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Life Cycle Assessment of PET bottles: closed and open loop recycling in Denmark and Lombardy region

Relatore: Prof. Rigamonti Lucia
Correlatore: Dr. Ing. Niero Monia

Giulia Valentino
Matr. 840581

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ABSTRACT

Plastic industry plays an important role in modern society, providing a wide variety of products for any kind of application. The abundance of plastic goods in the daily life results in an ever-increasing generation of wastes, whose presence in the environment could be damaging if not managed properly.

Nowadays, the arising concern on the risks and potential damages on the environment associated to plastics has led to pursue more sustainable patterns both in product and waste management. Thus, in a context where concepts as “environmental sustainability” and “circular economy” are prevailing to the old - more impacting- management schemes, activities as material and energy recovery are playing a fundamental role. In particular, the material recovery, namely the recycling, represents a big challenge within the plastic industry: even though a lot of improvements have been done in technologies and strategies (e.g. integrated waste management system), the recycling may be not always the best efficient and convenient solution.

Therefore, the present master thesis focuses on the topic of plastic recycling, choosing as example the recycling of PET (polyethylene terephthalate) bottles. The aim of the work is to investigate the best solution for PET bottle recycling from an environmental point of view. Thus, it is carried out a Life Cycle Assessment (LCA) to analyse the potential environmental impacts generated by PET bottles throughout their entire life, comparing two different recycling scenarios: closed-loop recycling, i.e. bottle-to-bottle and the possibility of multiple recycling; and open-loop recycling, i.e. bottle-to-fibre. The analysis is performed for the two contexts of Lombardy region (Italy) and Denmark, in order to compare the different management systems.

From a methodological point of view, the study has been supported by: a Material Flow Analysis (MFA), to investigate the potential multiple recycling loops within the two contexts; the use of two different approaches for the end-of-

life modelling (i.e. the modelling of recycling), which are the System Expansion method with Substitution (SES) and the Circular Footprint Formula (CFF). In particular, when implementing the CFF, there were investigated: different ways of definition of the quality ratio, expressing the variation in the physical properties of the material during the recycling process; the applicability of the new Formula to the multiple-recycling case, representing a novelty within the methodology.

The obtained results show that when preferring a recycling scenario with respect to another, it is important and necessary to state the reason, thus referring the impact category(ies) in which the chosen scenario is better. The life-cycle phases that contribute in relevant way to the final results are the "bottle production" and the "secondary production" ones: this last phase represents benefits to the systems and it strongly depends on the choice of modelling, i.e. on the selection of the dataset representing the avoided production of virgin material.

SOMMARIO

L'industria della plastica gioca un ruolo molto importante nella società moderna, offrendo una grande varietà di prodotti per qualsiasi applicazione. La grande quantità di prodotti plastici presenti nella vita quotidiana genera al tempo stesso un quantitativo di rifiuti sempre più in aumento, la cui presenza nell'ambiente può rappresentare un danno non indifferente.

Al giorno d'oggi, la crescente preoccupazione riguardo ai danni causati dalla plastica sull'ambiente ha portato a ricercare modelli più sostenibili sia per la gestione dei prodotti in plastica, sia per la gestione dei suoi rifiuti. Da qui, operazioni come il recupero di materia e il recupero energetico giocano un ruolo fondamentale, specialmente in un contesto dove concetti come "sostenibilità ambientale" ed "economia circolare" predominano ormai sui vecchi -e più impattanti- schemi. In particolare, il recupero di materia, ovvero il riciclo, rappresenta una grande sfida all'interno dell'industria della plastica, dal momento che, nonostante i molti miglioramenti tecnologici e strategici (e.g. gestione integrata dei rifiuti), spesso non risulta la soluzione migliore sia dal punto di vista dell'efficienza che della convenienza economica.

Pertanto, il presente lavoro di tesi magistrale s'incentra sul tema del riciclo della plastica, scegliendo quale elemento di studio il riciclo delle bottiglie in PET (polietilene tereftalato).

L'obiettivo dello studio è quello di investigare la migliore soluzione per il riciclo delle bottiglie in PET da un punto di vista ambientale. È stata, quindi, condotta un'Analisi del ciclo di vita (Life Cycle Assessment, LCA) al fine di analizzare i potenziali impatti ambientali generati dalle bottiglie in PET lungo tutta la loro vita, andando a confrontare due differenti scenari di riciclo: riciclo ad anello chiuso (closed-loop), ovvero da bottiglia-a-bottiglia e la possibilità di ricicli multipli; riciclo ad anello aperto (open-loop), ovvero da bottiglia-a-fibra. L'analisi è stata svolta nei due contesti della regione Lombardia (Italia) e Danimarca, al fine di confrontare i due differenti sistemi di gestione.

Dal punto di vista metodologico, lo studio è stato supportato da un'Analisi di flusso di materia (Material Flow Analysis, MFA), al fine di investigare i potenziali multipli cicli di riciclo nei due contesti e dall'uso di due diverse metodologie per la modellizzazione del fine-vita (i.e. la modellizzazione del riciclo), che sono l'espansione dei confini del sistema tramite il metodo dei carichi evitati (System Expansion method with Substitution, SES) e la Circular Footprint Formula (CFF). In particolare, nell'utilizzo della CFF sono stati esaminati differenti possibilità di definizione del rapporto di qualità, che esprime la variazione delle proprietà fisiche del materiale durante il processo di riciclo; e l'applicabilità della nuova Formula al caso di riciclo multiplo, rappresentando una novità metodologica.

I risultati ottenuti mostrano che nel momento in cui si predilige uno scenario di riciclo rispetto a un altro, è importante e necessario motivarne la ragione, ovvero riferire per quale/i categoria/e di impatto lo scenario scelto risulta essere il migliore. Inoltre, le fasi del ciclo di vita che contribuiscono maggiormente ai risultati finali sono “la produzione di bottiglie” e “la produzione secondaria”: in particolare, quest'ultima rappresenta i benefici del sistema e dipende fortemente da come viene modellizzata, cioè da quale dataset viene rappresentata la produzione evitata di materiale vergine.

INTRODUCTION

Plastic industry plays an important role in modern society, providing a wide variety of products for any kind of application. Its phenomenal growth over the past years comes from the fact that plastics have substantial benefits in terms of their low weight, durability and lower cost with respect to many other materials (Hopewell et al., 2009). The worldwide plastic production grew from 1.5 million tonnes (Mt) per annum in 1950 to 322 Mt in 2015, with 58 Mt in Europe alone (European Commision, 2013; PlasticsEurope, 2016). It is estimated (under a business as usual scenario) that 66.5 Mt of plastic will be placed on the EU market in 2020 and global plastic production could triple by 2050 (European Commision, 2013).

Globally, about 50% of plastics are used for single-use disposable applications, such as packaging, agricultural films and disposable consumer items, while 20-25% for long-term infrastructure such as pipes, cable coatings and structural materials, and the remaining part for durable household applications with intermediate lifespan, such as in electronic goods, furniture, etc.

On the other hand, this abundance of plastic goods leads to an ever-increasing generation of wastes, whose presence on the environment could be damaging if not managed properly. The big challenge in the plastic waste management comes from the fact that different reprocessing and treatments are required with respect to the type of polymer(s) and the different product design. It is estimated that post-consumer plastic waste generation across the European Union was 25.8 Mt in 2014: of this 30.8% was landfilled while 69.2% went to recovery, and only 29.2% was recycled (PlasticsEurope, 2016). These numbers are the result of effective policies at the European and national level (see chapter 1.2), but there is still a long way to go because landfilling and incineration remain the predominant actions.

In the last decades, the awareness of the risks and potential damages on the environment associated to plastics is arisen. Concepts as "environmental sustainability" and "circular economy" are implemented at the industrial level, moving towards more sustainable patterns, such as recycling and prevention. The rationale behind this is considering the waste as a valuable resource, thus finding the best optimization strategies aimed at the reduction of the associated environmental impacts (European Commision, 2015). In particular, the circular economy stands on the idea that a transition from a linear value chain, take-make-dispose, to a circular one is needed to reduce the environmental burdens of productive systems and to increase the overall efficiency of the economy.

Within this context, recycling has always been a key point, and a lot of improvements have been done in technologies and strategies (i.e. integrated waste management system), in order to make the recycling as much efficient and convenient as possible.

The present master thesis focuses the study on PET (polyethylene terephthalate) bottles, chosen as example to further analyse the key aspects within the plastic sector, from the production until the waste management systems, and particularly to the specific treatment of recycling.

Therefore, the main objective of the present study is to investigate the best solution for PET bottle recycling from an environmental point of view, given a specific plastic waste management system. In order to understand the potential environmental impacts associated to this product system, a comprehensive life cycle assessment (LCA) will be conducted.

Thus, PET bottles are going to be analysed throughout their entire life, comparing two different valorisation paths:

- Closed-loop recycling: Bottle-to-Bottle and the possibility of multiple recycling loops;
- Open-loop recycling: Bottle-to-Fibre.

The LCA methodology will be applied comparing two different management systems: the specific cases of Denmark and Lombardy region (Italy) have been chosen, as representative and realistic examples. Such comparison leads to analyse the performance of the plastic management system, investigating the influence of the specific local conditions and infrastructures on the selection of the best option for PET valorisation.

The study aims to answer the following research questions:

- *According to the context (i.e. Denmark and Lombardy region), which kind of PET recycling route is environmentally better?*
- *To which extent performing multi-recycling loops is reasonable and environmentally sustainable for PET?*

1. PLASTIC INDUSTRY AND SUSTAINABILITY

Plastics represent an important constant in the daily life of modern society. The sensational growth of the plastics industry during the past several decades has resulted in a vast amount of various kinds of plastics produced worldwide every year, contributing to the materialistic affluence in human living (Song & Hyun, 1999). The increasing demand led the worldwide production of plastics to 322 million tonnes (Mt) in the year 2015, not including the synthetic fibres but only the polymers like thermoplastics, thermoset, adhesive and coating (PlasticsEurope, 2016). It has been estimated that the global plastic production could triple by 2050 (European Commision, 2013).

Because of the unique properties of plastic materials, they are used in a wide range of application sectors, such as packaging, building and construction, automotive and aeronautics, electrical and electronic equipment, agriculture, leisure and sports equipment or medical and health products (PlasticsEurope, 2016).

The features of plastics are lightweight, durable, and more cost-effective materials with respect to many others, which make them highly competitive in the market.

On the other hand, this abundance of plastic goods causes the generation of environmental impacts associated with both production and disposal: the former involves consumption of fossil fuels and a high energy demand, while an ever-increasing amount of plastic wastes leads to disposal management problems, from greenhouse gases (GHGs) emissions to the accumulation in the environment, especially without proper treatment. Indeed, once in the environment plastic waste can persist for hundreds of years (European Commision, 2013).

Hence, as the plastic demand will continue to increase, especially in the packaging sector, the waste issue will remain unresolved and growing. Thus, improvements are necessary in product design and in waste management measures, in order to decouple the plastic waste generation with the plastic production (European Commision, 2013).

1.1. Plastic production in Europe

Europe represents the second main producer of plastic materials after China, accounting for a percentage of about 20% of the total in 2013 and reaching a production of around 270 million tonnes in 2015 (PlasticsEurope, 2015 and 2016).

The plastics demand in the European market is dominated by plastic packaging (around 40%) followed by the building and construction sector (22.4%) as it can be seen in Figure 1-1; the plastics industry expects a long-term growth of around 4% globally (European Commision, 2013).

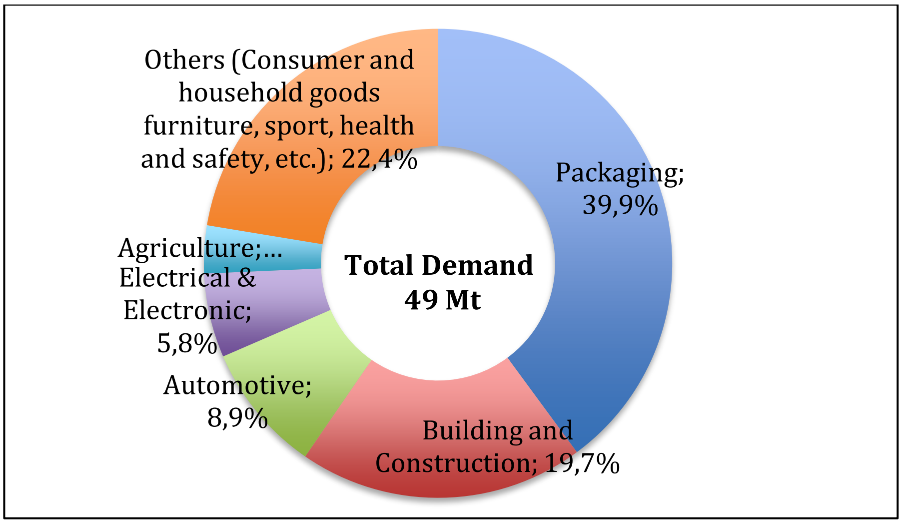

Figure 1-1 European plastic demand by 2015 (EU-27+NO/CH) (source: PlasticsEurope 2014 and 2016)

Data clearly shows that the packaging sector has the most influence in the plastic industry, and therefore constitutes one of the main sources of the plastic waste generation.

Post-consumer plastic waste generated across the European Union (EU) in 2014 was around 25.8 Mt, where 69.2% was recovered through recycling (29.7%) and energy recovery (39.5%) and 30.8% was landfilled (PlasticsEurope, 2016).

Plastic packaging has the highest recycling and energy recovery rates with respect to the other end markets, and in 2012 contributed to 62% of all plastic waste, and represented the 82% of all plastics recycled (EPRO, 2017).

1.2. Legislation on plastic waste in Europe

The great production of plastic goods leads to a greater generation of plastic waste, which has to be managed in a proper way in order to avoid or limit the damages on the environment. Therefore, an appropriate legislation is necessary and important to boost a sustainable management system of plastics.

The principal reference in Europe is the Waste Framework Directive (WFD) 2008/98/EC, where the concept of waste hierarchy within the waste management (Figure 1-2) is delineated: the strategic actions shall follow a preferential order, giving the precedence to prevention, then reuse and recycling over recovery (energy recovery included), and disposal.

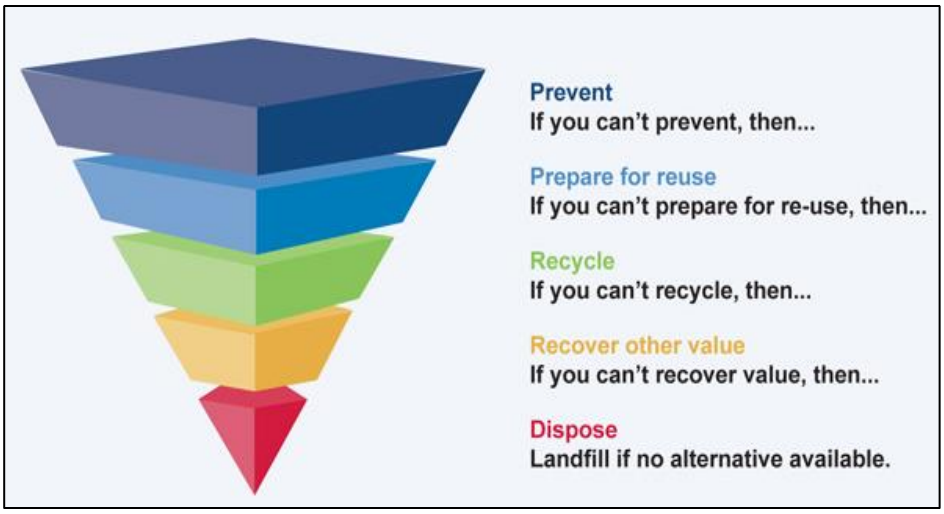

Figure 1-2 Waste hierarchy accordinf to the Waste Framework Directice (WFD) 2008/98/CE (source: http://www.environment.scotland.gov.uk)

According to the directive: "When applying the waste hierarchy, Member States shall take measures to encourage the options that deliver the best overall environmental outcome. This may require specific waste streams departing from the hierarchy where this is justified by life-cycle thinking on the overall impacts of the generation and management of such waste" (European Commisssion, 2008). Using the Life-Cycle Thinking (LCT) approach means considering all the potential reductions on resource consumption in each life cycle stage of the products: this is a helpful approach to complement the waste hierarchy, assessing the benefits and trade-offs associated.

When dealing with waste management, the WFD introduces the "polluter pays principle" and the "extended producer responsibility" (EPR): in the former the producer or holder of waste or the manufacturer of the product that became waste shall pay the waste treatment costs or dispose of the waste and is responsible for the abatement of environmental pollution caused by the waste;

while the principle of extended producer responsibility shifts the burden of product waste management (collection, recovery and disposal) back onto those companies that make the products becoming waste later (Justice and Environment, 2012).

Nevertheless, most producers and users have decided to transfer this responsibility on to an approved national organization, named Producer Responsible Organizers (PROs), which are juridical and/or economically responsible for establishing recovery systems for packaging.

The WFD includes targets for recycling and recovery that has to be achieved by 2020: 50% preparing for re-use and recycling of certain waste materials from households and other origins similar to households, and 70% preparing for re-use, recycling and other recovery of construction and demolition waste. Moreover, the Directive requires that Member States shall adopt waste management plans and waste prevention programmes.

Regarding the plastic industry specifically, the starting reference legislation is of the year 1994, the European Union Directive on Packaging and Packaging waste (94/62/EC), then revised in 2004 with a new proposal under the code 2004/12/EC, which was implemented in autumn 2005. The latter stipulates that each Member State shall set up a collection system for recovering used packages (European Commission, 2004). As well as the WFD, this Directive sets targets for recovery and recycling specifically for the packaging streams: the first targets, supposed to be achieved by the year 2008, were setting an overall recovery rate of minimum 60%, and an overall recycling rate of minimum 55%. In addition, the Directive poses for each material stream its individual recycling target, thus for plastics was 22.5% by 2008, counting exclusively material that is recycled back into plastics (European Commission, 2004).

In the context of a Resource Efficient Europe, increasing the reusing and recycling of materials is considered a high priority for realising the vision of a circular economy within the EU. In July 2014, the European Commission published the Circular Economy Package, which includes, among other things, a

Proposal reviewing the targets set out in the Waste Framework Directive (WFD), Packaging and Packaging Waste Directive (PPWD) and Landfill Directive (European Commission, 2014). This proposal sets higher minimum rates for re-use and recycling, and in particular, regarding the different packaging materials, for plastics the recycling targets are 45% by 2020 and 60% by 2025 (European Commission, 2014).

1.2.1. Legislation for recycling

The Waste Framework Directive gives this definition of recycling: "Any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or backfilling operations" (European Commisssion, 2008).

A Recycling Regulation (282/2008/EC) sets the criteria among the processing of recycled plastics intended to come in contact with foods: the European Commission gave the European Food Safety Authority (EFSA) the mandate to evaluate the recycling petitions. It is important in a recycling process to demonstrate an efficient reduction of potential contamination to a level that does not pose a risk to human health: the contaminants should only migrate in levels comparable to or well below levels demonstrated in challenge tests of that recycling process or in other appropriate analytical tests, and should comply with the requirements of Regulation (EC) No 1935/2004 (European Commission, 2008). A further safety assessment should verify that the recycling processes fulfil the criteria.

These so-called "challenge tests" were established to measure whether a recycling process can reduce any chemical contamination below a set limit and thus comply with the legal requirements.

As an example, contaminations in PET containers can be from different sources: a previously filled with non-food liquids, non-food-contact grade PET or other types of polymers entering the recycling stream; further PET degradation products, process chemicals or sorbed food components can result in unwanted impurities (Geueke, 2014).

Currently, 127 recycling processes, which can be found using the keyword RECYC, have been registered and partially evaluated by the European Food Safety Authority (EFSA), but none of the evaluated recycling processes has been authorized by the European Commission up to this point. It is interesting to note that more than 80% of these processes describe the recycling of PET, showing a big effort with respect to this kind of material, since it is the most favourable recyclable material, together with the polymer high-density polyethylene (HDPE) (Geueke, 2014).

1.3. Plastics and circular economy in Europe

Nowadays, the development is heading more towards a sustainable development where, "*the needs of the present are met without compromising the ability of the future generations to meet their own needs*" and this includes the concepts of environmental sustainability and circular economy.

The European Commission adopted in 2014 an ambitious Circular Economy Package which consists of an EU Action Plan for the Circular Economy that establishes a concrete and ambitious programme of action, with measures covering each step of the value chain: from production and consumption, repair and manufacturing, waste management and secondary raw materials that are fed back into the economy (European Commission, 2016a).

In this direction, the economy is making a big effort on changing from a linear model to a circular one. Here, the value of the products, materials and resources is maintained in in the economy for as long as possible, and the generation of waste is minimised (European Commision, 2015): thus, the main objectives of this new concept are resource preservation and efficiency, plus waste minimisation.

The “take, make, dispose” linear model relies on large quantities of easily accessible materials and energy and reaching its physical limits. The purpose of the circular economy is to provide multiple value creation mechanisms that are decoupled from the consumption of finite resources (Ellen MacArthur Foundation, 2015).

The role of the European Union then is to ensure the right regulatory framework is in place for the development of circular economy in the single market, and to give clear signals to economic operators and society at large on the way forward with long term waste targets and actions which are to be carried out by 2020. These objectives and measures shall be implemented on the perspective of breaking the link between economic growth and environmental impacts, mainly associated with the generation of waste.

The concept of circular economy is characterized as an economy that is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value, distinguishing between technical and biological cycles (Ellen MacArthur Foundation, 2015). This means optimising resource yields by circulating resources into bio-cycles or recovering and restoring them in the technical cycle.

Legislative proposals on waste, adopted together with the EU action plan, include long-term targets to reduce landfill and to increase preparation for reuse and recycling of key waste streams such as municipal waste and packaging waste. The targets should gradually lead Member States to converge on best-practice levels and encourage the required investment in waste management (European Commision, 2015).

Hence, waste management plays a critical role in circular economy: in the field of material recovery, high recycling rates shall be reached, thus boosting improvements in collection and sorting systems, as well as integrated waste management systems.

The EU Action Plan on Circular Economy highlights some priority areas where it is important to put efforts and challenges into the context of circular economy, because of the specificities of their products or value-chains, their environmental footprint or dependency on material from outside Europe.

The first sector highlighted in the legislation is plastics: especially regarding the plastics waste generation. The Plan incentives actions through the entire lifecycle of plastics, enhancing recycling, eco-design and quality standards and giving importance to the reduction of the marine litter. This is in line with the "Green paper on Plastic Waste" (2013), which presents the issues and challenges around the plastics sector. One of the most important actions, following the waste hierarchy, is recycling: parameters affecting the recycling rates are the type of collection, the waste composition and quality (not all the plastics are suitable for recycling), waste management systems, whereas it is included in the amount of waste incinerated or landfilled.

The landfill bans had encouraged many Member States to decrease the waste disposal to landfill to levels below the 5% mark, and this is the case of Germany, the Netherlands, Denmark, Sweden, Belgium and Austria: these countries have achieved recovery rates between 80-100%. However, some Member States with high recovery rates and landfill bans still have modest plastic recycling rates of around 28% on average (European Commision, 2013). Is important to note that a landfill ban generating an automatic preponderance of energy recovery over recycling would not be in line with the waste hierarchy. An example could be the case of Denmark, which poses the waste management more towards incineration than recycling: nevertheless, in the recent years this country has developed a waste strategy to encourage the way of recycling over incineration (and landfill) (The Danish Government, 2013).

A study on European waste generation projections to 2035 assessed the introduction of strong policies to extend recycling, and found plastic to have the largest potential for reducing the environmental impacts of waste (European Commision, 2013): *"More sustainable patterns of plastic production and better plastic waste management - particularly higher recycling rates - offer considerable potential for improving resource efficiency. At the same time, they* *would help to reduce imports of raw materials as well as greenhouse gas emissions. Resource savings can be significant"*.

Hence, recycling as a waste-management strategy is an example of implementing the concept of industrial ecology, whereas in a natural ecosystem there are no wastes but only products, thus considering waste as a valuable resource (Hopewell et al., 2009).

1.3.1. Circular economy in Denmark

Denmark is internationally recognised as a front-runner in the circular economy having a long and rich tradition of innovation policies oriented to the circular economy. The main important steps toward this are the introduction of the very first deposit-refund scheme for beverage containers in 2000, and the landfill ban in 1997 (Dansk Retursystem A/S, 2017; Kjaer Birgitte, 2013). In line with this, in 2011 a target to be fully independent from fossil fuels by 2050 was set. Ending to the latest waste management strategy in 2013, disclosed in two reports "Danish Without Waste I/II", focusing on moving from incineration to recycling and waste prevention respectively (The Danish Government, 2013).

Therefore, through increased circularity and the associated reduction in resource consumption Denmark would lower its carbon intensity of the producing sector, reducing the imports of high-carbon-embodied goods, and increasing Denmark's exports of lower-carbon-embodied goods (Ellen MacArthur Foundation, 2015).

Nevertheless, Denmark still presents points of weakness: it has the highest municipal waste production per capita in the EU (in 2015 789 kg/cap vs 476 kg/cap EU28 average) and still the waste management system accounts for more on incineration as a recovery operation (Toft et al., 2016). As a representative example, plastic packaging has the lowest percentage of collection for recycling, around 29%, and only around 15% of it is collected for recycling from households (Ellen MacArthur Foundation, 2015).

1.3.2. Circular economy in Italy

Implementing the European Directives, Italy has been doing a lot throughout all these years to accomplish the targets. Recycling rates are increasing every year, reaching in 2015 a recycling of 43.5% of the total municipal waste, while 30% is incinerated (Eurostat, 2017).

Since the packaging represents one of the biggest fractions in municipal wastes in Italy, a consortium has been introduced by the national legislation in order to coordinate the activities of recovery of the different packaging materials (i.e. aluminium, glass, paper, plastic, steel and wood). This consortium named CONAI (National Packaging Consortium) is able to create a network together the municipalities for the management of packaging waste, promoting sustainable approaches, such as material and energy recovery.

In the last two decades, CONAI has been assigned to sent to recycling 50 million tonnes of packaging waste over the entire national territory. This data keeps growing over the years, starting from 190 thousand tonnes in 1998 to 4 million tonnes in 2016, leading to about 130 million metric cubes of packaging diverted from landfill (CONAI, 2017). In 2015, plastic packaging collected for recycling amounted to 38%, exceeding the target of 22.5% of the European Directive (Corepla & Stramare, 2013) .

Italy contributes to circular economy from different perspectives: among entities like municipalities, cooperatives, start-up, and local realities, a 65% operate on activities referred to the reduction of the use of virgin materials, another 53% on waste prevention activities, and 48% on activities that contribute to resource savings (water, energy and primary materials). Other percentages give an idea on the management of the post-use phase: 38% recycles wastes in other productive cycles, while 26% in its own type and the remaining 36% deals with reuse activities, avoiding those products become wastes (Legambiente, 2017).

Despite such large-scale achievements, Italy still has a lot of work to do, since still a big amount of waste ends up in landfill, e.g. in 2014 still a rate of 28% of wastes were landfilled (ISPRA, 2016). Moreover, since there is no national scheme on waste management, the performance of the country varies among regions.

1.4. Plastic Waste Management

As observed so far, in the EU, there is a wide range of waste-management prioritisations for municipal solid waste (MSW), from countries still more oriented to landfill, and others weighted towards incineration.

Regarding the plastics waste, as stated before from PlasticsEurope, in 2014 still a percentage of 30.8% goes to landfill, and most of it is packaging. Moreover, it should also be taken into consideration the amount of plastics not recovered at all and left in the environment. Figure 1-3 shows the general situation in Europe in 2012 that gives an idea of the different management systems of Member States.

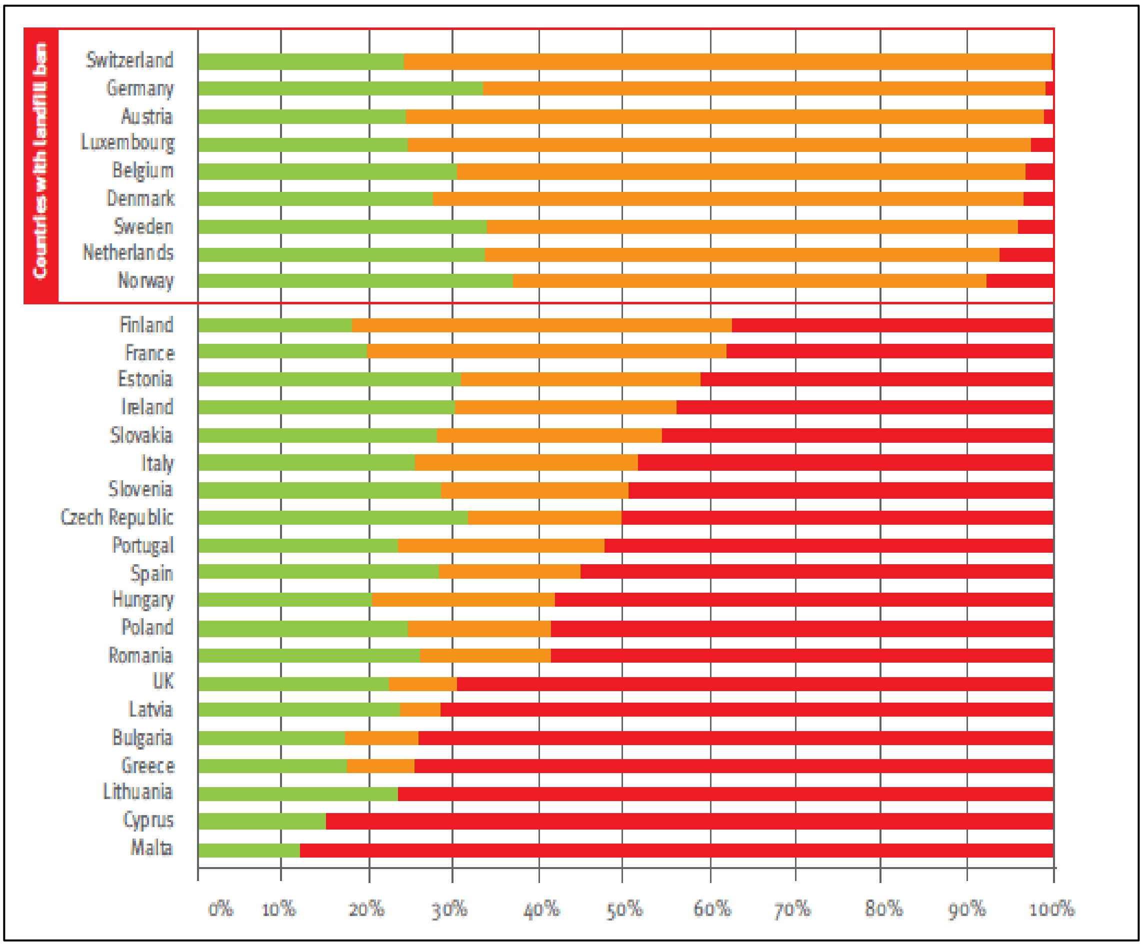

Figure 1-3 - Post consumer plastics waste treatments in Europe in 2012 (source: PlasticsEurope 2014). Legend: green: recycling rate; orange: energy recovery rate; red: landfill rate.

Both material and energy recovery can be performed in the plastics waste stream, and different separate collection schemes can be implemented. It is up to each single Member State, and in some cases each single municipality, to decide which collection method is most suitable, among (Hopewell et al., 2009):

- Kerbside collection: requires that citizens separate recyclable materials from their other household waste, by putting them into specific waste bags. The bags are then collected from each household. Kerbside collection is convenient for both households and reclaimers, and it offers the advantage of a low degree of material contamination. Furthermore, since a wide range of recyclables is included in this type of collection, overall costs can be reduced quite significantly;

- Drop-off collection: requires citizens to collect their recyclables and dispose of them at specific locations. Drop-off collection entails quite a high contamination level;
- Deposit system: entails bottles to be sold with refundable deposits. Those are redeemable upon return of the bottle to participating retailers (e.g. by using reverse vending machines that accept used beverage containers and return money to the user). Deposits may be charged on both refillable and single-use bottles. This approach is most common in Scandinavian countries, the Netherlands, Germany and Switzerland.

Bring-schemes (drop-off) tend to result in low collection rates in the absence of either highly committed public behaviour or deposit refund schemes that impose a direct economic incentive to participate. To maximize the cost efficiency of the collection schemes, most kerbside collections are of co-mingled recyclables (paper/board, glass, aluminium, steel and plastic containers) (Hopewell et al., 2009).

Concerning the packaging stream, the related Directive (94/62/EC) has promoted incentives to material recovery by using the “Extended Producer Responsibility” system or the “deposit-refund” system. Within the former, the most well-known is the packaging waste Duale System Deutschland (DSD) (or Green Dot system) that was firstly applied in Germany: the basic idea is to establish a privately organized channel assuring that all primary packaging can be collected from the consumers and service providers. The “Green Dot” label on packaging material is used to identify the product belonging to the dual system.

While for the “deposit-refund” system, the Danish “Dansk Retursystem” is the oldest one and it is applicable for refillable, non-refillable, reusable and disposal, and ready-to drink beverages and mineral bottles (Pires et al., 2011).

Subsequently, in their waste management plans Member States decide the preferred options in treating (and then disposing) the collected waste. The common practices in the plastic waste treatments give priority to the mechanical recycling (the chemical one is still not so economically convenient), and to the recovery technologies that produce high quality recyclates; the second preferred option is to use plastic in the production of refuse derived fuel (RDF) or as a reducing agent in blast furnaces (Rigamonti et al., 2014).

Within the plastics waste treatments, recycling, that is the focus of the present study, still remains a challenging area in the plastic waste management sector, being in low percentage with respect to incineration and landfilling. Hence, recycling, applied with great success to other waste materials (e.g. aluminium, paper), is promoted for plastics with more effort.

Plastic recycling includes (Geueke, 2014):

- Mechanical recycling: reprocessing into secondary products that can replace the primary material. In the case of plastic, there are limits on full applications of the secondary material, since inherent losses of properties can take place during the reprocessing;
- Chemical recycling: (feedstock recycling) recovery of chemical constituents, through depolymerisation processes. The products can serve as starting materials for new polymerization reactions or other chemical processes;
- Thermal recycling: process aimed at recovering heat energy from plastics through incineration.

Recycling operations cover a wide number of processes, which vary among polymer type, the product type and for packaging material, the package design. Consumer plastics are composed of a big variety of different polymers and other materials such as metals, paper, inks and adhesives that can increase the difficulty of the recycling process.

Other aspects that affect the efficiency of the recycling operations are: the level and quality of separation from source contamination and the behaviour of the polymer against degradation during reprocessing and subsequent use.

Therefore, operations as collection, sorting, cleaning, size reduction and separation may lead to reduce contamination and improve the purity of recovered plastic feed and the property requirements of the product to be made.

Thus, quality of plastic recycling is of a major concern: recycled plastics are substituting products otherwise produced from virgin materials, and the quality of the recyclates governs the substitution ratio. The lower the quality of the recycled plastics is, the lower the substitution ratio will be, and smaller the benefits from their recycling will be (Lazarevic et al., 2010; Pivnenko et al., 2015).

In the case of substitution of the same virgin material, it is often not technically feasible to add recovered plastic without decreasing at least some quality attributes of the virgin plastic such as colour, clarity or mechanical properties. Most uses of recycled resin usually blend the recycled resin with virgin resin.

1.4.1. Plastic waste management in literature: a review

Within plastics waste management, literature provides a wide range of studies that cover several different aspects of the topic, focusing in particular on the role of recycling. Given its priority in the waste management over incineration and disposal, the studies have investigated the points of strength and weakness, in order to optimize as much as possible this type of recovery.

The first main issue discussed in literature concerns the quality of the recycled material, and so the efficiency of the recycling process: when technologies and proper management schemes are not allowing to obtain a "good" secondary product, then the benefits from recycling are not consistent anymore and energy/thermal recovery is the preferred option (Lazarevic et al., 2010; Pivnenko et al., 2015). The main problem comes from the fact that is missing a clear definition of "good" recycled material, which leads to a difference of opinions, especially based on different assumptions. Even though this limitation, Pivnenko et al. (2015) have tried to identify the "weak" points in assuring quality plastics recycling, pointing out the factors with significant influence, such as polymer cross contamination, additives, non-polymer impurities, and degradation. These types of contamination can come from different sources, and can take place in all over the steps of plastic value chain, from the production to the manufacture and design, until the collection and reprocessing.

Within the waste management chain, Snell et al. (2017) analysed how much the collection scheme could influence the quality of the final product, studying the case of PET. Taking the case study of Germany, various collection systems for PET beverage packaging are compared, from the deposit-refund system, to the reusable packaging system and the "Green Dot" (dual system). To determine the level of quality, the criterion taken was the amount of contamination of PET flakes with other polymers, metals and other substances. In the end, the analysis demonstrated that material from the deposit systems resulted in a better quality of PET flakes, over household collection.

A second important aspect considered in literature about the recycling is the existence of a market for the secondary product: when the demand is low, recycling may be not very convenient. Kuczenski et al. (2010) analysed the feasibility of plastic recycling, with the aim at understanding to what extent it is reasonable with respect to the reduction of primary production of polymers. By implementing a Material Flow Analysis for the case of PET in the US, the study was able to analyse the interaction between primary and secondary PET in manufacturing and to estimate the potential for PET recycling to reduce demand for virgin material. The current PET recycling industry suggests that closed-loop mechanical recycling is economically viable. The utility generated by a unit of primary material increases with the number of times the material cycles through the system before being lost. Currently, only rigid packaging (mainly bottles) appears to provide a viable stream of recycled polymer, but only a small fraction of secondary material is used for bottles. The majority of recycled PET, in particular low-quality grade material, is consumed for fibre applications and post-consumer textiles are not closed-loop recycled. Hence, recycled PET is likely to pass through the system just one additional time before being lost.

