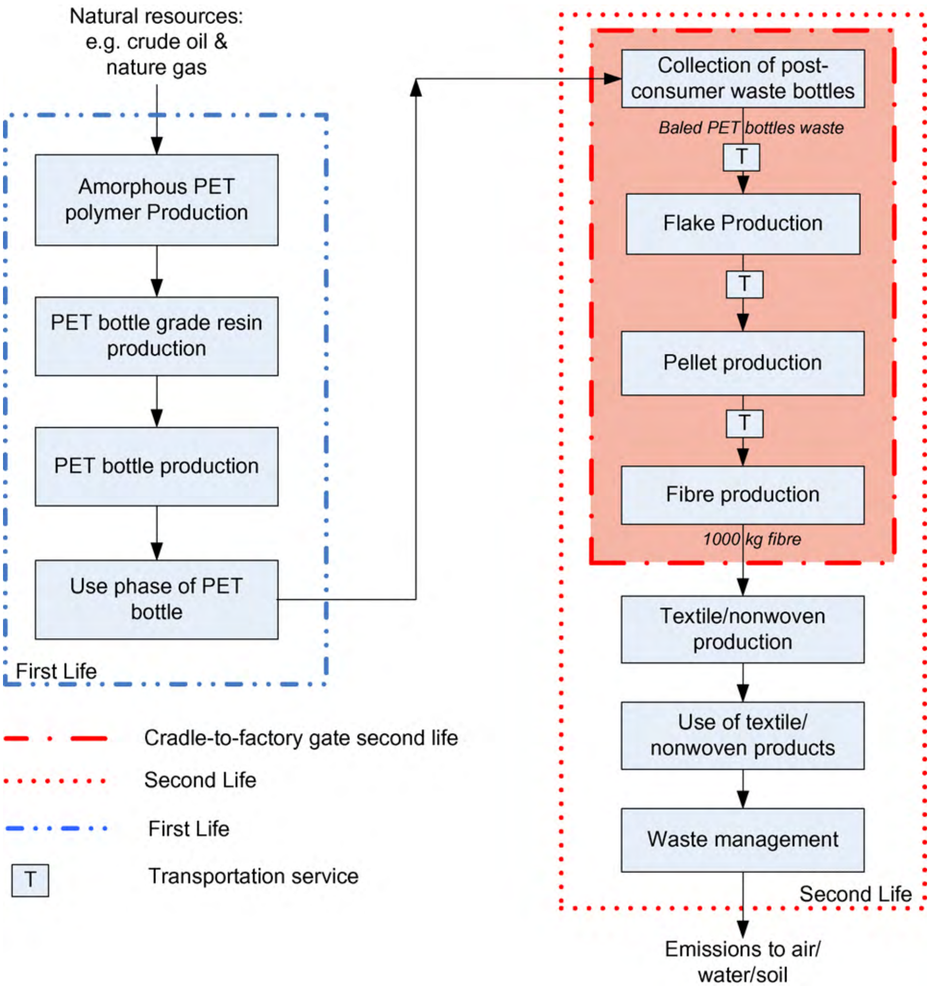

Fig. 3. Cradle-to-factory gate system boundary of recycling PET fibres from waste PET bottles, splitting the first life and the second life based on the "cut-off" approach.

2.1. Goal, functional unit and system boundary

2.1.1. Goal and functional unit

The goal of this LCA is to assess the environmental impacts of recycled PET fibre compared with virgin PET fibre. The functional unit is defined as "*one metric tonne of fibre*". Fibres are important intermediate products for the textile and nonwoven industry. There are two types of PET fibre, staple fibre and POY (partially oriented yarn, which is generally called filament fibre). It should be noted that staple fibre and POY are different products in terms of material properties and consequently, they are used for different end-use applications (see Table 1). The goal of this LCA is not to compare staple fibre with POY, but to understand the environmental impacts of recycled PET fibres compared with the two main types of virgin PET fibres.

The chosen functional unit implies the assumption that recycled PET fibre and virgin PET fibre are functionally equivalent. One may argue that recycled fibre might not reach the same quality as virgin fibre. However, it depends on the recycling technology and the scope of such a comparison. For chemical recycling back-to-monomers, the quality of the recycled polymer is identical with virgin polymer. PET fibre produced by chemical recycling back-to-oligomers has very similar properties as virgin fibres except for dyeability, which is generally inferior to that of virgin fibre (Private communication with Far Eastern New Century Co., Ltd.). For mechanical and semi-mechanical recycling, the quality of recycled fibre strongly depends on the purity of the waste stream. According to one of the recycling companies investigated in this study, recycled staple fibre can reach the same quality as virgin staple fibre if a clean bottle source is used, bottles are properly sorted and the impurities are carefully removed. In addition, because polyester has such a wide range of applications, it is always possible to find suitable applications for recycled fibres, where virgin fibres are also used.

2.1.2. System boundary

The scope of this LCA is *cradle-to-factory gate*. For a virgin product, this includes all steps from the extraction and transportation of raw materials and fuels, followed by all conversion steps until the product – i.e. fibre – is delivered at the factory gate. The production of the end product (e.g. a shirt), the use phase and the post-consumer waste management are excluded. A *cradle-to-grave* analysis, including the waste disposal phase but excluding the use phase, is discussed in Section 5.2.

For open-loop recycling, it is typically a problem to define the "cradle" stage of the recycled product. As default case, we choose the conventional "cut-off" approach to define the system boundary.[2] Fig. 3 illustrates the concept of the "cut-off" approach: the first life and second life are cut into two independent product

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[2] It is considered "conventional" because this method has been applied for many recycled products, such as secondary steel, aluminium and glass (Frischknecht et al., 2007a; ISO, 2006a).

Table 2
Data sources of this study.

Data	Sources	Note
PET bottle-to-fibre recycling	Collected from three recycled PET fibre producers (Wellman, LJG and FENC).	Site-specific, for year 2008.
Grid electricity	Ecoinvent v2.0 (Frischknecht et al., 2007b); OECD and non-OECD country energy balances 2005/2006 (IEA, 2008a; 2008b).	Country-specific. European electricity mix: 65% from the UCTE[a] grid, 13% from the NORDEL[a] grid, 9% from the CENTREL[a] grid, 12% from the UK grid and 1% from the Irish grid. Taiwan electricity fuel mix: 58% coal, 20% nuclear, 12% natural gas, 8% oil and 3% renewables.
Production and combustion of natural gas, LPG, fuel oil and diesel	Ecoinvent v2.0 (Jungbluth, 2007; Faist Emmenegger et al., 2007); EIA statistics(EIA, 2008); US EPA report (USEPA, 2008).	Country-specific energy profiles, except for LPG[a] for which global data is used based on Ecoinvent database.
Production of chemicals	Ecoinvent v2.0 (Althaus et al., 2007a).	Western Europe mid-2000 technology level.
Transportation distances and means for raw materials, chemicals and intermediate products	Collected from three recycled PET fibre producers (Wellman, LJG and FENC).	
Road and water transportation	Ecoinvent v2.0 (Spielmann et al., 2007).	32 t lorry for road transportation. Water transportation refers to transoceanic shipping.
Rail transportation	Ecoinvent v2.0 (Frischknecht et al., 2007b; Spielmann et al., 2007).	Only occurs in France, modified by French grid electricity data in Ecoinvent.
Waste management – sanitary landfilling	Ecoinvent v2.0 (Doka, 2007).	Switzerland mid-2000 technology level.
Waste management – incineration with energy recovery	Ecoinvent v2.0 (Doka, 2007); CEWEP report (Reimann, 2006); EPA reports (TWEPA, 2009b) (TWEPA, 2009a).	Country-specific.
Virgin polymer production	Plastics Europe Eco-Profiles (Boustead, 2005a,b).	Western Europe polymer production.
Energy use for staple and filament fibre spinning process (for melt-spinning virgin PET fibre)	Assumption based on (Brown et al., 1985): 0.64 kWh electricity and 5 MJ heat (from fossil fuel) per kg fibre.	This data was cross-checked by polyester industry experts.

[a] Abbreviation: 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. LPG stands for Liquefied Petroleum Gas.

systems. Based on the cut-off principle, the used bottles from the first life are considered to be waste; waste does not bear any environmental burden from the first life. We follow this rule and define the “cradle” of the second life as the collection and transportation of used PET bottles.

Next to the “cut-off” approach we introduce, apply and discuss two alternative methods, in Chapter 5, namely the “waste valuation” method and the “system expansion” method. The “waste valuation” method has the same scope as the “cut-off” approach, i.e. cradle-to-factory gate. The “system expansion” method covers the entire system from cradle-to-grave.

2.2. General data and assumptions

The geographic boundary covers Western Europe and Taiwan depending on the product system (Table 1). All three companies recycle PET bottles on a large scale. Wellman International Ltd. (in short “Wellman”) recycles about 10% of the collected bottles in Europe every year. Both Long John Group (in short “LJG”) and Far Eastern New Century Co., Ltd. (in short “FENC”) are among the largest recycling companies in Taiwan. Thus, the result of this analysis is expected to be representative for mechanical recycling of PET in Europe and in Taiwan. The virgin PET fibre produced in Western Europe is chosen as the reference system. The LCI data of virgin PET polymer production is based on average technology in Western Europe (PlasticsEurope, 2009b). The transportation of raw materials, intermediate products and fuel is included in the system boundaries. A detailed description of the recycling process can be found in Chapter 3.

For all three recycling companies, the inventory data was provided for the year of 2008. For both virgin polymer production and the inventory data from the Ecoinvent database, the production represents the technologies in the 2000s (Frischknecht et al., 2007a; PlasticsEurope, 2009b).

The data for heat and power generation, chemical production, transportation, waste management and virgin polymer production were obtained from various sources including LCA databases, scientific publications, governmental statistics and personal communication. Table 2 provides a summary of the general data and assumptions. For chemical recycling back to dimethyl terephthalate (DMT), our attempt to obtain data was not successful due to confidentiality issues. The analysis was carried out based on the information available from the public domain. The detailed assumptions and data sources used for this case are described in Section 3.4.2.

Since the chosen allocation methods may strongly influence the outcome of LCA studies we summarize here which methods are applied and which system they refer to:

1. As mentioned in Section 2.1, the “cut-off” approach is applied as the default method for open-loop recycling. An alternative allocation based on economic values (“waste valuation” method)

Table 3
CML normalisation factors, global impact per year, World 2000 (Sleeswijk et al., 2008).

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

and an approach which follows the "system expansion" principle will be discussed in Chapter 5.