1.4.2. Plastic waste management in Lombardy (Italy)

The general context

The Waste Framework Directive (WFD) was transposed in Italy by the Legislative Decree 205/2010 (and last modified in 2012), amending the Legislative Decree 152/2006, which is the consolidated Act on the Environment. All the requirements of the WFD have been transposed into national legal requirement: thus, the stringent target for separate waste collection of municipal waste of 65% by the year 2012 was set up. Additional requirements are included regarding the promotion of high quality recycling and quality standards for recycling.

Although the target rates from the Directive have been achieved in certain areas (regions like Lombardy, municipalities or enlarged areas called “Ambito Territoriale Ottimale”, or simply “ATO”, with integrated management systems) the national rate achieved is still low: for the separate collection, Italy accounted in 2015 a rate of 48% (Lombardy region 59%) (ISPRA, 2015a, 2015b).

This is due to the fact that no homogeneous criteria to reach neither targets nor specific measures to “promote high quality recycling” have been identified at national level, because there is no National Waste Management Plan.

Regulated by the legislation cited before (D.lgs. 152, 2006), a general flow of the municipal solid waste of the Italian situation is now described.

The municipal waste is collected with a selective mono- or multi-material collection through kerbside, street containers or civic amenities schemes, in order to obtain the selected stream. Then a sorting phase is necessary to obtain the individual fractions, which are ready to be sent to recovery operations, such as recycling. The residues fraction is usually sent to energy recovery, or to a mechanical-biological treatment (MBT) or landfill.

In this way, the packaging materials are being separated at the source, promoting an easier management of the waste. The scheme described is managed by the consortium CONAI (see chapter 1.3.2).

Plastic waste management

Once explained the general scenario of the waste management system in Italy, it is now described in the specific the part related to the packaging waste, and so the plastic packaging one, being the focus of the study.

The role of CONAI is to ensure the achievement of recovery and recycling targets for packaging waste and ensuring the necessary connection between the packaging waste collection system (managed by the local authorities) and the economic operators involved in the management chain. The consortium charges packaging producers and users a cost for subsequent separated collection, recovery and recycling through the so-called “environmental contribution”.

CONAI directs the activities and guarantees the recovery results of 6 Consortia for each packaging material: steel (Ricrea), aluminium (Cial), paper/cardboard (Comieco), wood (Rilegno), plastic (Corepla) and glass (Coreve), ensuring the necessary link between these Consortiums and Public Administration.

COREPLA manages the separate collection, the sorting of plastic packaging waste, the recycling of mixed plastic fractions, the sale of sorted materials (PET and HDPE bottles, films and crates) and the energy recovery of residual waste from sorting plants, thorough direct combustion or alternative fuel production (EPRO, 2017) .

In 2013, almost 800.000 tons of household plastic packaging were sent to recycling (recycling rate of 38.6%), with PET bottles constituting around 25-29% of it (Corepla & Stramare, 2013, 2014).

Figure 1-4 shows a representative scheme for the plastic packaging management system through the consortium Corepla.

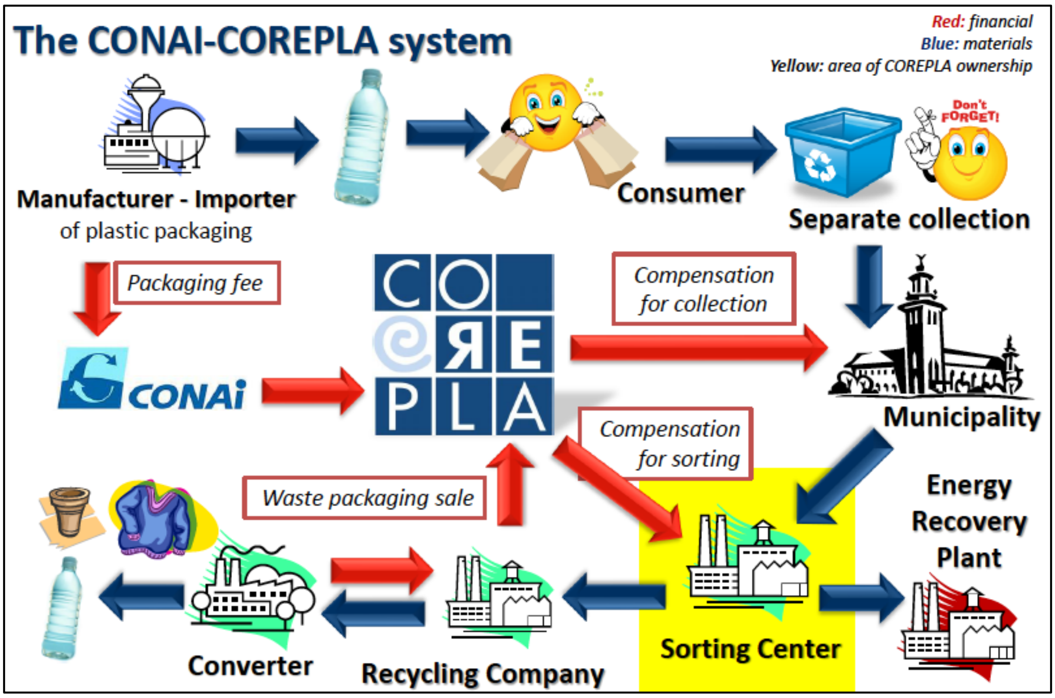

Figure 1-4 - Plastic packaging management system (source: Corepla 2014)

Each step in the system of plastic recovery has a certain efficiency, thus along the life cycle of the material there are residues and material losses, that have to be managed (disposed) properly.

The specific situation in the Lombardy region represents one of the best performing integrated waste management systems. The highest efficiencies are from a mono-material collection through kerbside system, which represents the major percentage of plastic collection with 58.7% and with a sorting efficiency of 84.5% (Rigamonti et al., 2012).

A regional project (GERLA-Waste Management in the Lombardy Region: Life Cycle Assessment) has proved that there is still a lot that can be done for further improvement: actions based, on one hand, on a further increase in recycling rates and, on the other hand, on a series of technological modifications, can be undertaken to improve the overall system (Rigamonti et al., 2013).

1.4.3. Plastic waste management in Denmark

The general context

The Environmental Protection Agency in Denmark has issued over the years Statutory Orders on Waste that regulate the waste management: as an EU Member State, Denmark implemented the Waste Framework Directive in the Statutory Order on Waste n°1309/2012.

Although the Directive is not transposed directly, the Danish legislation implements most of the same goals (European Commission, 2015).

In order to move Denmark up the waste hierarchy and further encourage the transition from "waste" management to "resource" management, the Danish waste management strategies mainly started in 2010, ending up with the National Resource Strategy in 2013, where the main goal was to implement action plans to "recycle more and incinerate less" and "waste prevention".

This can be already verified with recent data, that show an increment in the recycling rate of the total waste from 61% in 2011 to 67.1% in 2014 (Danish Government, 2013; Toft et al., 2016). However, the household fraction has the lowest proportion of waste for recycling (44% in 2014 against the share for incineration of 52%) (Toft et al., 2016).

The Resource plan's target for household recycling is 50% by 2022: this target covers seven selected waste fractions: food waste, paper, cardboard, glass, wood, plastics and metal waste from households. Data of the past years show that the strategy has been quite effective, moving from a recycling rate of 22% in 2011 up to 31% in 2014 (Danish Government, 2013; Toft et al., 2016). On the other hand, recycling of paper, cardboard, glass, metal and plastic packaging from the service sector increased by 25%: the actual recycling rate is 53% and the expected level in 2018 is 70%.

According to PlasticsEurope, Denmark's improvements in plastic recovery have increased, reaching about 25% of recycling and 70% of energy recovery in 2010, resulting in a total 95% recovery rate: the shares of recycling and energy recovery in these recent years have been changed toward the former as it can be seen in the Figure 1-3 in the previous paragraph.

With respect to plastic packaging waste, the values reached 29.4% of collection for recycling in 2012, 40-45% of which comes from the service sector and 14-15% from household: through its management system and new initiative to enhance the recycling, Denmark could increase the amount of plastic packaging collected for recycling up to 40% by 2020 (20% households and 60% services) (Ellen MacArthur Foundation, 2015).

Going into the specific, internationally recognized as the "The Danish Waste Model", the waste management system in Denmark is considered to be one of the most efficient. It is based on the following principles (Danish Environmental Protection Agency, 2001) concerning the structure of the waste management system:

- The system includes all types of waste (e.g. household, industrial, and hazardous waste);
- The responsibility for the waste management system lies solely with the local authorities;
- The duty to assign waste treatment and disposal facilities lies with the local authorities, and waste generators are bound to use them;
- The local authorities are in charge of regulation and control of waste generators, carriers and treatment plants;
- Financing of the system rests on the polluter-pays-principle;
- Waste collection and waste treatment rest on the principle of source separation.

These principles explain the fact that in Denmark there is no producer-responsibility scheme, in essence no separate management system for specific waste streams, such as packaging. It enters in the Producers Responsible Organizers (PRO) system, where the responsibility of the waste management system falls only under the municipalities' authority.

The municipalities have the right to decide on the collection scheme as well as the obligation to secure the necessary processing capacities for collected waste. Source separation of recyclable waste fractions is performed by a combination of kerbside collection schemes and bring-scheme systems. The residual waste is mainly incinerated, and only non-combustible waste is landfilled, according to the landfill ban of the year 1997.

Waste fractions such as glass, paper, cardboard, plastic and metal can either be collected at bring points or at ecological centres.

The collection of composite material (beverage packaging) is administered by the company Dansk Retursystem A/S, representing the deposit-refund system (European Commission, 2015) in Denmark, according to the legislation n°1129 of September 2010 (Fråne et al., 2014). More than 95% of the bottles in this system are returned and thereby kept out of the municipal waste collection (Life, 2012).

Plastic waste management

Since the focus of the study is the beverage packaging, it is now described the related waste management, highlighting the values for PET plastic bottles. In particular, the deposit-and-return system will be described.

Established in the year 2000, the Danish deposit-and-return system DanskReturSystem (DRS) provides the organisational and legal framework for the taking back and depositing of one-way and refillable packaging (including ready-to-drink beverages and mineral water bottles) (Life, 2012). The take back involves the consumers to return these items and it is generally organized by Reverse Vending Machines (RVS) located at points of sale in the city: these empty items collected can then be recycled into new ones and returned to the beverage packaging industry for filling with new beverages, or used for other manufacturing purposes. Figure 1-4 shows a general scheme representing the deposit-system for one-way items, with its actors involved. When breweries and importers (suppliers) sell beverages in one-way items to grocery stores and shops (points of sale), they charge a deposit per item and an administrative fee to DRS, covering the costs of the system. Then the shop is compensated by the DRS for the handling of the items (Fråne et al., 2014). Subsequently, when consumers buy a beverage item, a deposit fee is included in the price, which is then given back once the item is returned back to the point of sale (refund).

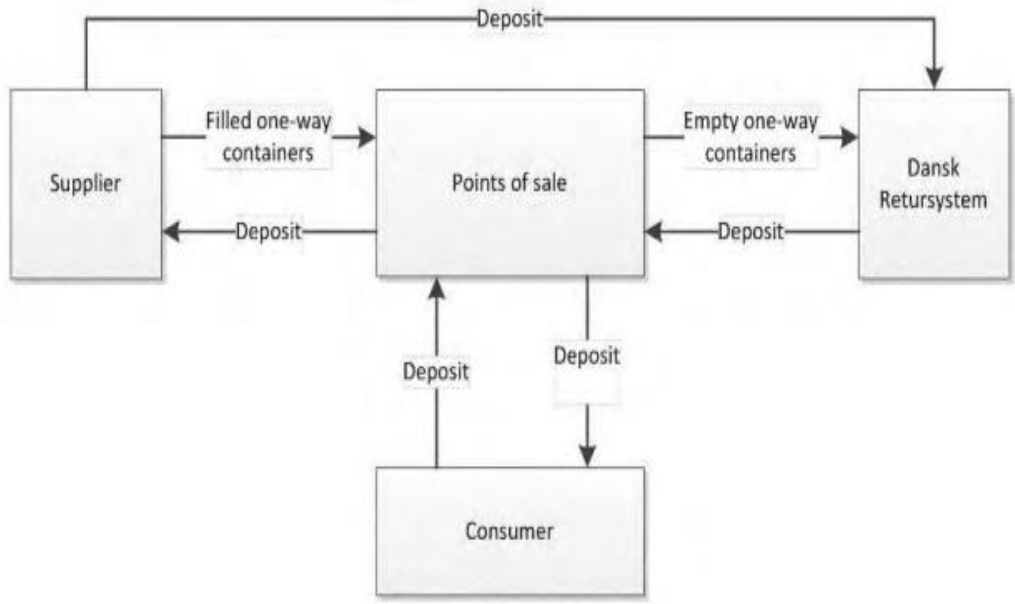

Figure 1-5 – Bottle - and deposit-flow in the Danish one-way beverage packaging deposit system (source: Dansk Retursystem; (Fråne et al., 2014))

The system mainly covers beverage containers, including metal cans (ferrous or non-ferrous), PET plastics bottles and glass bottles.

The collected wastes are then sent to the recovery facility where a sorting step is performed in order to separate the different packaging materials (aluminium, glass and plastic) and eliminate the undesired elements. After this step, the sorted bottles and cans are ready to be sent to the recycling plant, where they are reprocessed for their secondary life.

In 2013, around 950 million of empty items of drinks packaging on which deposits were paid – glass bottles, plastic bottles, and aluminium cans - were returned (Dansk Retursystem A/S, 2017): 89% of all one-way packaging was returned to the system and the average returns percentage for plastic packaging was 92%. For refillable packaging, the returns percentage was 106%. This is due to the fact that the amount of drinks sold in refillables is decreasing, and so consumers are returning more empty refillable bottles than filled bottles sold. Refillables are mainly glass and PET bottles.

Among available data, it can be estimated that plastic bottles represent more than 40% of the total empty items of packaging in the DRS system (Life, 2012; “Dansk Retursystem A/S,” n.d.).

The system comprises three types of deposit, and each one is refundable on delivery of the packaging to the store or outlet (Dansk Retursystem, 2017).

One-way bottles and cans must be labelled with one of the following Danish deposit labels, which correspond to the relative refund (for the consumer) in Danish Kroner (DKK)[1]:

- “Pant A” – DKK 1.00 (€ 0.134): All bottles and cans smaller than 1 liter (not PET bottles);
- “Pant B” – DKK 1.50 (€ 0.201): All PET bottles smaller than 1 liter;
- “Pant C” – DKK 3.00 (€0.403): All bottles and cans from 1 to 20 litres.

Refillable bottles have no label, hence the following deposits are:

- Glass bottles smaller than 0.5 litre: DKK 1.00 (€ 0.134);
- Glass bottles equal or larger than 0.5 litre: 3.00 (€ 0.403);
- PET bottles smaller than 1 litre: DKK 1.50(€ 0.201);
- PET bottles equal to or larger than 1 litre: DKK 3.00 (€ 0.403).

As a general principle, Dansk Retursystem tends to sell again the recycled PET for reprocessing for similar purposes, i.e. bottle grade recycled PET.

[1] Economic conversions Danish Kroner-Euro referred to the actual market (2017)

2. POLYETHYLENE TEREPHTHALATE (PET) CASE

Within the plastics industry, the PET represents one of the most used thermoplastic polymer: thanks to its excellent performances, it has a wide range of applications, and in particular in the packaging and textile sectors.

In the packaging sector, as it will be observed later on, PET is often the preferred material for water and soft-drink bottles, with its unbreakability and very low weight that make it competitive to glass and aluminium.

Thus, both PET demand and production are increasing worldwide: in 2010 the PET production reached 35 million tonnes, with an annual growth rate of 4-8% (Gouissem et al, 2014) representing 8% of the total demand of standard plastics[2]. In addition, PETCORE reports that in 2015 the amount of collected post-consumer PET bottle waste in Europe grew from 1,26 Mt in 2008 to over 1,8 Mt. Still in 2015 about 59% of all used PET bottles in Europe were collected for recycling, outlining an increase of 2% points compared to the 2014 ("Petcore Europe," 2017)

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[2] PlasticsEurope's definition for Standard Plastics: refers to standard thermoplastics, including PE (polyethylene), PP (polypropylene), PVC (polyvinylchloride), PS (polystyrene), EPS (expanded polystyrene) and PET (bottle grade); (Shen et al., 2010).

The reasons behind this success are the exceptional properties and low costs, resulting in simple manufacture processes and every-expanding applications.

2.1. PET Manufacture Process

In the PET production, the starting raw materials are two monomers: ethylene glycol (EG) and terephthalic acid (TPA) or terephthalic methyl ester (DMT). Through the process of esterification (or transesterification when DMT is used), the PET monomer Bis(2-Hydroxyethyl) terephthalate (BHET) is obtained, with formation of by-products (water or methanol). Then a polycondensation of monomers (polymerisation) reaction, through a catalyst like antimony trioxide (Sb_2O_3), produces amorphous PET pellets (see Figure 2-1). A middle step of pre-condensation is required in order to set the adequate viscosity of PET polymer: this melt phase is in the range of 280-350°C. It follows an additional under vacuum condition that removes the reaction by-products.

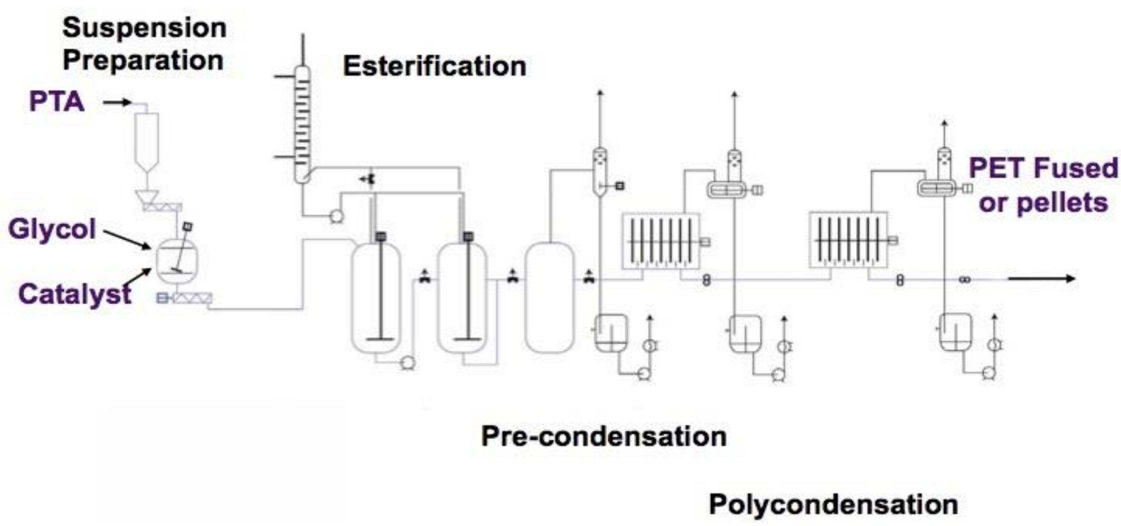

Figure 2-1 - PET manufacturing process (Source: teaching material prof. Attilio Citterio (Citterio, 2016)**)**

The main property of PET polymer that influences its performance is the molecular weight (MW) which is strictly related to the Intrinsic Viscosity (IV) (η): this latter reflects the material's melting point, the crystallinity and tensile strength.

According to the different application in which the PET pellet is intended to be used, further processing could be required in order to obtain the right characteristics and so the right PET-grade: the amorphous PET obtained from the basic process explained before, typically has an Intrinsic Viscosity of around 0.6 dL/g and is suitable to be spun into fibre or extruded as film (Kuczenski & Geyer, 2010).

Increasing the IV means an increase in the tensile strength (i.e. in pressure containers) and on the stress crack resistance, and a reduction in the crystallization rate (to have clear preforms), improving the performances of the material. Pressure and temperature conditions are key points in ensuring the desirable mechanical properties, basically of chain extension, deformation and orientation. These properties are mostly important when dealing with the production of higher quality products, such as bottles.

Therefore, it is common to implement a further condensation reaction, which is typically done in a Solid State Post-Condensation (SSP) reaction. Through this processing it is possible to obtain a bottle-grade PET, which requires high values of IV (0.72-0.86 dL/g).

Subsequently, to produce a bottle the following processes are contemplated: injection of the bottle-grade PET pellets into a cold mould, from which is obtained an amorphous preform; this preform is then subjected to a blow-moulding process, resulting in the final product of the PET bottle, ready to be filled, caped and labelled (Komly et al., 2012).

2.2. PET as a packaging material

In the recent years, the global market for PET resin has been driven by strong demand from the food and particularly beverage packaging industries, with carbonated soft drinks and bottled water representing the largest single markets.

In 2010, almost 70% of all bottled water and soft drinks sold globally was supplied in PET bottles (Welle, 2013), as shown in Figure 2-2.

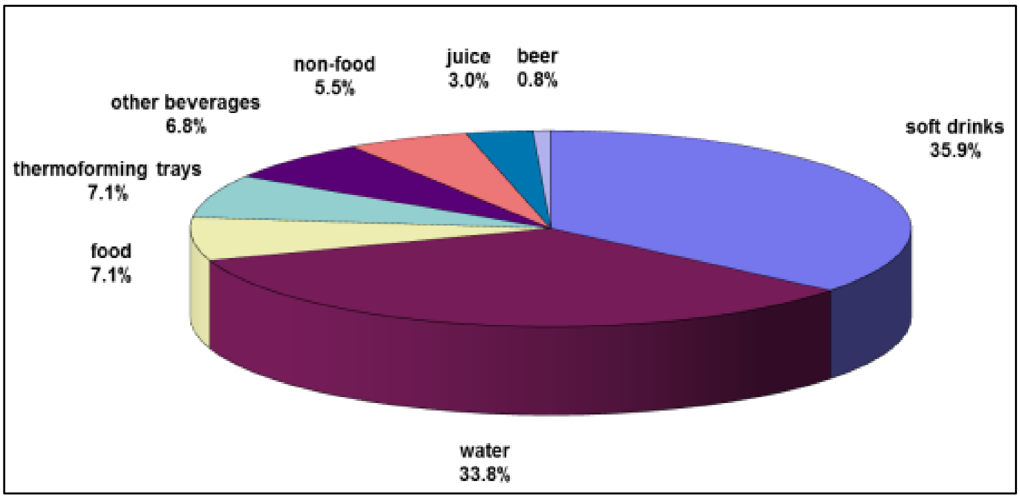

Figure 2-2 - Global uses of PET packaging in 2010 (excluding fibre) (source: EFBW, Welle, 2013)

Thus, as stated before, PET represents one of the best choices within packaging materials. The reasons behind this huge success in the packaging sector are several: starting from its simplicity in the manufacturing to its reliability in the performance in the use stage.

Indeed, it is suitable for a lot of uses: being strong, shatterproof and inert material, it can be used to contain a wide variety of foods and drinks, without compromising the freshness, or affecting human health. In addition, its lightweight and transparency serve a more convenient package, easy to store, carry, clean up and re-seal (NAPCOR, 2010).

A progressing innovation in the design of PET package offers the possibility to increase the efficiencies in material production, for example reducing the weight of the product, and so reducing the need of raw materials, the transport and treatment as well as environmental impacts.

Regarding its environmental sustainability, it is important to report the PET's high recyclability. In fact, in line with the legislation's efforts to divert wastes into landfill, it is the most widely recycled plastic in the world (NAPCOR, 2010). The benefits of PET recycling are related to the preservation of raw materials, and so the reduction in the demand of virgin material, less energy requirements lead to reductions in Greenhouse Gases (GHG) missions.

PET bottles represent a large fraction of total packaging waste and are easy to sort automatically. This means that they can be considered as the principal source of recycled PET (Gouissem et al., 2014).

In Europe in 2015, over 1.8 million tonnes of PET bottles were collected for recycling, which means that nearly 59% of all bottles placed in the European market were collected for recycling (PETCORE, 2017b).

Thus, over recent years the PET bottle recycling industry has grown into a well-established business as evidence from the fact that PET bottles are being recycled into a wide variety of end products including: fibre, carpets, strapping, food and non-food bottles, and thermoformed PET packaging (Figure 2-3).

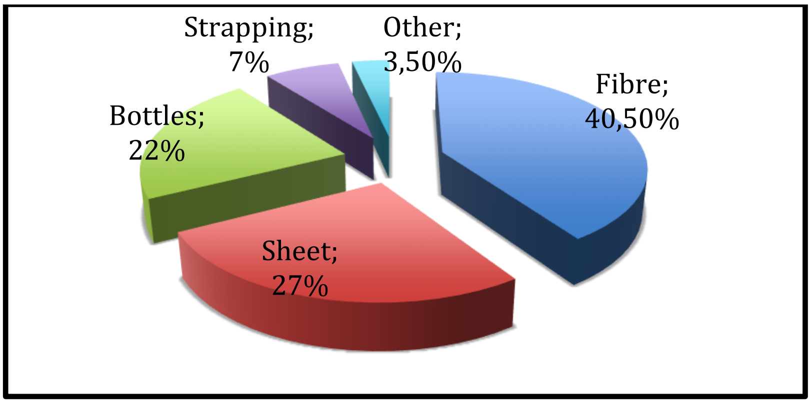

Figure 2-3 - End use market shares of recycled PET in 2009 (Source Welle, 2011)

More recent data from PETCORE and the European PET Bottle Platform (EPBP) show a dramatic decrease in the fibre market from 39.4% in 2011 to 26.4% in

2014. Opposite trend is for the bottle market, which grew from 25.3% to 29.8% in 2014 ("EPBP" , 2017 n.d.).

Post-consumer PET bottles, as stated before, are easy to recover and the different collection schemes, following the Packaging Directive (2004/12/EC), show different performances (PETCORE, 2017a):

- The kerbside collection has typically 40-60% of targeted recyclables returned. Here PET bottles are collected together with other packaging materials, thus the input material for the recycling process might contain PET bottles from both food and non-food applications.
- Drop-off locations reach about 10%-15% of recovery;
- The refill and deposit system achieves very high return rates (90%) with very low levels of contaminations of the post-consumer PET.

Once collected and transferred to a Material Recovery Facility (MRF), PET bottles wastes are sorted (caps and labels removal), compacted in bales and then sent to the reprocessing plant. Here, different recycling treatments can be realized, according to the final intended product.

2.3. PET recycling

In order to have a complete understanding of the various possibilities that can be obtained by PET recycling, a brief description of the different options is now presented.

Mechanical recycling (conventional recycling): bales are opened to be washed and then grinded into flakes. Detergents and 2-3% sodium hydroxide solutions are used as washing additives to remove dirt, labels, glue, and food leftovers from the surface of the polymer. The flakes obtained after this conventional recycling process are typically used for non-food applications, mostly stable fibres and sheets. A further extrusion leads to obtain PET pellets from flakes, which can be used for food applications (trays), strapping and non-food containers.

Chemical recycling (feedstock recycling): partial or total depolymerisation of PET to oligomers (BHET) or monomers (EG, PTA or DMT). The principal methods are glycolysis, methanolysis, and hydrolysis: actually, only the first two ones are mostly developed. Although the advantage of obtaining a higher quality recyclate, this recycling process is still not well established in the market.

Energy recovery (thermal recycling): PET bottles are included in the municipal waste that is sent to incinerators to recover heat or electricity. Another treatments such as pyrolysis, hydrogenation and gasification, lead to the feedstock/thermal recycling, where the primary energy sources, like gas or fuel, are recovered (Komly et al., 2012).

When the aim of the recycling is the production of secondary products, the most common process is the mechanical one. Here, the process to be successful has to achieve a quality of PET recyclates that meet certain minimum requirements (Figure 2-4).

Property	Value
$[\eta]$	$>0.7\ dl\ g^{-1}$
T_m	$>240\ °C$
Water content	<0.02 wt.%
Flake size	0.4 mm < D < 8 mm
Dye content	<10 ppm
Yellowing index	<20
Metal content	<3 ppm
PVC content	<50 ppm
Polyolefin content	<10 ppm

Figure 2-4 - Minimum requirements for recycled post-consumer PET (source :Awaja & Pavel, 2005)

Therefore, in order to achieve the value of IV (η) almost equivalent to that of virgin PET, PET recycled pellets could be further processed through Solid State Polycondensation. The pellets obtained through this process have the right properties to be used for the production of new bottles, although it is still not possible to have a bottle from a 100% recycled PET. The reason for this limitation is now explained.

The PET polymer during mechanical recycling is affected to degradation, which leads to the reduction of its average molecular weight as well as to mechanical properties deterioration. Moreover, the nature and level of contaminants (e.g. PVC, coloured plastics, metals, level of moisture, etc.) present in the flakes can affect the suitability of the post-consumer flake for recycling (Awaja & Pavel, 2005; WRAP, 2013).

Thus, for food-contact products, further processes like the SSP are necessary also to decontaminate post-consumer PET. Usually they consist in high temperature treatments, vacuum or inert gas treatments and surface treatments with non-hazardous chemicals to obtain so-called super-clean PET (Geueke, 2014). This kind of treatment is able to decontaminate PET to concentration levels of virgin PET materials.

Hence, due to the required rigorous decontamination levels in recycled PET for food and beverage applications, there are still limitations on the recycled content: these include reprocessing with virgin resin with blending (multi-layered products) or a content up to 35% of recycled material that can be incorporated into new product. Above this limit, there is a risk of colouration, which is unacceptable for commercial use (Shen et al., 2011).

These restrictions on the reuse of post-consumer PET in food-contact applications are covered in Europe by the Recycling Regulation, published by the European Commission in 2008, on recycled plastic materials intended to come into contact with food (282/2008/EC). In this regulation, the European Commission gave the European Food Safety Authority the mandate to evaluate the recycling petitions. Stricter work has been carried out in the United States, where the Food and Drug Administration has published guidelines on how to determine the cleaning efficiency of a recycling process: any recycling process must demonstrate its ability to remove potential contaminants due to consumer misuse, through the so-called “challenge tests”. In addition, criteria for the evaluation of the results are given in the form of a migration threshold for post-consumer substances (Welle, 2011).

To conclude, regarding the recyclability of PET, the issue around the quality assurance of recycled PET has been discussed in many studies, where different kinds of treatments and technologies have been implemented in order to understand the degradation behaviour of the polymer and find the best way of recycling.

Different trials from a WRAP's project (Waste and Resource Action Programme) have demonstrated that recycled PET (rPET) can be successfully used in the production of new retail packaging: starting from indicating the industrial processes that give a recycled PET suitable for food and beverage products, such as the Cleanaway, Amcor and Wellman recycling treatments (Martin, 2006), until evaluating their quality achievements through batch systems (Kosior & Graeme, 2006) and assessing the factors affecting the quality of recycled PET (WRAP, 2013). Nevertheless, these studies provide only the confirmation of the applicability of recycled PET only to a limited content, according to the type of treatment, level of contamination, etc. Moreover, in the quality report of WRAP (WRAP, 2013) the main problem related to the recyclability of PET is the discolouration and colour variability: it shows that the presence of contaminants such foreign polymers (PVC in particular), metals, coloured plastics or loose labels, may result in black specs in recycled PET, representing an issue for reprocessors and converters that melt filter PET flake, thus compromising its applicability to food-contact materials.

However, the dyeability of the material comes after its mechanical performance, considered the principal feature on which assess the quality level of the recycled material. Indeed, scientists like Rieckmann et al. (2011) or Elamri et al (2015), have put their research on understanding the behaviour of the mechanical (and also chemical) properties that go under degradation during the reprocessing. The principal aim of these studies is always to compare the recycled polymer to the virgin one, thus analysing the conditions necessary to achieve the specification of the quality parameters. In particular, Rieckmann investigates the changes in quality parameters (e.g. IV, TPA and Acetaldehyde concentrations) during a “closed-loop” bottle-to-bottle recycling process, with the conclusion that the PET is susceptible to hydrolysis or to a lower reactivity, meaning that its performance is not 100% reliable to a fully application, but it always needs to be blended or mixed with virgin material. Elamri reaches the same conclusion, but highlighting the mechanical losses (i.e. IV), with respect to virgin material, during reprocessing at high temperatures.

These studies, and others similar have helped to find realistic and representative values of physical properties for both recycled and virgin PET. This may lead to analyse from the physical point of view the amount of recycled material that potentially replaces the virgin one, thus defining a “technical substitution ratio” where the quality factor (QF) is accounted. On Table 2-1 there are illustrated the relevant findings, focusing on the IV values present in these studies. It can be observed that the quality factor (QF), expressing the difference between the physical properties of recycled and virgin material, is not so easy to identify uniquely, since the values of intrinsic viscosity change according to the intended application: those of virgin PET change among the desired grade of PET, and those of recycled PET among the ways of reprocessing and the desired secondary product.

Table 2-1 - Summary of the IV values of recycled and virgin PET present in literature

INTRINSIC VISCOSITY (dL/g)				
SOURCE	VIRGIN PET	r-PET	NOTES	QF
WRAP, 2006 "Large-scale demonstration of viability of recycled PET in retail packaging" (M&S, Boots)	0.84 +/- 0.02	Cleanaway: 0.75 +/- 0.04; Vaucurema: 0.79	Different recycling processes. Cleanaway: recycling with extrusion; Vaucurema: two stages under vacuum treatment system	Cleanaway: 0.89; Vaucurema: 0.94
Paper: Rieckmann et al., 2011 "Modelling of PET Quality parameters for a Closed-Loop recycling system for Food Contact."	0.78	0.7788	Virgin value referred to the Loop "0": quality parameter of virgin PET bottles after manufacture, filling and use. The rPET value is for the 5^{th} rec. loop.	0.99
Degree thesis: Plastics Technology, 2013 "Using recycled polyethylene terephthalate (PET) in the production of bottle trays."	1.05	0.90	Tests where after extrusion and under certain conditions of screw rotating speed and melting flow index, the IV's values reach higher values.	0.86
American Journal of Nano Research and Application: Elamri et al., 2015 "Characterization of Recycled/ Virgin PET Polymers and their Composites."	0.74 (PET-C)	0.63 (PET-B); 0.67 (PET-A)	A fibre-grade PET (PET-C) was used as the virgin PET resin. Recycled PET (PET-A) comes from blue post-consumer bottles. Recycled PET (PET-B) arises from heterogeneous deposits of various coloured bottles (white, green ...etc).	PET-B=0.85; PET-A=0.90

3. LIFE CYCLE ASSESSMENT METHODOLOGY

During the last three decades, the demand for studying the environmental impacts of products and systems has continuously increased, with the Life Cycle Assessment (LCA) methodology being the preferred methodology. LCA is applied in several fields and has become an important tool in environmental policy and decision-making.

The LCA methodology is defined by the International Organization for Standardization (ISO) standards 14040 and 14044: the first describes the principles and framework (ISO, 2006a), while the second presents the requirements and guidelines (ISO, 2006b) on how to conduct Life Cycle Assessment.

Thus, according to these ISO standards, the LCA methodology is carried out in four distinct phases: Goal and Scope definition, Life Cycle Inventory analysis (LCI), Life Cycle Impact Assessment (LCIA) and Interpretation. All four phases are interconnected and performed iteratively. Here follows a synthetic description of the LCA phases.

1. *Goal and Scope definition*

The first step is the goal and scope definition. The goal of the LCA should contain the intended application, the reasons for carrying out the study, the intended audience, and whether the results are to be used in comparative assertions disclosed to the public (ISO, 2006a). While defining the scope, the product system and its boundary are defined. The function of the product system delivered is also defined with the functional unit. The functional unit expresses and quantifies the function of the products, and, thereby, is defined as the "quantified performance of a product system for use as a reference unit".

In the presence of multiple-output systems (i.e. co-production), multiple-input systems (e.g. waste treatment processes) and multiple-use or "cascaded use" systems (e.g. recycling) the problem of the so-called multi-functionality shall be deal with. The scope definition further establishes the procedures to solve the cases of multi-functionality, following then definition of the procedures for the LCIA methodology, the assumptions made, the type of impacts, and so the data quality requirements.

2. *Life Cycle Inventory analysis (LCI)*

This is the phase of the LCA involving the compilation and quantification of inputs and outputs for a product throughout its life cycle (ISO 2006). It consists in the construction of a model of the reality that shall represent all the exchanges among the single unit processes of the analyzed system. The main challenge of this step is the data collection.

The input and output data shall be referenced to the functional unit. The major headings under which data may be classified include: energy inputs, raw material inputs, ancillary inputs, other physical inputs; products, co-products and waste; releases to air, water and soil; and other environmental aspects (e.g. land use).

3. *Life Cycle Impact Assessment (LCIA)*

In this phase, the objective is to understand and evaluate the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product.

At the LCIA phase, the LCI results are converted to common units, and an aggregation of the converted results are reported within the same impact category. In essence, this process involves associating inventory data with specific environmental impact categories and category indicators.

The conversion process follows several phases, depending on the level of detail required in the study. Those phases are classification, characterization, normalization, grouping and weighting.

The classification consists in the assignment of the inventory results to the selected environmental impacts, represented by the established environmental impact categories.