2. By-products from the flake production, mainly consisting of coloured bottles and polyethylene (PE) and accounting for about 6–11% of the total mass of the input, are allocated based on economic values. The average selling prices of both by-products and main products (flakes) were provided by the companies for the year 2008, resulting in the economic value of the by-products of typically 5–6% of the total value of the products.
3. The system expansion method is applied for the process waste and for post-consumer solid waste which is assumed to be disposed of in a municipal solid waste incineration (MSWI) facility with energy recovery. Credits were assigned to the recovered electricity and/or heat since the production of the grid electricity and/or heat can be avoided. In Western Europe, the energy recovery rate in primary energy terms is approximately 60% in primary energy term (private communication with Dr. Reimann of CEWEP) (IEA, 2008b; Reimann, 2006). In Taiwan, the energy recovery rate of an average waste-to-energy facility is approximately 43% in primary energy term (TWEPA, 2009a,b).

2.3. Environmental impact assessment

In life-cycle impact assessment (LCIA), the life-cycle inventory data, which represent all emissions released by the product system to the environment and all raw material requirements, are converted into environmental impact categories. The results are generally referred to as LCA mid-point results. In this study, the environmental indicators are: NREU (non-renewable energy use), GWP (global warming potential) (IPCC, 2007) and the indicators from the CML 2 baseline 2001[3] impact assessment method (Guinée et al., 2001; CML, 2008), namely abiotic depletion, acidification, eutrophication, human toxicity, fresh water aquatic ecotoxicity, terrestrial ecotoxicity and photochemical oxidant formation. For chemical recycling via the DMT route, due to the limited data availability, only NREU and GWP were assessed.

In addition, normalisation was performed using CML normalisation factors for World 2000 (see Table 3). This step determines the relative contribution of the product system to the impact categories at a global level. The normalised results do not imply weighting of the impact categories, they merely give an indication to which extent the product system contributes to the total environmental loads of a region for a given year.

3. Recycling PET bottles into fibre

3.1. Collection of used PET bottles

In Western Europe, used PET bottles are collected either under the GreenDot scheme (http://www.gruener-punkt.de), or under other schemes, such as a mandatory deposit system (PlasticsEurope, 2008). In Taiwan, used PET bottles are collected either together with other household waste before they are sorted out manually (http://www.epa.gov.tw), or via the deposit–refund system (TWEPA, 2004). In all cases, used PET bottles are collected on a local scale, e.g. they are from consumers and brought to a waste separation centre where bottles are sorted out, baled and compacted. The energy consumption related to sorting, baling and compacting is very small compared to the energy requirements of the recycling process (Arena et al., 2003; Detzel et al., 2004). In this study we assume that the energy requirements associated with sorting, baling and compacting are negligible.

The major environmental burdens from the collection step are related to the fuel consumption and air emissions from the transportation of baled bottles (i.e. from waste separation centres to flake production facilities). In the case of Wellman's recycling operation in Western Europe, the baled bottles are transported by truck over a distance of about 300–400 km. In the case of the two recycling companies in Taiwan, the baled bottles are transported by truck for about 100–350 km.

3.2. Production of recycled PET flakes

Fig. 4 shows the flowsheet of the production of recycled PET flakes. After baled bottles are opened, loose bottles are sorted by colour and material type. Transparent (uncoloured) bottles have a higher economic value than blue and green ones. The unwanted colour fractions and unwanted materials (e.g. paper and metal) are either sold as by-products, or disposed of in local municipal solid waste (MSW) management facilities or landfilled, depending on the available local infrastructure. MSW can be incinerated with or without energy recovery. Next, the bottles are sorted. The typical plant in Europe uses automated sorting (through colour recognition technology), while the Asian producers use manual sorting. Some producers wash the bottles with hot water to remove the labels before the sorting process. The plastics labels are either sold as by-products (mainly consisting of LDPE and/or PVC), or sent to local MSW management. The bottles are then chopped into flakes, followed by a float separation step to separate PET from other plastics (e.g. HDPE caps) based on density differences. PE obtained from this step is sold as a by-product. The PET flakes are then washed in a cleaning solution, rinsed and dried. In some production lines, a second chopping step (also called "fine crushing") is required to ensure that the PET flakes meet the quality requirements. Finally, the dried PET flakes are ready to be transported to a pellet plant or a fibre plant.

3.3. Mechanical and semi-mechanical recycling

Mechanical recycling is the physical conversion of flakes into fibre or other products by melt-extrusion. Currently, there are two ways to produce recycled fibre from mechanical recycling:

(1) directly extrude flakes into fibre; or more commonly,
(2) first convert flakes into pellets or chips (pelletizing) and then melt-extrude pellets or chips into fibre.

3.3.1. Flake to fibre (mechanical, Wellman International Ltd.)

Wellman produces recycled PET staple fibre directly from melt extrusion of recycled PET flakes (see the left graph of Fig. 5). After

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[3] CML: Centrum voor Milieuwetenschappen Leiden (Institute of Environmental Sciences), Leiden University, the Netherlands.

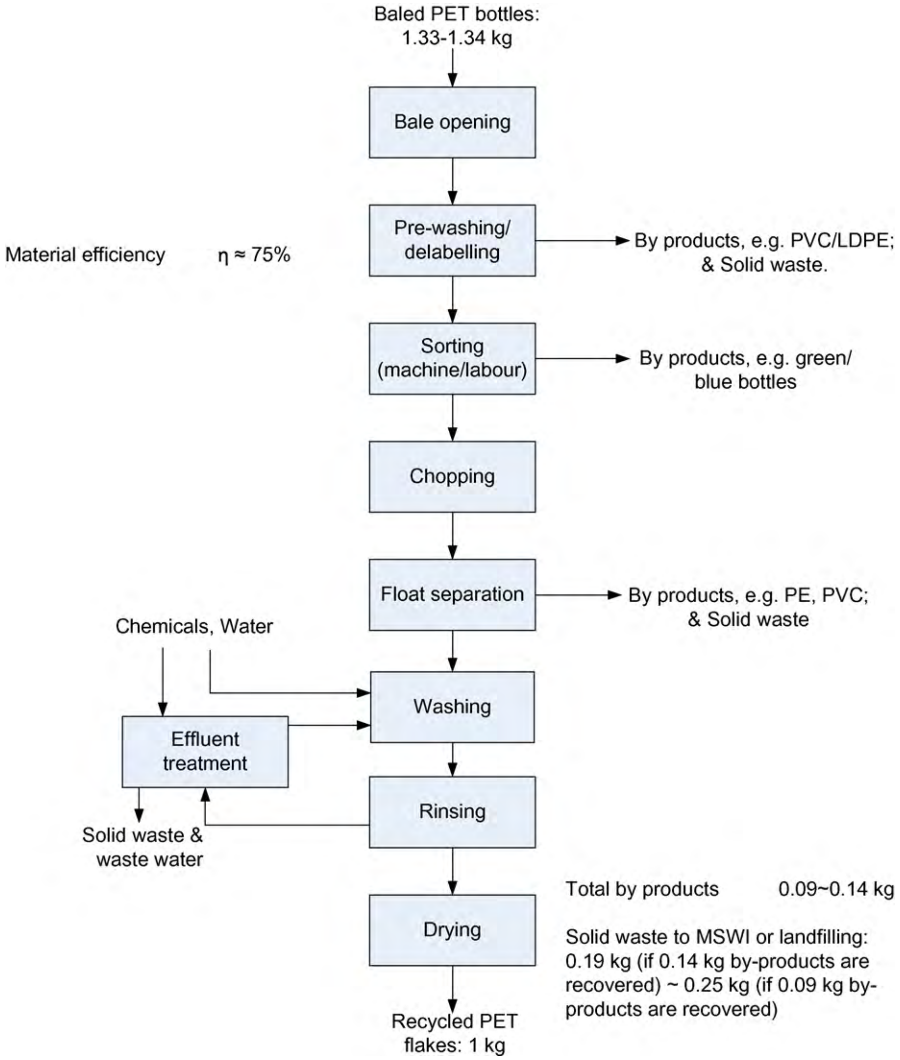


Fig. 4. Producing recycled PET flakes from baled PET bottles.

flakes are off-loaded, they are dried in a column dryer before they are melt-extruded. The extruded polymer is filtered before it passes through the spinneret where filament spinning takes place. After the filaments pass a denier setter, they enter the finishing process where the spun filaments are drawn, dried, cut into staple fibre and baled. Approximately 1% of the flakes end up as solid waste which is disposed of in a landfill.

3.3.2. *Flake to pellet, then to fibre (semi-mechanical, Long John Group)*

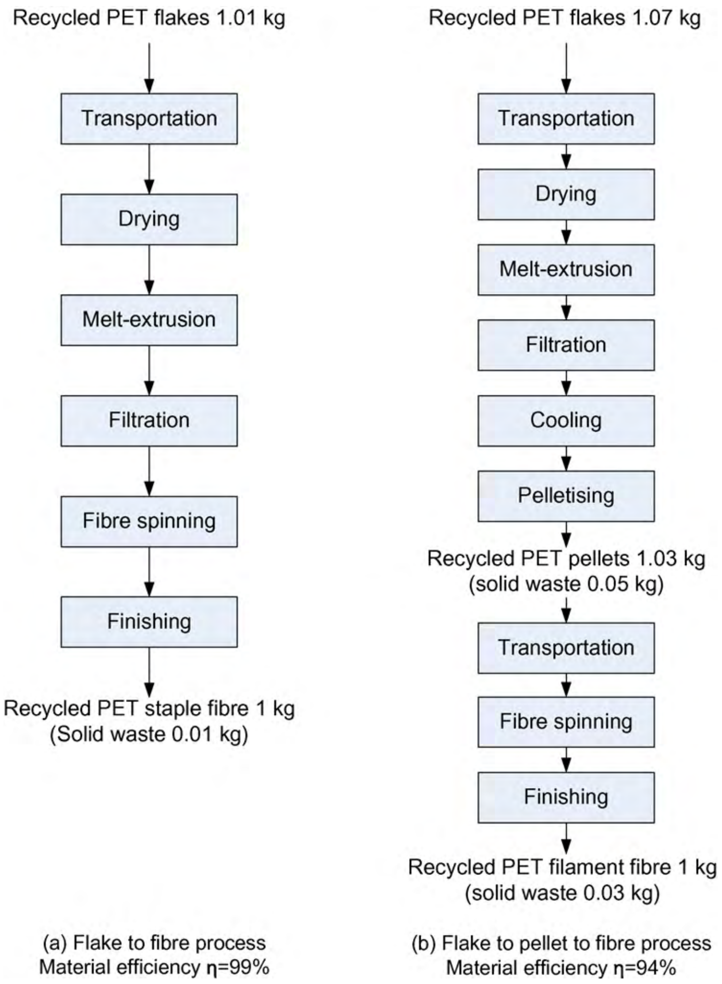
In many other mechanical recycling plants, flakes are first extruded into pellets and then converted into fibre and other products. LJG (Long John Group) produces recycled PET fibre through the flake-pellet-fibre route (see the right graph of Fig. 5). PET flakes are dried prior to the melt-extrusion step. The extruded polymer is further purified through a filtration step. After a cooling process, the polymer is pelletized and dried. The PET pellets are then transported to the fibre spinning plant where they are melt-spun into filament fibre (POY). In LJG's process, a small amount of ethylene glycol (EG) is added to meet the final quality requirements. We therefore classify LJG's process as a semi-mechanical recycling process. The solid waste from the recycling process is disposed of in a MSWI with electricity recovery (recovery rate = 43%, see Section 2.2).

3.4. *Chemical recycling*

In chemical recycling, PET polymer is broken down into monomers or oligomers via various depolymerisation technologies. Chemical recycling is more expensive than mechanical recycling. It usually requires a large scale in order to become economically feasible (Petcore, 2009a). The important advantage of chemical recycling is that the quality of virgin PET can be achieved. Current commercially available chemical recycling technologies include glycolysis, methanolysis and alkaline hydrolysis (Petcore, 2009a). In our study, recycled PET produced via the glycolysis route was analysed based on data received from Far Eastern New Century (FENC). The methanolysis route was analysed based on publicly available data.

3.4.1. *Glycolysis to BHET (chemical recycling, back-to-oligomer, Far Eastern New Century Co., Ltd. (FENC))*

Fig. 6 shows the back-to-oligomer recycling by FENC. The glycolysis of PET yields the oligomer bis-hydroxyl ethylene terephthalate (BHET). The process is usually conducted in a temperature range between 180 and 250 °C with excess EG and in the presence of catalysts (Paszun and Spychaj, 1997). After the glycolysis process, the oligomer passes through a fine filtration step before it is repolymerised into PET. The recycled polymer is then spun



(a) Flake to fibre process
Material efficiency η=99%

(b) Flake to pellet to fibre process
Material efficiency η=94%

Fig. 5. Producing recycled PET fibre from PET flakes via mechanical (left) and semi-mechanical (right) recycling.

into fibre. The process solid waste is disposed of in a MSWI facility with electricity recovery (recovery rate = 43%, see Section 2.2).

3.4.2. *Methanolysis to DMT (chemical recycling, back to monomer)*

In methanolysis, PET is depolymerised with methanol to DMT and EG in the presence of catalysts under a pressure of 2–4 MPa and a temperature of 180–280 °C (Paszun and Spychaj, 1997). The reaction mix is cooled and DMT is recovered from the mix via precipitation, centrifugation and crystallization (Paszun and Spychaj, 1997). Fig. 7 shows the flowsheet for chemical recycling of PET via the methanolysis route. The recycled polymer is then converted into fibre via spinning and finishing processes.

A recent patent by Teijin (Nakao et al., 2003) illustrates that PET is depolymerised with EG and sodium carbonate to yield BHET; the BHET is then further broken down into DMT with methanol (Delattre et al., 1976). This process is considered more economically attractive than the direct methanolysis of PET into DMT (Lorenzetti et al., 2006).

The methanolysis route is commercially operated but no process data could be obtained. In this study, we use publicly available data to estimate the NREU and GWP (the available data did not allow to also include the environmental impact categories according to the CML method).

Our estimate is primarily based on the LCA published by Patagonia (2005) for recycled DMT. According to Patagonia's LCA results, the cradle-to-factory gate non-renewable energy requirements (NREU) and GHG emissions of 1 t of recycled DMT are 11.96 GJ and 0.98 t CO_2 equiv., respectively. The “cradle” of Patagonia's LCA follows the “cut-off” rule since the cradle was defined as collection of PET waste.

Based on the stoichiometric equation, depolymerising 1000 kg of PET requires 333 kg methanol and yields 1010 kg of DMT (or 76% by weight) and 323 kg EG (or 24% by weight). Patagonia's LCA results were allocated based on the weight of the products. Using this information we estimate that the NREU and GWP values for the total process yielding 1 t of DMT and 0.32 t of EG are 15.78 GJ/t DMT and 1.29 t CO_2 equiv./t DMT, respectively (here, the energy use and the emissions related to EG production have been assigned to DMT).

The material efficiencies and the monomer recovery rates are not published by Patagonia. We assume three cases, namely, a low case, a high case and an average case. In the low case, the PET loss is assumed zero, which is the theoretical optimum (stoichiometric conversion). In the high case, we assume 10% PET loss based on Marathe et al. (1980) who reported that the yield of methanolysis does not exceed 90%. The loss of 10% refers to rather clean and sorted PET waste, while the losses may be substantially larger for other products, e.g. finished textiles (due to the use of textile auxiliaries, dyes, etc.). As average case, we assume that the loss is somewhere in-between, i.e. 5%. Furthermore, the net methanol input (the “make-up” in Fig. 7) is assumed to be zero for the low case, 10% for the high case and 5% for the average.

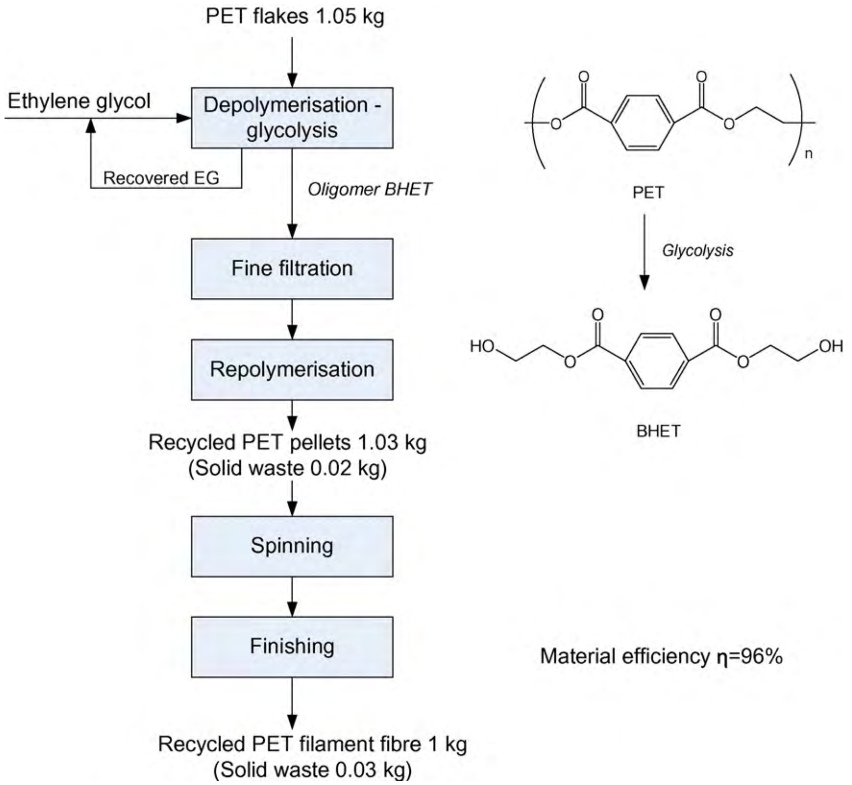


Fig. 6. Chemical recycling PET via the glycolysis process.

Since Patagonia's study only reports the production of DMT, it is not known whether and how much EG is recovered and reused in the repolymerisation step. In the low case, the recovery and reuse of EG is assumed to be 100% (stoichiometric conversion and complete recovery). In the high case, we assume that EG is not recovered at all and that the EG required for repolymerisation, which is estimated at 323 kg EG/t PET based on the stoichiometric equation, is purchased. In industrial practice the unrecovered EG may be incinerated together with other compounds, with or without energy recovery. In the low case, we assume that there is no energy recovery. In the average case, 50% of EG is assumed to be recovered and the rest 50% is purchased externally. Finally, in the high case, no energy credits are assigned to the lost amounts of EG. The environmental impact of the purchased EG is obtained from the Ecoinvent database for "Ethylene glycol, at plant" (Althaus et al., 2007a): the cradle-to-factory gate NREU and GWP100a of EG are 52 GJ/t and 0.82 t CO_2 equiv./t.

The repolymerisation step is technically identical with the polymerisation process leading to virgin PET. According to an earlier publication of AMPE (Boustead, 2002), the NREU for synthesizing 1 t of PET via the PTA/EG route is 10.16 GJ and the GWP100a is 0.61 t CO_2 equiv. We assume that the repolymerisa-

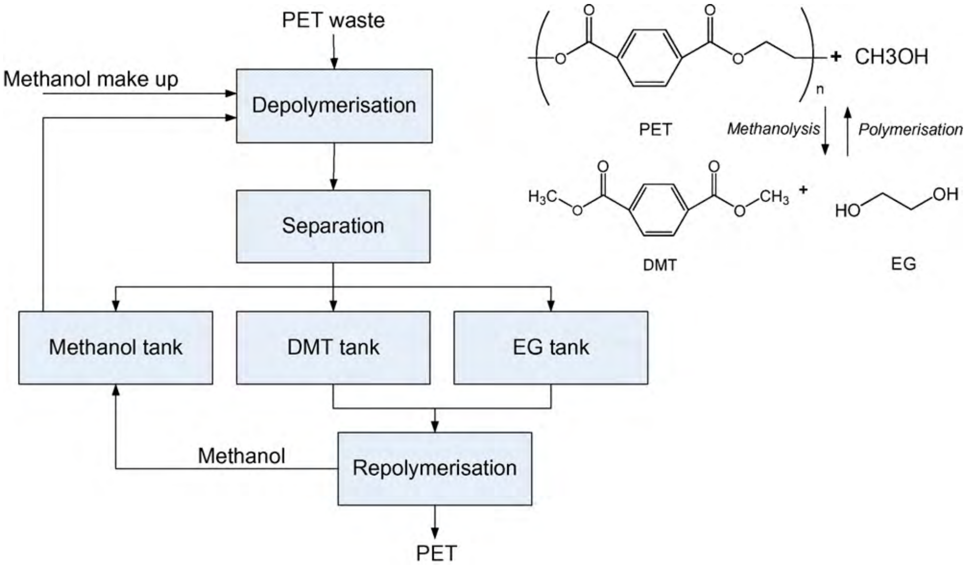


Fig. 7. Chemical recycling PET via the methanolysis process (Paszun and Spychaj, 1997).

Table 4
Data and assumptions for chemical recycling through methanolysis.