Subsequently, the results are multiplied by the characterization factors (and so converted into common units) and then aggregated within the same impact category: this represents the characterization phase, where characterization factors are used to express properly the different magnitude of each substance in determining the impacts.

Afterwards, the phases of normalization, grouping and weighting are optional and their implementation depends on the goal and scope of the LCA study.

4. *Interpretation*

According to ISOs, interpretation is defined as the phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations.

It permits to identify the main issues and extrapolate the significant results. In addition, sensitivity, completeness and consistency analyses allow checking the performance and reliability of the study, evaluating the quality of the data used and the uncertainty level.

Conclusions extrapolated in this phase serve to identify limitations and make recommendations with respect to the case study.

3.1. Key aspects in LCA methodology

When carrying out an LCA study, it is important to define some key points. Clearly, the decisions have to be consistent with the goal and scope of the study, hence all the assumptions and considerations shall be stated for the sake of transparency and better understanding of the study itself.

A technical guidance of the International Reference Life Cycle Data System (ILCD), named the ILCD Handbook, provides a common basis for consistent and quality-assured life cycle data and robust studies (ILCD, 2010).

Hereafter the key points in developing the LCA are presented, following the ISO standards and the ILCD Handbook.

3.1.1. The decision context

In the goal definition phase, the ISO standards require the description of the intended application, the audience and the reasons for carrying out the study. In addition, the ILCD Handbook includes also the need to define the decision context of the study. Indeed, it plays an important role especially in the modelling and methodological issues as it serves for *"defining the most appropriate methods for the LCI model, i.e. the LCI modelling framework (i.e. "attributional" or "consequential") and the related LCI method approaches (i.e. "allocation" or "substitution") to be applied" (*(ILCD, 2010).

Within the ILCD Handbook, the decision context has been classified among three situations: situations A, B and C (ILCD, 2010; Rigamonti, 2015).

SITUATION A): The LCA study serves as support to a decision on the analysed system, but the extent of changes that the decision implies in the background system (materials and energy exchanged with the activities of the analysed system) and in other systems are "small" (i.e. non-structural changes). Typically, this case is a small-scale study with a short/medium term (up to 5 years).

SITUATION B): The LCA study serves as support to a decision on the analysed system and the extent of changes that the decision implies in the background system and in other systems are "big" (i.e. structural changes). This study is usually characterized by a medium/long term (from 5 years to above), it involves a large scale, and it is typically a strategic study

SITUATION C): The LCA is not used to support a decision on the analysed system, but has an accounting/monitoring character. For this case, two further situations can be possible: the studies that are interested in including any existing benefits outside the system (e.g. recycling) represent the SITUATION C1; while, the studies that aim at analysing the system in isolation, without considering such interactions, are defined as SITUATION C2.

A summary of the decision-context situations is presented in Table 3-1:

Table 3-1 - Decision-context situations according to the ILCD Handbook Guidance (Source: ILCD, 2010)

<table>
<tr><td rowspan="4">DECISION SUPPORT?</td><td rowspan="3">YES</td><td colspan="2">Kind of process-changes in background system / other systems</td></tr>
<tr><td>None or small-scale</td><td>Large-scale</td></tr>
<tr><td>Situation A
"micro-level decision support"</td><td>Situation B
"meso/macro-level decision support</td></tr>
<tr><td>NO</td><td colspan="2">Situation C
"accounting"
(C1: including interactions with other systems; C2: excluding if interactions with other systems)</td></tr>
</table>

3.1.2. Attributional and Consequential modelling

The distinction between the two modelling approaches originates from the fact that LCA modelling depends on the goal of the study.

An accounting or cause-oriented LCA study is known as attributional LCA: this approach is conducted to learn about existing impacts, to identify areas for improvement or to make market claims (Schrijvers et al., 2016).

On the other side, a consequential approach means a prospective, effect-oriented LCA, studying the effects of direct and indirect changes in the system, as a consequence of a decision or a change in demand for a product. In practice, this approach is mostly used in decision making (Schrijvers et al., 2016).

The difficulties in modelling through these two approaches lay on the choice of data (current or marginal data) and the management of multifunctionality (to be discussed later on in chapter 3.1.3).

Since a proper definition of attributional and consequential modelling is not mentioned in the ISO standards (ISO, 2006a, 2006b), there is not a clear distinction accepted conventionally. However, the ILCD Handbook has provided different simplified provisions according to the decision context (ILCD, 2010): a representative scheme (Laurent et al., 2014) of these provisions is shown in Figure 3-1.

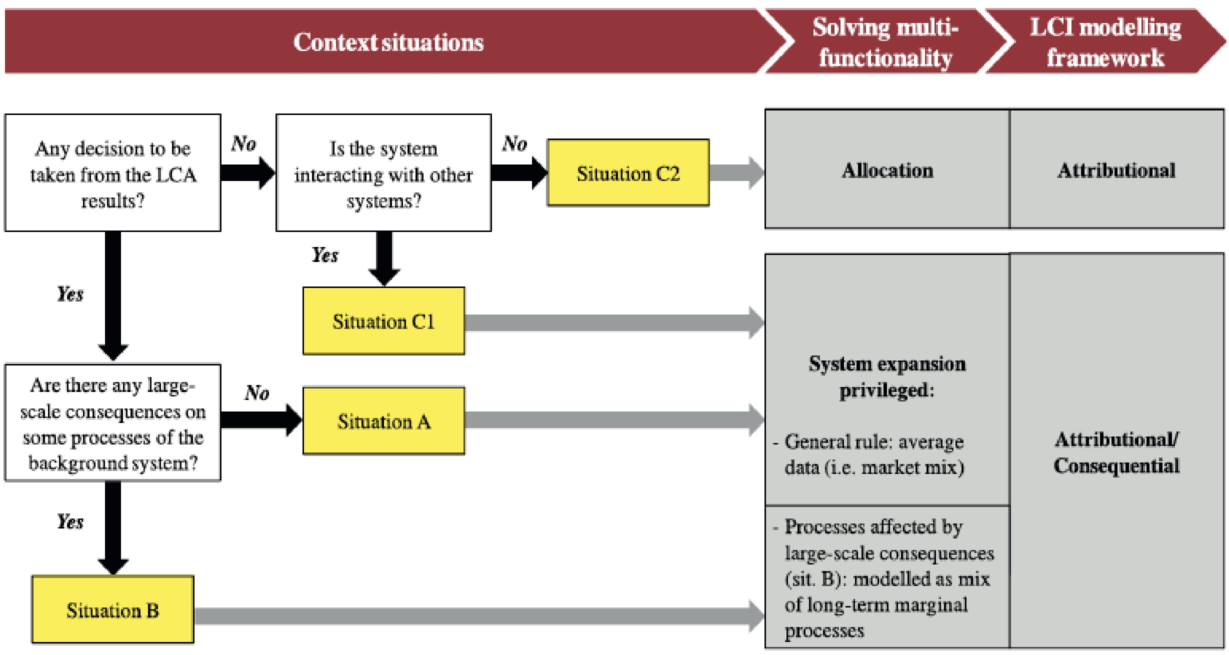

Figure 3-1 - Identification of context situations and LCI modelling framework as described by the ILCD Handbook (Source: Laurent et al., 2014)

Nevertheless, this practice is still under debate, and presents a lot of criticism about inconsistences and the proper application on the specific study (Ekvall et al., 2016).

In conclusions, practitioners shall be aware of the limits of the ILCD Handbook, thus applying reasonably and carefully the proper modelling framework with respect to the specific goal of the study.

3.1.3. Methodological approaches solving multifunctionality

The multifunctionality issue in LCA methodology is solved with allocation, for which many procedures are available. The ISO standard 14044 provides a stepwise procedure to solve the allocation issue. The first solution intends to avoid allocation by subdividing the unit process into mono-functional processes or expanding the product system to include the additional functions of the co-products in the functional unit (ISO, 2006b). When allocation cannot be avoided, the inputs and outputs of the system are partitioned between its different co-products of functions reflecting underlying physical relationships or, if these provide no basis for partitioning, other types of relationship, such as the economic value or mass (ISO, 2006b).

The ISO procedure is the general guidance, and difficulties on identifying the correct allocation approach to the specific case study cause a large number of combinations of methods to exist in scientific literature (Schrijvers et al., 2016). Hence, the methodology is lacking a clear and commonly accepted procedure that can be applied to each different case.

Moreover, when choosing the right methodology for multifunctionality, the goal of the study has to be taken into consideration, and so the decision context defined. This means that it should contemplate the link between the allocation procedure and the attributional or consequential approaches seen before. About this, the ILCD Handbook has drawn explicitly recommendations, and in particular in Annex C it provides possible procedures to handle the multifunctionality in the case of recycling (ILCD, 2010).

The present study will not enter in the specific debate on the proper definitions and procedures for solving multifunctionality, but it will focus only on the main issues that have been encountered during the work, and these are the ones related with the recycling end-of-life scenario.

3.1.4. Modelling recycling

Similarly to the case of the production of co-products, recycling processes involves other product systems and make the product under study multifunctional. The procedures, as well as the related issues, that have been explained before, are also valid for the case of recycling and re-use.

Three different forms of recycling are possible (ILCD, 2010; ISO, 2006b):

- Closed-loop recycling: when the recycled material obtained is then used as a material input in the same product system; in essence, it enters again in the same supply-chain, replacing the input of newly produced material (Rigamonti, 2015).
- Open-loop recycling (same primary route): the recycled material is used in another system, i.e. it is replacing the same material but for making a different product;
- Open-loop recycling (different primary route): the material from one product system is recycled in a complete different product system;

It is important to be aware of the fact that the “downcycling” phenomenon (in essence the loss of inherent properties of the material) can take place both in closed-loop and open-loop recycling. Examples of downcycling are in the case of recycled polymers or paper fibres: primary material cannot be avoided in every application due to shorter polymer chains or fibre lengths (downcycling phenomenon), but in a mixture with primary material the amount of the latter can be reduced (Schrijvers et al., 2016).

When dealing with recycling, two main functions are to be considered: the treatment of the waste and the production of a secondary material. Therefore, the impacts associated to recycling must be allocated between these two functions. Moreover, a material can potentially be recycled multiple times, thus the number of recycling loops should be considered as well. This means that it is not obvious at all to which product system (waste treatment and secondary material production) the environmental impacts of the multifunctional process should be attributed (van der Harst et al., 2016).

Different methods are used in LCAs to assign both the environmental impacts of the recycling process and the environmental benefits of the recycled material to the product system producing the recycled material and the product system using the recycled material (van der Harst et al., 2016). The practitioner must be aware of the fact that these different methods can result in different LCA outcomes for the same product system.

Only two methods will be addressed in the present study: the Circular Footprint Formula (CFF) and the System Expansion Method with substitution (SES). The arising interest on the new version of the PEF (Product Environmental Footprint) End-of-Life Formula (the CFF) has posed here the intent to compare it with the widely used method of System Expansion with substitution.

It now follows a general description of the two approaches chosen.

The System Expansion method

Following the ISO 14044 procedure, the first method to solve the multifunctionality is the system expansion. This approach includes the co-functions in the investigated system, thus the related systems need to be accounted.

The method can be implemented into two ways: system expansion in stricter sense or system expansion with substitution.

The first methodology looks at including the co-functions of the process of product in the functional unit. Therefore, in the case of recycling, the functional unit comprises both the life cycle that produces and the life cycle that consumes the recycled material (Schrijvers et al., 2016): it means that another system is added (the life cycle that consumes the recycled material).

On the other side, in the system expansion method with substitution the multifunctionality is solved by expanding the system boundaries and substituting the not required function with an alternative way of providing it, i.e. the process(es) or product(s) that the not required function supersedes. The practice of this method is common when the co-product of a system can replace one or more other products: for example, heat from co-generation to substitute heat from oil, or recovery of energy or material from a waste. Hence, thanks to this substitution, the activities related to the primary production of the product (heat, energy or material) are avoided. This leads to an allocation of the environmental burdens of the main product or service that includes "credits" for the avoided activities: their related environmental burdens are subtracted from the total burdens in the system. Substitution methods are often referred to as the "end-of-life", "avoided burden", or "recyclability substitution" approach(van der Harst et al., 2016).

A general representative scheme of the two approaches explained is shown in Figure 3-2.

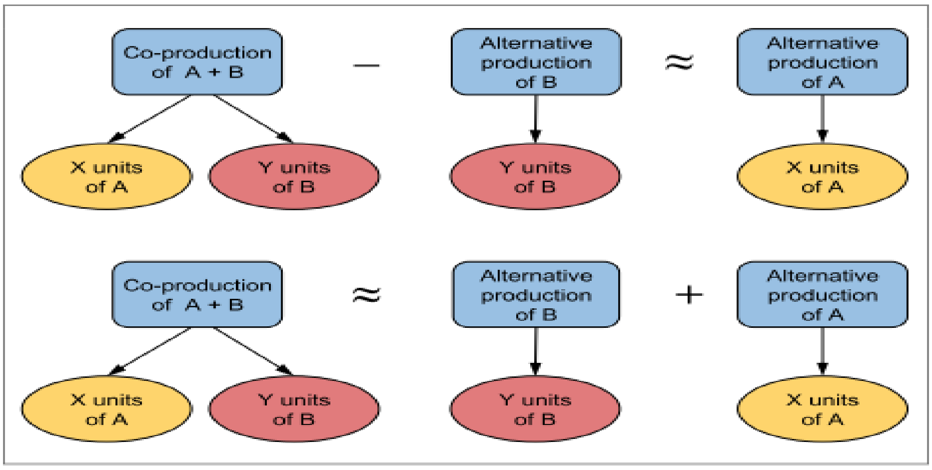

Figure 3-2 - Solving the multifunctionality problem by system expansion method with substitution (above) and in stricter sense (below) (Source: (ILCD, 2010))

The application of the substitution by system expansion method is usually used in modelling the multifunctionality of recycling, and can be applied in both closed-loop and open-loop systems (van der Harst et al., 2016). The production of recycled material is considered as replacing the conventional (primary) production of this material. By using the "avoided burden method", the impacts due to the recycling activity are accounted for and the impacts of a primary production of the material (the displaced or substituted activity) are subtracted. Thus, the avoided inventory of primary production is credited to the end-of-life product or waste according to the degree that it is recyclable (ILCD, 2010).

The Circular Footprint Formula

The methods used in modelling recycling are often represented by mathematical formulas: in the last years, the European Commission have tried to develop a comprehensive method to calculate the Environmental Footprint of Products (PEF). The intention is to find a commonly accepted standard for measuring the environmental performance of a product or service: a first guide for PEF (Recommendation 2013/179/EU) provided a method for modelling the environmental impacts of the flows of material/energy and the emissions and wastes associated to a product throughout its life cycle. This guide introduced an end-of-life formula where it is accounted: the energy recovery, the downcycling and the allocation of burdens and benefits of recycling between the producer and the user of the recycled material. The baseline formula is here presented (JRC-EU, 2014):

$$\left(1-\frac{R_1}{2}\right)\times E_V+\frac{R_1}{2}\times E_{recycled}+\frac{R_2}{2}\times\left(E_{recyclingEoL}-E^*_V\times\frac{Q_S}{Q_P}\right)+R_3\times$$
$$(E_{ER}-LHV\times X_{ER,heat}\times E_{SE,heat}-LHV\times X_{ER,elec}\times E_{SE,elec})+\left(1-\frac{R_2}{2}-R_3\right)E_D-\frac{R_1}{2}\times E^*_D$$

Formula 1 – Baseline PEF formula (Source: European Commission, 2016b)

Where:

R_1 [dimensionless]: “recycled (or reused) content of material”. It is the proportion of material in the input to the production that has been recycled from a previous system.

R_2 [dimensionless]: “recycling (or reuse) fraction of material”. It is the proportion of the material in the product that will be recycled (or reused) in a subsequent system. R2 shall therefore take into account the inefficiencies in the collection and recycling (or reuse) processes. R2 shall be measured at the output of the recycling plant.

R_3 [dimensionless]: It is the proportion of the material in the product that is used for energy recovery at EoL.

E_V: specific emissions and resources consumed (per unit of analysis) arising from the acquisition and pre-processing of virgin material.

E^*_V: specific emissions and resources consumed (per unit of analysis) arising from the acquisition and pre-processing of virgin material assumed to be substituted by recyclable materials.

$E_{recycled}$: specific emissions and resources consumed (per unit of analysis) arising from the recycling process of the recycled (or reused) material, including collection, sorting and transportation processes.

$E_{recyclingEoL}$: specific emissions and resources consumed (per unit of analysis) arising from the recycling process at the end-of-life stage, including collection, sorting and transportation.

E_D: specific emissions and resources consumed (per unit of analysis) arising from disposal of waste material at the EoL of the analysed product (e.g. landfilling, incineration, pyrolysis).

E^*_D: specific emissions and resources consumed (per unit of analysis) arising from disposal of waste material (e.g. landfilling, incineration, pyrolysis) at the EoL of the material where the recycled content is taken from.

E_{ER}: specific emissions and resources consumed (per unit of analysis) arising from the energy recovery process

$E_{SE,heat}$: specific emissions and resources consumed (impact per MJ e.g. [kg CO2e/MJ]) that would have arisen from the specific substituted energy source, heat.

$E_{SE,elec}$: specific emissions and resources consumed (impact per MJ e.g. [kg CO2e/MJ]) that would have arisen from the specific substituted energy source, electricity.

LHV: Lower Heating Value [e.g. MJ/kg] of the material in the product that is used for energy recovery. This should be determined with an appropriate laboratory method.

$X_{ER,heat}$ [dimensionless]: the efficiency of the energy recovery process ($0<XER<1$) for both heat and electricity, i.e. the ratio between the energy content of output (e.g. output of heat or electricity) and the energy content of the material in the product that is used for energy recovery. XER shall therefore take into account the inefficiencies of the energy recovery process.

$X_{ER,elec}$ [dimensionless]: the efficiency of the energy recovery process ($0<XER<1$) for both heat and electricity, i.e. the ratio between the energy content of output (e.g. output of heat or electricity) and the energy content of the material in the product that is used for energy recovery. XER shall therefore take into account the inefficiencies of the energy recovery process.

Q_s: quality of the secondary material, i.e. the quality of the recycled or reused material.

Q_p: quality of the primary material, i.e. the quality of the virgin material.

Even though the PEF formula is suitable generally for all the cases, since it includes all the aspects related to the multifunctionality (recyclability, recoverability, disposal and applications for both open and closed loop recycling), some criticisms have been encountered in its application (Finkbeiner, 2014; Lehmann et al., 2015).

Therefore, a new version of the PEF formula has been developed in order to consider and solve the previous criticisms: the Circular Footprint Formula (CFF) (Formula 2).

material
$$(1-R_1)E_V + R_1 \times \left(AE_{recycled} + (1-A)E_V \times \frac{Q_{Sin}}{Q_P} \right) + (1-A)R_2 \times \left(E_{recyclingEoL} - E^*_V \times \frac{Q_{Sout}}{Q_P} \right)$$

energy
$$(1-B)R_3 \times \left(E_{ER} - LHV \times X_{ER,heat} \times E_{SE,heat} - LHV \times X_{ER,elec} \times E_{SE,elec} \right)$$

disposal
$$(1-R_2-R_3) \times E_D$$

Formula 1 - Circular Footprint Formula (Source: European Commission, 2016b)

Where:

A: Allocation factor of burdens and credits between supplier and user of recycled materials.

B: allocation factor of energy recovery processes: it applies both to burdens and credits.

Q_{sin}: quality of the ingoing secondary material, i.e. the quality of the recycled material at the point of substitution

Q_{sout}: quality of the outgoing secondary material, i.e. the quality of the recyclable material at the point of substitution

Q_P: Quality of the primary material, i.e. quality of the virgin material.

It can be noticed that from the first version of the formula the following changes have been introduced:

Firstly, with the distinction of the quality parameters Q_{sin} and Q_{sout}, two quality ratios take into account the quality of both ingoing and outgoing recycled materials.

The introduction of an "A" factor for recycling, instead of ½ factor previously used: this is for allocate burdens and credits between two life cycles and it aims at reflecting market situations. Therefore, from the analysis of the market reality, it is possible to determine the different values of the “A” factor:

A=0.2: When the production of secondary material is low and the demand high. The formula focuses on recycling at the end-of-life. This value applies to glass, metals, paper.

A=0.5: When there is equilibrium between supply and demand for secondary material. The focus is both on the use and the production of secondary material. This value applies to plastics.

A=0.8: When the production of secondary material is high and the demand low. The formula then favours the use of recycled material. This value applies to textiles.

Another factor similar to the “A” is introduced: “B” factor to account the energy recovery at end-of-life.

The formula is intended to be applied to a specific cycle of a product; hence, the present study will try to investigate its applicability also to the case of multiple-recycling loops.

3.1.5. Selection of impact categories, category indicators and characterization models

When implementing an LCA, it is important to define the impact categories, category indicators and characterization models consistently with the goal and scope of the LCA.

The selection of impact categories shall reflect a comprehensive set of environmental issues related to the product system being studied, taking the goal and scope into consideration.

Two characterization methods are here introduced, which will be used later on in the implementation of the LCA.

The first is the ILCD 2011 Midpoint method, released by the European Commission, Joint Research Centre in 2012. It supports the correct use of the characterisation factors for impact assessment as recommended in the ILCD Handbook document "Recommendations for Life Cycle Impact Assessment in the European context - based on existing environmental impact assessment models and factors”. For the LCIA, the method includes 16 impact categories, which are listed below with the respective characterization factors (CF) (Joint Research Centre, 2010; Stranddorf et al., 2005):

1 - Climate change: related to the effect of increasing temperature in the lower atmosphere, leading to the so-called “greenhouse effect”. CF: Global Warming Potential [kg Co2 eq] calculating the radiative forcing over a time horizon of 100 years.

2 - Ozone depletion: related to the decomposition of the stratospheric ozone layer that is causing increased incoming UV-radiation, leading to impacts on humans, natural organisms and ecosystems. CF: Ozone Depletion Potential (ODP) [kg CFC-11 eq] calculating the destructive effects on the stratospheric ozone layer over a time horizon of 100 years.

3 - Human toxicity, cancer effects: related to all substances that are toxic to humans. CF: Comparative Toxic Unit for humans (CTUh) expressing the estimated increase in morbidity in the total human population per unit mass of a chemical emitted (cases per kilogram).

4 - Human toxicity, non-cancer effects: related to all substances that are toxic to humans. CF: Comparative Toxic Unit for humans (CTUh) expressing the estimated increase in morbidity in the total human population per unit mass of a chemical emitted (cases per kilogram).

5 - Particulate matter: concern on the respiratory impacts. CF: Quantification of the impact of premature death or disability that particulates/respiratory inorganics have on the population, in comparison to PM2.5 [kg PM2.5].

6 - Ionizing radiation HH (human health): related to the routine releases of radioactive material to the environment (for damage to human health). CF:

Quantification of the impact of ionizing radiation on the population, in comparison to Uranium 235 [kBq U235].

7 - Ionizing radiation E (ecosystems): related to the routine releases of radioactive material to the environment (for damage to ecosystem). Comparative Toxic Unit for ecosystems (CTUe) expressing an estimate of the potentially affected fraction of species (PAF) integrated over time and volume per unit mass of a radionucleide emitted (PAF m3 year/kg).

8 - Photochemical ozone formation: related to the degradation of volatile organic compounds (VOC) in the presence of light and nitrogen oxide (NOx) ("smog" as a local impact and "tropospheric ozone" as a regional impact). Exposure of plants to ozone may result in damage of the leaf surface, leading to damage of the photosynthetic function, discolouring of the leaves, dieback of leaves and finally the whole plant. Exposure of humans to ozone may result in eye irritation, respiratory problems, and chronic damage of the respiratory system. CF: expression of the potential contribution to photochemical ozone formation [kg NMVOC]. Only for Europe.

9 - Acidification: related to the release of protons in the terrestrial or aquatic ecosystems. In the terrestrial ecosystem, the effects are seen in softwood forests (e.g. spruce) as inefficient growth and as a final consequence dieback of the forest. CF: Accumulated Exceedance (AE) characterizing the change in critical load exceedance of the sensitive area in terrestrial and main freshwater ecosystems, to which acidifying substances deposit. European-country dependent.

10 - Terrestrial eutrophication: related to all substances that are toxic to the terrestrial environment. CF: Accumulated Exceedance (AE) characterizing the change in critical load exceedance of the sensitive area. European-country dependent.

11 - Freshwater eutrophication: related to the enrichment of aquatic ecosystems with nutrients leading to increased production of plankton, algae and higher aquatic plants leading to a deterioration of the water quality and a reduction in

the value of the utilisation of the aquatic ecosystem. CF: expression of the degree to which the emitted nutrients reach the freshwater end compartment (phosphorus considered as limiting factor in freshwater) [kg N eq]. European validity.

12 - Marine eutrophication: related to the enrichment of aquatic ecosystems with nutrients leading to increased production of plankton, algae and higher aquatic plants leading to a deterioration of the water quality and a reduction in the value of the utilisation of the aquatic ecosystem. CF: expression of the degree to which the emitted nutrients reach the marine end compartment (nitrogen considered as limiting factor in marine water) [kg N eq]. European validity.

13 - Freshwater ecotoxicity: related to all substances that are toxic to the aquatic environment. CF:Comparative Toxic Unit for ecosystems (CTUe) expressing an estimate of the potentially affected fraction of species (PAF) integrated over time and volume per unit mass of a chemical emitted (PAF m3 year/kg).

14 - Land use: relates to waste management as well as other activities is land use. CF: Soil Organic Matter (SOM) based on changes in SOM, measured in (kg C/m2/a).

15 - Water resource depletion: the principal concern is that use of the water resource leads to a reduced availability of the same resource for future generations. CF: Freshwater scarcity: Scarcity-adjusted amount of water used.

16 - Mineral, fossil & renewable resource depletion: the principal concern is that use of a given resource leads to a reduced availability of the same resource for future generations. CF: Scarcity of mineral resource with the scarcity calculated as 'Reserve base' [kg Sb eq].

When performing a LCA, sometimes the study requires to be more specific within the selection of the impact categories, in order to obtain the results as much relevant and consistent as possible.

Therefore, the study has seen the necessity to use a characterization method specific for the assessment of the environmental impacts associated with the water consumption: within the available methods, it has been chosen the Pfister Method (2009)[3].

With respect to the other methods, it intends to specify better all the features related to water consumption, from the source to the geographical location; moreover, it calculates the impacts (damages) on three areas of protection: human health, ecosystem quality and resources.

The regionalized inventory is based on "virtual water" database, i.e. on "*the amount of water evaporated in the production of, and incorporation into, agricultural products, neglecting runoff*" (Pfister et al., 2009). Theoretically, the virtual water consists in green and blue water flows, where the first is related to the precipitation and soil moisture consumed on-site by vegetation, while the second denotes the consumption of any surface and groundwater (deprivation in the watershed). The method focuses its inventory on the blue virtual water consumption and the relative impact assessment is performed using regionalized Water Stress Indexes (WSI).

The regionalization of the characterization factors for water use is an essential feature, since the impacts of water use vary greatly as a function of location. The WSI serve to indicate the ratio of water consumed that deprives other users in the same watershed of water, i.e. is based on a withdrawal to availability (WTA) ratio and modelled using a logistic function (S-curve) in order to fit the resulting indicator to values between 0.01 and 1 m^3 deprived/m^3 consumed.

Thanks to these features, the Pfister method produces more geographically-representative and accurate results, thus is also preferred to the Swiss Ecological Scarcity Method by Frischknecht et al. (2008), which is recommended by the ILCD Handbook (EFBW, 2016).

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3 The rationale behind this choice will be explained in the chapter 5.2.2 "Identification of the most relevant impact categories".

3.2. LCA and plastic waste management: a literature review

LCA is an important tool widely used within the plastics industry, helping to analyse the environmental performances throughout the plastic value chain. Thus, the scientific literature provides several LCA studies that cover different aspects of the topic, and in particular the plastic recycling.

Rigamonti et al. (2013) evaluated different plastic recovery routes, trying to understand which improvement in the plastic waste management could be potentially better. The results were quite sensitive to the quality of the produced plastic and thus on the types and levels of collection, source separation, collection and sorting efficiencies. None of the scenarios examined performed as the best for all the impact categories: however, a higher material recycling reached in the scenario where plastics are only mechanically sorted from residual waste prior to incineration, resulted as the best option in most impact categories.

Chilton et al. (2010) and Arena et al. (2003) evaluated the efficiency of recycling compared to landfill and incineration (the former focusing on PET, while the second on general plastic waste). Both stated the superiority of mechanical recycling: the basis of this convenience relies especially on the presence of a stable market for the recycled PET, then on a good collection system and extensive cleaning.

Shen et al. (2011) compared open and closed loop recycling applied on the case of PET bottles: these are reprocessed into bottles again (closed-loop) and fibres (open-loop). This comparison led to analyses the different effects of the end-use markets shares. Moreover, they assess the benefits of multiple recycling loops, which can further reduce the environmental impacts: however, the savings become negligible after the third trip. When the bottle-to-bottle market is preferred, high impact reductions are achieved, and when no extra virgin PET is required for make-up purpose, the quantities of recycled PET are maximised and so the savings.

A study by Komly et al. (2012) confirmed the conclusions of the previous studies: either mechanical or chemical recycling is always preferable to thermal recycling. Moreover, within closed loop recycling, mechanical pathway is preferred to glycolysis followed by repolymerization, being now feasible (thanks to the technical development in the last decades) and economically convenient; multi-recycling loops result to be effective with respect to minimization of impacts when the trips are at least three.

In conclusion, literature brings the attention to recycling and the overall conclusion is that it is still very challenging, and still a lot of improvements can be done towards a better-quality recycling and a market more open to secondary products.

4. CASE STUDY: LCA OF PET BOTTLES

The present chapter presents the Life Cycle Assessment (LCA) of the chosen case study.

4.1. Goal and Scope Definition

4.1.1. Goal definition

The aim of the work is to analyse the potential environmental impacts generated by PET bottles throughout their entire life, comparing two different recycling scenarios (closed and open loop recycling) in the two contexts of Denmark and Lombardy region (Italy).

The reason for carrying out this study is the development of the final Master Thesis in Environmental Engineering for Sustainability.

The study has basically an accounting/monitoring character and it is not considered to be used as an additional tool in decision-making within the plastic management sector for the two different systems analysed - even if potentially it could. It includes the analysis of existing benefits the system may have with the outside, in essence the environmental savings related to recycling activities. Therefore, according to the ILCD Handbook classification explained in chapter 3.2.1 this study is associated to the Situation C1 (ILCD, 2010).

The study can be directed to both audiences of scientific community and waste managers.

Since the Master Thesis will be disclosed to the public, comparisons may be possible. However, it will not go under critical review.

The work has been commissioned by the Research Group AWARE (Assessment on Waste and Resources) of Politecnico of Milano, Department of Civil and Environmental Engineering, with the partnership of the Division of Quantitative Sustainability Assessment belonging to DTU (Technical University of Denmark), Department of Management Engineering.

4.1.2. Scope definition

The product analysed in the study is the PET bottle, with main function to contain and deliver all kind of beverages. In specific, a PET bottle of 1.5 l and weight 28.8 gr (EFBW, 2017a), containing natural water has been chosen as representative product. This product has been elected as representative of the product system of PET bottles, due to the fact that water PET bottles are present in the beverage packaging market in the highest percentage, representing the most common product (EFBW, 2017; Welle, 2013).

The functional unit considered is *"the containment and delivery of 52,08 l of water in 1.5 l PET bottles in Denmark and Lombardy region"*. It means that 34,72 bottles are needed to fulfil the functional unit: hence, the reference flow is represented by 1 kg of PET bottles.

The entire life cycle of the PET bottle is assessed, from the manufacturing stages until its end-of-life: in particular, the focus will be on the different valorisation paths of recycling, in essence closed-loop (bottle-to-bottle) recycling and open-loop (bottle-to-fibre) recycling.

The modelling framework consists in an attributional modelling, because of the accounting character of the study and its decision context (Situation C1).

The analysis of the Danish and Italian systems and the comparison between the two different recycling routes of the PET bottles will be supported by two modelling approaches. In essence, the issue of multifunctionality from the recycling treatment will be handled with: the System Expansion Method with substitution (hereafter SES) and the Circular Footprint Formula (hereafter CFF) (see chapter 3.1.4).

When dealing with the CFF a difference between the two cases of closed and open loop recycling must be set.

In the case of closed-loop recycling, it has been taken into account that the applicability of the CFF is limited to only a specific cycle and it is still not possible to include multiple cycles all together; thus, there is not yet a proper procedure that accounts and models the multiple recycling loops in the systems considered. Therefore, the present case study investigates this issue by defining four scenarios, in which the parameters R1, R2 and the quality ratios Q_{sin}/Q_p and Q_{sout}/Q_p are selected in different ways. The first three scenarios are applied to only the first cycle and will serve as evaluation on different methods of calculating the quality ratios Q_{si}/Qp; while the parameters R1 and R2 are kept constant for the all the three scenarios. The fourth scenario, instead, will consider the other recycling loops by changing the parameters R1 and R2 according to the specific cycle; whereas the quality ratios are defined only in one way. A specific description of each scenario is presented below:

- ***Scenario 1: CFF_B2B_IV***. The value of R1 is equal to zero, and the value R2 equal to the products of the yield of collection, sorting and recycling stages. When R1 is equal to zero, it eliminates the second part of the formula that accounts for the emissions and resources consumed arising from the recycling process of the recycled material (related to $E_{recycled}$ and Q_{sin}/Q_p). Thus, the remaining quality ratio Q_{sout}/Q_p is defined accounting the degradation of the material, i.e. the variations in the values of Intrinsic Viscosity. These values will be defined for each system later on in the inventory analysis (chapter 4.3).

- ***Scenario 2: CFF_B2B_N.*** Same situation of the previous scenario, with the exception in defining the quality ratio Q_{sout}/Q_p: it is here calculated using the formula proposed by Rigamonti (2009) that considers the number of times (N) in which the material can be recycled in the system:

$$\frac{Q_{sout}}{Q_p} = \frac{1}{N+1}.$$

  N changes within the two contexts of Denmark and Lombardy region, thus its value will be defined respectively in the inventory analysis (chapter 4.3).

- ***Scenario 3: CFF_B2B_Econ.*** Again, R1 and R2 defined as the previous two scenarios (and so the second part of the formula is eliminated). While the quality factor Q_{sout}/Q_p is here accounting the economic values of the material, and so the market prices of the recycled and virgin PET. These values will be defined in the inventory analysis (chapter 4.3).

- ***Scenario 4: CFF_B2B_R1,R2=N Loops.*** The values of R1 and R2 are specific for each cycle: R1 after the first cycle will not be any more equal to zero, but it will account for the proportion of the recycled material that is used for the secondary production; equally R2 will consider the proportion of the recycled material available after the collection, sorting and recycling stages. Looking at the quality ratios, this time both Q_{sin}/Q_p and Q_{sout}/Q_p appear in the formula and are here defined accounting the degradation of the material, i.e. the variations in the values of Intrinsic Viscosity. All the values will be specified for each system directly in the inventory analysis (chapter 4.3).

In the case of open-loop recycling the situation is different, since it is assumed that the recycled fibres cannot be further recycled. Hence, as only one life cycle is analysed, the values R1 and R2 will be defined just once: R1 equal to zero and R2 equal to the product of yields of collection, sorting and recycling. Therefore, the application of the formula will only investigate the different ways of defining the quality ratios. As happens in the first three B2B scenarios, the part of the formula with Q_{sin}/Q_p is deleted, so only Q_{sout}/Q_p must be defined. Thus, two scenarios are developed:

- ***Scenario 1: CFF_B2F_IV.*** The quality factor is accounting the physical properties, in essence the intrinsic viscosity.
- ***Scenario 2: CFF_B2F_Econ.*** The quality factor is considering the economic values.

The values of the parameters R1, R2 and Q_{sout}/Q_p selected for these scenarios will be shown in the inventory analysis (chapter 4.4).

This kind of distinction of scenarios within the CFF approach will help to understand its applicability on multifunctional systems: thus, the final results will be compared with the SES approach in order to observe the main differences between the two approaches.

System Description and System Boundary

The following life stages are included in the system boundaries: virgin material production, bottle production, collection and sorting phase, and as end-of-life only the recycling treatment, with the related efficiencies (Y=Yield), followed by the secondary production phase. The virgin material production is referred to only the PET polymer, and there are not considered the additional materials necessary for the production of the bottle (such as the ones for lid and labels). Other phases not included in the analysis, are the water filling (bottling) and the use phase, together with the related transport. The rationale behind these exclusions is that these phases are considered negligible with respect to the other life-cycle stages of the system under study.

With respect to the secondary production phases, the analysis involves the first treatments necessary for the production of the secondary good (bottle or fibre textile): hence, for the secondary bottles production it has been considered the up-grading process of Solid State Polycondensation (SSP), through which the recycled PET flakes are converted into bottle-grade PET ready for further processing for the bottle production (without material losses); while, in the fibre case, the only spinning process has been considered for the conversion of the PET flakes into fibre[4] (ready to be converted into fabrics).

In order to track the path of the initial 1 kg of PET bottles produced at the first life cycle, a Material Flow Analysis (MFA) is conducted.

Within the bottle-to-bottle (B2B) scenarios, the secondary production of bottles has the constraint of 35% of recycled content (Komly et al., 2012) representing the limit of applicability of recycled material in food-contact-materials production: hence, it is necessary a make-up of virgin PET for the production of secondary bottles. For the evaluation of the potential multiple recycling loops in the system, in the MFA the initial 1 kg of PET has been kept isolated throughout all the phases, even though in the reality when producing the secondary bottles there is no distinction between recycled and virgin material.