	Low case	High case	Average
NREU of depolymerisation (GJ/t DMT)[a]		15.78	
GWP100a of depolymerisation (t CO_2 equiv./t DMT)[a]		1.29	
Overall PET loss (by weight)[b]	0	10%	5%
Overall MeOH make-up (by weight)[c]	0	10%	5%
EG recovery (by weight)[c]	0	100%	50%
External EG required (by weight)[c]	100%	0%	50%
Repolymerisation[d]			
Fuel (GJ/t)		1.63	
Electricity (GJ/t)		0.70	
Steam (t/t)		0.94	

[a] Data source: Patagonia (2005). The allocation is based on mass.
[b] Assumed based on Marathe et al. (1980).
[c] Own estimate or assumption.
[d] Data source: Boustead (2002).

tion of recycled PET via the DMT/EG route has the same energy requirements.

Next, the recycled amorphous PET polymer is sent to the fibre production plant. It is assumed that the energy requirement of fibre spinning is the same as for virgin fibre production (see Table 2). Typically, monomer recycling is combined with filament production because the value of the high purity of the recycled compounds is fully exploited; this will be taken into account in the interpretation of this study. Table 4 shows the summary of the data and assumptions for chemical recycling via the methanolysis route.

4. LCA results based on the “cut-off” approach

Table 5 shows the cradle-to-factory gate LCA results for 1 t of recycled PET fibre based on the “cut-off” approach. Recycled fibres offer 45–85% of NREU savings compared to the virgin fibre. Note that due to the cut-off approach, the embedded energy (calorific value) of the recycled PET is set to zero, whereas for virgin PET fibre, the embedded energy accounts for about 40% of its total NREU.

As Table 5 shows, recycled PET fibres offer significant GWP savings compared to virgin PET fibres. The GWP of recycled PET fibres is 76% (mechanical recycling), 54% (semi-mechanical recycling), 36% (back-to-oligomer recycling) and 24% (back-to-monomer recycling) lower than that of virgin PET.

Compared to virgin fibres, mechanically and semi-mechanically recycled fibres offer lower impacts for all seven CML environmental categories except for freshwater aquatic ecotoxicity. Back-to-oligomer recycling offers a lower impact in six out of nine categories. The exceptions are eutrophication, freshwater ecotoxicity and terrestrial ecotoxicity. For all three recycling companies investigated, the impact of freshwater aquatic ecotoxicity originates from the incineration of solid waste from flake production. More than 90% of the freshwater ecotoxicity impact can be traced back to the water emission of a small amount of vanadium. Vanadium oxides are commonly used in municipal waste incineration plants as catalysts to treat NO_X emissions (Doka, 2007). About 50% of the eutrophication impact of FENC’s fibre originates from the production of chemicals (e.g. EG) used for the chemical recycling process. Atmospheric emissions of vanadium (from fuel oil combustion) are responsible for more than 60% of its terrestrial ecotoxicity impact.

Mechanical recycling (Wellman) causes the lowest impact in eight out of nine environmental categories, compared to the other three product systems shown in Table 5. Process energy use is responsible for the major part of the environmental impacts, represented by NREU, GWP, abiotic depletion, acidification, terrestrial ecotoxicity and photochemical oxidant formation. The process waste management in flake production, including both emissions from waste water treatment (e.g. COD) and from solid waste management (e.g. MSWI), is the most important factor for eutrophication, human toxicity and freshwater aquatic ecotoxicity. The production of chemicals and the transportation of raw materials, intermediate products and solid waste treatment contributes very little (<10%) to the overall environmental impact.

The process energy use of the semi-mechanical recycling (LJG) is the most important factor for eight out of nine environmental indicators. The exception is freshwater aquatic ecotoxicity. The process energy use for fibre production from flakes is the most important contributor (40–70%) to NREU, GWP, abiotic depletion and photochemical oxidant formation. The process energy use of flake production is the most important contributor (40–80%) to acidification, eutrophication, human toxicity and terrestrial ecotoxicity. Fresh aquatic ecotoxicity is mainly caused by the solid waste which is sent to MSWI. Compared to flake production and fibre production, pellet production causes

Table 5
LCA result for 1 t of recycled PET fibre, based on the “cut-off” approach, cradle-to-factory gate for second life.

Recycling route	Mechanical	Semi-mechanical	Chemical, BHET	Chemical, DMT	V-PET fibre (W. Europe)
Company	Wellman	LJG	FENC	n/a	n/a
Fibre type	Staple	POY	POY	POY	Staple or POY
Non-renewable energy use (GJ equiv.)	13	23	39	51 (40–62)[a]	95
Global warming potential 100a (t CO_2 equiv.)	0.96	1.88	2.59	3.08 (2.71–3.44)[a]	4.06
Abiotic depletion (kg Sb equiv.)	6	11	18		45
Acidification (kg SO_2 equiv.)	3	9	14		21
Eutrophication (kg PO_4^{3-} equiv.)	0.8	0.7	2.3		1.2
Human toxicity (kg 1,4-DB equiv.)	362	415	745	n/a	4393
Fresh water aquatic ecotoxicity (kg 1,4-DB equiv.)	296	250	303		58
Terrestrial ecotoxicity (kg 1,4-DB equiv.)	7	7	17		12
Photochemical oxidant formation (kg C_2H_4 equuiv.)	0.2	0.3	0.6		1.0

[a] For chemical recycling via the DMT route only NREU and GWP were assessed. The range in bracket represents the low case and the high case (see Table 4).

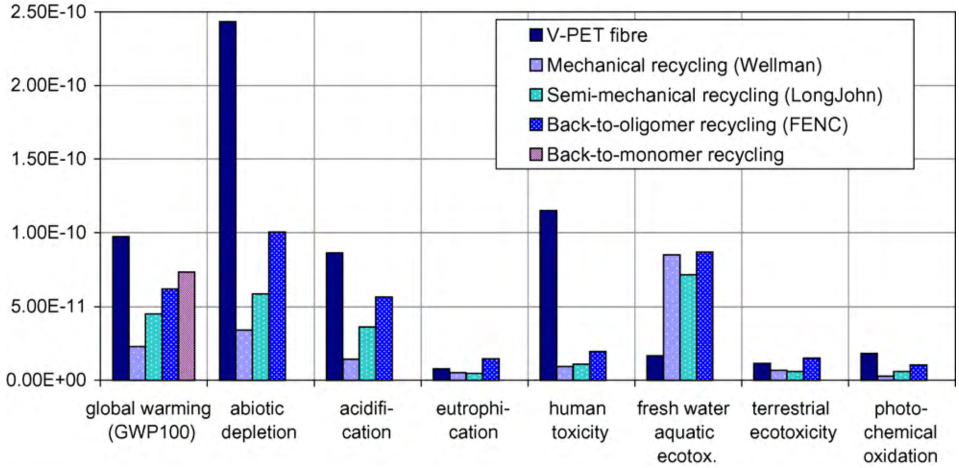


Fig. 8. Normalised results for 1 t of PET fibre, “cut-off” approach, cradle-to-factory gate for second life, normalised to World 2000.

smaller environmental impacts. Transportation and the production of chemicals (e.g. small amount of EG) have minor impact (<5%).

For back-to-oligomer recycling by FENC, the glycolysis process contributes most to the overall environmental profile. The chemicals and energy use (electricity and fuels) are responsible for the major part of NREU, GWP, abiotic depletion, acidification, eutrophication, human toxicity, terrestrial ecotoxicity and photochemical oxidant formation. Like Wellman and LJG, FENC’s freshwater aquatic ecotoxicity originates from solid waste management.

For back-to-monomer recycling, only NREU and GWP were analysed because of the lack of information (see Section 2.1.1). The depolymerisation process contributes most to the overall impact, with shares of 30–40% of the total NREU and 45–50% of the total GWP.

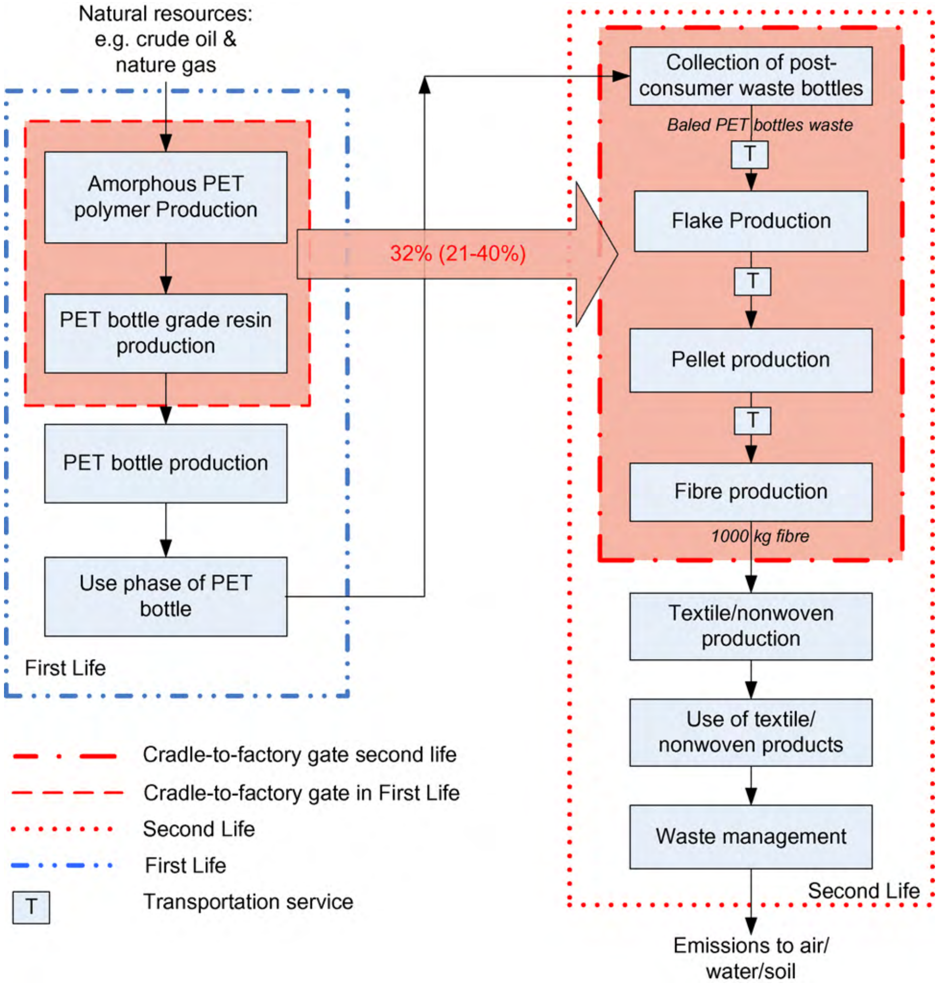


Fig. 9. System boundary based on the “waste valuation” method.