There are now presented the system boundaries for both the Danish and Italian context.

Bottle-to-Bottle scenario in Lombardy

The scheme below (Figure 4-1) is showing the system boundary in Lombardy region. It considers the path of PET bottles from production until collection and end-of-life. The efficiencies related to collection and recycling are representing the regional context and their values will be better explained in the inventory analysis (chapter 4.3). The collection phase is considering that only the PET bottles are collected, hence in the following steps of sorting and recycling, the stream is considered already only PET: this means that the efficiency of the sorting stage is assumed 100%.

According on how the MFA has been set, it can be supposed that the initial 1 kg of PET bottles tracked in the Lombardy context can reach up to two recycling loops: this because the amount of recycled PET available -coming from the

[4] In the reality, for the fibre production also chemicals are needed, but their addition depends on the intended application of the fibre. Due to the lack of data this phase is accounting only the spinning process.

initial 1 kg- results to be not sufficient for a further recycling after the second loop.

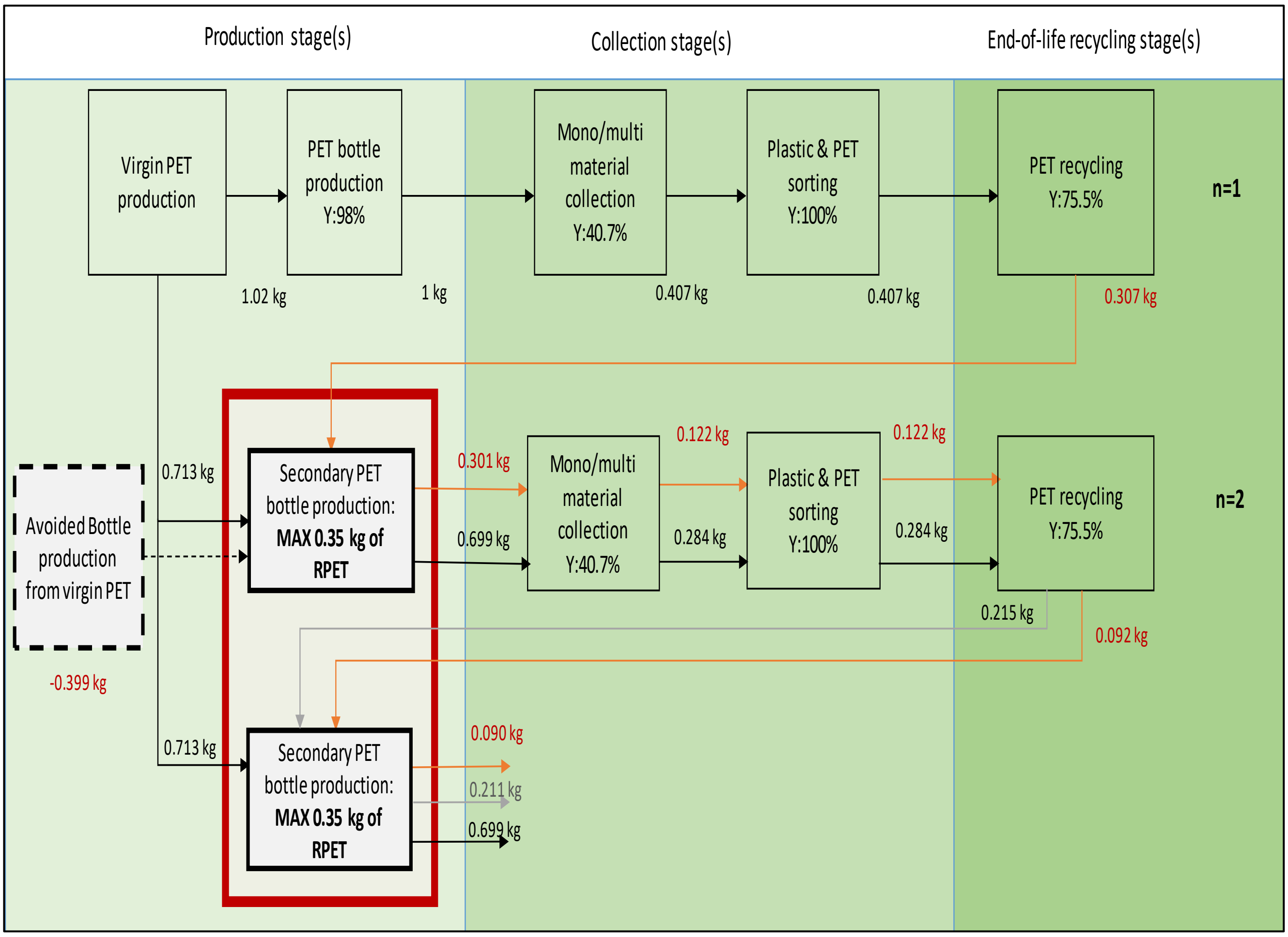

Figure 4-1 – System Boundary and Material Flow Analysis for Bottle-to-bottle scenario in Lombardy region. Legend: n=number of cycle; flows: virgin PET (black); 1st recycled PET (red); 2nd recycled PET (grey).

Bottle-to-bottle scenario in Denmark

For the case of Denmark, the system boundary accounts for the same phases considered in the Lombardy case. The collection is assumed to be implemented only by the deposit system, as it will be explained in detail in the inventory analysis (chapter 4.3). Thanks to this type of collection, the sorting phase is analysed together with the collection phase.

Similarly to what has been done for the Lombardy case, from the MFA set, it can be supposed that the initial 1 kg of PET bottles tracked in the Danish context can reach up to four recycling loops: after the four loop the amount of recycled PET available coming from the initial 1 kg results to be not sufficient for a further recycling and it is assumed to be sent to incineration together with the other municipal wastes. In this situation, when considering the constraint of maximum 35% of recycled content in the secondary production of PET bottles, the amount of recycled material available from the first cycle is higher than the one that can be sent to the bottle manufacturer: hence, the surplus is assumed to be sent to other recycling routes, such as fibre production. This phase is not considered in the analysis, to avoid increasing the complexity of the study.

Figure 4-2 shows the scheme above described.

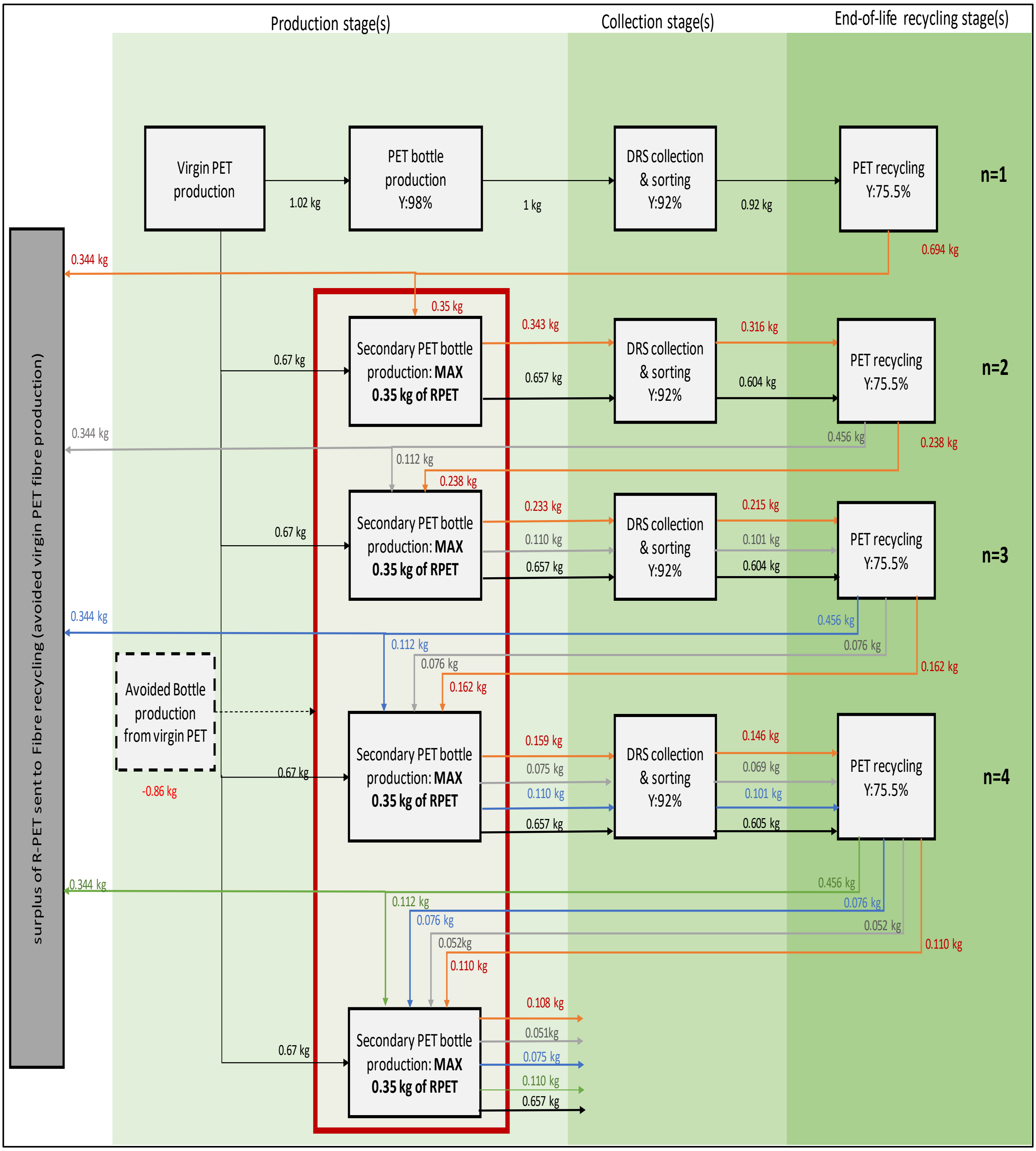

Figure 4-2 – Boundary System and Material Flow Analysis for Bottle-to-bottle scenario in Denmark. Legend: n=number of cycle; flows: virgin PET (black); 1st recycled PET (red); 2nd recycled PET (grey); 3rd recycled PET (blue); 4th recycled PET (green).

Bottle-to-fibre scenario in Lombardy

For the case of B2F scenario, the phases and efficiencies considered are equals to the ones of the B2B scenario, with the exception of the final step of recycling: it is assumed a 100% of efficiency in for the spinning process[5], meaning that the recycled PET obtained from the recycling can be converted into fibres without material losses, or it is not necessary to add a virgin material to increase the performance of the secondary product. Figure 4.3 represents the case of Lombardy region.

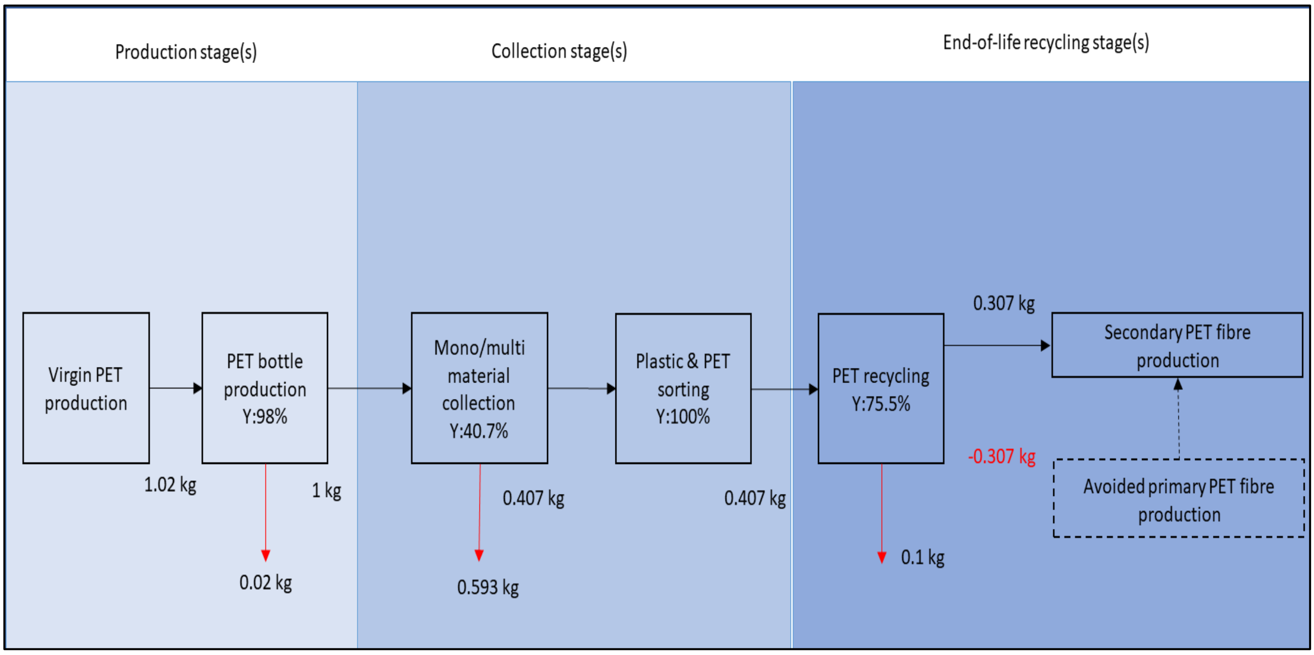

Figure 4-3 – Boundary System and Material Flow Analysis for Bottle to fibre scenario in Lombardy. Legend: PET bottle life-cycle until recycling (black line); Material losses (red line).

Bottle-to-fibre scenario in Denmark

Same considerations explained above are valid in this case: Figure 4-4 reports the Danish situation.

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[5] Without source. However, the research done for the study did not encountered any different statements: i.e. when looking for the fibre production and spinning processes, no material losses were considered.

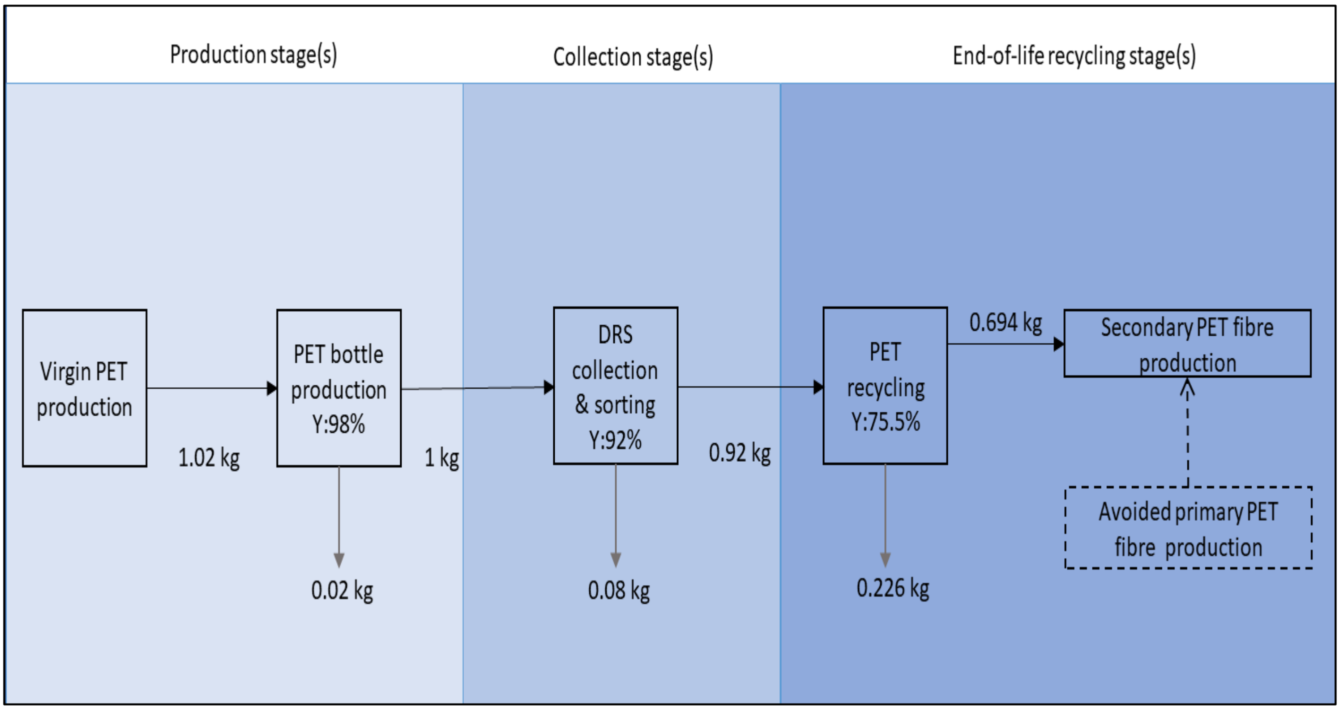

Figure 4-4 - Boundary System and Material Flow Analysis for Bottle to fibre scenario in Lombardy. Legend: PET bottle life-cycle until recycling (black line); Material losses (red line).

4.2. Inventory analysis

This phase is necessary to quantify all the materials, resources and emissions associated to the life stages considered in the system. Each stage has been modelled by using the software Simapro 8.3. This kind of software allows to model and analyse life cycles of products and services, measuring their environmental impacts: hence, in addition to the LCI model, it is possible to carry out the LCIA of the interested system.

4.2.1. The Lombardy case

The present chapter contains a detailed description of the data used in modelling the Italian system. A previous data collection phase was necessary to obtain the correct and consistent data representative of the interested system.

Hereafter all the phases included in the model are reported.

Phase 1. PET bottles production

This phase is split into two parts because it is necessary to account for the different location of the polymer production and the bottle production.

a) Virgin PET manufacture

For the primary material production (i.e. PET granules) the bottle-grade PET is here considered, therefore to model this phase the dataset of ecoinvent 3: used is *Polyethylene terephthalate, granulate, bottle grade [RER] | production | alloc Def, U.* This dataset uses data based on the average unit process from the Eco-Profiles of the European plastic industry (PlasticsEurope, 2017). An efficiency of 100% is here assumed.

The manufacturing plant assumed is the JBF RAK Europe BVBA, a 100% subsidiary of JBF Group and the single largest PET manufacturing site in Europe, located in Geel, Belgium ("JBF RAK", 2017). The plant provides different types of PET bottle grade, thus the product chosen which accomplish the ideal properties of the present system product is the ARYA PET CHIPS - AP0076 with the features reported in Table 4-1:

Table 4-1- features of the ARYA PET CHIP - AP0076 produced in JBF's plant in Geel (source: ("JBF RAK LLC," 2017)

Property	STM (Standard Test Method)	UNIT	VALUES
Intrinsic Viscosity	ASTM 2857	dl/gm	0.760±0.02
Carboxyl End groups	Titrometric	Meq/Kg	Max .35
Colour Value	Hunter Scale (L, a, b)		<1.5 ; >80.0
Acetaldehyde	G.C	(PPM)	<1.0
Melting Point	Hot stage microscope	°C	248±2
Moisture	Manometric	%	<0.10

b) Bottle production

This phase accounts for the production of PET bottles, considering the reference flow of 1 kg of PET bottles, in accordance with the goal and scope definition. The inputs considered here are the previous module of virgin PET granules and the process of Stretch Blow Molding necessary to obtain the final bottle. This process accounts for the energy and material consumptions, as well as its efficiency (98% (Kuczenski et al., 2011)) and the related dataset is *Stretch blow moulding {RER}| production | Alloc Def, U*. This dataset is accounting already itself the treatment of residuals coming from the process: "1 kg of this process equals 0.978 kg of stretch blow moulded plastics".

The manufacturing plant assumed for the bottle production in Italy is the San Pellegrino Spa Nestlè Waters Italia, located in Cespina Valdisotto (Sondrio). The plant produces the type of water bottle which can be representative of the case study: the 1.5L LEVISSIMA water bottle. San Pellegrino company is one of the major groups in the bottle production (being within the first eight producers in Italy in 2016 (Bevitalia, 2016)).

Moreover, the transport of the virgin material to the bottle manufacturing plant needs to be accounted: the distance between the two plants considered is of 933 km, and the dataset used is *Transport, freight, lorry 3.5-7.5 metric ton, EURO4 {RER}| Alloc Def, U*.

Phase 2. Collection

In order to trace the path of the post-consumer PET bottles, it is necessary to have the data of plastic waste collection in the Lombardy region. By using the data provided by the Consortium COREPLA, the starting value considered is 40.7%, representing the rate of total plastic collected for recycling in Italy in 2015 (Corepla, 2016). Due to the lack of region-specific and polymer (PET)-specific data this value has been chosen as representative for the collection of the PET bottles in Lombardy region.

When counting for the transport related to this phase, it has been considered the distance covered by the municipal collection trucks, among kerbside, street containers, ecological centres and multi-material collection: the value used, equal to 0.00234 kg·km, refers to the data from Rigamonti (2012), which is 28.2 km/t. In order to be as much realistic as possible, it has been created ex novo in ecoinvent a module that comprises two different datasets of transport: for 50% a dataset for small trucks (*Transport, freight, lorry 3.5-7.5 metric ton, EURO4 {RER}| Alloc Def, U* and for the remaining 50% the dataset for bigger trucks (*Transport, freight, lorry 16-32 metric ton, EURO4 {RER}| Alloc Def, U.*

The amount of PET bottles not collected are then sent to incineration: this goes under the hypothesis that the prevalence of the wastes in Lombardy are treated through incineration. The dataset used is *Municipal solid waste {IT}| treatment of, incineration | Alloc Def, U.* When quantifying the amount, it must be taken into consideration the difference between the B2B and B2F scenario: in the first one the total amount of PET bottles not collected is 0.772 kg, considering the two recycling loops; instead in the B2F scenario the amount is 0.593 kg.

3. Sorting

The collected plastics are sent to the material recovery facilities where a sorting phase is implemented to separate the different fractions (and so the different polymers) and to eliminate the first undesired elements (labels, films, foreign materials, ect.). Since in the previous phase it has been assumed that the material collected is already PET (bottles), the efficiency of sorting is considered equal to 100%. Moreover, the subsequent phases of bottle sorting (by colour), compacting and baling are considered negligible (Shen et al., 2011).

Hence, when modelling this sorting phase, only energy consumptions and transport are accounted for.

The energy consumption of this phase is associated to the sorting machineries and its average value is 26.6 kWh/ton of electric energy and 84 MJ/ton of diesel (Rigamonti et al., 2012). The value of electricity is consistent also if the consumption of the single machineries is accounted separately: summing up the energy consumption of the near infra-red (NIR) separator, the film removing phase, the sieves, the magnets, the eddy current separator (ECS) and the bag trimmer values derived from the paper Rigamonti et al. (2013), a very similar value is obtained.

The ecoinvent datasets used are: for energy: *Electricity, medium voltage {IT}| market for | Alloc Def, U*; for diesel *Diesel, burned in diesel-electric generating set {GLO}| market for | Alloc Def, U.*

Regarding the transport of the collected material to the sorting facility, an average value of 10 km is defined (Rigamonti et al., 2012). The related dataset used is *Transport, freight, lorry >32 metric ton, EURO4 {RER} | Alloc Def, U.*

Phase 5. PET recycling

The PET recycling includes inputs of energy and materials necessary to obtain the recycled flakes. The data derived from Rigamonti et al. (2013) are referred all to kg of recycled PET, and they are: electric energy consumption of 0.32 kWh/kg (*Electricity, medium voltage {IT}| market for | Alloc Def, U)*; methane consumption of 2.56 MJ/kg (*Methane, 96% by volume, from biogas, high pressure, at user {GLO}| market for | Alloc Def, U)*; water and sodium hydroxide respectively of 2.96 kg/kg *Tap water {RER}| market group for | Alloc Def, U)* and 0.003 kg/kg (*Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Alloc Def, U).*

For the transport of the collected and sorted PET to the recycling plant, a distance of 50 km is assumed and the ecoinvent dataset used is *Transport, freight, lorry >32 metric ton, EURO4 {RER}| transport, freight, lorry >32 metric ton, EURO4 | Alloc Def, U.*

It is also modelled the treatment of residuals coming from the efficiency of the process, which is equal to 75.55% (Rigamonti et al., 2012): the related dataset is *Municipal solid waste {IT}| treatment of, incineration | Alloc Def, U.* As observed in the collection phase, the amount of residuals differs among the B2B and B2F scenarios: in the first is 0.129 kg, and in the second is 0.099 kg.

Phase 6. Secondary productions

Bottle-to-bottle scenario

The secondary bottle production phase has been modelled accounting for the following features:

- ✓ The treatment necessary for the secondary bottle production: the PET flakes obtained from recycling must be upgraded to bottle-grade quality, through a process of Solid State Polycondensation. This process has been created as a new model ex novo in Simapro accounting for the energy consumption (1.96 MJ/kg); its value is taken from Shen et al. (2011).
- ✓ The transport from the recycling plant to the bottle manufacturer (San Pellegrino Spa Nestlè Waters in Sondrio) is added: a distance of 150 km is estimated by taking the Montello S.p.A (Bergamo) as a representative PET recycling plant. The related model used is the ecoinvent dataset: *Transport, freight, lorry 7.5-16 metric ton, EURO3 {RER}| transport, freight, lorry 7.5-16 metric ton, EURO3 | Alloc Def, U.*

The two different approaches of modelling the closed-loop scenario are described.

- Modelling with the system expansion method with substitution (SES)

The phase of PET bottles production using the recycled material is here modelled through the system expansion approach. The impacts of all the processes described above are summed up, thus adding the avoided production of virgin PET (bottle-grade) as impact savings. This avoided production is accounted in Simapro with the dataset *Polyethylene terephthalate, granulate, bottle grade {RER}| production | Alloc Def, U*. The related amount is 0.399 kg, which correspond to the total amount of recycled material sent to the bottle production (within the concept of recycling leading to avoid the production of primary material.

- Modelling with the Circular Footprint Formula (CFF)

According to what has been explained in the scope definition (chapter 4.1.2), the Formula will be implemented in four scenarios, where different values are chosen for the parameters R1, R2 and Q_{si}/Q_p. The other elements that have to be defined when applying the formula are: the factor A, and the selection of the processes corresponding the different "E_i" (emissions and resources consumed). As it has been explained in chapter 3.1.4, the proper value for the A factor is 0.5. Then, for the E_i:

- E_v: the bottle production;
- $E_{recyclingEoL}$: the recycling phase;
- E^*_v: the secondary production;
- E_D: the disposal treatment;
- $E_{recycled}$: -when is possible to define it- is assumed to be related again to the secondary production phase.

For the following first three scenarios, the parameters of R1 and R2 are equal for all, since are referred to the first life cycle: R1 equal to zero and R2 equal to 0.307 (given by the product of the yields of the PET life cycle from collection to recycling). Whereas the quality ratio has been considered differently for each scenario, as following:

Scenario 1 CFF_B2B_IV: quality factors accounting for the degradation of the material are taken from Rieckmann et al. (2011). The value of Q_{sout} is derived by the average value of the Intrinsic Viscosity values of each recycling cycle (0.7788 dL/g); the value of Q_p is equal to 0.780 and refers to the value of Virgin PET bottles (after manufacture, filling and use). Thus, the final Q_{sout}/Q_p is equal to 0.998.

Scenario 2 CFF_B2B_N: the quality ratio Qsout/Qp is defined by the formula expressed in chapter 4.1.2. and it is equal to 0.333, since only two cycles (N=2) are possible in the context of Lombardy region.

Scenario 3 CFF_B2B_Econ: quality factor accounting for the economic value of the materials, and so the prices of the recycled and virgin PET. These two values have been taken from the ICIS website, which is the world's largest petrochemical market information provider (ICIS, 2017): the values are referred to the European situation in 2015 and the virgin PET price is equal to 1080-1210 €/ton, whereas the R-PET flakes costs 800-850 €/ton. Therefore, the quality ratio Q_{sout}/Q_p and is equal to 0.72.

For the fourth scenario, the further recycling loops are taken into consideration: the values of R1 and R2 are specific for each cycle, while it has been assumed that no variation in the quality ratio takes place. This leads to the assumption of Q_{sin}/Q_p equal to Q_{sout}/Q_p (see note in the table 4-2).

Scenario 4 CFF_B2B_R1,R2=N loops: R1 is representing the proportion of the material in the product that has been recycled: hence, in the first loop R1 is equal to zero and in the second one is equal to 0.307. R2 is the proportion of the material in the product that will be recycled in the subsequent system: thus, in the first loop R2 is equal to 0.307 and in the second one is equal to 0.092. Every loop has been developed separately in Simapro; an arithmetic average of the related results has been computed in order to obtain a final scenario which accounts for all the recycling loops.

In the following table, the values used for each scenario are summarized.

Table 4-2– CFF scenarios for modelling the B2B case in Lombardy system.

Scenario	R_1 [-]	R_2 [-]	Q_{sout}	Q_p	Q_{sout}/Q_p [-]
CFF_B2B_IV	0	0.307	0.7788[a]	0.78[a]	0.998
CFF_B2B_N	0	0.307	-	-	0.333[1]
CFF_B2B_(Econ)	0	0.307	825[b]	1145[b]	0.721

CFF_B2B_R1,R2=1st loop	0	0.307	0.7788[a]	0.78[a]	0.998
CFF_B2B_R1,R2=2nd loop	0.307	0.092	0.7788[a]	0.78[a]	0.998

Legend: a) dL/g; b) €/ton). 1) formula from Rigamonti with N=2; 2) Experiment data in Rieckmann representing the average values of the IV within recycling loops, thus it has not been taken into consideration the Qsin/Qp ratio since the paper do not provide a valid number for the first two cycles.

Bottle-to-fibre scenario

The open-loop scenario is now described, taking into consideration the following features regarding the fibre production process:

- ✓ The spinning process needed to spun the r-PET flake into fibres is considered through its energy consumption, whose values are taken from Shen et al. (2010): the electricity (dataset *Electricity, medium voltage {RER}| market group for | Alloc Def, U*) of 0.64 kWh and heat (dataset *Heat, central or small-scale, natural gas {RER}| market group for | Alloc Def, U*) of 5 MJ.
- ✓ The transport of the recycled material to the fibre manufacturer has been considered with distance of 100 km (assumed), and the model used is the ecoinvent dataset: *Transport, freight, lorry 7.5-16 metric ton, EURO4 {RER}| transport, freight, lorry 7.5-16 metric ton, EURO4 | Alloc Def, U.* To assume this distance, a research on the fibre manufacturers has been done, and in order to be as much as realistic as possible, the following firm has been chosen as reference location: the Noyfil SA in Switzerland, of RADICI Group, is specialized in the production of 100% recycled fibres, in addition to the virgin polyester fibres. Hence, assuming the Montello S.p.A as the representative recycling plant for PET, the distance of 100 km considered derives from an
- ✓ average distance between these two plants chosen.

Moreover, it has been taken into account that the secondary fibre cannot be further recycled (Shen et al., 2011), so no further recycling steps are contemplated.

The two different approaches used for modelling the open-loop scenario are here described.

- Modelling with the system expansion method with substitution (SES)

The phase of fibre production using the recycled material is here modelled through the system expansion approach. The impacts of all the modelled processes are summed up, thus adding the avoided production of virgin fibre as impact saving. This avoided production is accounted in Simapro with the dataset *Viscose fibre {GLO}| viscose production | Alloc Def, U*. The related amount is 0.307 kg, which correspond to the total amount of recycled material sent to the fibre production.

- Modelling with the Circular Footprint Formula (CFF)

According to what has been explained in the scope definition (chapter 4.1.2), when applying the formula in the B2F case, there are considered two scenarios: the first one defines the quality ratio through physical values (IV), and the second one through the economic values (Econ). Both scenarios define the parameters R1 and R2 equally, with R1 equal to zero and R2 equal to the product of the yields of the PET life cycle from collection to recycling, i.e. 0.124.

The other elements of the formula that have to be defined are: the factor A, and the different "E_i" (emissions and resources consumed). The former is equal to 0.5, while for the E_i:

- E_v: the bottle production;
- $E_{recyclingEoL}$: the recycling phase;
- E^*_v: the secondary production;
- E_D: the disposal treatment.

The values of the quality ratio in both scenarios are representative of the fibre system. Indeed:

Scenario 1 CFF_B2F_IV: Q_{sout} is the quality material of the recycled PET flakes from the bottle reprocessing and is equal to 0.67 dL/g (the flakes are not upgraded to bottle-grade PET). While, for the Q_p value representing the virgin fibre grade PET is assumed a value of 0.74 dL/g. Both values are taken from Elamri et al. (2015). Then final value of Q_{sout}/Q_p is 0.905.

Scenario 2 CFF_B2F_Econ: Q_{sout} and Q_p values have been taken from the ICIS website, which is the world's largest petrochemical market information provider (ICIS, 2015): Q_{sout} is equal to 500 US/ton and Q_p to 830 US/ton. Their ratio (Q_{sout}/Q_p) is 0.602.

In the following table, there are summarized the values used for each scenario.

Table 4-3– CFF scenarios for modelling the B2F case in Lombardy system. Legend for units of measure: a) dL/g; b) US/ton).

Scenario	R_1 [-]	R_2 [-]	Q_{sout}	Q_p	Q_{sout}/Q_p [-]
CFF_B2F_IV	0	0.307	0.67^a	0.74^a	0.905
CFF_B2F_Econ	0	0.307	500^b	830^b	0.602

4.2.2. The Denmark case

The modelling implemented the Denmark system is similar to the Lombardy one: hence, to avoid repetitions, there are here presented only the variations from the Italian case.

Phase 1. PET bottles production

For this phase, the difference takes place in the choice of the bottle manufacturing plant. Indeed, in the Danish context the assumed manufacturing plant is the Mineralvandsfabrikken Frem A/S located in Ribe (Jutland). The Mineralvandsfabrikken Frem A/S company is also one of the actionists of the Dansk ReturSystem A/S.

Thus, accounting the transport of the virgin material to the bottle manufacturing plant considered, it results in a distance of 746 km. The dataset used is *Transport, freight, lorry 3.5-7.5 metric ton, EURO4 {RER}| Alloc Def, U.*

Phase 2. Collection and sorting

As explained in the chapter 1.4.1, PET bottles collection in Denmark is regulated by the deposit system Dansk ReturSystem (DRS). Even though a portion of PET bottles present in the market may end up into the general household waste stream, in this study only the collection from the deposit system is considered.

Once collected the waste from the deposit system, it is responsibility of the DRS to sort and separate the different packaging materials at the recovery facility: here the different fractions are sorted and the undesired materials are eliminated.

On the basis of how the DRS works, two fundamental considerations have been pointed out: it is assumed that the collection occurs directly from a store (i.e. a supermarket) to the recovery facility, without covering other routes for further stores[6]; the two phases of collection and sorting are contemplated together since the amount of waste returned to the stores is directly collected and sorted at the recovery facility (sorting centre).

The efficiency considered for this phase is 92%, representing the amount of PET bottles collected and sorted at the recovery plant (Life, 2012).

It has been assumed an average distance of 10 km covered from the store to the recovery facility and the related ecoinvent dataset is *Transport, freight, lorry 16-32 metric ton, EURO4 {RER}| transport, freight, lorry 16-32 metric ton, EURO4 | Alloc Def, U.*

Then, this phase is accounting also for the energy consumption associated to the sorting machineries: due to the lack of country-specific data, there are used the same data of the Lombardy case (average values of 26.6 kWh/ton of electric energy and 84 MJ/ton of diesel (Rigamonti et al., 2012)). Thus, the ecoinvent datasets are the same, except for the electricity one, which is here *Electricity, medium voltage {DK}| market for | Alloc Def, U* (country-specific).

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[6] No sources available for this assumption. However, it is hypothesized that the amount of waste collected in a store or a supermarket is considerable, and so sufficient to fill the collection truck.

Finally, because of the efficiency of the process, there are also waste not intercepted by the collection, which have to be taken into account. As well as in Lombardy, it is assumed that the waste not collected is sent to incineration: the related dataset is *Municipal solid waste {DK}| treatment of, incineration | Alloc Def, U* and the amount is 0.138 kg in the case of B2B scenario, and 0.08 kg in the B2F scenario.

Phase 3. PET recycling

In the recycling phase, the data used (both values and datasets) are equivalent to the ones in the Lombardy system, except for the dataset related to the electricity consumption, which is country-specific: *Electricity, medium voltage {DK}| market for | Alloc Def, U.*

With regard to the residuals (material losses) from the recycling process, it is still assumed that are sent to incineration and the dataset related to this treatment is *Municipal solid waste {DK}| treatment of, incineration | Alloc Def, U.* The quantities in Denmark are 0.391 kg in the B2B scenario and 0.226 in the B2F one.

Phase 4. Secondary productions

Bottle-to-bottle scenario

The data changed in this phase is only the transport from the recycling plant to the bottle manufacturer (Mineralvandsfabrikken Frem A/S in Ribe): a distance of 120 km is estimated by taking as a representative PET recycling plant, one located near Odense, namely the STENA recycling. The related model used is the ecoinvent dataset: *Transport, freight, lorry 7.5-16 metric ton, EURO4 {RER}| transport, freight, lorry 7.5-16 metric ton, EURO4 | Alloc Def, U.*

There are now described the two different approaches used for modelling the closed-loop scenario.

- Modelling with the system expansion method with substitution (SES)

What changes from the Italian system is the amount of avoided virgin material production: in the Danish system it is 0.86 kg, corresponding to the total amount of recycled material sent to the bottle production.

- Modelling with the Circular Footprint Formula (CFF)

The changes within the CFF modelling are only in the values of the parameters R1 and R2, while the definition of the other elements of the formula (A and E_i) remain the same. With regard to the ratio Q_{si}/Q_p, the values are considered equal to Italian case -since are not country-specific-, with the only exception for the scenario CFF(N), which depends on the number of cycles assumed in the system under study.

Scenario 1 CFF_IV: R1 equal to zero and R2 equal to 0.694 (given by the product of the yields of the PET life cycle from collection to recycling).

Scenario 2 CFF_N: the quality ratio Q_{sout}/Q_p is defined by the formula expressed in chapter 4.1.2. and it is equal to 0.2, since four cycles (N=4) are possible in the Denmark context.

Scenario 3 CFF_Econ: R1 equal to zero and R2 equal to 0.694 (given by the product of the yields of the PET life cycle from collection to recycling).

Scenario 4 CFF_R1,R2=N loops: R1 is representing the proportion of the material in the product that has been recycled: hence, in the first loop R1 is equal to zero and in the second one is equal to 0.694. R2 is the proportion of the material in the product that will be recycled in the subsequent system: thus, in the first loop R2 is equal to 0.35 (from the hypothesis of the maximum recycled content acceptable for the secondary bottle production) and in the second one is equal to 0.238. And so on until the fourth loop. In the table below there are illustrated all the values.

In the following table, there are summarized the values used for each scenario.

Table 4-4– CFF scenarios for modelling the B2B case in Denmark system

Scenario	R_1 [-]	R_2 [-]	Q_{sout}	Q_p	Q_{sout}/Q_p [-]
CFF_B2B_IV	0	0.694	0.7788[a]	0.78[a]	0.998
CFF_B2B_ N	0	0.2	0.7788[a]	0.78[a]	0.998
CFF_B2B_(Econ)	0	0.694	825[b]	1145[b]	0.721
CFF_B2B_R1,R2=1st loop	0	0.694	0.7788[a]	0.78[a]	0.998
CFF_B2B_R1,R2=2nd loop	0.35	0.238	0.7788[a]	0.78[a]	0.998
CFF_B2B_R1,R2=3rd loop	0.238	0.162	0.7788[a]	0.78[a]	0.998
CFF_B2B_R1,R2=4th loop	0.162	0.11	0.7788[a]	0.78[a]	0.998

Legend for units of measure: a) dL/g; b) US/ton).

Bottle-to-fibre scenario

In the Danish system, the transport of the recycled material to the fibre manufacturer has been considered with distance of 150 km (assumed), and the model used is the ecoinvent dataset: *Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {RER}| transport, freight, lorry 3.5-7.5 metric ton, EURO3 | Alloc Def, U*. As well as in the Lombardy case, to assume this distance, a research on the fibre manufacturers has been done: after an evaluation of the major fibre producers in northern Europe, an average value between these ones was chosen; then, taking as reference a recycling plant located near Odense (STENA recycling), the path considered from the recycling plant to the manufacturer gives a rounding value of 150 km.

It follows now the description of the two different approaches used for modelling the open-loop scenario.

- Modelling with the system expansion method with substitution (SES)

What changes from the Italian system is the amount of avoided virgin material production: in the Danish system it is 0.694 kg, corresponding to the total amount of recycled material sent to the fibre production.

- Modelling with the Circular Footprint Formula(CFF)

The changes are only in the R1 and R2 values: the former is equal to zero and the latter is equal to the product of the yields of the PET life cycle from collection to recycling, i.e. 0.694.

In the following table, there are summarized the values used for each scenario.

Table 4-5 - CFF scenarios for modelling the B2F case in Denmark system

Scenario	R_1 [-]	R_2 [-]	Q_{sout}	Q_p	Q_{sout}/Q_p [-]
CFF_B2F_IV	0	0.694	0.67[a]	0.74[a]	0.905
CFF_B2F_Econ	0	0.694	500[b]	830[b]	0.602

Legend for units of measure: a) dL/g; b) US/ton).

5. RESULTS AND DISCUSSION

It is now possible to move on to the next phases of the LCA: the impact assessment and the interpretation.

5.1. Impact assessment

The phase of impact assessment is fundamental for the evaluation and understanding of the magnitude and significance of the potential environmental impacts of the studied system. This process has been implemented through the software Simapro 8.3 and the characterization method selected for the analysis is the ILCD 2011 Midpoint+ version 1.09: this method accounts for 16 midpoint impact categories, which are the ones illustrated in chapter 3.1.5. Later on, there will be examined also the results of the analysis using the method by Pfister et al. (2009) (explained in chapter 3.1.5).

The results are presented and discussed in line with the goal of the study (chapter 4.1.1):

"...analyse the potential environmental impacts generated by PET bottles throughout their entire life, comparing two different recycling scenarios (closed and open loop recycling) in the two contexts of Denmark and Lombardy region.".

Thus, they are illustrated for the two contexts of Lombardy region and Denmark separately. According to the scope definition (chapter 4.1.2), each context contemplates in total eight scenarios among the B2B and B2F recycling scenarios, and among the different modelling scenarios considered for the SES and CFF methodologies.

5.1.1. The Lombardy case

The results of the characterization phase done for the B2B and B2F scenarios are shown in Figures 5-1,2 and Tables 5-1,2[7]. It can be observed that, for many of the impact categories, the B2F scenarios present values lower than the B2B one. Nevertheless, in order to define quantitatively this difference, it is necessary a more detailed analysis within the results from the SES and CFF modelling scenarios.

Looking at the results obtained through the SES method, the B2F scenario shows lower impacts with respect to the B2B one for several impact categories (namely 12), in particular for the Ozone Depletion, Particulate Matter and Land Use impact categories, where the differences are in the range of 31-52%. An opposite outcome is given for the following impact categories: for Climate Change, Human Toxicity-cancer effects, and both Ionizing Radiation HH and E (Interim) impact categories, is the B2B scenario that presents lower values with respect to the B2F one, (but only up to 9%).

Similar results can be observed looking at the CFF results: the general trend is that the B2B scenarios in mostly all the impact categories give higher impacts with respect to the B2F ones (up to 35%). Nevertheless, the fourth B2B scenario presents in more than half of the impact categories results lower than the B2F scenarios. This particular behaviour is investigated later on, when the SES and CFF results are analysed in detail.

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[7] In order to facilitate the comprehension of the results, they have been split out in two figures and tables (eight impact categories per each).

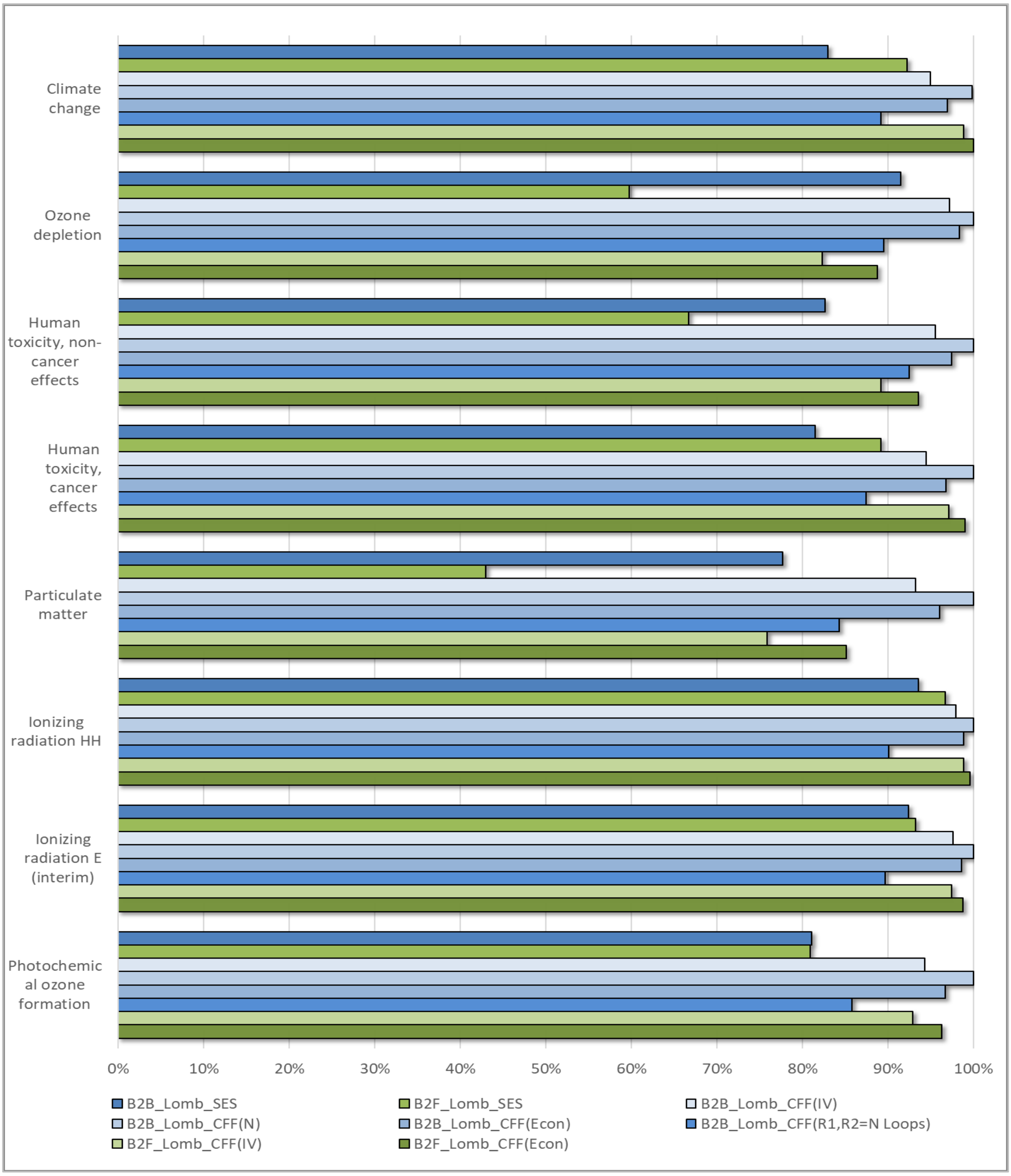


Figure 5-1- Results of LCIA for 1 kg of PET bottles recycled into both bottles (B2B scenario) and fibres (B2F scenario) in the context of Lombardy region (eight impact categories).

Table 5-1- Results of LCIA for 1 kg of PET bottles recycled into both bottles (B2B scenario) and fibres (B2F scenario) in the context of Lombardy region (eight impact categories).

Impact Category	B2B_ SES	B2F_ SES	B2B_ CFF (IV)	B2B_ CFF (N)	B2B_ CFF (Econ)	B2B_ CFF (R1,R2=N Loops)	B2F_ CFF (IV)	B2F_ CFF (Econ)
Climate change *(kg CO2 eq)*	4.66	5.19	5.34	5.61	5.45	5.01	5.56	5.63
Ozone depletion *(kg CFC-11 eq)*	3.84E-07	2.51E-07	4.08E-07	4.20E-07	4.13E-07	3.75E-07	3.45E-07	3.72E-07
Human toxicity, non-cancer effects *(CTUh)*	1.46E-06	1.18E-06	1.68E-06	1.76E-06	1.72E-06	1.63E-06	1.57E-06	1.65E-06
Human toxicity, cancer effects *(CTUh)*	2.80E-07	3.06E-07	3.24E-07	3.43E-07	3.32E-07	3.00E-07	3.33E-07	3.40E-07
Particulate matter *(kg PM2.5 eq)*	0.00236	0.00131	0.00283	0.00304	0.00292	0.00256	0.00231	0.00259
Ionizing radiation HH *(kBq U235 eq)*	0.86	0.89	0.90	0.92	0.90	0.82	0.91	0.91
Ionizing radiation E (interim) *(CTUe)*	2.41E-06	2.44E-06	2.55E-06	2.61E-06	2.58E-06	2.34E-06	2.55E-06	2.58E-06
Photochemical ozone formation *(kg NMVOC eq)*	0.0119	0.0119	0.0139	0.0147	0.0142	0.0126	0.0137	0.0142

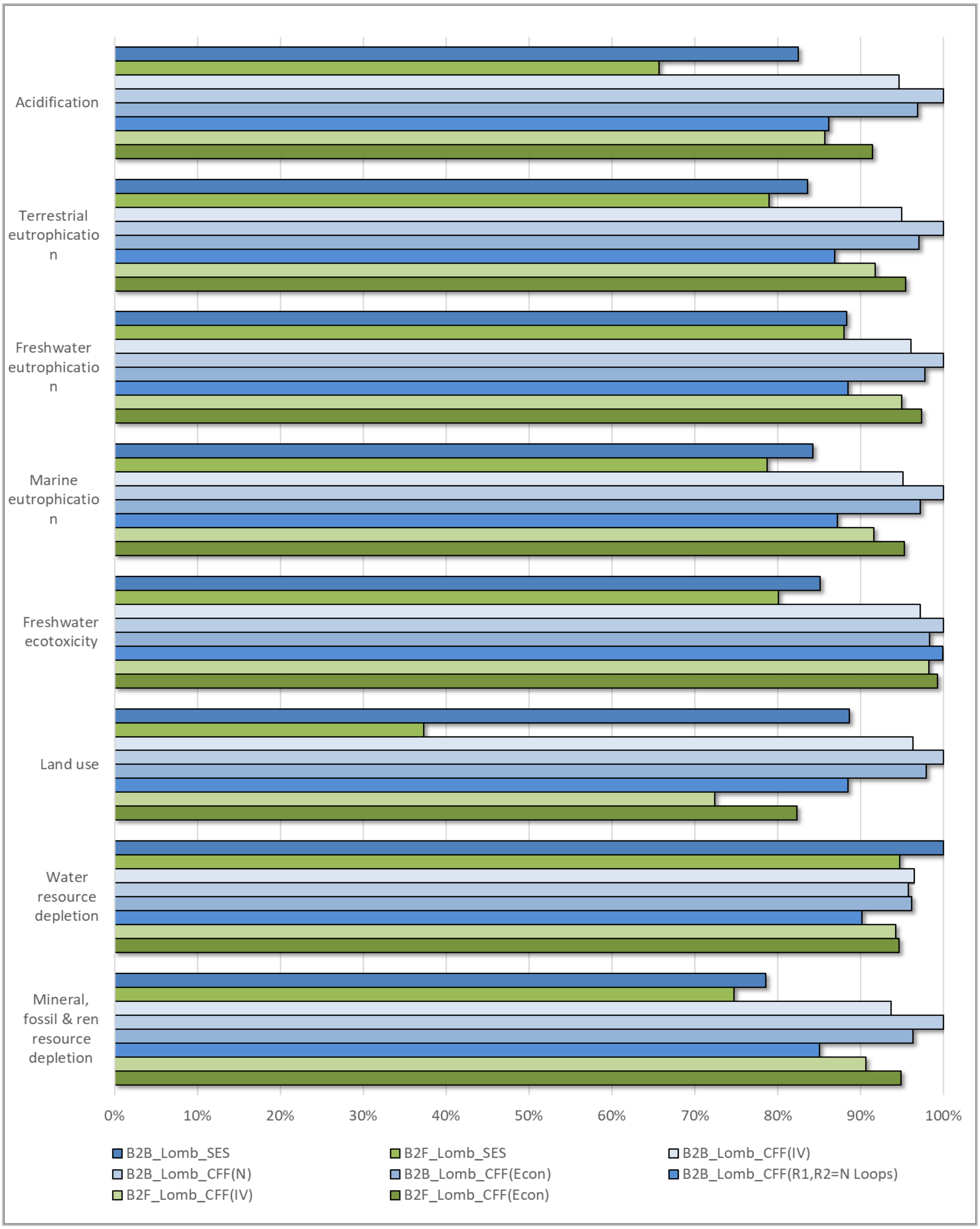


Figure 5-2- Results of LCIA for 1 kg of PET bottles recycled into both bottles (B2B scenario) and fibres (B2F scenario) in the context of Lombardy region (eight impact categories).

Table 5-2- Results of LCIA for 1 kg of PET bottles recycled into both bottles (B2B scenario) and fibres (B2F scenario) in the context of Lombardy region (eight impact categories).

Impact Category	B2B_ SES	B2F_ SES	B2B_ CFF (IV)	B2B_ CFF (N)	B2B_ CFF (Econ)	B2B_ CFF (R1,R2=N Loops)	B2F_ CFF (IV)	B2F_ CFF (Econ)
Acidification *(molc H+ eq)*	0.0222	0.0177	0.0255	0.0269	0.0261	0.0232	0.0231	0.0246
Terrestrial eutrophication *(molc N eq)*	0.0383	0.0362	0.0435	0.0459	0.0445	0.0398	0.0421	0.0438
Freshwater eutrophication *(kg P eq)*	0.00205	0.00204	0.00223	0.00232	0.00227	0.00205	0.00220	0.00226
Marine eutrophication *(kg N eq)*	0.00388	0.00363	0.00438	0.00461	0.00448	0.00402	0.00422	0.00439
Freshwater ecotoxicity *(CTUe)*	65.69	61.77	74.98	77.19	75.90	77.12	75.80	76.64
Land use *(kg C deficit)*	5.55	2.34	6.03	6.26	6.13	5.54	4.53	5.16
Water resource depletion *(m3 water eq)*	0.0185	0.0175	0.0178	0.0177	0.0178	0.0167	0.0174	0.0175
Mineral, fossil & ren resource depletion *(kg Sb eq)*	0.000196	0.000186	0.000233	0.000249	0.000240	0.000212	0.000226	0.000236

From the figures and tables above it is also possible to examine the differences between the two methodologies, in order to understand how the choice of modelling can influence the results. Generally, for both B2B and B2F scenarios, the SES results are lower than the CFF ones, except for the Water Resource Depletion impact category. To define quantitatively these differences, the SES and CFF results are analysed (and compared) for each recycling scenario (B2B and B2F).

B2B modelling. The SES method presents lower values with respect to the CFF in the range of 5-21%, with the only exception of the CFF(R1,R2=N loops) for the

Ozone Depletion and Ionizing Radiation (both) impact categories. It is important to note that this particular scenario, among the CFF scenarios, presents results that are generally closest to the SES ones. The SES and CFF(R1,R2=N loops) scenarios have in common that are accounting for the multiple recycling loops, whereas the remaining three CFF scenarios not. Implementing the multiple loops in the CFF(R1,R2=N loops) scenario means that the parameters involved change, hence the contributions of E_v, $E_{recycled}$ and Q_{sin}/Q_p from the second part of the formula are included; the direct consequence is that E_v($=E^*_v$ in the case of B2B), representing the "bottle production" phase, results to be lower than the one accounted in the others scenarios[8]. Among the remaining three scenarios the difference takes place in the definition of the quality ratio: as it can be detected from the Figures 5-1,2, the scenario CFF(IV) gives the lowest results, followed by the CFF(Econ) and CFF(N); again, the Water Resource Depletion impact category presents a different trend, with the CFF(IV) giving the highest results. Apart from this exception, the results highlight that lower values (and so impacts) are obtained if referring the quality ratio to the variation of the physical properties of the material or also to the economic values: indeed, the two scenarios CFF(IV) and CFF(Econ) do not exhibit big differences in the results (only up to 6%).

B2F modelling. As well as in the B2B case, the SES results are lower than the CFF one (up to 45%); the most relevant differences can be noted in the Particulate Matter (43%) and Land Use impact categories (43%). Regarding the CFF scenarios, the scenario accounting for the IV in the quality ratio presents results lower than in the other scenario accounting for the economic values: as well as in the B2B, the differences in the results are not very significant (3-9%).

[8] The specific results of each scenario are illustrated in the Annex.

5.1.2. The Denmark case

In Figures 5-3,4 and Tables 5-3,4 there are illustrated[9] the results of the characterization phase for the B2B and B2F scenarios in the Danish context.

The trend in the results is similar to the one in Lombardy, thus analogous considerations can be deduced.

When comparing the B2B and B2F scenarios, the first one generally presents higher results with respect to the B2F ones: the impact categories showing this trend are the same of the Lombardy case, with the addition of the Ionizing Radiation E(interim) impact category, thus 13 in total. The most pronounced differences take place also here for the Ozone Depletion, Particulate Matter and Land Use impact categories (up to 84%).

Looking at the SES scenarios, the B2F results are lower than the B2B ones for mostly all the impact categories: in particular, within the Particulate Matter and Land Use impact categories, the B2F scenario reaches negative values (respectively -38% and -52%). This means that the resulting impacts allocated to the recycling of the PET bottles into the Viscose Fibre are negative (i.e. they are benefits). On other hand, the B2B scenario gives lower impacts with respect to the B2F one only for the Climate Change, Human Toxicity-cancer effects and Ionizing radiation HH impact categories (in the range of 5-25%).

Regarding the CFF method, the general trend, as well as in the Italian case, is that the B2B scenarios in mostly all the impact categories give higher impacts with respect to B2F. The exception is for the fourth B2B scenario CFF(R1,R2=N loops), which presents results lower than the B2F scenarios for the same impact categories of SES (adding also the second Ionizing Radiation category).

[9] In order to facilitate the comprehension of the results, they have been split out in two figures and tables (eight impact categories per each).

As addressed in the Italian case, the discussion on the results entails also the analysis on the differences between the two methodologies, to further investigate how the different ways of modelling can influence the final results.

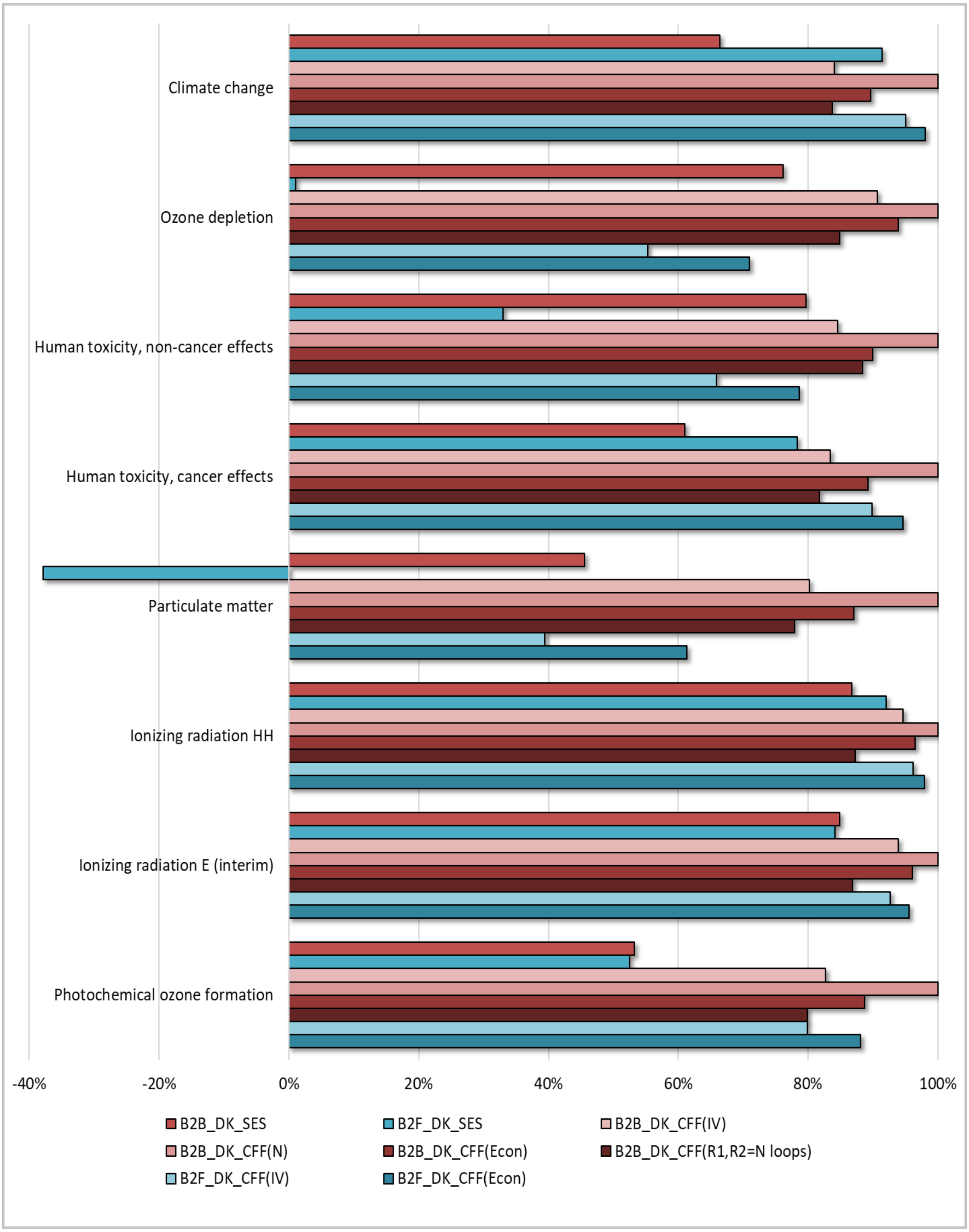

Climate change
Ozone depletion
Human toxicity, non-cancer effects
Human toxicity, cancer effects
Particulate matter
Ionizing radiation HH
Ionizing radiation E (interim)
Photochemical ozone formation
-40%
-20%
0%
20%
40%
60%
80%
100%
B2B_DK_SES
B2F_DK_SES
B2B_DK_CFF(IV)
B2B_DK_CFF(N)
B2B_DK_CFF(Econ)
B2B_DK_CFF(R1,R2=N loops)
B2F_DK_CFF(IV)
B2F_DK_CFF(Econ)

Figure 5-3- Results of LCIA for 1 kg of PET bottles recycled into both bottles (B2B scenario) and fibres (B2F scenario) in the context of Denmark. (eight impact categories)

Table 5-3- Results of LCIA for 1 kg of PET bottles recycled into both bottles (B2B scenario) and fibres (B2F scenario) in the context of Denmark. (eight impact categories)

Impact Category	B2B_ SES	B2F_ SES	B2B_ CFF (IV)	B2B_ CFF (N)	B2B_ CFF (Econ)	B2B_ CFF(R1,R2= N loops)	B2F_ CFF (IV)	B2F_ CFF (Econ)
Climate change *(kg CO2 eq)*	3.22	4.43	4.07	4.84	4.34	4.05	4.60	4.75
Ozone depletion *(kg CFC-11 eq)*	2.95E-07	3.83E-09	3.52E-07	3.88E-07	3.64E-07	3.29E-07	2.15E-07	2.76E-07
Human toxicity, non-cancer effects *(CTUh)*	1.10E-06	4.55E-07	1.16E-06	1.38E-06	1.24E-06	1.22E-06	9.07E-07	1.08E-06
Human toxicity, cancer effects *(CTUh)*	1.90E-07	2.44E-07	2.60E-07	3.12E-07	2.78E-07	2.55E-07	2.80E-07	2.95E-07
Particulate matter *(kg PM2.5 eq)*	0.00132	-0.00110	0.00232	0.00290	0.00252	0.00226	0.00114	0.00178
Ionizing radiation HH *(kBq U235 eq)*	0.7809	0.8286	0.8521	0.9002	0.8689	0.7855	0.8664	0.8817
Ionizing radiation E (interim) *(CTUe)*	2.17E-06	2.15E-06	2.40E-06	2.55E-06	2.45E-06	2.22E-06	2.36E-06	2.44E-06
Photochemical ozone formation *(kg NMVOC eq)*	0.00731	0.00722	0.01136	0.01374	0.01219	0.0109	0.0109	0.01211

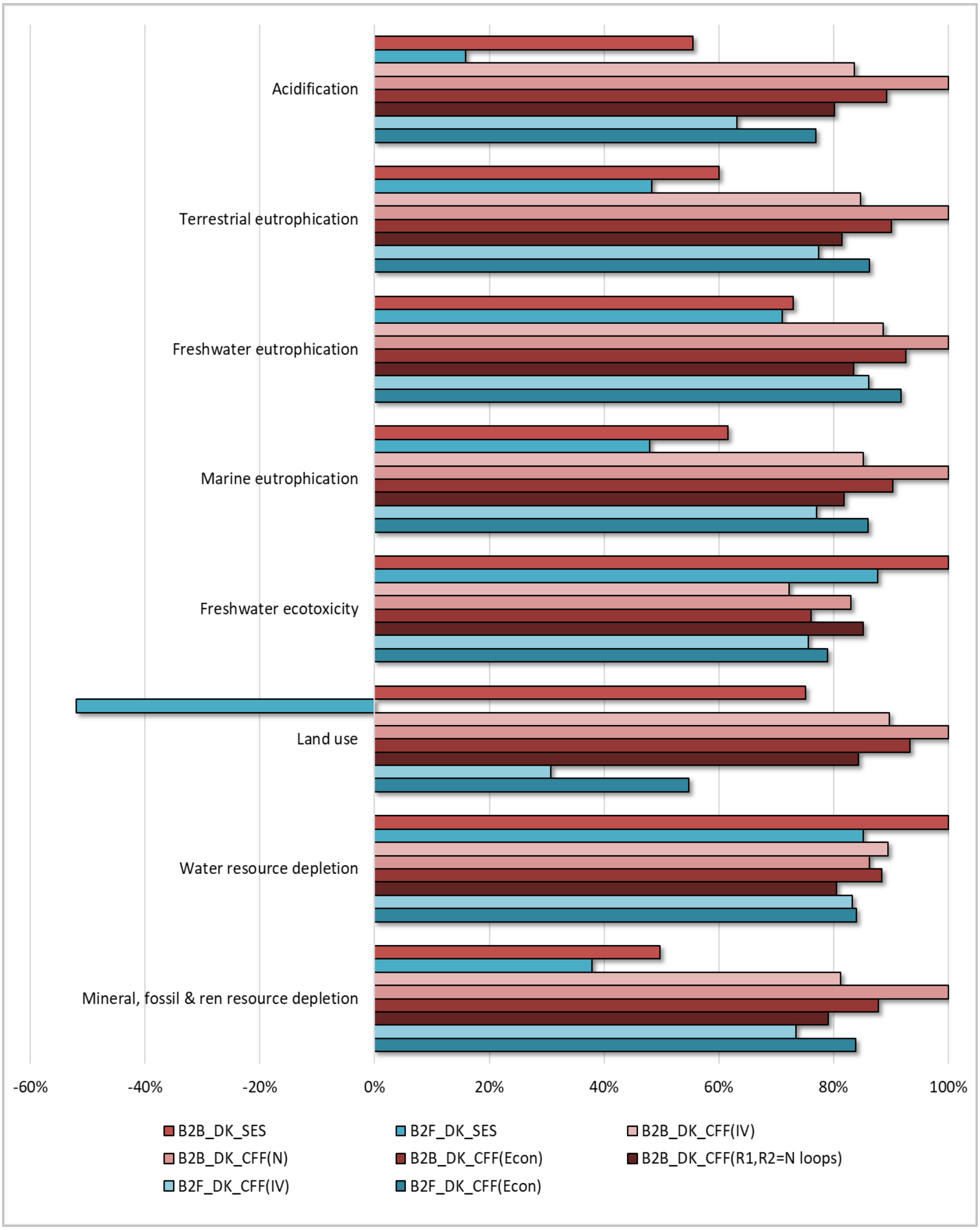


Figure 5-4- Results of LCIA for 1 kg of PET bottles recycled into both bottles (B2B scenario) and fibres (B2F scenario) in the context of Denmark. (eight impact categories)

Table 5-4- Results of LCIA for 1 kg of PET bottles recycled into both bottles (B2B scenario) and fibres (B2F scenario) in the context of Denmark. (eight impact categories)

Impact Category	B2B_ SES	B2F_ SES	B2B_ CFF (IV)	B2B_ CFF (N)	B2B_ CFF (Econ)	B2B_ CFF(R1,R2= N loops)	B2F_ CFF (IV)	B2F_ CFF (Econ)
Acidification *(molc H+ eq)*	0.01	0.00	0.02	0.03	0.02	0.02	0.02	0.02
Terrestrial eutrophication *(molc N eq)*	2.55E-02	2.06E-02	3.60E-02	4.25E-02	3.83E-02	3.46E-02	3.29E-02	3.67E-02
Freshwater eutrophication *(kg P eq)*	1.61E-03	1.57E-03	1.96E-03	2.21E-03	2.05E-03	1.84E-03	1.90E-03	2.03E-03
Marine eutrophication *(kg N eq)*	2.63E-03	2.05E-03	3.64E-03	4.28E-03	3.86E-03	3.50E-03	3.30E-03	3.68E-03
Freshwater ecotoxicity *(CTUe)*	55.86540	48.96882	40.37943	46.39138	42.47214	47.57477	42.21463	44.11634
Land use *(kg C deficit)*	4.3860	-3.0324	5.2359	5.8341	5.4441	4.9206	1.7912	3.1943
Water resource depletion *(m3 water eq)*	2.05E-02	1.74E-02	1.83E-02	1.77E-02	1.81E-02	1.65E-02	1.70E-02	1.72E-02
Mineral, fossil & ren resource depletion *(kg Sb eq)*	0.000114	0.000087	0.000186	0.000229	0.000201	0.000181	0.000168	0.000192

The considerations on the differences between the methodologies are basically similar to the ones deduced in the Lombardy case. The SES method shows results lower than the CFF method for both B2B and B2F scenarios, except for the Water Resource Depletion category.

the differences between the two methodologies can be defined quantitatively when looking at the specific recycling scenarios.

B2B modelling: the SES results are lower than the ones of the CFF from 5% up 55%. The highest differences take place with respect to the CFF(N) scenario, which basically for all the impact categories presents the highest impacts, except for the Water Resource Depletion. While the remaining three scenarios are different to the SES results up to 30% (highest values reached in Land Use and Photochemical Ozone Formation categories). Among the CFF scenarios the general trend is that the fourth scenario CFF(R1,R2=N loops) gives the lowest results, with the exception of Freshwater Ecotoxicity category, where instead is the highest. Apart this exception, the rationale behind the trend of this particular CFF scenario is the same explained in the Lombardy case: the fourth scenario is accounting for the multiple recycling loops (lower E_v), while the other three are related to only the first life cycle. While, among the first three CFF scenarios the general trend is that the CFF(IV) scenario has the lowest impacts, followed by the CFF(Econ) and finally the CFF(N); only for the Water Resource Depletion the trend is the opposite, with the order CFF(N), CFF(Econ) and CFF(IV).

B2F modelling. Similar consideration can be done for the B2F case: the SES results are still lower than the CFF scenarios, except for the Water Resource Depletion and Freshwater Ecotoxicity categories. In can be noted that the credits from the avoided production of Viscose fibre are significant, especially looking at the Particulate Matter and Land Use categories, where the SES results are negative. Among the CFF scenarios, as well as in the B2B case, the scenario accounting for the IV in the quality ratio presents lower results than the other one accounting for the economic value: nevertheless, their difference in the results is not very significant (up to 5%).

5.2. Interpretation

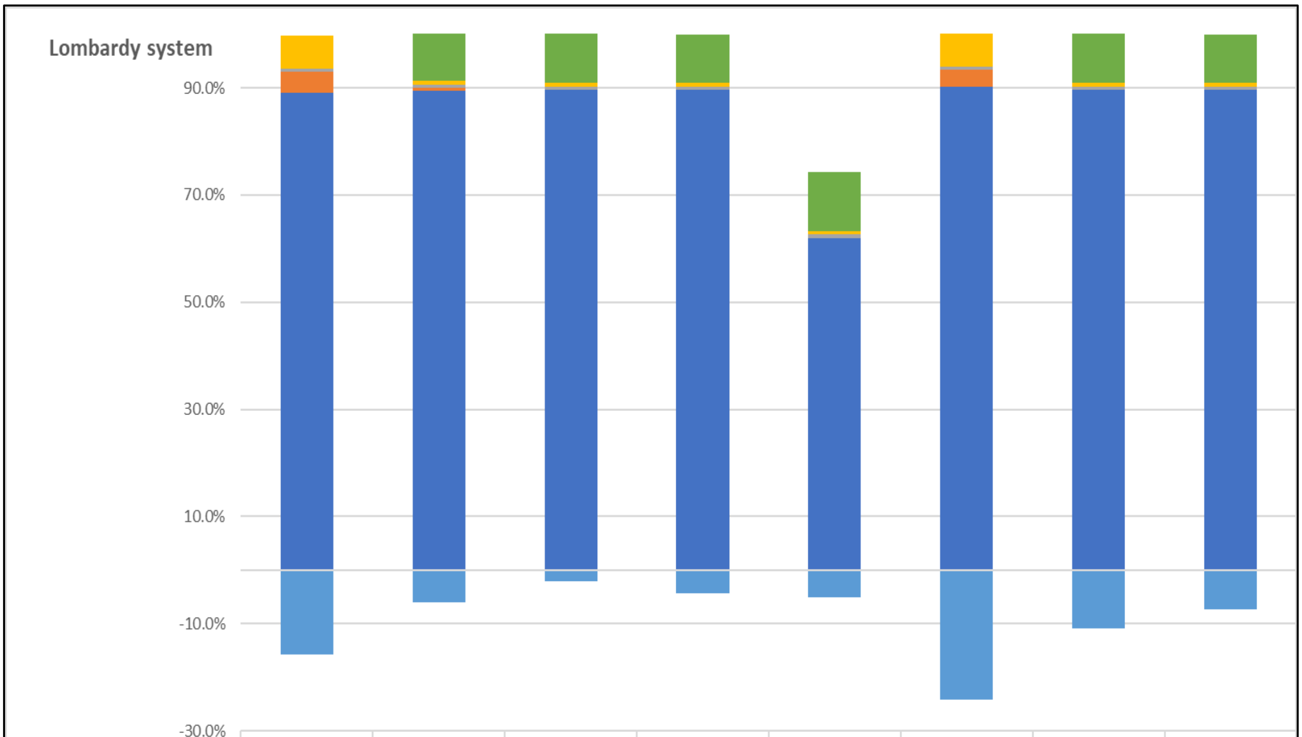
Based on what has been obtained in the LCI and LCIA phases, the interpretation step involves the analysis and discussion of the results, identifying the significant issues, in accordance with the goal and scope of the study.