Table 6
LCA result for 1 t of recycled PET fibre, based on the "waste valuation" approach, cradle-to-factory gate for second life.

	Mechanical	Semi-mechanical	Chemical, BHET	V-PET fibre (W.Europe)
Company	Wellman	LJG	FENC	
Type of fibre	Staple	POY	POY	Staple/POY
NREU (GJ equiv.)	40	49	66	95
GWP100a (t CO_2 equiv.)	2.03	2.95	3.66	4.06
Abiotic depletion (kg Sb equiv.)	19	23	31	45
Acidification (kg SO_2 equiv.)	8	14	19	21
Eutrophication (kg PO_4^{3-} equiv.)	1.1	1.0	2.6	1.2
Human toxicity (kg 1,4-DB equiv.)	1640	1700	2030	4390
Fresh water aquatic ecotoxicity (kg 1,4-DB equiv.)	300	250	305	58
Terrestrial ecotoxicity (kg 1,4-DB equiv.)	8	7	17	12
Photochemical oxidant formation (kg C_2H_4 equiv.)	0.4	0.6	0.8	1.0

Fig. 8 shows the LCA results normalised to World 2000. Compared to virgin production, recycled PET fibres cause substantially lower environmental impacts. Particularly, the impact reduction of abiotic depletion, acidification and human toxicity is substantial. Furthermore, for all PET fibres studied (both recycled and virgin), eutrophication, terrestrial ecotoxicity and photochemical oxidant formation are negligible in a global context. Recycled fibres cause a relatively high environmental impact on freshwater aquatic ecotoxicity compared to virgin PET because following the cut-off approach, all impacts from post-consumer waste management including fresh water ecotoxicity are exclusively assigned to the recycled product. Thus, the allocation method and the chosen system boundary have strong influence on the results of this open-loop recycling case.

5. Alternative approaches for open-loop recycling

5.1. "Waste valuation" method

Until now, we have only discussed the LCA results based on the "cut-off" approach. The environmental burden of the first life was not considered in the system boundary (see Fig. 3). However, one can argue that this method is oversimplified, because in reality bottle waste is traded and it does have a commercial value. In other words, waste is a valuable resource. Thus the environmental impact of the production of virgin polymer should be shared between the first life and the second life (see the illustration in Fig. 9).

ISO 14044 (2006) suggests the following order of allocation procedures for reuse and recycling (see Clause 4.3.4.3.4): "physical properties (e.g. mass); economic value (e.g. market value of the scrap material or recycled material in relation to market value of primary material); or the number of subsequent uses of the recycled material."

In this study, allocation based on mass is not a feasible choice, because bottles and fibres are different products. We therefore apply the second approach, i.e. economic allocation. In this article we name this alternative method "waste valuation" method. This represents a variant of the "cut-off" approach which makes use of economic values (prices):

$$E_{\mathrm{wv}} = E_{\text{cut-off}} + AF \times E_{\mathrm{vPET\ resin}}$$

where E_{wv} stands for the environmental impact of recycled PET fibre; $E_{\text{cut-off}}$ is the environmental impact of recycled PET fibre based on the "cut-off" approach; $E_{\mathrm{vPET\,resin}}$ is the environmental impact of virgin PET bottle grade resin; and AF is the allocation factor. $AF \times E_{\mathrm{vPET\,resin}}$ is the environmental burden which is shifted from the first to the second life.

The determination of the allocation factor is the key step for the "waste valuation" method. We define the allocation factor (AF) as the ratio of the market value of baled bottle waste to the market value of virgin PET bottle grade resin:

$$AF = \frac{\text{Price of baled bottle waste}}{\text{Price of virgin PET bottle grade resin}}$$

The price of baled bottle waste was collected from three companies as average value for the year 2008. The price of virgin PET bottle grade resin was obtained from the monthly prices of North America plastics resins published by Plastics Online Technology (PTO, 2009). Due to the regional differences and the strong fluctuation of crude oil prices in 2008, the AFs differ by companies, although not substantially. In general, the AF is in the range of 21–40%; the average AF is approximately 32%. For the "waste valuation" method, we therefore assumed that 32% (21–40%) of the environmental burden of virgin PET bottle grade resin is shifted to the recycled PET fibres. The LCA results are shown in Table 6.

Compared to virgin fibre, mechanically and semi-mechanically recycled PET fibres still offer environmental benefits in all categories except for freshwater aquatic ecotoxicity. Back-to-oligomer recycling offers an impact reduction in six out of nine categories. By analogy with the "cut-off" approach, recycled fibre produced from chemical recycling back-to-BHET has a relatively high impact on eutrophication, freshwater aquatic ecotoxicity and terrestrial ecotoxicity compared to virgin fibre. Due to lack of data, it is not possible to analyse

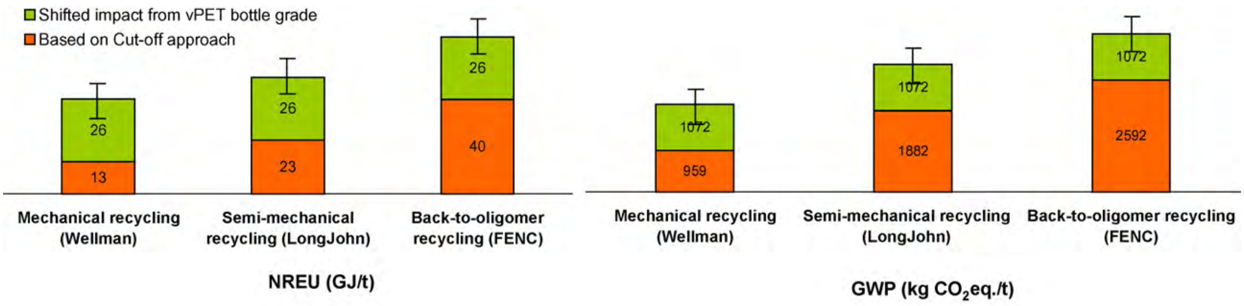


Fig. 10. Breakdown of NREU and GWP for 1 t recycled staple fibre, based on the "waste valuation" method, cradle-to-factory gate for second life.

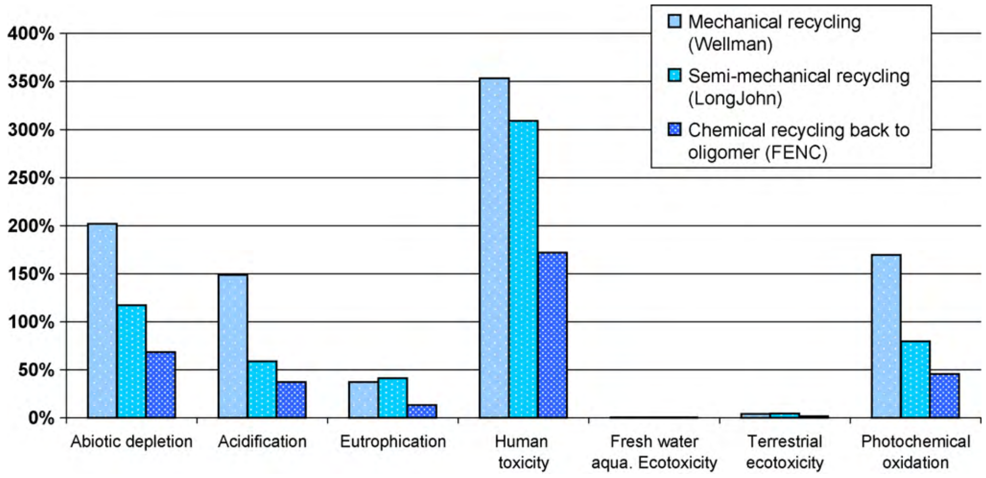


Fig. 11. Change of environmental impact from the "cut-off" method to the "waste valuation" method, cradle-to-factory gate for second life, for 1 t of recycled staple fibre, CML 2001 baseline method.

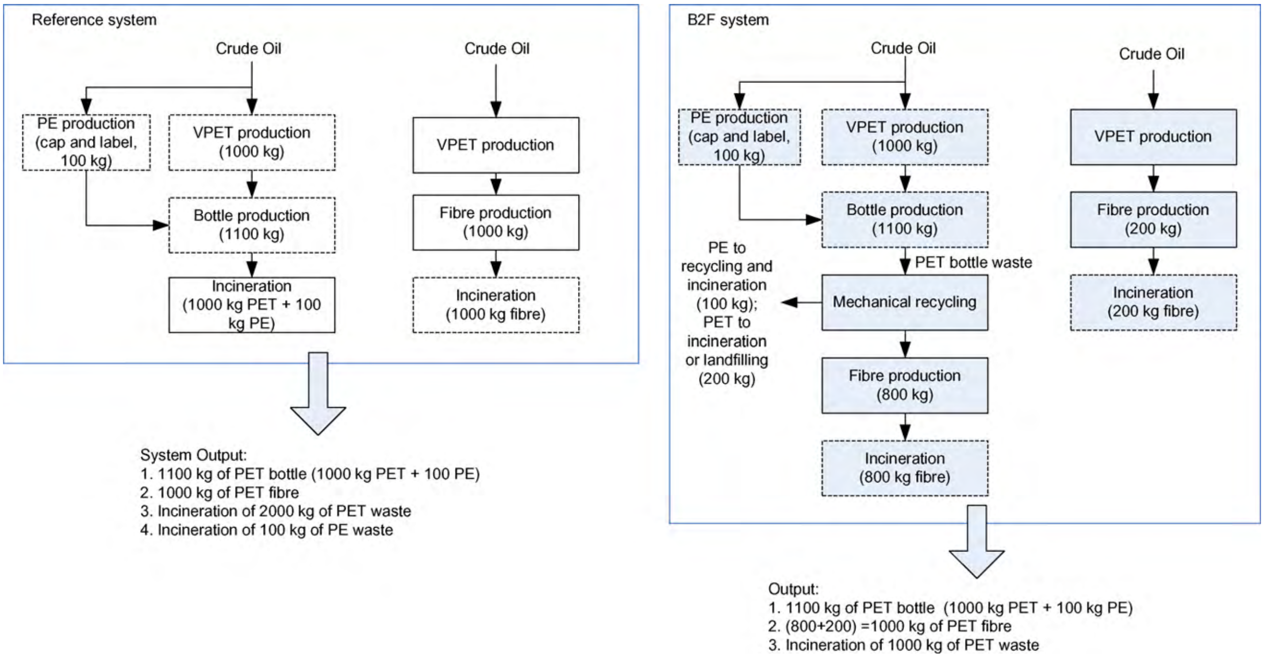


Fig. 12. "System expansion" method applied for open-loop recycling, functional unit 1 t of PET bottle and 1 t of PET fibre, cradle-to-grave without the use phase (the mass balances shown in the graph are indicative).

the back-to-monomer recycling based on the "waste valuation" method.