Therefore, with respect to the results reported in the previous chapter, the discussion reported in the following sub-chapters covers the principal aspects of the study.

5.2.1. Contribution analysis

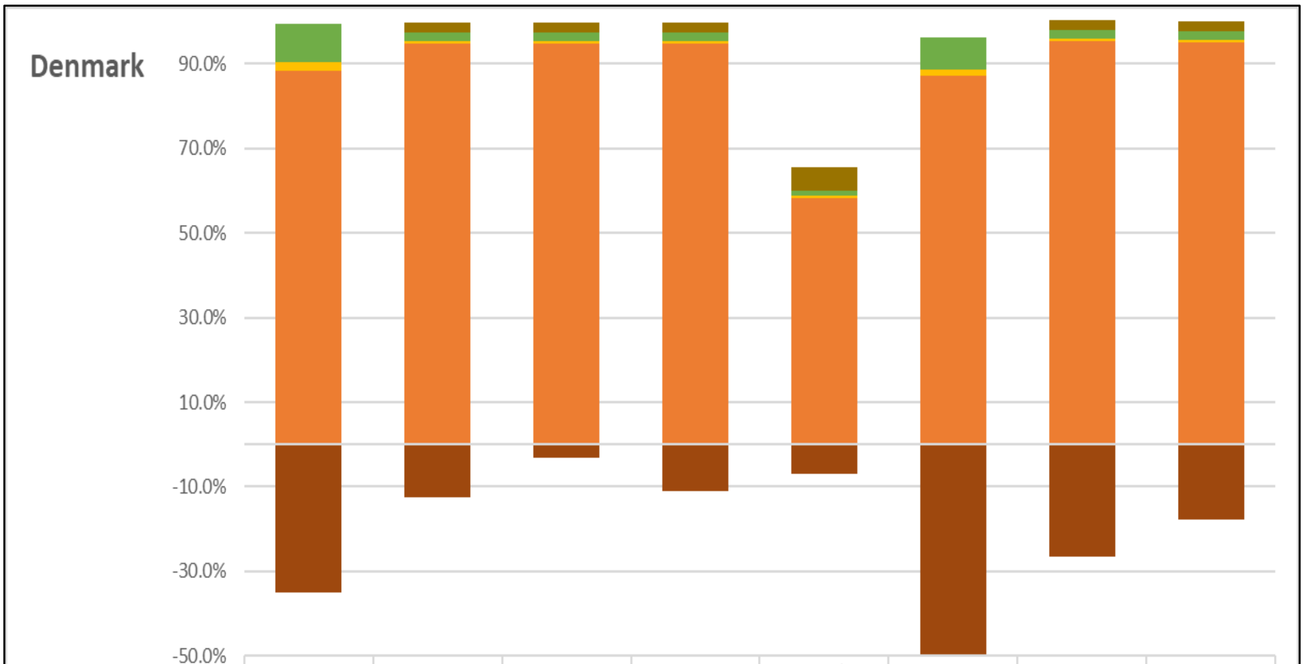
The implementation of a contribution analysis is a useful step to further understand which are the main factors influencing the final results within the systems under study.

Figures 5-5 and 5-6 presents the average contributions of every life-cycle phase modelled in each system of Lombardy region and Denmark (respectively), in order to see what are the most influencing phases within the single contexts. The related tables illustrating individually the contributions of every life-cycle phase to each impact category are listed in the Annex.



	B2B_SES	B2B_CFF(IV)	B2B_CFF(N)	B2B_CFF(Econ)	B2B_CFF(R1,R2 =N Loops)	B2F_SES	B2F_CFF(IV)	B2F_CFF(Econ)
6.Disposal		9.0%	9.0%	9.0%	11.1%		9.1%	9.1%
5.Secondary production	-15.7%	-6.1%	-2.0%	-4.4%	-5.1%	-24.1%	-10.9%	-7.2%
4.Recycling	6.3%	0.8%	0.8%	0.8%	0.6%	6.2%	0.8%	0.8%
3.Sorting	0.5%	0.5%	0.5%	0.5%	0.6%	0.5%	0.5%	0.5%
2.Collection	3.9%	0.6%	0.0%	0.0%	0.0%	3.2%	0.0%	0.0%
1.Bottles production	89.1%	89.5%	89.7%	89.6%	62.0%	90.3%	89.6%	89.6%

Figure 5-5 – Contribution analysis performed for the B2B and B2F scenarios within the Lombardy system. (the values are representing the average contribution to all the impact categories)



	B2B_SES	B2B_CFF(IV)	B2B_CFF(N)	B2B_CFF(Econ)	B2B_CFF(R1,R2=N Loops)	B2F_SES	B2F_CFF(IV)	B2F_CFF(Econ)
5.Disposal		2.4%	2.4%	2.4%	5.8%		2.4%	2.4%
4.Secondary producion	-34.9%	-12.6%	-3.0%	-11.0%	-6.9%	-51.1%	-26.6%	-17.7%
3.Recycling	8.9%	2.1%	2.0%	2.0%	1.0%	7.6%	2.0%	2.0%
2.Collection&sorting	2.2%	0.6%	0.6%	0.6%	0.7%	1.6%	0.6%	0.6%
1.Bottles production	88.3%	94.7%	94.7%	94.8%	58.1%	87.1%	95.2%	95.1%

Figure 5-6– Contribution analysis performed for the B2B and B2F scenarios within the Denmark system. (the values are representing the average contribution to all the impact categories)

It can be observed that the principal phase affecting considerably the final results (for both SES and CFF results) is the "Bottle production" in the range of 62-90.3% for the Lombardy system and 58-95% in Denmark. Next, the second phase which influences the results is the "secondary production": it contributes as negative impact, representing a benefit (i.e. savings) to the total system. In the B2B case, the "secondary bottle production" leads to savings up to 16% in Lombardy, while in Denmark up to 34%. On the other hand, in the B2F scenario the "secondary fibre production" phase achieves even more higher benefits (in Lombardy up to 24% and in Denmark 51%). This means that for both the contexts of Lombardy and Denmark the "secondary production" phase is more influencing in the B2F scenario, where there are savings higher than the B2B ones. This kind of result is strictly related to the avoided production of virgin material: i.e. the "avoided fibre production" selected in the model weighs more than the "avoided bottle production". Thus, even though within the multiple recycling loops (B2B scenario) it is possible to have a higher amount of recycled material (and so an equivalent amount of virgin material avoided), the savings in the B2F case are still greater than in the B2B one.

In addition, it is interesting to further analyse the results from "collection" and "recycling" phases in the two contexts: when modelling through both the two methods of SES and CFF, it has been observed that the principal factor influencing the final impacts is the disposal of the waste produced in these phases (i.e. the not collected wastes and the residues from the recycling treatment). This is highlighted in the results obtained through the CFF method, where the "Disposal" phase has been modelled separately in order to apply the respective part of the formula (see inventory analysis in chapter 4.2). Thus, the impacts related to these disposal treatments are in the Lombardy case higher than the ones in the Denmark system (respectively up to 12%, and up to 6%): this is mainly due to the respective amount of waste produced and sent to incineration (from the efficiencies of the processes). Indeed, the fundamental distinction between the two systems is on the collection phase: the different waste collection schemes lead to different efficiencies; thus, in Denmark the percentage of waste collected, derived from the deposit system, is higher than the one in Lombardy obtained from the integrated waste management system.

Looking in detail the results of SES and CFF method, two relevant differences can be observed: firstly, the percentages related to the "secondary production" phase in the SES results are higher than the ones in the CFF results; in the second place, the "bottle production" phase in the B2B scenario CFF(R1,R2=N loops) shows for both the two contexts a significative lower value with respect to the other scenarios (both SES and CFF). The reason behind these differences is basically related to the different way of modelling. In particular, the outcome for the CFF(R1,R2=N loops) scenario, as observed in the previous chapter of the impact assessment, comes from the implementation of the multiple recycling loops in the formula.

5.2.2. Identification of the most relevant impact categories

To make the discussion in line with the intended goal of the study, it is good to analyse what are the impact categories that influence in a significant way the results. Therefore, two approaches have been considered for their identification:

I. A first identification can be done through the normalization step, which allows calculating the magnitude for each indicator result of the product system, and so to what extent an impact category indicator result has a relatively high or low value compared to a reference information. This is done by dividing the indicator results by a selected reference value, thus obtaining all the indicators expressed with the same unit of measure. This means that the magnitude of the impact indicators can now be compared. (Rigamonti, 2015);

II. Another way is to consult the PEF methodological guidelines available and in particular, the Product Environmental Footprint category rules (PEFCRs). They are a useful and additional tool that allow to complement the general PEF guidance: indeed, being more product-type specific and life-cycle-based, they are focusing on aspects and parameters that matter the most for the specific case. This approach contributes to increase the relevance, reproducibility and consistency of the study (European Commission, 2016c).

For the case I. the normalization has been carried out through the software Simapro, analysing the results obtained for the two recycling scenarios in the two contexts of Denmark and Lombardy region using the SES method (Figure 5-7). The normalization factors are based on “EU27 domestic inventory”, i.e. an extensive collection of emissions into air, water and soil as well as resources extracted in EU. The data were derived from an update of the “Life Cycle

Indicators for Resources" updated for 2010 at EU-27 and country levels (Benini et al., 2014).

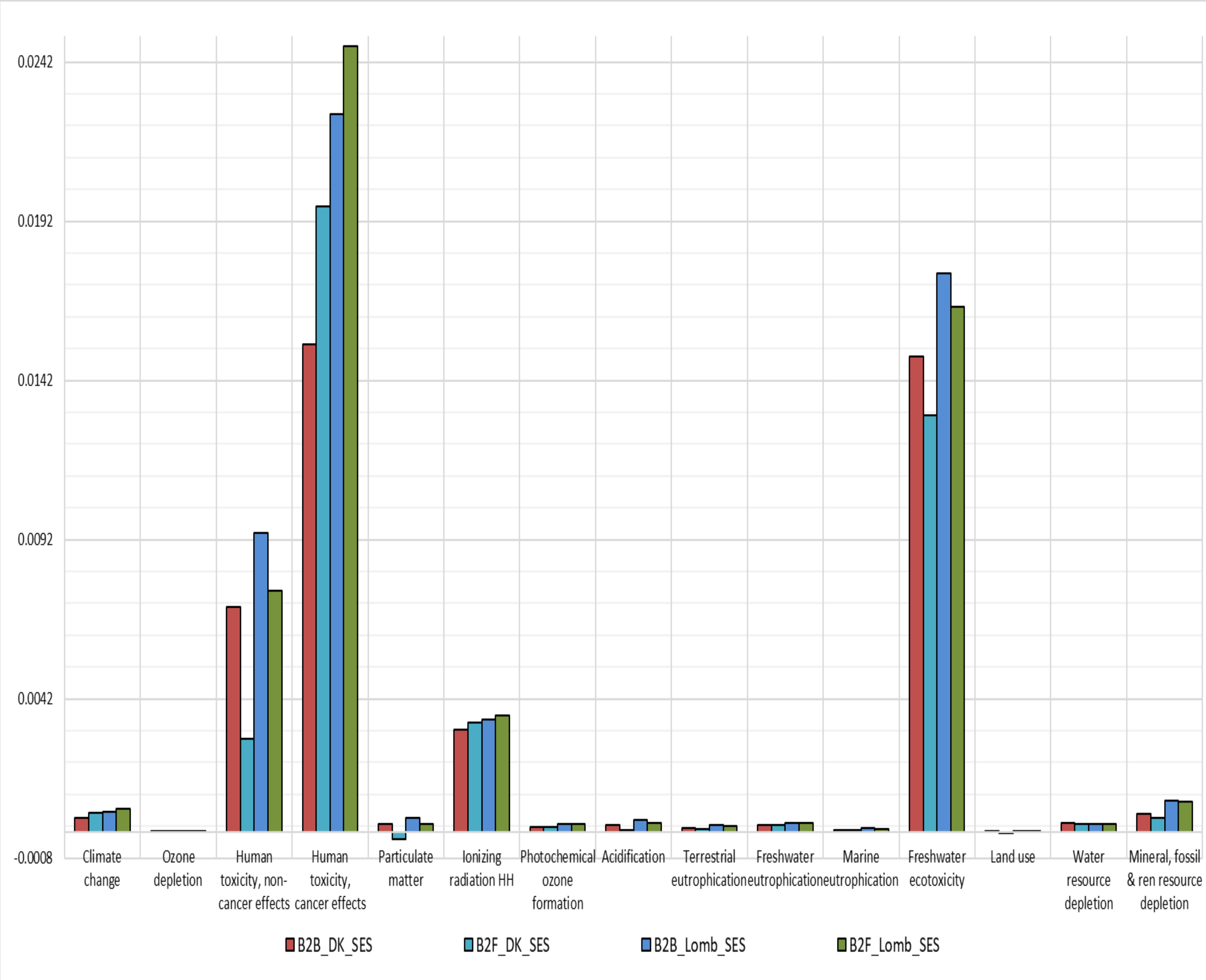


Figure 5-7 – Normalization for 1 kg of PET bottles recycled into both bottles (B2B scenario) and fibres (B2F scenario) in the two contexts of Denmark and Lombardy region using the SES method.

It can be observed that the most relevant impact categories within the product systems under study are (from the higher magnitude):

- Human Toxicity, cancer effects;
- Human Toxicity, non-cancer effects;
- Freshwater Ecotoxicity;

followed by these other three impact categories:

- Ionizing Radiation HH;
- Mineral, fossil and renewable resources depletion;
- Climate Change.

On the other hand, when consulting the PEFCR for Packed Water, three impact categories are considered as relevant for communication purposes for this kind of product system (EFBW, 2016):

- Climate Change;
- Water resource depletion;
- Mineral, fossil and renewable resources depletion.

The guidance reports that for the Water Resource Depletion category the ENVIFOOD protocol (European Food SCP Round Table (2013)) recommends the method by Ridoutt and Pfister (2010): this method assesses the water use using the regionalised water stress indexes (WSI) developed by Pfister et al. (2009). Hence, the analysis for this kind of category is carried out using the software Simapro and selecting the method Pfister et al. (2009) (Water Scarcity) version 1.02.

Therefore, from these considerations six impact categories should be selected for further analysis. However, a recent version of the PEF Guidance recommends the exclusion of the toxicity impact categories for communication purposes (European Commission, 2016c): this solution in temporarily, waiting for the finalisation of the ongoing work done in collaboration by the Commission and ECHA agency in Helsinki on developing new Characterization Factors (CF) based on REACH[10] data.

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[10] The ECHA agengy is the European Chemicals Agengy: it is the driving force among regulatory authorities in implementing the EU's groundbreaking chemicals legislation; REACH is a regulation by the European Union (2006) which addresses the production and use of chemical substances, and their potential impacts on both human health and the environment (ECHA, 2015).

Hence, based on this review, for the present study it has been chosen to follow the guidelines of the PEFCR for Packed Water: this means that from the initial six impact categories, there are now selected only the three from the PEFCR.

Finally, in Figures 5-8,9 and Tables 5-8,9 there are reported the final results for the selected impact categories (respectively for Lombardy and Denmark system).

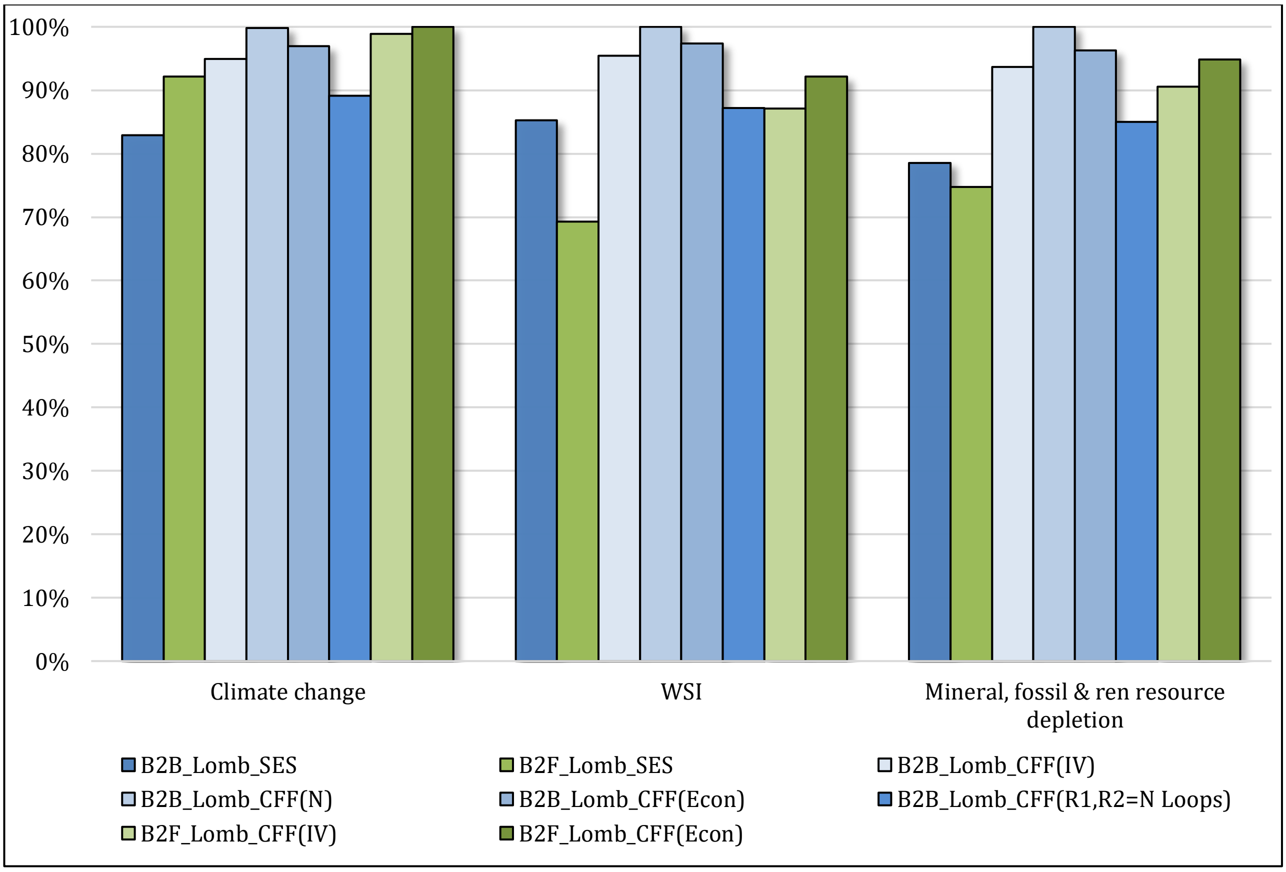

Figure 5-8 - Results of LCIA for 1 kg of PET bottles recycled into both bottles (B2B scenario) and fibres (B2F scenario) in the context of Lombardy region (selected impact categories).

Table 5-5 - Results of LCIA for 1 kg of PET bottles recycled into both bottles (B2B scenario) and fibres (B2F scenario) in the context of Lombardy region (selected impact categories).

Impact Category	B2B_ SES	B2F_ SES	B2B_ CFF (IV)	B2B_ CFF (N)	B2B_ CFF (Econ)	B2B_ CFF(R1,R 2=N Loops)	B2F_ CFF (IV)	B2F_ CFF (Econ)
Climate change *(kg CO2 eq)*	4.66	5.19	5.34	5.61	5.45	5.01	5.56	5.63
WSI *(m^3)*	0.0357	0.0290	0.0400	0.0419	0.0408	0.0365	0.0365	0.0386
Mineral, fossil & ren resource depletion *(kg Sb eq)*	0.000196	0.000186	0.000233	0.000249	0.000240	0.000212	0.000226	0.000236

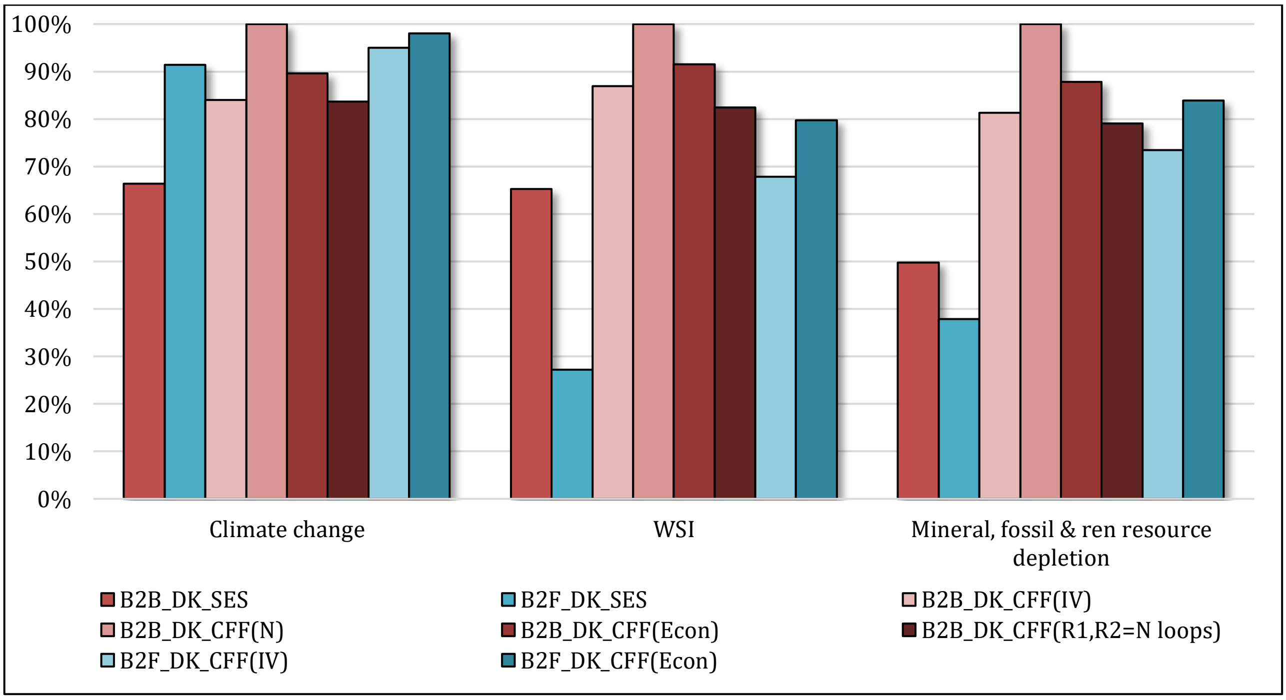

Figure 5-9 - Results of LCIA for 1 kg of PET bottles recycled into both bottles (B2B scenario) and fibres (B2F scenario) in the context of Denmark (selected impact categories).

Table 5-6 - Results of LCIA for 1 kg of PET bottles recycled into both bottles (B2B scenario) and fibres (B2F scenario) in the context of Denmark (selected impact categories).

Impact Category	B2B_ SES	B2F_ SES	B2B_ CFF (IV)	B2B_ CFF (N)	B2B_ CFF (Econ)	B2B_ CFF(R1,R2=N Loops)	B2F_ CFF (IV)	B2F_ CFF (Econ)
Climate change *(kg CO2 eq)*	3.22	4.43	4.07	4.84	4.34	4.05	4.60	4.75
WSI *(m^3)*	0.0264	0.0110	0.0352	0.0405	0.0371	0.0334	0.0275	0.0323
Mineral, fossil & ren resource depletion *(kg Sb eq)*	0.000114	0.000087	0.000186	0.000229	0.000201	0.000181	0.000168	0.000192

The new WSI impact category present results which are in line with the general trend of all the scenarios: indeed, while the Water Resource Depletion impact category was presenting different results with respect to the others (see impact assessment, chapter 5.1), the WSI is not.

Hence, the SES results for both B2B and B2F are never higher than the CFF ones (for both the two contexts): in Lombardy, the SES results are lower than the CFF ones in the range of 10-15% for the B2B scenario and 18-23% for the B2F one; while in Denmark, the difference is up to 35% in the B2B case, and up to 53% in the B2F.

5.2.3. Sensitivity analysis

It is now performed a sensitivity analysis to evaluate the influence of the main assumptions on the results.

- Modelling of the avoided virgin material in the case of B2F scenario using the Viscose Fibre module

When selecting the avoided production of primary fibre, a detailed research among the ecoinvent database was necessary: eventually, only the dataset *Viscose fibre {GLO}| viscose production | Alloc Def, U* was founded to suit the most the intended application. This unique choice represented a limit in the analysis, therefore in a potential future development of the study, it would be necessary to find other datasets-if present- among different databases.

Nevertheless, it is also possible to simply consider the avoided production of the granules of amorphous PET, which is the potential basic material for the fibre production: indeed, the case enters in the open-loop recycling (same primary route). Therefore, a sensitivity analysis can be implemented by modifying the *Viscose fibre* dataset with the dataset *Polyethylene terephthalate, granulate, amorphous {RER}| production | Alloc Def, U*. By doing this change, the recycling process needs to be modelled only until the production of the granules, thus not accounting for the process from the PET granules to the fibre.

Figure 5-10,11 shows the differences [11] in the results between the reference scenarios and the modified ones, respectively for the Lombardy and Denmark systems.

[11]Differences -in percentage- in absolute value.

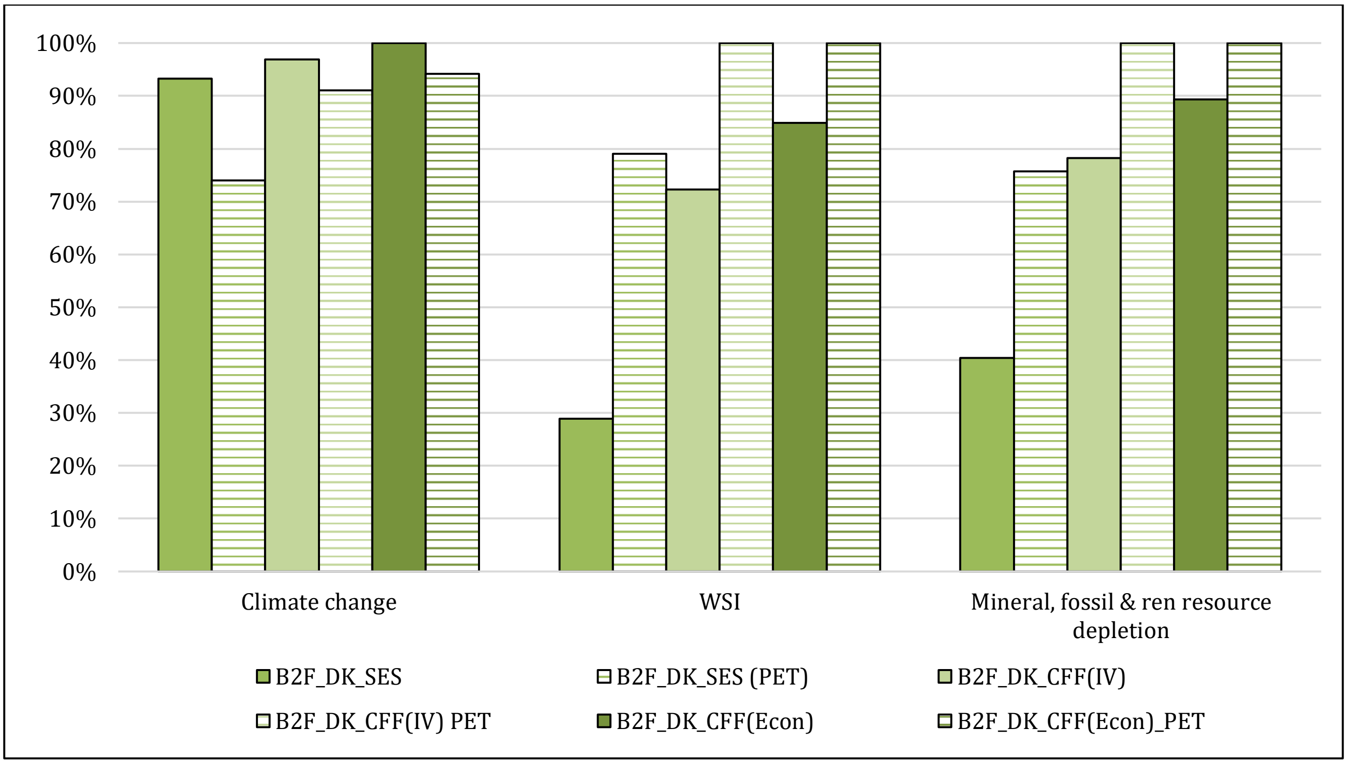

Figure 5-10 – Results of the Sensitivity analysis by using a different dataset for the avoided primary production (B2F scenario) in Lombardy region: comparison between the reference scenarios (totally coloured) and the modified ones (dashed).

Table 5-7 - Sensitivity analysis: results for the reference B2F_DK_SES scenario and for the modified B2F_DK_SES(PET)

	B2F_LOMB								
	SES	**SES (PET)**	**Δ (%)**	**CFF(IV)**	**CFF(IV) PET**	**Δ (%)**	**CFF(Econ)**	**CFF(Econ) _PET**	**Δ (%)**
Impact category	**Value**	**Value**		**Value**	**Value**		**Value**	**Value**	
Climate change *(kg CO2 eq)*	5.19	4.99	7%	5.56	5.47	2%	5.63	5.57	1%
WSI *(m³)*	0.0290	0.0378	20%	0.0365	0.0405	10%	0.0386	0.0413	6%
Mineral, fossil & ren resource depletion *(kg Sb eq)*	0.000186	0.000221	14%	0.000226	0.000242	6%	0.000236	0.000247	4%

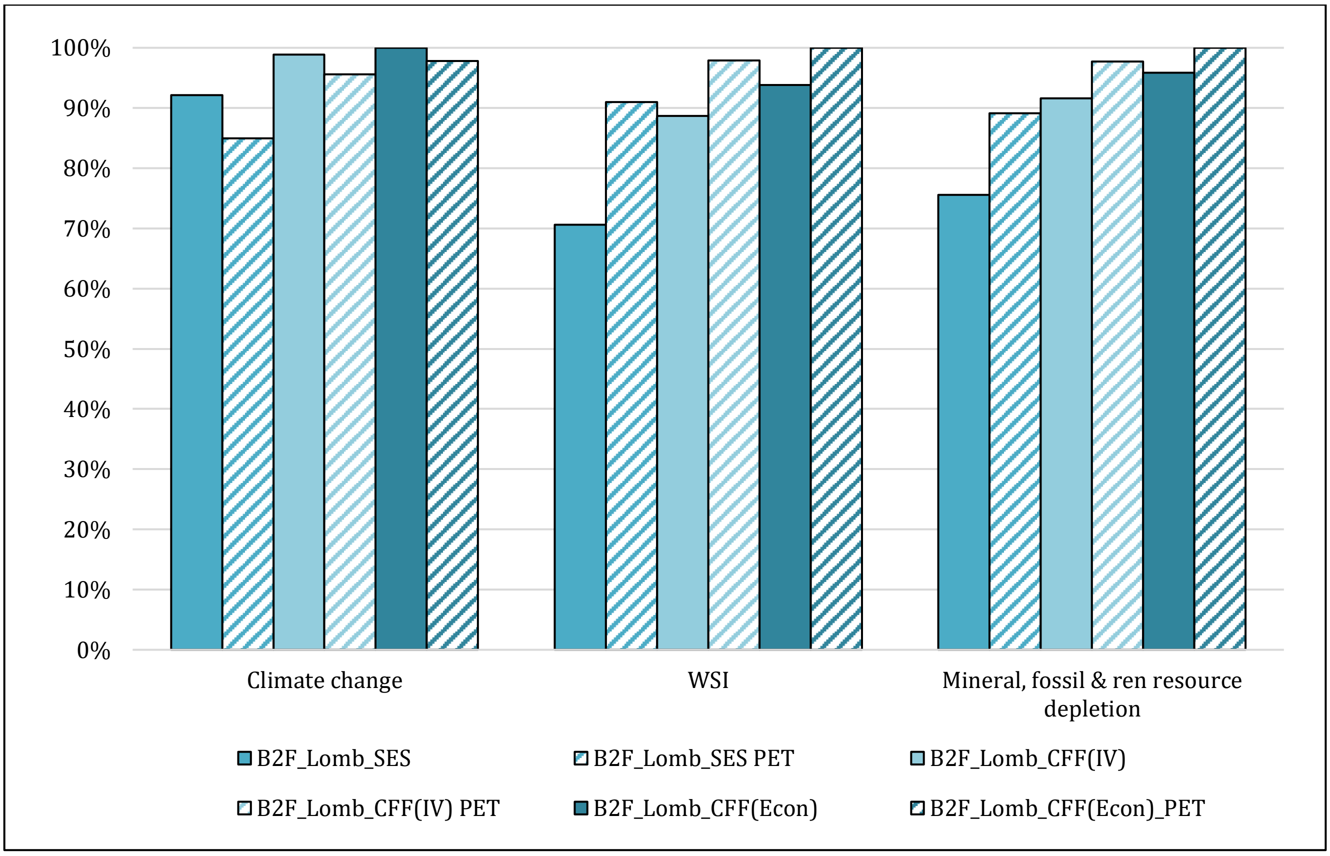

Figure 5-11– Results of the sensitivity analysis by using a different dataset for the avoided primary production (B2F scenario) in Denmark: comparison between the reference scenarios (totally coloured) and the modified ones (dashed).

Table 5-8 - Sensitivity analysis: results for the reference B2F_DK_SES scenario and for the modified B2F_DK_SES(PET)

	B2F_DK								
	SES	**SES (PET)**	**Δ (%)**	**CFF(IV)**	**CFF(IV) PET**	**Δ (%)**	**CFF(Econ)**	**CFF(Econ) _PET**	**Δ (%)**
Impact category	Value	Value		Value	Value		Value	Value	
Climate change *(kg CO2 eq)*	4.43	3.51	19%	4.60	4.40	6%	4.75	4.61	3%
WSI *(m³)*	0.0110	0.0308	50%	0.0275	0.0365	28%	0.0323	0.0383	16%
Mineral, fossil & ren resource depletion *(kg Sb eq)*	0.00008 7	0.000166	35%	0.000168	0.000204	22%	0.000192	0.000216	11%

It can be observed that the for the Climate Change impact category the changed systems ((PET) scenario) result in savings of about 3% in Lombardy and 9% in Denmark with respect to the reference systems. While looking at the remaining two impact categories the modified system has higher values: for the "Mineral, fossil, renewable resources depletion" category there is a difference up to 15% in Lombardy, and up to 37% in Denmark; the WSI impact category shows more dramatic differences, with 22% in Lombardy and 52% in Denmark. The highest differences for both the systems take place within the SES results, whereas in the CFF ones the difference is not so much pronounced.

Once observed this behaviour, it is interesting to see what would be the final results if this change in the avoided production is done. Figures 5-13 and 5-14 with Tables 5-9 and 5-10 (respectively for the Lombardy and Denmark system) show that the trend in the results is equal for all the selected impact categories: i.e. the B2B scenario results are not anymore higher than the B2F scenario in both the SES and CFF results (except for the scenario CFF(N) which still gives the highest values). This means that the choice of the module for the "avoided material production" influences in a relevant way the final results (as also observed in the contribution analysis in chapter 5.2.1).