Fig. 10 shows that the shifted environmental impact has a strong influence on NREU and GWP. The shifted NREU accounts for 40–65% of the total NREU and the shifted GWP is 30–50% of the total GWP. Fig. 11 shows the increase of the environmental impact (which is equal to the shifted burden from the virgin bottle grade) for the CML indicators. The shifted burden has the strongest influence on human toxicity which increases by 170–350%, because the production of PET has relatively high impact on human toxicity.[4] For abiotic depletion, acidification, eutrophication, photochemical oxidant formation, together with NREU and GWP, the increase ranges from 30% to 200%. For freshwater aquatic ecotoxicity and terrestrial ecotoxicity, the impact from the shifted environmental burden is negligible (≤5%).

5.2. *"System expansion" method (cradle-to-grave)*

Open-loop recycling faces two methodological problems. The first problem is how to allocate the environmental impact of the production of the original product throughout several life cycles. In this study, we have so far discussed two methods: the "cut-off" method and the "waste valuation" method. However, both methods are not entirely satisfactory. The "cut-off" method cannot be justified if waste is considered to be a valuable resource. The result from the "waste valuation" method depends on market prices, which are determined by supply and demand, the crude oil price and other economic aspects; they can therefore fluctuate considerably over time.

The second methodological problem is how to allocate the environmental burden of the ultimate "grave" of the product

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[4] The relatively high human toxicity of virgin PET fibre can be also seen in Table 6 or Fig. 8. More than 90% of the impact is caused by the air emission of PAH (polycyclic aromatic hydrocarbon) in virgin PET resin production (Boustead, 2005a).

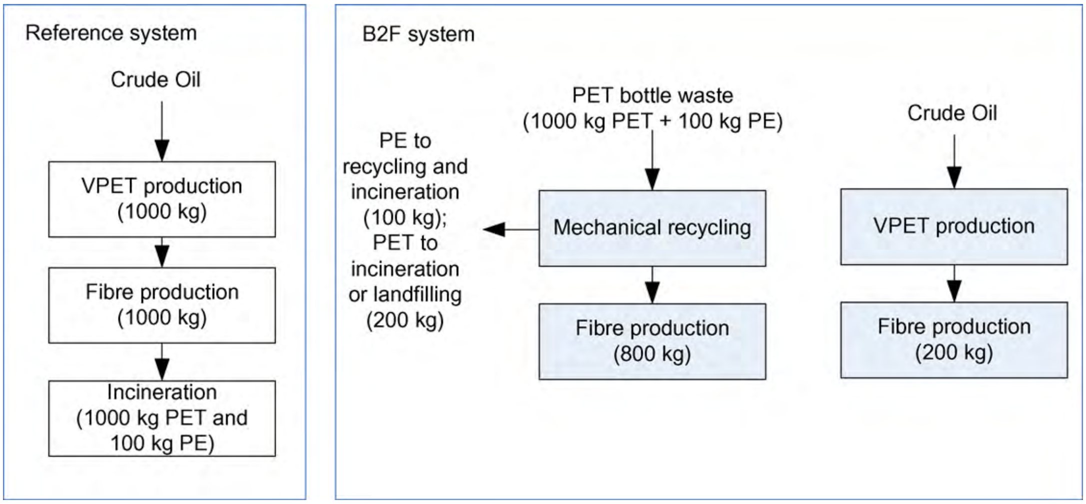

Fig. 13. "System expansion" method applied for the open-loop recycling, pruned from Fig. 12, functional unit 1 t of PET fibre, cradle-to-grave without the use phase (the mass balances shown in the graph are indicative).

Table 7
LCA result for 1 t of recycled PET fibre, based on the "system expansion" approach, cradle-to-grave, excluding the use phase.

Recycling Company Fibre type	Mechanical Wellman Staple	Semi-mechanical LJG POY	Chemical, BHET route FENC POY	V-PET fibre (W.Europe) Staple/POY
NREU (GJ equiv.)	23	33	48	79
GWP100a (t CO_2 equiv.)	1.33	2.21	2.82	5.54
Abiotic depletion (kg Sb equiv.)	11	16	22	38
Acidification (kg SO_2 equiv.)	5	10	15	19
Eutrophication (kg PO_4^{3-} equiv.)	0.9	0.8	2.1	1.5
Human toxicity (kg 1,4-DB equiv.)	845	1020	1310	6150
Fresh water aquatic ecotoxicity (kg 1,4-DB equiv.)	270	220	265	2,540
Terrestrial ecotoxicity (kg 1,4-DB equiv.)	8	8	16	10
Photochemical oxidant formation (kg C_2H_4 equiv.)	0.3	0.4	0.6	0.9

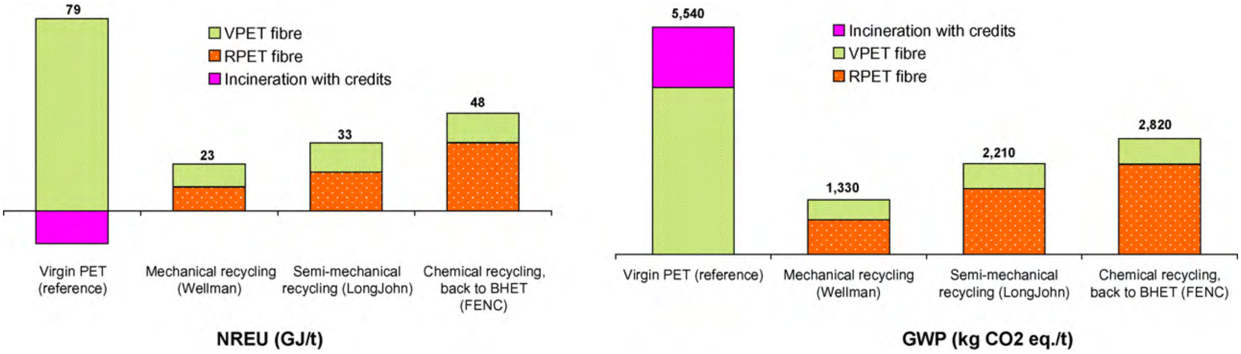

Fig. 14. Breakdown of NREU and GWP100a for 1 t of PET fibre for the three product systems, cradle-to-grave without use phase (the life cycles are shown in Fig. 13; B2F = bottle-to-fibre).

throughout several life cycles. So far this has not been included because the primary system boundary of this study is "cradle-to-factory gate". If we extend the product system to the "grave" stage, according to the "cut-off" principle, the environmental impact of end-of-life waste management (e.g. incineration) would be entirely allocated to the last recycled product, the recycled PET fibre. The first life (the virgin PET bottle) does not bear any environmental burden originating from the ultimate waste management.

In short, these two problems are both caused by allocation. The allocation problem for open-loop recycling has not been resolved in current ISO standards. In this study, we propose a method which follows the principle of system expansion.

In a complete cradle-to-grave bottle-to-fibre recycling system, two products are delivered in two lives, i.e. bottles and fibres. If a reference system is to be established for comparison, this system must deliver identical products: bottles and fibres. This concept is illustrated in Fig. 12. In the reference system, 1000 kg of virgin PET bottle grade, 100 kg PE (for caps and labels)[5] and 1000 kg of virgin fibre are produced and incinerated, i.e. the life cycles are complete.[6] In the bottle-to-fibre (B2F) product system, it is assumed that 1000 kg of virgin PET bottle grade is produced and

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[5] According to Detzel et al. (2004) depends on the size of bottles, the weight of caps and labels is approximately 10% (ranging from 7% to 13%) of the weight of PET in a bottle.

[6] The use phase is excluded, because it is the same for both product systems.

Table 8
Comparison of flake production with other studies.

Output: 1 t of recycled PET flake	This study	Arena et al. (2003)	Detzel et al. (2004)
Yield of PET flakes (or material efficiency, wt%)	75%	76%	80%
By-products (wt%)	7–10%	7%	5%
NREU (GJ/t flake)	2.5–6.0	2.7	n/a
GWP100a (kg CO_2 equiv./t flake)	310–720	635	n/a

recycled into approximately 800 kg of PET fibre.[7] The 100 kg of PE is separated and either sold as a by-product or disposed of in a MSWI plant with energy recovery. The 800 kg of recycled PET fibre is used and incinerated; and the life cycles are complete. In such a product system, 1000 kg of bottle grade and 800 kg of fibre are the output function of the product system. In order to make the functional unit comparable with the reference system in terms of mass, an additional 200 kg of fibre is required, which is assumed to be produced from crude oil (see Fig. 12).

To summarize, both the reference system and the B2F system have the same output in terms of mass, i.e. 1000 kg of PET bottle grade and 1000 kg of PET fibre. The difference is that in the reference system, 2000 kg of PET waste and 100 kg PE waste are incinerated, whereas in the B2F system, only 1000 kg of PET waste is incinerated (PE leaves the system either as a by-product or it is incinerated). In this way, it is possible to study the environmental impact of recycling versus single-use without cutting off life cycles. We name this method the "system expansion" method. An important pre-assumption of this method is that the quality of virgin PET fibre is assumed to be identical to the quality of recycled fibre. In other words, the 1000 kg (800 kg recycled + 200 kg virgin) of fibre from the B2F system is assumed to be fully comparable to the 1000 kg of virgin fibre from the reference system (see also Section 2.1 and Table 1).

Taking a close look at the two product systems in Fig. 12, we find that several unit processes are the same in the reference system and in the B2F system, for example, the production of virgin polymers (PET, PE), bottle production and the incineration of PET waste (see dashed boxes in Fig. 12). Since our primary focus is on the differences between the two product systems, removing the identical unit processes does not change the result of the comparison. Therefore, the dashed boxes in Fig. 12 can be trimmed out. The pruned product systems are shown in Fig. 13. In these two product systems, the production of virgin bottle is not presented. In other words, only fibres are studied. We could, in theory, rename the functional unit back to "one tonne of fibre" with the system boundary of cradle-to-grave (excluding the use phase).

The LCA results based on the "system expansion" method are shown in Table 7. Recycled fibres produced by mechanical and semi-mechanical recycling (Wellman and LJG) offer low environmental impacts for all nine indicators, compared to the single-use virgin fibre. Back-to-oligomer recycling (FENC) has a low environmental impact in all categories except for eutrophication and terrestrial ecotoxicity.