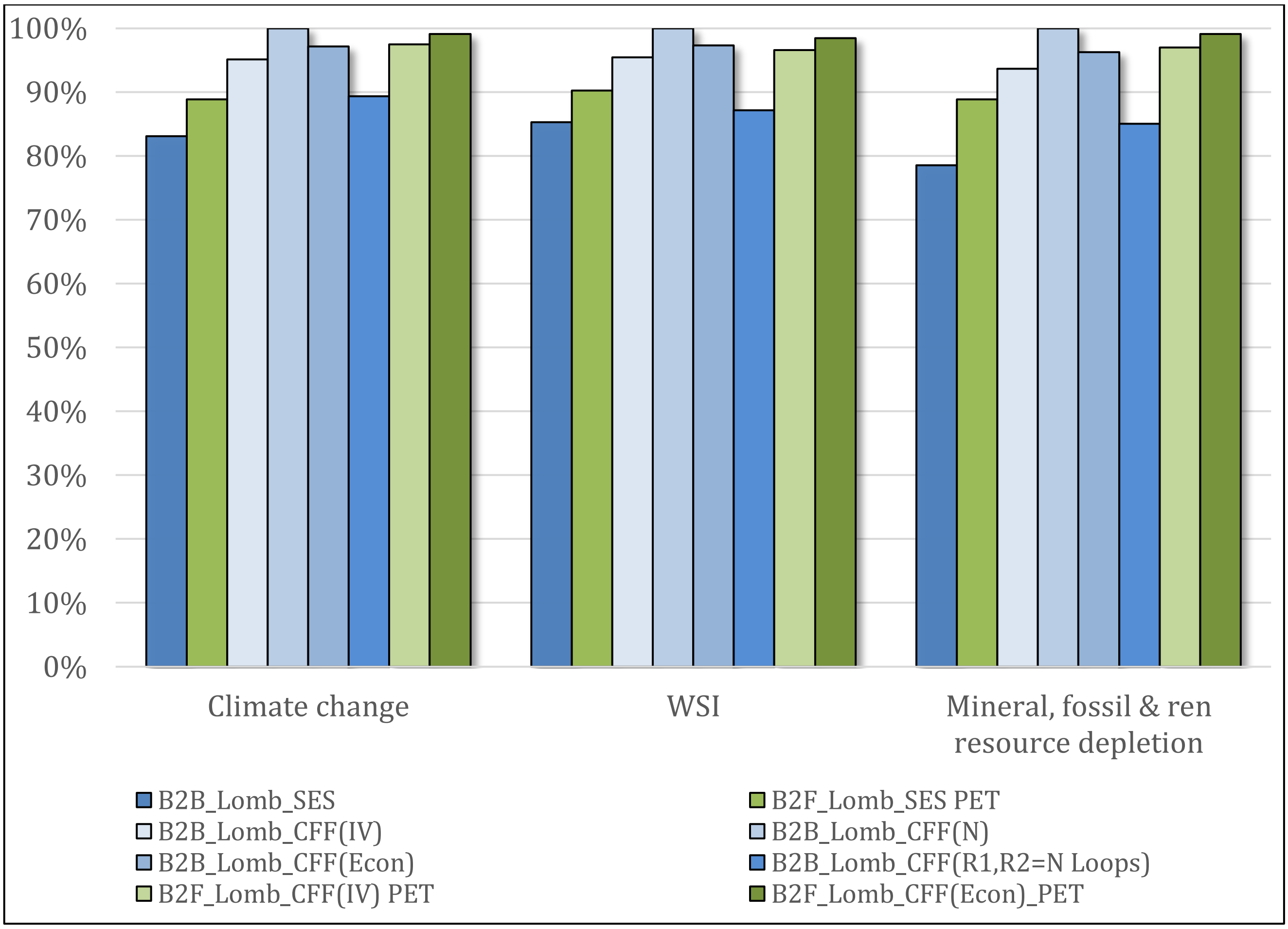

Figure 5-12 – Sensitivity Analysis results of LCIA for 1 kg of PET bottles recycled into both bottles (B2B scenario) and fibres (different dataset for the avoided primary production (B2F scenario)) in the context of Lombardy region.

Table 5-9 – Sensitivity Analysis results of LCIA for 1 kg of PET bottles recycled into both bottles (B2B scenario) and fibres (different dataset for the avoided primary production (B2F scenario)) in the context of Lombardy region.

Impact Category	B2B_ SES	B2F_ SES (PET)	B2B_ CFF (IV)	B2B_ CFF (N)	B2B_ CFF (Econ)	B2B_ CFF(R1,R 2=N Loops)	B2F_ CFF (IV)(PET)	B2F_ CFF (Econ)(PET)
Climate change *(kg CO2 eq)*	4.66	4.99	5.34	5.61	5.45	5.01	5.47	5.57
WSI *(m^3)*	0.0357	0.0290	0.0400	0.0419	0.0408	0.0365	0.0365	0.0386
Mineral, fossil & ren resource depletion *(kg Sb eq)*	0.000196	0.000186	0.000233	0.000249	0.000240	0.000212	0.000226	0.000236

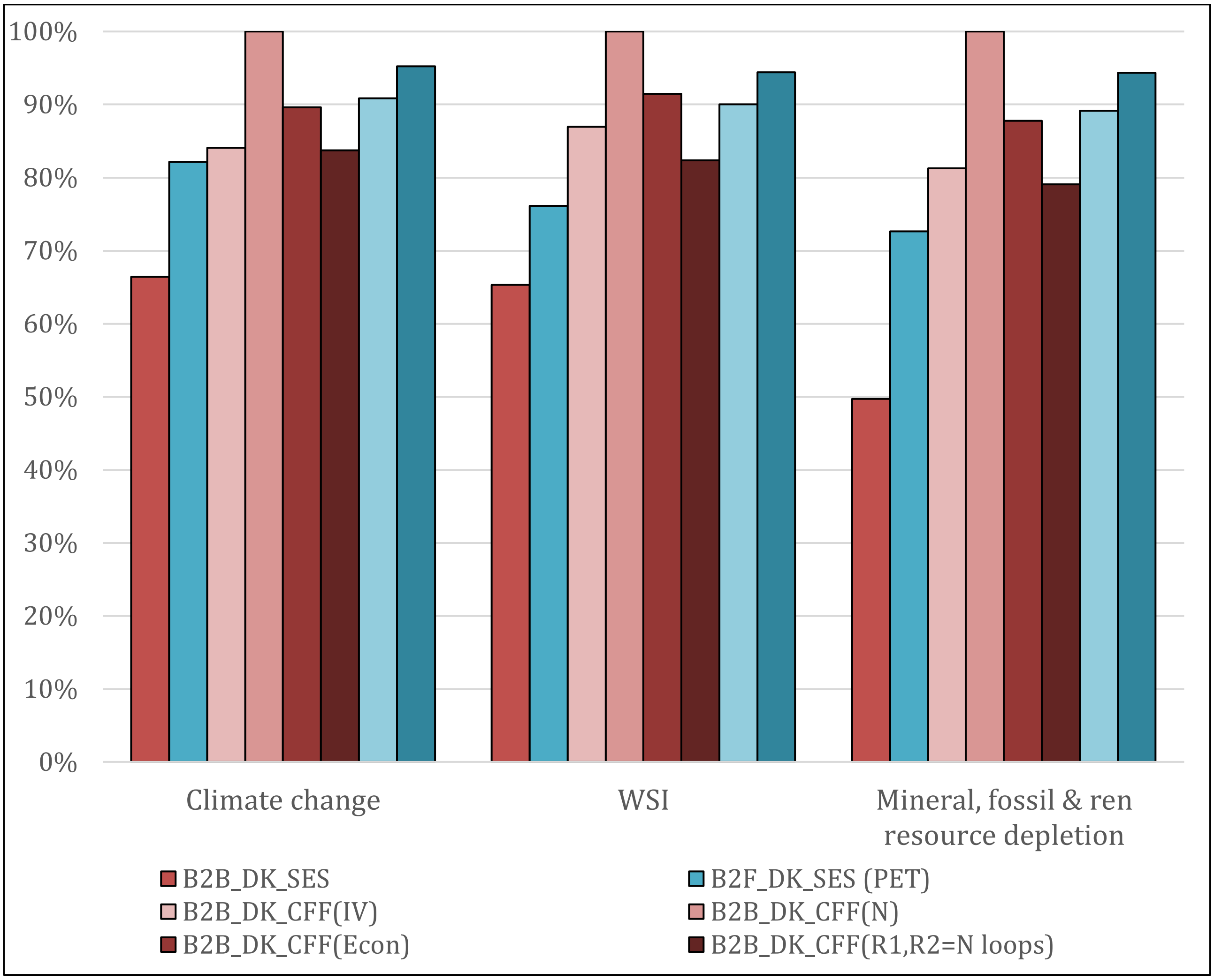

Figure 5-13 – Sensitivity Analysis results of LCIA for 1 kg of PET bottles recycled into both bottles (B2B scenario) and fibres (different dataset for the avoided primary production (B2F scenario)) in the context of Denmark.

Table 5-10 – Sensitivity Analysis results of LCIA for 1 kg of PET bottles recycled into both bottles (B2B scenario) and fibres (different dataset for the avoided primary production (B2F scenario)) in the context of Denmark.

Impact Category	B2B_ SES	B2F_ SES(PET)	B2B_ CFF (IV)	B2B_ CFF(N)	B2B_ CFF (Econ)	B2B_CFF (R1,R2=N loops)	B2F_ CFF (IV)(PET)	B2F_ CFF (Econ)(PET)
Climate change ($kg\ CO_2\ eq$)	3.22	3.51	4.07	4.84	4.34	4.05	4.40	4.61
WSI (m^3)	0.0264	0.0110	0.0352	0.0405	0.0371	0.0334	0.0275	0.0323
Mineral, fossil & ren resource depletion *(kg Sb eq)*	0.000114	0.000087	0.000186	0.000229	0.000201	0.000181	0.000168	0.000192

- The energy dataset country specific

Within the modules of "secondary production", it has been hypothesized the energy referred to the overall European market group: the rationale behind this is that the fibre plant has been assumed, hence the geographic location goes under uncertainty. As it will be explained in the next chapter, for each system a different fibre plant has been chosen, in order to create a more realistic scenario. Therefore, a sensitivity analysis is here performed by choosing the country-specific dataset for the energy consumption module. For the Danish system, a fibre plant is located still in Denmark (FiberVisions A/S in Varde), while in the Italian system, the Noyfil SPA plant is located in Canton Ticino, Switzerland. Therefore, the proper dataset was chosen: respectively Electricity, medium voltage {DK}| market for | Alloc Def, U and Electricity, medium voltage {CH}| market for | Alloc Def, U.

The results of this analysis are presented in Figure 5-14 and 5-15 for the two contexts of Lombardy and Denmark (respectively).

For both the cases it can be observed that the change of this parameter doesn't influence the final results.

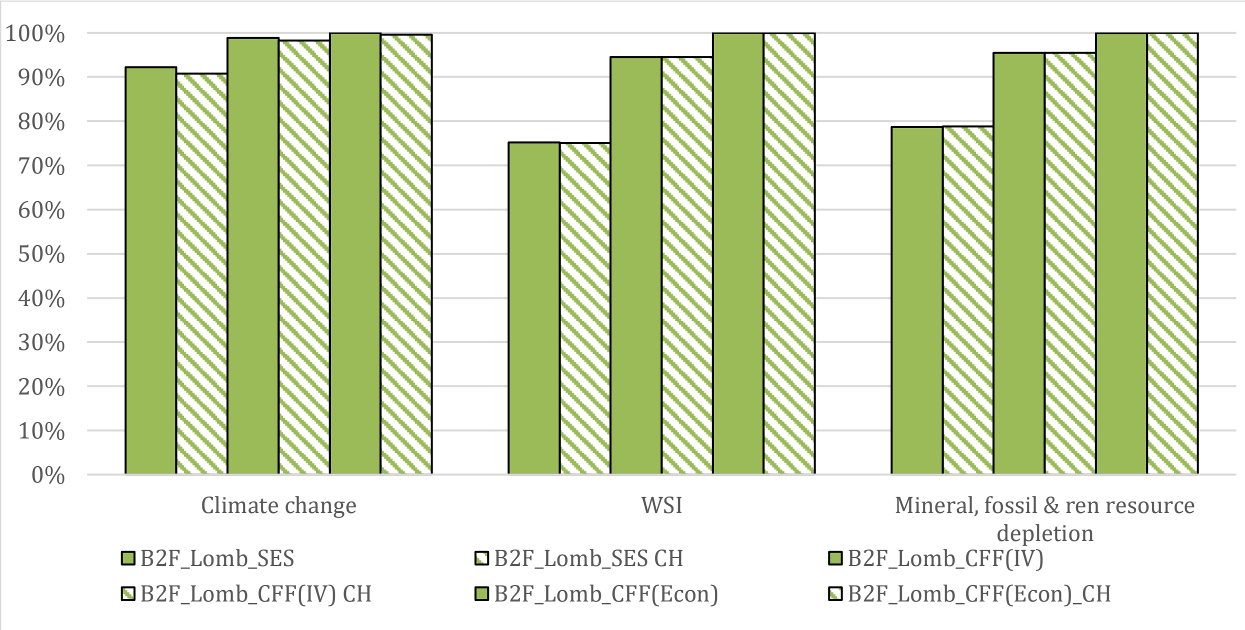

Figure 5-14 – Results of the Sensitivity analysis using a country-specific dataset for the secondary fibre production (B2F scenario)), in Lombardy region: comparison between the reference scenarios (totally coloured) and the modified ones (dashed).

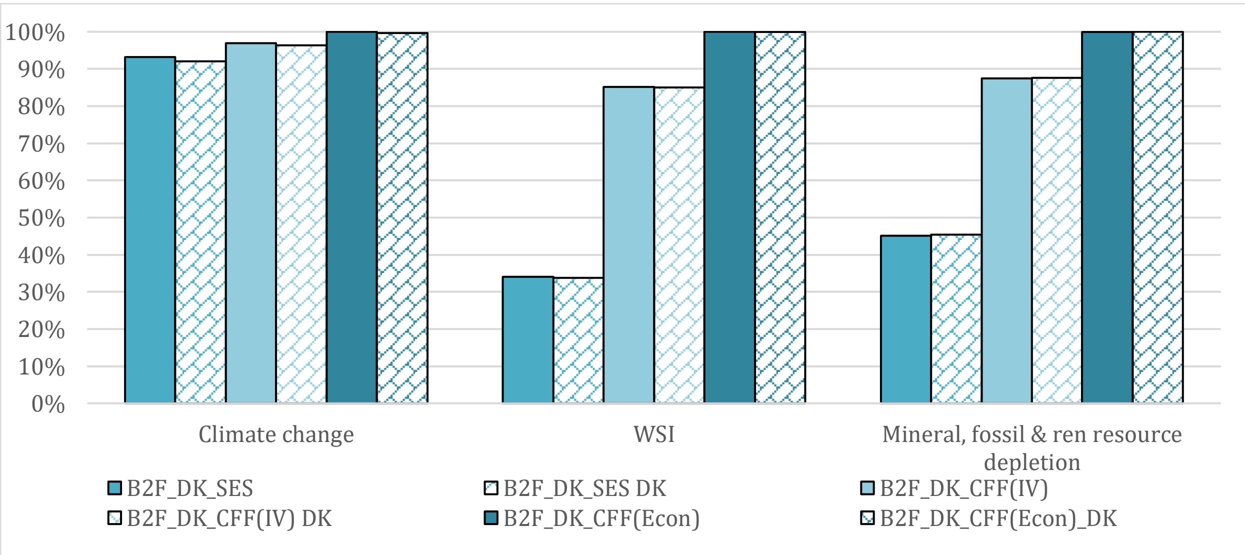

Figure 5-15- – Results of the Sensitivity analysis using a country-specific dataset for the secondary fibre production (B2F scenario), in Denmark: comparison between the reference scenarios (totally coloured) and the modified ones (dashed).

5.2.4. Consistency check

A further analysis must be performed to determine the consistency of the assumptions, data and methods used with the goal and scope of the study.

When implementing the LCA for the product system under study, all the data and methods are chosen in a consistent way with respect to the goal and scope defined.

Thus, the data collected aim at representing as much realistically as possible the two systems of Denmark and Lombardy region.

The assumptions made for this work are based on a detailed research for both the two contexts, in order to select the right information: hence, there are now discussed the principal assumptions made.

The manufacturing plants for both the bottle and fibre products have been chosen to represent the two contexts individually, as well as the material recovery facilities: since no direct data from industry were available, the assumptions of these plants are based on a research that has brought to identify the principal ones in the two different contexts. For the Italian case, a wider literature was available (Perugini 2003; Rigamonti, 2012, 2013) for the region-specific information, thus helping very much in choice; while for the Danish case, there were not sufficient data to validate the hypotheses with the respect to the reality. This issue can be observed on the transport distances assumed, in particular the ones from the recycling plant to the secondary fibre production. Within the Italian system, the Noyfil SPA has been chosen since that it is the fibre plant -that receives recycled PET- closer to the recycling plant in Lombardy region: hence the distance value selected in the modelling represents a punctual (region-specific) information. On the other hand, in the Danish situation it was not possible to find a specific fibre plant that can be assumed reasonably, thus an average value between some fibre plants that can be potentially considered as connected with the recycling plant in Denmark was taken into consideration. Therefore, the transport value in the Lombardy case can be considered reliable, while in the Denmark case is less consistent, since it is not a specific value but an average.

Another issue to consider within the consistency check is the allocation procedure when solving the multi-functionality of recycling. The choice of using two different methodologies has the purpose of analysing the possible differences in the results: therefore, it has been evaluated their applicability to the specific study, trying to be as much as consistent as possible. The major challenge has been encountered when handling the recycling multi-functionality with the CFF methodology: nevertheless, the results obtained give in general similar trends to the SES method, with in some cases bigger differences due to the fact that the two methods allocate differently the burdens related to each the life-cycle stages.

5.2.5. Validation check

This part of the study is important for validating the results obtained with the ones of other studies present in literature.

The large availability of LCA studies for plastic and PET products allows this validation check: however, several times the results of these studies are not directly comparable with the results of the present study, since the goal and functional units are different.

Therefore, when assessing the validation, each study has been analysed to find the results that can be comparable with the ones here obtained. For the comparison, it has been chosen as representative value the result for the Climate Change impact category.

The first reference taken into consideration is the Eco-Profile of bottle-grade PET from PlasticsEurope (version of 2011) (PlasticsEurope, 2011): here a LCA is performed for the production of 1 kg of bottle-grade PET and the final result for the Climate Change impact category is 2.15 kg CO_2eq/kg$_{PET}$.

Secondly, two studies from Shen (et al.) (2011, 2010) analyse also the steps of bottle production and recycling. In Shen (2010) the B2F recycling case is assessed through different methodologies to further develop the methodology for open-loop recycling, but the results of interest for the present study are the ones obtained from the System Expansion Method: for a functional unit of 1 ton of recycled fibre, the Climate Change impact category gives a value of 1.33 t $CO_2eq/t_{r\text{-}PET\ fibre}$. This value considers also an additional amount of virgin fibre produced, since the functional unit considered is 1 ton of fibre produced, therefore the relative value for only the recycled fibre is lower: furthermore, it has to be highlighted that the system boundary is different with respect to the one considered in the present study, since the phases of bottle production and collection are not accounted (because identical to the reference system). Thus, this difference must be taken into consideration, when comparing these results with the ones obtained in this study.

Similar situation occurs in the second paper of Shen (2011): the analysis is performed without considering the "bottle production" phase with its relative energy consumption (i.e. the one derived from the Stretch Blow Moulding process), and no collection efficiency is accounted. The results are referred to different functional units (FU) that consider the different shares of PET bottles recycled into fibres and bottles again: the final values for Climate Change impact category are about 0.25-0.3 t CO_2eq/FU.

Lastly, another study by Komly et al. (2012) analyses the recycling scenarios for PET bottles, in particular B2B scenario, in France: the results given are for an infinity recycling loops of 1 kg of PET bottles, and the relative Climate Change impact category is 3.12 kg CO_2eq.

The comparison of these results with the ones obtained in the present work needs to firstly consider that the principal difference takes place in the "Bottle Production" phase, since it is never accounted for its energy consumption. Therefore, by eliminating the Stretch Blow Moulding (SBM) in this phase, the results obtained are more comparable to the ones of the above-cited studies. As representative example, in Table 5-7 there are illustrated the results (only for the Climate Change impact category) obtained by the SES method.

Table 5-11- Comparison on the results between the recycling scenarios with and without the accounting of the SBM process (Lombardy region and Denmark).

Impact category	Unit	B2B_DK_SES	B2B_DK_SES (no SBM)	B2F_DK_SES	B2F_DK_SES (no SBM)
Climate change	kg CO_2 eq	3.22	1.92	4.42	2.68
		B2B_Lomb_SES	B2B_Lomb_SES (no SBM)	B2F_Lomb_SES	B2F_Lomb_SES (no SBM)
		4.66	3.37	5.242	3.89

As it can be observed from the table, the values seem to not fit well with those reported in the literature studies: the results of the present study are higher (up to 40%). However, the results can be proved to be consistent by considering that:

- If considering the value obtained by Komly, the results are in the same range (3.12 kg CO_2 eq of Komly and 2-4 kg CO_2 eq of the present study);
- If considering the value of the Eco-Profile bottle-grade PET as the basis of the process, the present study is adding also the bottle production process which increases this value: so, the results for this phase must be always above the 2.15 of the Eco-profile (see Tables 5-3 and 5-4);
- If considering the values with respect to the different system boundaries of the studies, the results are coherent: i.e. eliminating the processes not considered in literature the resulting values are similar.

In conclusion, the present study is in line with the studies present in literature, even though its structure is basically different to the others.

6. CONCLUSIONS

The present work has assessed the environmental impacts generated from the PET bottles throughout their life-cycle in the two contexts of Denmark and Lombardy region, considering two valorisation paths of recycling. The analysis was performed using two different methodologies, i.e. the System Expansion Method with Substitution (SES) and the recent version of the PEF formula, the Circular Footprint Formula.

This analysis and the related results obtained have given the possibility to investigate and identify the relevant factors within the two contexts influencing the two recycling scenarios for the PET bottles; thus providing answers to the research questions presented in the Introduction, i.e:

- *According to the context (i.e. Denmark and Lombardy region), which kind of PET recycling route is environmentally better?*
- *To which extent performing multi-recycling loops is reasonable and environmentally sustainable for PET?*

When answering to these questions, it is important to take into account different aspects: on which assumptions the LCA results are obtained; which impact category is intended to be considered for defining a scenario "environmentally better"; the analysis is not intended to conclude which context is better than the other, but is willing to investigate the principal elements influencing the different behavior of a context with respect to the other one.

Therefore, the principal outcomes of the study are:

Regarding the modelling issues and assumptions

- The recycling scenarios modelled with the SES method present lower impacts with respect to the ones modelled with the CFF method, due to the different way of allocating the environmental impacts: the first directly allocates the credits of the avoided primary material production to the end-of-life product, according to the degree that it is recyclable; whereas the second allocates the credits among the product system producing the recycled material and the product system using the recycled material.

  Within the B2B results, the CFF approach follows a trend closer to the SES method only for the scenario CFF(R1,R2=N Loops). This prove the feasibility of applying the Circular Footprint Formula to multiple recycling loops: however, this way of implementation of the Formula has its limitations, since lots of assumptions has been done to simplify the system under study (e.g. referring the values to the only path of the first 1 kg of PET bottles; or neglect the modelling of the surplus of recycled PET not sent to the bottle production in the closed-loop recycling; etc.).

  Meanwhile, the remaining three CFF scenarios do not account for the multiple recycling loops, but look at the different way of defining the quality ratios: the results highlight that lower values (and so impacts) are obtained if referring the quality ratio to the variation of the physical properties of the material (scenario CFF(IV)) or also to the economic values (scenario CFF(Econ)). Similar conclusions are valid also within the B2F results.
- The selection of the impact categories plays an important role in the analysis, since they are influencing the final results and outcomes. The study showed that for the case of the impact category related to the water resource consumption, the selection of the Pfister method (2009) gives more coherent results with respect to the one from the method ILCD - Midpoint 2011. This prove what the PEFCR of packed water suggests when dealing with products related to water packaging (EFBW, 2016).

Regarding the factors influencing the results

- It has been observed that the bottle production is the most relevant phase influencing the final results. Moreover, the secondary production phase is important for the savings brought to the system in terms of avoided production of virgin material. The highest savings come from the B2F scenario: this mainly depends on the choice of modelling, i.e. on the selection of the dataset representing the avoided production of virgin material; whereas the quantitative amount of the avoided material is influencing the results in a less significant way. Hence, even though from the B2B scenario it is available a greater amount of recycled material and is recycled multiple times, the recycling into fiber results into lower impacts.
- The principal difference between the two contexts takes place in the collection system: thanks to the deposit system, the amount of material sent to recycling in Denmark is higher than the amount in the Lombardy region (integrated municipal waste management system). When looking at the impacts to the collection, indeed, the Danish ones are lower, even if not very significantly, than the Italian ones.

Eventually, once taking into account for all of these considerations, the answers to the research questions are:

- The recycling scenarios show different results for the selected impact categories: the B2B presents lower impacts for the Climate Change impact category, but higher impacts for the other WSI and Mineral and Resource Depletion. Hence, when choosing the "environmentally better" recycling scenario, it is necessary to take into consideration which kind of impacts are interested. Therefore, when promoting a recycling treatment, it is always important to know which valorisation path is intended to be used, since higher or lower impacts can be obtained with respect to others, as observed in this study for B2B and B2F scenarios.

- The feasibility of the multiple-recycling is basically related to the collection efficiencies. Implementing the MFA is fundamental to investigate features of the overall system and what are the potential paths of the material: therefore, the convenience or not of the closed-loop recycling depends firstly on the waste management system, but also, as observed in literature, on the market shares, in terms of market demand. This last factor is important and it could be a limit when choosing the recycling as end-of-life treatment: indeed, in the present study it has been done a specific research of manufacturers plant that were receiving and producing recycled material, and it has not been particularly easy for both the two contexts of Denmark and Lombardy region.

To conclude, the outcomes of the study can support further research efforts in both the plastic waste management system and the application of the LCA methodology. With respect to the former, the study gives inputs to investigate more on the possibilities of improvements towards the valorisation paths of recycling, e.g. the enhancement of the collection system efficiencies or the choice of the secondary good in which convert the recycled material. About the LCA methodology, the present work provides good elements for future research regarding the implementation of the new CFF in the case of multiple-loops-recycling.

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ANNEX

In the present annex, there will be reported the specific results for all the scenarios modelled, among B2B-B2F and SES-CFF scenarios for both the two contexts of Lombardy region and Denmark.

B2B_LOMB_SES											
Impact category	Total	1.Bottles production		2.Collection		3.Sorting		4.Recycling		5.Secondary bottles	
	Value	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.
Climate change (kg CO2 eq)	4.66	4.85	*84.5%*	0.3993715	*6.96%*	0.0227065	*0.4%*	0.4642619	*8.1%*	-1.07011	*-18.7%*
Ozone depletionkg (CFC-11 eq)	3.84E-07	4.02E-07	*93.4%*	1.166E-09	*0.27%*	3.37E-09	*0.8%*	2.395E-08	*5.6%*	-4.63E-08	*-10.8%*
Human toxicity, non-cancer effects (CTUh)	1.46E-06	1.32E-06	*75.0%*	2.608E-07	*14.76%*	2.181E-09	*0.1%*	1.785E-07	*10.1%*	-3.1E-07	*-17.5%*
Human toxicity, cancer effects (CTUh)	2.8E-07	3.14E-07	*88.7%*	1.427E-08	*4.03%*	5.058E-10	*0.1%*	2.51E-08	*7.1%*	-7.44E-08	*-21.0%*
Particulate matter kg (PM2.5 eq)	0.002362	0.003022	*95.4%*	9.573E-06	*0.30%*	1.338E-05	*0.4%*	0.0001221	*3.9%*	-0.000805	*-25.4%*
Ionizing radiation HH (kBq U235 eq)	0.856406	0.900112	*96.7%*	0.0004702	*0.05%*	0.0028194	*0.3%*	0.0274938	*3.0%*	-0.074489	*-8.0%*
Ionizing radiation E (interim) (CTUe)	2.41E-06	2.57E-06	*96.6%*	2.196E-09	*0.08%*	9.56E-09	*0.4%*	7.756E-08	*2.9%*	-2.47E-07	*-9.3%*
Photochemical ozone formation (kg NMVOC eq)	0.011928	0.014351	*94.2%*	0.0001063	*0.70%*	0.0001661	*1.1%*	0.0006071	*4.0%*	-0.003303	*-21.7%*
Acidification (molc H+ eq)	0.022208	0.026318	*94.3%*	0.0001026	*0.37%*	0.0001856	*0.7%*	0.0013061	*4.7%*	-0.005704	*-20.4%*
Terrestrial eutrophication (molc N eq)	0.038343	0.043918	*92.7%*	0.0004332	*0.91%*	0.0006244	*1.3%*	0.0024262	*5.1%*	-0.009059	*-19.1%*
Freshwater eutrophication (kg P eq)	0.00205	0.002178	*90.4%*	1.283E-05	*0.53%*	4.221E-06	*0.2%*	0.0002137	*8.9%*	-0.000359	*-14.9%*
Marine eutrophication (kg N eq)	0.003883	0.004402	*92.5%*	5.044E-05	*1.06%*	5.782E-05	*1.2%*	0.0002504	*5.3%*	-0.000877	*-18.4%*
Freshwater ecotoxicity CTUe	65.68809	39.24763	*52.8%*	22.964205	*30.90%*	0.0873157	*0.1%*	12.02529	*16.2%*	-8.636351	*-11.6%*
Land use (kg C deficit)	5.551124	6.015703	*93.2%*	0.0240354	*0.37%*	0.038244	*0.6%*	0.3732861	*5.8%*	-0.900145	*-14.0%*
Water resource depletion (m3 water eq)	0.018487	0.01645	*89.0%*	-5.06E-05	*-0.27%*	0.000132	*0.7%*	0.0014053	*7.6%*	0.0005504	*3.0%*
Mineral, fossil & ren resource depletion (kg Sb eq)	0.000196	0.000247	*95.8%*	3.657E-06	*1.42%*	1.534E-07	*0.1%*	6.928E-06	*2.7%*	-6.18E-05	*-24.0%*
average value			**89.1%**		**3.9%**		**0.5%**		**6.3%**		**-15.7%**

Annex -1 – Results of LCIA for I kg of PET bottles recycled into bottles (B2B scenarios) in the context of Lombardy region. B2B(SES) method

B2B_LOMB_CFF(IV)													
Impact category	Total	1.Bottles production		2.Collection		3. Sorting		4.Recycling		5.Secondary bottles		6.Disposal	
	Value	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.
Climate change (kg CO2 eq)	5.339148	4.8485762	*84.3%*	0.02015261	*0.4%*	0.022706498	*0.4%*	0.05226181	*0.91%*	-0.41105054	*-7.1%*	0.82665213	*14.38%*
Ozone depletionkg (CFC-11 eq)	4.077E-07	4.017E-07	*94.4%*	3.1765E-09	*0.7%*	3.36994E-09	*0.8%*	3.6202E-09	*0.85%*	-1.7796E-08	*-4.2%*	1.6776E-08	*3.94%*
Human toxicity, non-cancer effects (CTUh)	1.683E-06	1.325E-06	*73.5%*	3.3117E-09	*0.2%*	2.18106E-09	*0.1%*	1.4998E-08	*0.83%*	-1.1902E-07	*-6.6%*	4.6053E-07	*25.55%*
Human toxicity, cancer effects (CTUh)	3.242E-07	3.142E-07	*89.1%*	5.8361E-10	*0.165%*	5.05813E-10	*0.1%*	3.174E-09	*0.90%*	-2.8567E-08	*-8.1%*	3.4945E-08	*9.91%*
Particulate matter kg (PM2.5 eq)	0.0028347	0.003022	*96.1%*	1.1716E-05	*0.373%*	1.33779E-05	*0.4%*	1.828E-05	*0.58%*	-0.00030929	*-9.8%*	9.0343E-05	*2.87%*
Ionizing radiation HH (kBq U235 eq)	0.8966238	0.9001119	*97.3%*	0.00350473	*0.379%*	0.002819389	*0.3%*	0.00419793	*0.45%*	-0.02861265	*-3.1%*	0.01810709	*1.96%*
Ionizing radiation E (interim) (CTUe)	2.55E-06	2.571E-06	*97.2%*	1.3397E-08	*0.507%*	9.5599E-09	*0.4%*	1.1801E-08	*0.45%*	-9.4807E-08	*-3.6%*	5.2238E-08	*1.98%*
Photochemical ozone formation (kg NMVOC eq)	0.0138646	0.0143515	*94.8%*	0.00015955	*1.05%*	0.000166112	*1.1%*	8.813E-05	*0.58%*	-0.00126857	*-8.4%*	0.00052745	*3.49%*
Acidification (molc H+ eq)	0.0254747	0.0263175	*95.1%*	0.00015508	*0.6%*	0.000185583	*0.7%*	0.0001956	*0.71%*	-0.00219099	*-7.9%*	0.00096703	*3.50%*
Terrestrial eutrophication	0.0435338	0.0439181	*93.4%*	0.00061588	*1.3%*	0.000624395	*1.3%*	0.00035181	*0.75%*	-0.00347963	*-7.4%*	0.00211907	*4.51%*
Freshwater eutrophication (kg P eq)	0.0022294	0.0021779	*92.0%*	3.7376E-06	*0.16%*	4.22077E-06	*0.2%*	3.2189E-05	*1.36%*	-0.00013782	*-5.8%*	0.00015293	*6.46%*
Marine eutrophication (kg N eq)	0.0043848	0.0044016	*93.2%*	5.6288E-05	*1.2%*	5.78155E-05	*1.2%*	3.6034E-05	*0.76%*	-0.00033702	*-7.1%*	0.00022633	*4.79%*
Freshwater ecotoxicity CTUe	74.976279	39.247625	*50.1%*	0.09969521	*0.127%*	0.087315708	*0.1%*	0.75322331	*0.96%*	-3.31739427	*-4.2%*	38.2054969	*48.80%*
Land use (kg C deficit)	6.0336766	6.0157034	*94.3%*	0.05365364	*0.841%*	0.038244002	*0.6%*	0.0561561	*0.88%*	-0.34576373	*-5.4%*	0.26933037	*4.22%*
Water resource depletion	0.0178372	0.0164495	*91.4%*	0.00016632	*0.93%*	0.000132026	*0.7%*	0.00021812	*1.21%*	0.00021141	*1.2%*	0.00082612	*4.59%*
Mineral, fossil & ren resource depletion (kg Sb eq)	0.0002333	0.0002467	*96.0%*	4.4147E-07	*0.2%*	1.53402E-07	*0.1%*	8.8938E-07	*0.35%*	-2.3756E-05	*-9.2%*	9.2718E-06	*3.61%*
average value			**89.5%**		**0.6%**		**0.5%**		**0.8%**		**-6.1%**		**9.0%**

Annex -2 – Results of LCIA for I kg of PET bottles recycled into bottles (B2B scenarios) in the context of Lombardy region. B2B(CFF(IV)) method

B2B_LOMB_CFF(N)												
Impact category	Total	1.Bottles production		2.Collection		3. Sorting		4.Recycling		5.Secondary bottles		6.Disposal	
	Value	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.
Climate change (kg CO2 eq)	5.6131078	4.8485762	*84.3%*	1.9117E-06	*0.0%*	0.022706498	*0.4%*	0.05226181	*0.91%*	-0.13709074	*-2.4%*	0.82665213	*14.38%*
Ozone depletionkg (CFC-11 eq)	4.196E-07	4.017E-07	*94.4%*	3.4715E-13	*0.0%*	3.36994E-09	*0.8%*	3.6202E-09	*0.85%*	-5.9352E-09	*-1.4%*	1.6776E-08	*3.94%*
Human toxicity, non-cancer effects (CTUh)	1.763E-06	1.325E-06	*73.5%*	4.7984E-13	*0.0%*	2.18106E-09	*0.1%*	1.4998E-08	*0.83%*	-3.9695E-08	*-2.2%*	4.6053E-07	*25.55%*
Human toxicity, cancer effects (CTUh)	3.433E-07	3.142E-07	*89.1%*	7.9663E-14	*0.000%*	5.05813E-10	*0.1%*	3.174E-09	*0.90%*	-9.5276E-09	*-2.7%*	3.4945E-08	*9.91%*
Particulate matter kg (PM2.5 eq)	0.0030409	0.003022	*96.1%*	8.8425E-10	*0.000%*	1.33779E-05	*0.4%*	1.828E-05	*0.58%*	-0.00010315	*-3.3%*	9.0343E-05	*2.87%*
Ionizing radiation HH (kBq U235 eq)	0.9156937	0.9001119	*97.3%*	1.5762E-07	*0.000%*	0.002819389	*0.3%*	0.00419793	*0.45%*	-0.00954269	*-1.0%*	0.01810709	*1.96%*
Ionizing radiation E (interim) (CTUe)	2.613E-06	2.571E-06	*97.2%*	9.2429E-13	*0.000%*	9.5599E-09	*0.4%*	1.1801E-08	*0.45%*	-3.1619E-08	*-1.2%*	5.2238E-08	*1.98%*
Photochemical ozone formation (kg NMVOC eq)	0.0147101	0.0143515	*94.8%*	9.1986E-09	*0.00%*	0.000166112	*1.1%*	8.813E-05	*0.58%*	-0.00042309	*-2.8%*	0.00052745	*3.49%*
Acidification (molc H+ eq)	0.026935	0.0263175	*95.1%*	9.5452E-09	*0.0%*	0.000185583	*0.7%*	0.0001956	*0.71%*	-0.00073073	*-2.6%*	0.00096703	*3.50%*
Terrestrial eutrophication (molc N eq)	0.0458529	0.0439181	*93.4%*	3.2671E-08	*0.0%*	0.000624395	*1.3%*	0.00035181	*0.75%*	-0.0011605	*-2.5%*	0.00211907	*4.51%*
Freshwater eutrophication (kg P eq)	0.0023213	0.0021779	*92.0%*	1.8582E-10	*0.00%*	4.22077E-06	*0.2%*	3.2189E-05	*1.36%*	-4.5964E-05	*-1.9%*	0.00015293	*6.46%*
Marine eutrophication (kg N eq)	0.0046094	0.0044016	*93.2%*	2.9946E-09	*0.0%*	5.78155E-05	*1.2%*	3.6034E-05	*0.76%*	-0.0001124	*-2.4%*	0.00022633	*4.79%*
Freshwater ecotoxicity (CTUe)	77.187278	39.247625	*50.1%*	1.1874E-05	*0.000%*	0.087315708	*0.1%*	0.75322331	*0.96%*	-1.10639444	*-1.4%*	38.2054969	*48.80%*
Land use (kg C deficit)	6.2641236	6.0157034	*94.3%*	6.4561E-06	*0.000%*	0.038244002	*0.6%*	0.0561561	*0.88%*	-0.11531673	*-1.8%*	0.26933037	*4.22%*
Water resource depletion (m3 water eq)	0.0176963	0.0164495	*93.7%*	9.1271E-11	*0.00%*	0.000132026	*0.8%*	0.00021812	*1.24%*	7.0509E-05	*0.4%*	0.00082612	*4.70%*
Mineral, fossil & ren resource depletion (kg Sb eq)	0.0002491	0.0002467	*96.0%*	2.0436E-10	*0.0%*	1.53402E-07	*0.1%*	8.8938E-07	*0.35%*	-7.9231E-06	*-3.1%*	9.2718E-06	*3.61%*
average value			**89.7%**		**0.0%**		**0.5%**		**0.8%**		**-2.0%**		**9.0%**