From cradle-to-grave, the NREU of recycled fibre is 70% (Wellman), 60% (LJG) and 40% (FENC) lower than that of virgin fibre; the GWP of recycled fibre is 76% (Wellman), 60% (LJG) and 50% (FENC) lower compared to virgin fibre. Fig. 14 shows the breakdown of NREU and GWP based on different life-cycle phases. In the cradle-to-grave B2F recycling systems, post-consumer waste incineration is avoided. The major part of the impact on energy and GHG emissions is related to the recycling processes which are referred to as "r-PET fibre" in Fig. 14. For each recycling system, the impact from the virgin PET fibre is different (see "V-PET fibre" in the figure for the three recycling companies), depending on the recycling efficiency, it ranges from 80% to 90%.

6. Discussion

6.1. Comparison with other studies

As mentioned in the introduction, most PET recycling studies have focused on waste management rather than the production of recycled products (Detzel et al., 2004; Song and Hyun, 1999; Song et al., 1999). The results of these LCA studies are not directly comparable with our results because the goal and the functional units are different. Moreover, a transparent dataset on PET recycling is hardly available in public domain. A few studies reported inventory data of flake production. The comparison of flake production shows that the inventory data and the results reported by this study fit well with those reported by Arena et al. (2003) and Detzel et al. (2004) (see Table 8).

6.2. Use of LCA results from the three methods

In this study, three methods were applied for the B2F open-loop recycling case. The three methods take different perspectives. The "cut-off" approach follows the natural business-to-business boundary and is the most commonly used LCA method for recycled products. It is easy to apply and no data is required from outside of the investigated product system. The disadvantage is that the method oversimplifies the environmental impact of the "cradle" and the "grave" stages.

The "waste valuation" method uses economic values to elaborate the "cradle stage" by shifting part of the environmental impact from the virgin polymer to the second life cycle. It is also a method which is easy to apply. However, the allocation factor strongly depends on the market prices that are determined by demand and supply and the macroeconomic development. It is possible to further elaborate the "waste valuation" method by introducing more comprehensive economic indicators (e.g. long-term price elasticity) (Ekvall, 2000; Werner and Richter, 2000). These methods are usually more complicated and require data from economic models.

The third approach we applied, the "system expansion" method, takes the real "cradle" and "grave", merges two life cycles into one product system and compares systems with and without recycling. The most important advantage of this method is that it avoids allocation. This method applies life-cycle thinking to the whole system. It is our preferred method for open-loop recycling. The disadvantage of this method is that it is not easy to apply; it results in large systems and the data requirements from extended product systems can be demanding (Ekvall and Tillman, 1997).

The use of these LCA results depends on the perspective of a decision maker. From a manufacturer's point of view, it is important to reduce the environmental impact of the production process and the suppliers. The system boundary of cradle-to-factory gate (the "cut-off" and "waste valuation" methods) fits well to the business

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[7] This recycling efficiency (80%) is indicative; it does not coincide exactly with the values received from the companies. In general, the recycling efficiency of the *PET material flow* is about 80–90%, according to the inventory data provided by the companies.

boundary. Both methods are easy to apply and to communicate. From a life-cycle-thinking perspective, the benefit of recycling is the improvement of the material utilization efficiency by avoiding further resource extraction and waste management. The overall impact can only be assessed when the entire system and the effect of the system are considered. Therefore, the "system expansion" method represents a life-cycle-thinking perspective.

6.3. Comparison with other commodity fibres and renewable alternatives

So far, we only compared PET fibres. It is also interesting to understand the position of recycled PET fibre among other commodity fibres, such as cotton, viscose and PP, as well as novel bio-based fibres, such as Tencel and PLA. Figs. 15 and 16 show the comparisons of NREU and GWP among these fibres. The LCA results of Lenzing Viscose and Tencel fibres were obtained from Shen and Patel (2010). The cotton data is a weighted average of Chinese and US cotton (Althaus et al., 2007b; Dinkel and Stettler, 2008 (unpublished work)). The eco-profiles of PP resin and PLA resin are obtained from Plastics Europe (Boustead, 2005c) and NatureWorks LLC (NatureWorks LLC, 2009; NREL, 2009), respectively. The energy consumption of melt-spinning PP and PLA is assumed to be the same as that of PET (see Table 2).

Fig. 15(a) shows the results for the system boundary cradle-to-factory gate. For recycled fibres, the default method is the "cut-off" method (for the second life), with the error bar showing the results based on the "waste valuation" method. For recycled fibre produced from the DMT route, only the "cut-off" method was applied; the error bar shows the results based on the high and low cases assumptions (see Section 3.3). Fig. 15(b) shows the cradle-to-grave comparison without the use phase. For recycled PET fibres, the "system expansion" method is applied (except for chemical recycled fibre produced via the DMT route). For other fibres, it is assumed that all the fibre products are used and disposed of in Western Europe in an average MSWI plant with energy recovery (recovery rate = 60%, see Section 2.2).

Based on the "cut-off" approach, staple fibre produced from mechanical recycling (Wellman) has the lowest cradle-to-factory gate NREU among all fibre studied; recycled PET fibre produced from semi-mechanical recycling (LJG) has slightly higher NREU than Lenzing Viscose Austria; the NREU of chemically recycled fibre produced by FENC is slightly higher compared to cotton; and chemical recycled fibre via the DMT route has a higher NREU value than Tencel Austria. All recycled PET fibres have lower NREU values than virgin PET and virgin PP, based on the three methods.

Fig. 16(a) presents the comparison of cradle-to-factory gate GWP100a based on the "cut-off" method with the error bar showing the results based on the "waste valuation" method. For chemically recycled fibres based on the DMT route, only the "cut-off" approach was applied. Fig. 16(b) shows the cradle-to-grave comparison without the use phase. For recycled PET fibres, the "system expansion" method is applied. For other fibres in the case study, it is assumed that the fibre products are single-use and the post-consumer waste is incinerated with energy recovery.

Based on the "cut-off" approach (Fig. 16a), recycled fibre produced via mechanical recycling (Wellman) has a lower GWP value than all the other fibres listed except for Lenzing Viscose Austria; recycled fibre produced from semi-mechanical recycling (LJG) is has a slightly lower GWP than PLA and cotton; recycled fibres produced via chemical recycling (BHET route and DMT route) are comparable with virgin PP. Based on all three methods applied, all studied recycled PET fibres have lower GWP than Lenzing Viscose Asia and virgin PET.

When we compare the energy use and GWP of various fibre products (as in Figs. 15 and 16), it should also be taken into account that fibres are intermediate products. The fibres studied are designed to delivery different functionalities and to fulfill various end-use purposes, and they cannot always replace each other. Table 9 shows that the mechanical, thermal and water retention properties of fibres compared are very different. Therefore, if fibre A has a higher environmental impact than fibre B, it does not immediately imply that fibre A should be replaced by fibre B.

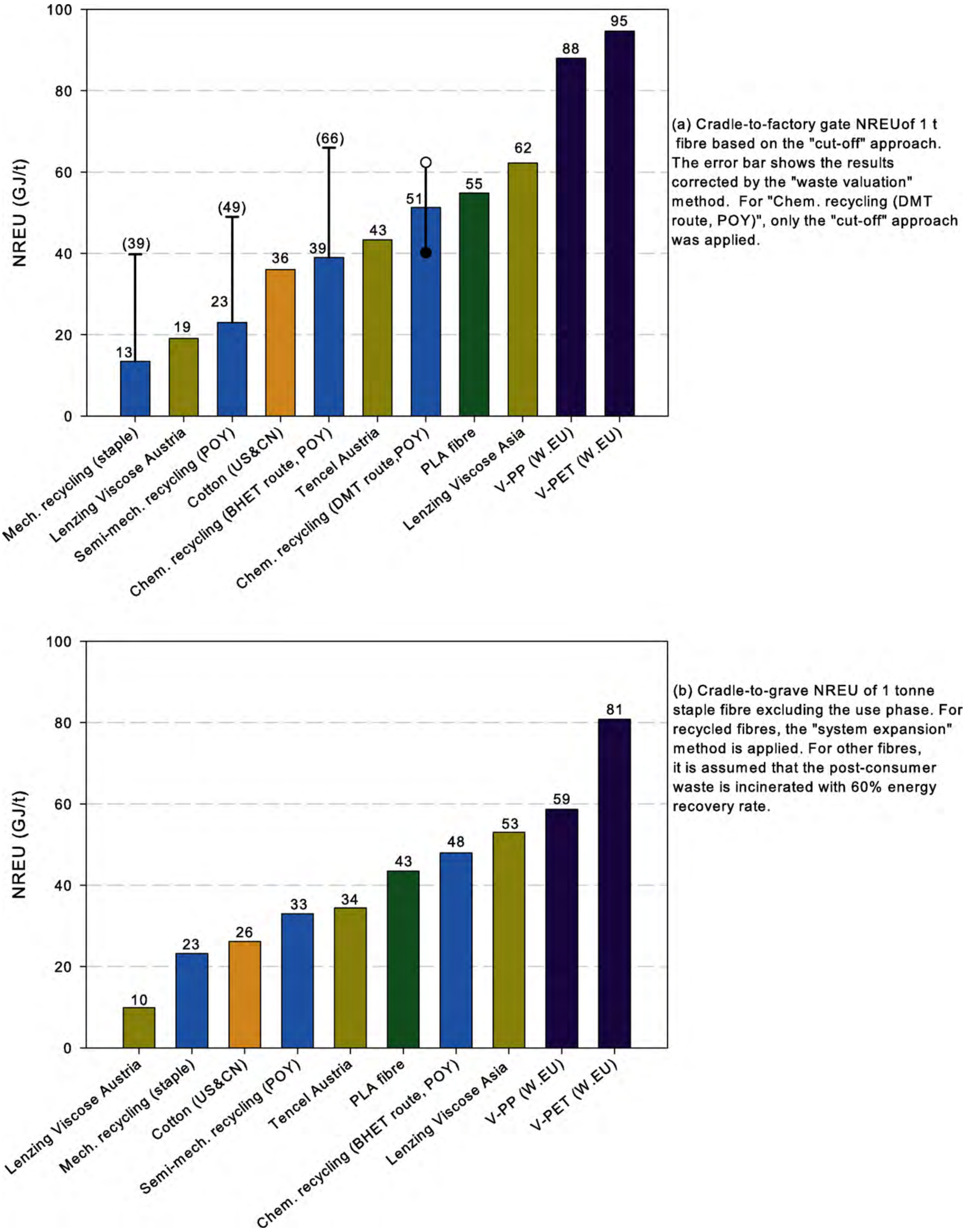
Furthermore, in both Figs. 15(b) and 16(b) the use phase is excluded. Here, the use phase includes the fabric and the end product (e.g. shirt) manufacturing stages and the use of the end product. Depending on the type of fibre, the environmental impacts in the use phase can be substantially different. For example, different types of fibres have different energy requirements, chemical use and generate different types of waste in dyeing, finishing, washing and drying processes; the type of fibre/fabric also determines the life time of product.

7. Summary, conclusions and future research

In this study, the environmental impacts of bottle-to-fibre (B2F) recycling were assessed. We investigated four recycling technologies, namely mechanical recycling, semi-mechanical recycling, back-to-oligomer recycling and back-to-monomer recycling. The LCA results were compared with the eco-profile of virgin PET fibre. Three methods were applied for this open-loop recycling case, namely, the "cut-off", "waste valuation" and "system expansion" methods. The "cut-off" and the "waste valuation" methods follow the system boundary of cradle-to-factory gate. The cradle-to-grave system is analysed based on the "system expansion" method. The use phase is excluded in this LCA.

Based on all three methods, recycled PET fibre offers 40–85% non-renewable energy savings and 25–75% GWP savings compared to virgin PET, depending on the technology, the chosen allocation method and/or system boundaries. Based on all three methods, bottle-to-fibre recycling reduces impacts for most of the environmental categories studied. In addition, in terms of NREU and GWP100a, recycled PET fibres are comparable to cotton, modern viscose (i.e. Lenzing Viscose Austria), Tencel and PLA, and they are better than PP, traditional viscose (i.e. Lenzing Viscose Asia) and virgin PET. Both mechanical and semi-mechanical recycling have lower impacts than chemical recycling via the BHET route. However, it must be acknowledged that fibres produced from chemical recycling can be applied more widely than fibres produced from (semi-) mechanically recycled fibres. This also applies to chemical recycling via methanolysis, which has the highest impacts on NREU and GWP100a among the four recycling technologies investigated, but yields the highest product quality.

The three methods applied in this study take different perspectives. The "cut-off" method is easy to apply and straightforward to communicate. It focuses only on the recycled product and no data is required outside of the investigated product system. However, it simplifies the open-loop allocation issues especially for the "cradle" and the "grave" stages. The "waste valuation" method can be seen as an elaborated "cut-off" method. It uses economic values to allocate the environmental impacts of the production of virgin polymer (which is used for both life cycles). This method follows the suggested procedures by ISO/TR 14049 for recycling. However, the price fluctuation may lead to significant uncertainties for this method. The "system expansion" takes the perspectives of life-cycle thinking. The "system expansion" method is our preferred method to deal with open-loop recycling, although this method is not easy to apply because it requires detailed data outside of the life cycle of the investigated product.



(a) Cradle-to-factory gate NREUof 1 t fibre based on the "cut-off" approach. The error bar shows the results corrected by the "waste valuation" method. For "Chem. recycling (DMT route, POY)", only the "cut-off" approach was applied.

(b) Cradle-to-grave NREU of 1 tonne staple fibre excluding the use phase. For recycled fibres, the "system expansion" method is applied. For other fibres, it is assumed that the post-consumer waste is incinerated with 60% energy recovery rate.

Fig. 15. Comparison of NREU among recycled PET, virgin PET, virgin polypropylene, cotton, viscose, Tencel and PLA. Data sources (except for recycled PET): (Boustead, 2005a,c; Brown et al., 1985; Dinkel and Stettler, 2008 (unpublished); NatureWorks LLC, 2009; NREL, 2009; Shen and Patel, 2010).

Among the three methods we applied, the “cut-off” approach reflects current environmental policy (e.g. emission trading), where companies or sectors are addressed as individual actors and their actual energy use and emissions are fully taken into account. This is not the case for the “waste valuation” method because it shifts part of the impacts from primary to secondary production. Compared to the “cut-off” approach the “waste valuation” method is less favourable for the recycling industry. However, it can encourage the product design for recyclability because producing recyclable product results in a credit by shifting part of the impacts to the recy-

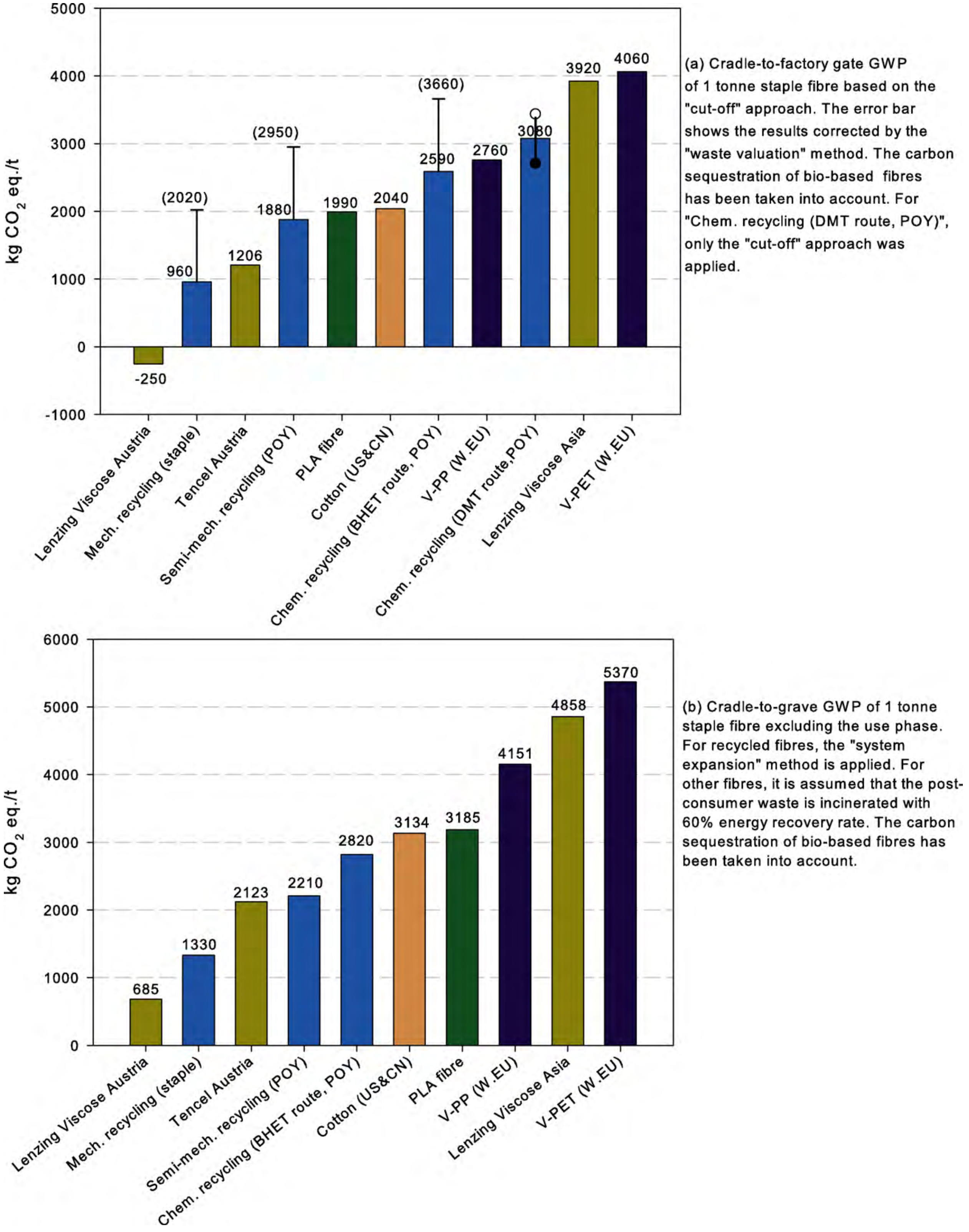


Fig. 16. Comparison of GWP100a among recycled PET, virgin PET, virgin polypropylene, cotton, viscose, Tencel and PLA. Data sources (except for recycled PET): (Boustead, 2005a,c; Brown et al., 1985; Dinkel and Stettler, 2008 (unpublished); NatureWorks LLC, 2009; NREL, 2009; Shen and Patel, 2010).

cled products. The "system expansion" method reflects the overall efficiency of material utilization without distinguishing different players. In a policy context where responsibilities are assigned to individual companies or sectors, it is difficult to apply the "system expansion" method.

We conclude that PET B2F recycling offers important environmental benefits over single-use virgin PET fibre. PET fibre is a product that cannot be further recycled via mechanical recycling. Chemical recycling is technically possible, but the economic viability of large scale operation is still to be proven.

Table 9
Selected mechanical, thermal and water retention properties of fibres.

Fibre name	Fibre type	Company or trade name	Density (g/cm^3)	Tenacity[a] (wet) (cN/tex)	Tenacity[a] (dry) (cN/tex)	Water retention (%)	Melting point (°C)
r-PET[c]	Staple	Wellman	1.36–1.40	30–48	28–48	0–2	245–260
r-PET[d]	Filament	FENC	1.36–1.41	35–45	35–45	3–5	240–250
v-PET[e]	Staple	Dacron®	1.36–1.41	30–55	28–55	3–5	250–260
v-PET[e]	Filament	Serene®	1.36–1.41	40–60	38–60	3–5	250–260
Cotton	Staple		1.5–1.54[e]	26–40[f]	24–36	38–45[g]	n/a[b]
Viscose	Staple	Lenzing Viscose®	1.52–1.54[e]	10–13[f]	24–26	90–100[g]	n/a[b]
PP[e]	Staple	Herculon®	0.9–0.92	25–60	25–60	0	160–175
PLA[h]	Staple	Ingeo™	1.25	n/a [b]	32–36	n/a [b]	170

[a] Tenacity is expressed in relative to the fineness (1 tex = 1 g/1000 m). 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.
[c] Private communication with Wellman International Ltd. (2009).
[d] Private communication with Far Eastern New Century Co. (2009).
[e] Schultze-Gebhardt and Herlinger (2002).
[f] Abu-Rous and Schuster (2006).
[g] Lenzing (2006).
[h] NatureWorks LLC (2006).

Another important way of recycling PET bottles is bottle-to-bottle recycling (see Fig. 1). This is an example for closed-loop recycling system. In theory, PET can be recycled multiple times before it is finally converted into fibre. The environmental impact of such recycling systems, the effect of the number of cycles and the influence from different allocation methods for open-loop and/or closed-loop recycling should be further investigated.

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