Annex -3 – Resu
region. B2B(CF

Annex -3 – Results of LCIA for I kg of PET bottles recycled into bottles (B2B scenarios) in the context of Lombardy region. B2B(CFF(N)) method

B2B_LOMB_CFF(Econ)													
Impact category	Total	1.Bottles production		2.Collection		3. Sorting		4.Recycling		5.Secondary bottles		6.Disposal	
	Value	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.
Climate change (kg CO2 eq)	5.4535704	4.8485762	*84.3%*	1.9117E-06	*0.0%*	0.022706498	*0.4%*	0.05226181	*0.91%*	-0.29662813	*-5.2%*	0.82665213	*14.38%*
Ozone depletionkg (CFC-11 eq)	4.127E-07	4.017E-07	*94.4%*	3.4715E-13	*0.0%*	3.36994E-09	*0.8%*	3.6202E-09	*0.85%*	-1.2842E-08	*-3.0%*	1.6776E-08	*3.94%*
Human toxicity, non-cancer effects (CTUh)	1.717E-06	1.325E-06	*73.5%*	4.7984E-13	*0.0%*	2.18106E-09	*0.1%*	1.4998E-08	*0.83%*	-8.589E-08	*-4.8%*	4.6053E-07	*25.55%*
Human toxicity, cancer effects (CTUh)	3.322E-07	3.142E-07	*89.1%*	7.9663E-14	*0.000%*	5.05813E-10	*0.1%*	3.174E-09	*0.90%*	-2.0615E-08	*-5.8%*	3.4945E-08	*9.91%*
Particulate matter kg (PM2.5 eq)	0.0029208	0.003022	*96.1%*	8.8425E-10	*0.000%*	1.33779E-05	*0.4%*	1.828E-05	*0.58%*	-0.00022319	*-7.1%*	9.0343E-05	*2.87%*
Ionizing radiation HH (kBq U235 eq)	0.9045886	0.9001119	*97.3%*	1.5762E-07	*0.000%*	0.002819389	*0.3%*	0.00419793	*0.45%*	-0.02064787	*-2.2%*	0.01810709	*1.96%*
Ionizing radiation E (interim) (CTUe)	2.576E-06	2.571E-06	*97.2%*	9.2429E-13	*0.000%*	9.5599E-09	*0.4%*	1.1801E-08	*0.45%*	-6.8416E-08	*-2.6%*	5.2238E-08	*1.98%*
Photochemical ozone formation (kg NMVOC eq)	0.0142177	0.0143515	*94.8%*	9.1986E-09	*0.00%*	0.000166112	*1.1%*	8.813E-05	*0.58%*	-0.00091545	*-6.0%*	0.00052745	*3.49%*
Acidification (molc H+ eq)	0.0260846	0.0263175	*95.1%*	9.5452E-09	*0.0%*	0.000185583	*0.7%*	0.0001956	*0.71%*	-0.0015811	*-5.7%*	0.00096703	*3.50%*
Terrestrial eutrophication (molc N eq)	0.0445024	0.0439181	*93.4%*	3.2671E-08	*0.0%*	0.000624395	*1.3%*	0.00035181	*0.75%*	-0.00251102	*-5.3%*	0.00211907	*4.51%*
Freshwater eutrophication (kg P eq)	0.0022678	0.0021779	*92.0%*	1.8582E-10	*0.00%*	4.22077E-06	*0.2%*	3.2189E-05	*1.36%*	-9.9455E-05	*-4.2%*	0.00015293	*6.46%*
Marine eutrophication (kg N eq)	0.0044786	0.0044016	*93.2%*	2.9946E-09	*0.0%*	5.78155E-05	*1.2%*	3.6034E-05	*0.76%*	-0.0002432	*-5.2%*	0.00022633	*4.79%*
Freshwater ecotoxicity CTUe	75.899728	39.247625	*50.1%*	1.1874E-05	*0.000%*	0.087315708	*0.1%*	0.75322331	*0.96%*	-2.39394524	*-3.1%*	38.2054969	*48.80%*
Land use (kg C deficit)	6.1299254	6.0157034	*94.3%*	6.4561E-06	*0.000%*	0.038244002	*0.6%*	0.0561561	*0.88%*	-0.24951494	*-3.9%*	0.26933037	*4.22%*
Water resource depletion (m3 water eq)	0.0177784	0.0164495	*93.2%*	9.1271E-11	*0.00%*	0.000132026	*0.7%*	0.00021812	*1.24%*	0.00015256	*0.9%*	0.00082612	*4.68%*
Mineral, fossil & ren resource depletion (kg Sb eq)	0.0002399	0.0002467	*96.0%*	2.0436E-10	*0.0%*	1.53402E-07	*0.1%*	8.8938E-07	*0.35%*	-1.7143E-05	*-6.7%*	9.2718E-06	*3.61%*
average value			**89.6%**		**0.0%**		**0.5%**		**0.8%**		**-4.4%**		**9.0%**

Annex -4 – Results of LCIA for I kg of PET bottles recycled into bottles (B2B scenarios) in the context of Lombardy region. B2B(CFF(Econ)) method

B2B_LOMB_CFF(R1,R2=N Loops)													
Impact category	Total	1.Bottles production		2.Collection		3. Sorting		4.Recycling		5.Secondary bottles		6.Disposal	
	Value	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.
Climate change (kg CO2 eq)	5.0144723	2.983917	*56.0%*	1.9117E-06	*0.0%*	0.022706498	*0.4%*	0.03396166	*0.64%*	-0.31530523	*-5.9%*	0.9548846	*17.92%*
Ozone depletionkg (CFC-11 eq)	3.755E-07	2.472E-07	*63.5%*	3.4715E-13	*0.0%*	3.36994E-09	*0.9%*	2.3526E-09	*0.60%*	-1.3651E-08	*-3.5%*	1.9379E-08	*4.98%*
Human toxicity, non-cancer effects (CTUh)	1.63E-06	8.153E-07	*47.4%*	4.7984E-13	*0.0%*	2.18106E-09	*0.1%*	9.7465E-09	*0.57%*	-9.1299E-08	*-5.3%*	5.3197E-07	*30.91%*
Human toxicity, cancer effects (CTUh)	3.001E-07	1.933E-07	*60.0%*	7.9663E-14	*0.000%*	5.05813E-10	*0.2%*	2.0626E-09	*0.64%*	-2.1913E-08	*-6.8%*	4.0366E-08	*12.54%*
Particulate matter kg (PM2.5 eq)	0.0025635	0.0018598	*66.4%*	8.8425E-10	*0.000%*	1.33779E-05	*0.5%*	1.1879E-05	*0.42%*	-0.00023725	*-8.5%*	0.00010436	*3.73%*
Ionizing radiation HH (kBq U235 eq)	0.8244635	0.553948	*65.4%*	1.5762E-07	*0.000%*	0.002819389	*0.3%*	0.00272797	*0.32%*	-0.02194795	*-2.6%*	0.02091591	*2.47%*
Ionizing radiation E (interim) (CTUe)	2.342E-06	1.582E-06	*65.5%*	9.2429E-13	*0.000%*	9.5599E-09	*0.4%*	7.6689E-09	*0.32%*	-7.2723E-08	*-3.0%*	6.0342E-08	*2.50%*
Photochemical ozone formation (kg NMVOC eq)	0.0126213	0.0088322	*65.0%*	9.1986E-09	*0.00%*	0.000166112	*1.2%*	5.727E-05	*0.42%*	-0.00097309	*-7.2%*	0.00060927	*4.48%*
Acidification (molc H+ eq)	0.0232033	0.0161964	*65.1%*	9.5452E-09	*0.0%*	0.000185583	*0.7%*	0.00012711	*0.51%*	-0.00168065	*-6.8%*	0.00111703	*4.49%*
Terrestrial eutrophication (molc N eq)	0.0398394	0.0270281	*63.6%*	3.2671E-08	*0.0%*	0.000624395	*1.5%*	0.00022862	*0.54%*	-0.00266912	*-6.3%*	0.00244779	*5.76%*
Freshwater eutrophication (kg P eq)	0.0020537	0.0013403	*62.1%*	1.8582E-10	*0.00%*	4.22077E-06	*0.2%*	2.0918E-05	*0.97%*	-0.00010572	*-4.9%*	0.00017666	*8.18%*
Marine eutrophication (kg N eq)	0.0040182	0.0027088	*63.3%*	2.9946E-09	*0.0%*	5.78155E-05	*1.4%*	2.3416E-05	*0.55%*	-0.00025852	*-6.0%*	0.00026143	*6.11%*
Freshwater ecotoxicity CTUe	77.122552	24.153824	*30.3%*	1.1874E-05	*0.000%*	0.087315708	*0.1%*	0.48947248	*0.61%*	-2.54467926	*-3.2%*	44.132035	*55.40%*
Land use (kg C deficit)	5.5413019	3.7021919	*63.8%*	6.4561E-06	*0.000%*	0.038244002	*0.7%*	0.03649232	*0.63%*	-0.26522557	*-4.6%*	0.31110961	*5.36%*
Water resource depletion (m3 water eq)	0.0166564	0.0101234	*88.9%*	9.1271E-11	*0.00%*	0.000132026	*1.2%*	0.00014174	*1.25%*	0.00016217	*1.4%*	0.00095427	*8.38%*
Mineral, fossil & ren resource depletion (kg Sb eq)	0.0002119	0.0001518	*66.0%*	2.0436E-10	*0.0%*	1.53402E-07	*0.1%*	5.7795E-07	*0.25%*	-1.8223E-05	*-7.9%*	1.071E-05	*4.65%*
average value			**62.0%**		**0.0%**		**0.6%**		**0.6%**		**-5.1%**		**11.1%**

Annex -5 – Results of LCIA for I kg of PET bottles recycled into bottles (B2B scenarios) in the context of Lombardy region. B2B(CFF(R1,R2=N loops)) method

B2F_LOMB_SES										
Impact category	Total	1.Bottles production		2.Collection		3.Sorting		4.Recycling		5.Secondary bottles
	Value	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.
Climate change (kg CO2 eq)	5.18506751	4.848576256	*86.4%*	0.306771526	*5.46%*	0.022706498	*0.4%*	0.435472566	*7.8%*	-0.42845934	*-7.6%*
Ozone depletionkg (CFC-11 eq)	2.50722E-07	4.01727E-07	*93.5%*	8.95357E-10	*0.21%*	3.36994E-09	*0.8%*	2.38618E-08	*5.6%*	-1.7913E-07	*-41.7%*
Human toxicity, non-cancer effects (CTUh)	1.17526E-06	1.32475E-06	*78.5%*	2.00303E-07	*11.87%*	2.18106E-09	*0.1%*	1.59742E-07	*9.5%*	-5.1172E-07	*-30.3%*
Human toxicity, cancer effects (CTUh)	3.06072E-07	3.14163E-07	*89.8%*	1.09593E-08	*3.13%*	5.05813E-10	*0.1%*	2.40714E-08	*6.9%*	-4.3627E-08	*-12.5%*
Particulate matter kg (PM2.5 eq)	0.001307608	0.003022018	*95.5%*	7.3532E-06	*0.23%*	1.33779E-05	*0.4%*	0.000121363	*3.8%*	-0.0018565	*-58.7%*
Ionizing radiation HH (kBq U235 eq)	0.885571502	0.900111868	*96.7%*	0.000361226	*0.04%*	0.002819389	*0.3%*	0.027459916	*3.0%*	-0.0451809	*-4.9%*
Ionizing radiation E (interim) (CTUe)	2.43639E-06	2.57094E-06	*96.7%*	1.68709E-09	*0.06%*	9.5599E-09	*0.4%*	7.74034E-08	*2.9%*	-2.2321E-07	*-8.4%*
Photochemical ozone formation (kg NMVOC eq)	0.011903276	0.014351483	*94.4%*	8.16519E-05	*0.54%*	0.000166112	*1.1%*	0.00059942	*3.9%*	-0.00329539	*-21.7%*
Acidification (molc H+ eq)	0.017686606	0.026317505	*94.4%*	7.88403E-05	*0.28%*	0.000185583	*0.7%*	0.001298683	*4.7%*	-0.01019401	*-36.6%*
Terrestrial eutrophication (molc N eq)	0.036212148	0.043918101	*92.9%*	0.000332738	*0.70%*	0.000624395	*1.3%*	0.002394967	*5.1%*	-0.01105805	*-23.4%*
Freshwater eutrophication (kg P eq)	0.002042373	0.002177881	*90.6%*	9.85297E-06	*0.41%*	4.22077E-06	*0.2%*	0.000212754	*8.8%*	-0.00036233	*-15.1%*
Marine eutrophication (kg N eq)	0.003627673	0.004401598	*92.8%*	3.87466E-05	*0.82%*	5.78155E-05	*1.2%*	0.000246748	*5.2%*	-0.00111724	*-23.5%*
Freshwater ecotoxicity CTUe	61.77283351	39.24762535	*58.3%*	17.63960596	*26.19%*	0.087315709	*0.1%*	10.36987187	*15.4%*	-5.57158537	*-8.3%*
Land use (kg C deficit)	2.335610284	6.01570343	*93.4%*	0.018463898	*0.29%*	0.038244002	*0.6%*	0.371553956	*5.8%*	-4.108355	*-63.8%*
Water resource depletion (m3 water eq)	0.01750007	0.01644954	*94.0%*	-3.8901E-05	*-0.22%*	0.000132026	*0.8%*	0.001408919	*8.1%*	-0.00045151	*-2.6%*
Mineral, fossil & ren resource depletion (kg Sb eq)	0.000186129	0.000246728	*96.2%*	2.80939E-06	*1.10%*	1.53402E-07	*0.1%*	6.66399E-06	*2.6%*	-7.0226E-05	*-27.4%*
average value			**90.3%**		**3.2%**		**0.5%**		**6.2%**		**-24.1%**

Annex -6 – Results of LCIA for I kg of PET bottles recycled into fibres (B2f scenarios) in the context of Lombardy region. B2B(SES) method

B2F_LOMB_CFF(IV)													
Impact category	Total	1.Bottles production		2.Collection		3. Sorting		4.Recycling		5.Secondary bottles		6.Disposal	
	Value	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.
Climate change (kg CO2 eq)	5.560396215	4.848576208	*84.3%*	0.001911701	*0.0%*	0.022706497	*0.4%*	0.052261808	*0.91%*	-0.1939647	*-3.4%*	0.828905	*14.40%*
Ozone depletionkg (CFC-11 eq)	3.45156E-07	4.01727E-07	*94.2%*	3.47148E-10	*0.1%*	3.36994E-09	*0.8%*	3.62024E-09	*0.85%*	-8.1094E-08	*-19.0%*	1.72E-08	*4.03%*
Human toxicity, non-cancer effects (CTUh)	1.57185E-06	1.32475E-06	*73.5%*	4.79839E-10	*0.0%*	2.18106E-09	*0.1%*	1.49984E-08	*0.83%*	-2.3166E-07	*-12.8%*	4.61E-07	*25.57%*
Human toxicity, cancer effects (CTUh)	3.33211E-07	3.14163E-07	*89.0%*	7.96629E-11	*0.023%*	5.05813E-10	*0.1%*	3.17399E-09	*0.90%*	-1.975E-08	*-5.6%*	3.5E-08	*9.93%*
Particulate matter kg (PM2.5 eq)	0.002305501	0.003022018	*96.1%*	8.84247E-07	*0.028%*	1.33779E-05	*0.4%*	1.82797E-05	*0.58%*	-0.00084044	*-26.7%*	9.14E-05	*2.90%*
Ionizing radiation HH (kBq U235 eq)	0.905126102	0.90011185	*97.2%*	0.000157624	*0.017%*	0.002819389	*0.3%*	0.004197933	*0.45%*	-0.02045351	*-2.2%*	0.018293	*1.98%*
Ionizing radiation E (interim) (CTUe)	2.54551E-06	2.57094E-06	*97.1%*	9.24291E-10	*0.035%*	9.5599E-09	*0.4%*	1.18013E-08	*0.45%*	-1.0105E-07	*-3.8%*	5.33E-08	*2.01%*
Photochemical ozone formation (kg NMVOC eq)	0.013661382	0.014351483	*94.7%*	9.19856E-06	*0.06%*	0.000166112	*1.1%*	8.81298E-05	*0.58%*	-0.00149183	*-9.8%*	0.000538	*3.55%*
Acidification (molc H+ eq)	0.023071653	0.026317505	*95.1%*	9.54522E-06	*0.0%*	0.000185583	*0.7%*	0.0001956	*0.71%*	-0.00461485	*-16.7%*	0.000978	*3.53%*
Terrestrial eutrophication (molc N eq)	0.042078538	0.043918101	*93.3%*	3.26712E-05	*0.1%*	0.000624395	*1.3%*	0.000351811	*0.75%*	-0.00500601	*-10.6%*	0.002158	*4.58%*
Freshwater eutrophication (kg P eq)	0.002203598	0.00217788	*92.0%*	1.85825E-07	*0.01%*	4.22077E-06	*0.2%*	3.21893E-05	*1.36%*	-0.00016403	*-6.9%*	0.000153	*6.47%*
Marine eutrophication (kg N eq)	0.004222522	0.004401598	*93.1%*	2.99463E-06	*0.1%*	5.78155E-05	*1.2%*	3.6034E-05	*0.76%*	-0.00050578	*-10.7%*	0.00023	*4.86%*
Freshwater ecotoxicity CTUe	75.79725389	39.24762483	*50.1%*	0.011873851	*0.015%*	0.087315708	*0.1%*	0.753223309	*0.96%*	-2.52227174	*-3.2%*	38.21949	*48.80%*
Land use (kg C deficit)	4.53363372	6.015703378	*94.1%*	0.006456053	*0.101%*	0.038244002	*0.6%*	0.056156101	*0.88%*	-1.8598634	*-29.1%*	0.276938	*4.33%*
Water resource depletion (m3 water eq)	0.017421599	0.016449539	*94.4%*	9.12713E-08	*0.00%*	0.000132026	*0.8%*	0.000218118	*1.25%*	-0.0002044	*-1.2%*	0.000826	*4.74%*
Mineral, fossil & ren resource depletion (kg Sb eq)	0.000225696	0.000246728	*95.8%*	2.04357E-07	*0.1%*	1.53402E-07	*0.1%*	8.8938E-07	*0.35%*	-3.1792E-05	*-12.3%*	9.51E-06	*3.69%*
average value			**89.6%**		**0.0%**		**0.5%**		**0.8%**		**-10.9%**		**9.1%**

Annex -7 – Results of LCIA for I kg of PET bottles recycled into fibre (B2F scenarios) in the context of Lombardy region. B2B(CFF(IV)) method

B2F_LOMB_CFF(Econ)												
Impact category	Total	1.Bottles production		2.Collection		3. Sorting		4.Recycling		5.Secondary bottles		6.Disposal	
	Value	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.
Climate change (kg CO2 eq)	5.625306897	4.848576208	*84.3%*	0.001911701	*0.0%*	0.022706497	*0.4%*	0.052261808	*0.91%*	-0.12905402	*-2.2%*	0.828905	*14.40%*
Ozone depletionkg (CFC-11 eq)	3.72294E-07	4.01727E-07	*94.2%*	3.47148E-10	*0.1%*	3.36994E-09	*0.8%*	3.62024E-09	*0.85%*	-5.3956E-08	*-12.7%*	1.72E-08	*4.03%*
Human toxicity, non-cancer effects (CTUh)	1.64938E-06	1.32475E-06	*73.5%*	4.79839E-10	*0.0%*	2.18106E-09	*0.1%*	1.49984E-08	*0.83%*	-1.5413E-07	*-8.5%*	4.61E-07	*25.57%*
Human toxicity, cancer effects (CTUh)	3.39821E-07	3.14163E-07	*89.0%*	7.96629E-11	*0.023%*	5.05813E-10	*0.1%*	3.17399E-09	*0.90%*	-1.3141E-08	*-3.7%*	3.5E-08	*9.93%*
Particulate matter kg (PM2.5 eq)	0.002586757	0.003022018	*96.1%*	8.84247E-07	*0.028%*	1.33779E-05	*0.4%*	1.82797E-05	*0.58%*	-0.00055919	*-17.8%*	9.14E-05	*2.90%*
Ionizing radiation HH (kBq U235 eq)	0.911970912	0.90011185	*97.2%*	0.000157624	*0.017%*	0.002819389	*0.3%*	0.004197933	*0.45%*	-0.0136087	*-1.5%*	0.018293	*1.98%*
Ionizing radiation E (interim) (CTUe)	2.57933E-06	2.57094E-06	*97.1%*	9.24291E-10	*0.035%*	9.5599E-09	*0.4%*	1.18013E-08	*0.45%*	-6.7231E-08	*-2.5%*	5.33E-08	*2.01%*
Photochemical ozone formation (kg NMVOC eq)	0.014160626	0.014351483	*94.7%*	9.19856E-06	*0.06%*	0.000166112	*1.1%*	8.81298E-05	*0.58%*	-0.00099259	*-6.6%*	0.000538	*3.55%*
Acidification (molc H+ eq)	0.024616023	0.026317505	*95.1%*	9.54522E-06	*0.0%*	0.000185583	*0.7%*	0.0001956	*0.71%*	-0.00307048	*-11.1%*	0.000978	*3.53%*
Terrestrial eutrophication (molc N eq)	0.043753809	0.043918101	*93.3%*	3.26712E-05	*0.1%*	0.000624395	*1.3%*	0.000351811	*0.75%*	-0.00333074	*-7.1%*	0.002158	*4.58%*
Freshwater eutrophication (kg P eq)	0.002258491	0.00217788	*92.0%*	1.85825E-07	*0.01%*	4.22077E-06	*0.2%*	3.21893E-05	*1.36%*	-0.00010914	*-4.6%*	0.000153	*6.47%*
Marine eutrophication (kg N eq)	0.00439178	0.004401598	*93.1%*	2.99463E-06	*0.1%*	5.78155E-05	*1.2%*	3.6034E-05	*0.76%*	-0.00033652	*-7.1%*	0.00023	*4.86%*
Freshwater ecotoxicity CTUe	76.64133727	39.24762483	*50.1%*	0.011873851	*0.015%*	0.087315708	*0.1%*	0.753223309	*0.96%*	-1.67818836	*-2.1%*	38.21949	*48.80%*
Land use (kg C deficit)	5.156040804	6.015703378	*94.1%*	0.006456053	*0.101%*	0.038244002	*0.6%*	0.056156101	*0.88%*	-1.23745632	*-19.4%*	0.276938	*4.33%*
Water resource depletion (m3 water eq)	0.017490003	0.016449539	*93.3%*	9.12713E-08	*0.00%*	0.000132026	*0.7%*	0.000218118	*1.24%*	-0.000136	*-0.8%*	0.000826	*4.69%*
Mineral, fossil & ren resource depletion (kg Sb eq)	0.000236335	0.000246728	*95.8%*	2.04357E-07	*0.1%*	1.53402E-07	*0.1%*	8.8938E-07	*0.35%*	-2.1153E-05	*-8.2%*	9.51E-06	*3.69%*
average value			**89.6%**		**0.0%**		**0.5%**		**0.8%**		**-7.2%**		**9.1%**

Annex -8 – Results of LCIA for I kg of PET bottles recycled into fibres (B2F scenarios) in the context of Lombardy region. B2B(CFF(Econ)) method

B2B_DK_SES									
Impact category	Total	1.Bottles production		2.Collection&sorting		3.Recycling		4.Secondary bottles	
	Value	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.
Climate change (kg CO2 eq)	3.22	4.75	*84.7%*	0.18	*3.23%*	0.68	*12.1%*	-2.40	*-42.7%*
Ozone depletionkg (CFC-11 eq)	2.95E-07	3.85E-07	*94.2%*	3.65E-09	*0.894%*	1.99E-08	*4.88%*	-1.13E-07	*-27.6%*
Human toxicity, non-cancer effects (CTUh)	1.09769E-06	1.29985E-06	*74%*	1.08679E-07	*6.18%*	3.4905E-07	*19.9%*	-6.59892E-07	*-37.5%*
Human toxicity, cancer effects (CTUh)	1.90035E-07	3.09792E-07	*88%*	6.34857E-09	*1.81%*	3.42974E-08	*9.79%*	-1.60403E-07	*-45.8%*
Particulate matter kg (PM2.5 eq)	0.001320426	0.002978198	*96%*	1.55836E-05	*0.502%*	0.0001089	*3.51%*	-0.001782255	*-54.7%*
Ionizing radiation HH (kBq U235 eq)	0.781	0.892	*95.9%*	0.004	*0.397%*	0.034	*3.7%*	-0.150	*-16.1%*
Ionizing radiation E (interim) (CTUe)	2.16778E-06	2.52529E-06	*95.3%*	1.42839E-08	*0.539%*	1.09947E-07	*4.15%*	-4.81736E-07	*-18.2%*
Photochemical ozone formation (kg NMVOC eq)	0.00731	0.01390	*94.6%*	0.00020	*1.38%*	0.00059	*4%*	-0.00738	*-50.3%*
Acidification (molc H+ eq)	0.014117744	0.025841686	*95.4%*	0.00019655	*0.725%*	0.001062498	*3.92%*	-0.01298299	*-47.9%*
Terrestrial eutrophication (molc N eq)	0.025513801	0.042328477	*92.7%*	0.0007909	*1.73%*	0.002547292	*5.58%*	-0.020152867	*-44.1%*
Freshwater eutrophication (kg P eq)	0.00161	0.00217	*90.5%*	0.00001	*0.373%*	0.00022	*9.1%*	-0.00078	*-32.6%*
Marine eutrophication (kg N eq)	0.00263	0.00426	*92.6%*	0.00008	*1.67%*	0.00026	*5.69%*	-0.00196	*-42.7%*
Freshwater ecotoxicity CTUe	55.87	38.63	*51.8%*	9.38	*12.6%*	26.52	*35.6%*	-18.66	*-25%*
Land use (kg C deficit)	4.39	5.70	*91.4%*	0.06	*1.01%*	0.47	*7.6%*	-1.86	*-29.7%*
Water resource depletion (m3 water eq)	0.02047	0.01645	*80.4%*	0.00015	*0.751%*	0.00183	*8.95%*	0.00204	*9.94%*
Mineral, fossil & ren resource depletion (kg Sb eq)	0.000113888	0.000235204	*95.2%*	1.91921E-06	*0.777%*	9.86206E-06	*3.99%*	-0.000133098	*-53.9%*
average value			**88.3%**		**2.2%**		**8.9%**		**-34.9%**

Annex - 9 – Results of LCIA for I kg of PET bottles recycled into bottles (B2B scenarios) in the context of Denmark

B2B(SES) method

B2B_DK_CFF(IV)											
Impact category	Total	1.Bottles production		2.Collection&sorting		3.Recycling		4.Secondary bottles		5.Disposal	
	Value	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.
Climate change (kg CO2 eq)	4.070745365	4.752259849	*94.4%*	0.020152614	*0.4%*	0.105297015	*3.15%*	-0.965354417	*-19.2%*	0.1583903	*2.09%*
Ozone depletionkg (CFC-11 eq)	3.5186E-07	3.84523E-07	*96.8%*	3.17652E-09	*0.8%*	6.5324E-09	*1.64%*	-4.5372E-08	*-11.4%*	2.999E-09	*3.15%*
Human toxicity, non-cancer effects (CTUh)	1.16419E-06	1.29985E-06	*90.0%*	3.3117E-09	*0.2%*	3.61063E-08	*2.52%*	-2.65849E-07	*-18.6%*	9.077E-08	*0.76%*
Human toxicity, cancer effects (CTUh)	2.59893E-07	3.09792E-07	*95.5%*	5.83608E-10	*0.180%*	7.24982E-09	*2.23%*	-6.46214E-08	*-19.9%*	6.889E-09	*6.35%*
Particulate matter kg (PM2.5 eq)	0.002322972	0.002978198	*97.9%*	1.1716E-05	*0.385%*	3.46678E-05	*1.14%*	-0.000718013	*-23.6%*	1.64E-05	*2.12%*
Ionizing radiation HH (kBq U235 eq)	0.852084667	0.892330789	*97.8%*	0.003504729	*0.384%*	0.011780723	*1.29%*	-0.060229676	*-6.6%*	0.0046981	*0.56%*
Ionizing radiation E (interim) (CTUe)	2.39741E-06	2.52529E-06	*97.4%*	1.33969E-08	*0.517%*	3.7436E-08	*1.44%*	-1.94076E-07	*-7.5%*	1.537E-08	*0.54%*
Photochemical ozone formation (kg NMVOC eq)	0.011365455	0.01390347	*97.0%*	0.000159554	*1.11%*	0.000169094	*1.18%*	-0.0029748	*20.7%*	0.0001081	*0.54%*
Acidification (molc H+ eq)	0.021267426	0.025841686	*97.5%*	0.000155082	*0.6%*	0.000335229	*1.27%*	-0.005230426	*-19.7%*	0.0001659	*0.76%*
Terrestrial eutrophication (molc N eq)	0.036024437	0.042328477	*95.9%*	0.000615883	*1.4%*	0.000742701	*1.68%*	-0.008118938	*-18.4%*	0.0004563	*0.63%*
Freshwater eutrophication (kg P eq)	0.001957686	0.002167745	*95.4%*	3.73755E-06	*0.16%*	7.1473E-05	*3.14%*	-0.00031496	*-13.9%*	2.969E-05	*1.03%*
Marine eutrophication (kg N eq)	0.003643179	0.00425585	*96.0%*	5.62878E-05	*1.3%*	7.42455E-05	*1.67%*	-0.000790408	*-17.8%*	4.72E-05	*1.31%*
Freshwater ecotoxicity CTUe	40.37942692	38.63153555	*80.7%*	0.099695211	*0.208%*	1.714267707	*3.58%*	-7.517838382	*-15.7%*	7.4517668	*1.06%*
Land use (kg C deficit)	5.235865633	5.704916501	*95.3%*	0.053653635	*0.897%*	0.156802573	*2.62%*	-0.748036847	*-12.5%*	0.0685298	*15.60%*
Water resource depletion (m3 water eq)	0.018317654	0.016447685	*89.8%*	0.000166318	*0.91%*	0.00064567	*3.52%*	0.000820026	*4.5%*	0.000238	*1.15%*
Mineral, fossil & ren resource depletion (kg Sb eq)	0.000186183	0.000235204	*98.1%*	4.41469E-07	*0.2%*	2.22984E-06	*0.93%*	-5.36207E-05	*-22.4%*	1.928E-06	*0.80%*
average value			**94.7%**		**0.6%**		**2.1%**		**-12.6%**		**2.4%**

Annex -10 – Results of LCIA for I kg of PET bottles recycled into bottles (B2B scenarios) in the context of Denmark B2B(CFF(IV)) method

B2B_DK_CFF(N)										
Impact category	Total	1.Bottles production		2.Collection&sorting		3.Recycling		4.Secondary bottles		5.Disposal	
	Value	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.
Climate change (kg CO2 eq)	4.842731408	4.752259849	*94.4%*	0.020152614	*0.40%*	0.105297015	*2.09%*	-0.193368373	*-3.8%*	0.1583903	*3.15%*
Ozone depletionkg (CFC-11 eq)	3.88143E-07	3.84523E-07	*96.8%*	3.17652E-09	*0.80%*	6.5324E-09	*1.64%*	-9.08838E-09	*-2.3%*	2.999E-09	*0.76%*
Human toxicity, non-cancer effects (CTUh)	1.37679E-06	1.29985E-06	*90.0%*	3.3117E-09	*0.23%*	3.61063E-08	*2.52%*	-5.32518E-08	*-3.7%*	9.077E-08	*6.35%*
Human toxicity, cancer effects (CTUh)	3.1157E-07	3.09792E-07	*95.5%*	5.83608E-10	*0.18%*	7.24982E-09	*2.23%*	-1.29442E-08	*-4.0%*	6.889E-09	*2.12%*
Particulate matter kg (PM2.5 eq)	0.002897161	0.002978198	*97.9%*	1.1716E-05	*0.39%*	3.46678E-05	*1.14%*	-0.000143824	*-4.7%*	1.64E-05	*0.54%*
Ionizing radiation HH (kBq U235 eq)	0.900249847	0.892330789	*97.8%*	0.003504729	*0.38%*	0.011780723	*1.29%*	-0.012064496	*-1.3%*	0.0046981	*0.51%*
Ionizing radiation E (interim) (CTUe)	2.55261E-06	2.52529E-06	*97.4%*	1.33969E-08	*0.52%*	3.7436E-08	*1.44%*	-3.88749E-08	*-1.5%*	1.537E-08	*0.59%*
Photochemical ozone formation (kg NMVOC eq)	0.013744379	0.01390347	*97.0%*	0.000159554	*1.11%*	0.000169094	*1.18%*	-0.000595877	*-4.2%*	0.0001081	*0.75%*
Acidification (molc H+ eq)	0.025450156	0.025841686	*97.5%*	0.000155082	*0.59%*	0.000335229	*1.27%*	-0.001047697	*-4.0%*	0.0001659	*0.63%*
Terrestrial eutrophication (molc N eq)	0.042517086	0.042328477	*95.9%*	0.000615883	*1.40%*	0.000742701	*1.68%*	-0.00162629	*-3.7%*	0.0004563	*1.03%*
Freshwater eutrophication (kg P eq)	0.002209556	0.002167745	*95.4%*	3.73755E-06	*0.16%*	7.1473E-05	*3.14%*	-6.3089E-05	*-2.8%*	2.969E-05	*1.31%*
Marine eutrophication (kg N eq)	0.004275262	0.00425585	*96.0%*	5.62878E-05	*1.27%*	7.42455E-05	*1.67%*	-0.000158325	*-3.6%*	4.72E-05	*1.06%*
Freshwater ecotoxicity CTUe	46.39138088	38.63153555	*80.7%*	0.099695211	*0.21%*	1.714267707	*3.58%*	-1.505884422	*-3.1%*	7.4517668	*15.56%*
Land use (kg C deficit)	5.834064591	5.704916501	*95.3%*	0.053653635	*0.90%*	0.156802573	*2.62%*	-0.149837889	*-2.5%*	0.0685298	*1.15%*
Water resource depletion (m3 water eq)	0.017661886	0.016447685	*89.8%*	0.000166318	*0.94%*	0.00064567	*3.66%*	0.000164258	*0.9%*	0.000238	*1.36%*
Mineral, fossil & ren resource depletion (kg Sb eq)	0.000229063	0.000235204	*98.1%*	4.41469E-07	*0.18%*	2.22984E-06	*0.93%*	-1.07407E-05	*-4.5%*	1.928E-06	*0.80%*
average value			**94.7%**		**0.6%**		**2.0%**		**-3.0%**		**2.4%**

Annex -11 – Results of LCIA for I kg of PET bottles recycled into bottles (B2B scenarios) in the context of Denmark.

B2B(CFF(Econ)) method

B2B_DK_CFF(Econ)										
Impact category	Total	1.Bottles production		2.Collection&sorting		3.Recycling		4.Secondary bottles		5.Disposal	
	Value	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.
Climate change (kg CO2 eq)	4.339466996	4.752259849	94.4%	0.020152614	0.40%	0.105297015	2.09%	-0.696632785	-13.8%	0.1583903	3.15%
Ozone depletionkg (CFC-11 eq)	3.6449E-07	3.84523E-07	96.8%	3.17652E-09	0.80%	6.5324E-09	1.64%	-3.2742E-08	-8.2%	2.999E-09	0.76%
Human toxicity, non-cancer effects (CTUh)	1.2382E-06	1.29985E-06	90.9%	3.3117E-09	0.23%	3.61063E-08	2.52%	-1.91846E-07	-13.4%	9.077E-08	6.35%
Human toxicity, cancer effects (CTUh)	2.77882E-07	3.09792E-07	95.5%	5.83608E-10	0.18%	7.24982E-09	2.23%	-4.6633E-08	-14.4%	6.889E-09	2.12%
Particulate matter kg (PM2.5 eq)	0.002522842	0.002978198	97.9%	1.1716E-05	0.39%	3.46678E-05	1.14%	-0.000518143	-17.0%	1.64E-05	0.54%
Ionizing radiation HH (kBq U235 eq)	0.868850547	0.892330789	97.8%	0.003504729	0.38%	0.011780723	1.29%	-0.043463796	-4.8%	0.0046981	0.51%
Ionizing radiation E (interim) (CTUe)	2.45143E-06	2.52529E-06	97.4%	1.33969E-08	0.52%	3.7436E-08	1.44%	-1.40052E-07	-5.4%	1.537E-08	0.59%
Photochemical ozone formation (kg NMVOC eq)	0.012193538	0.01390347	97.0%	0.000159554	1.11%	0.000169094	1.18%	-0.002146718	-15.0%	0.0001081	0.75%
Acidification (molc H+ eq)	0.022723398	0.025841686	97.5%	0.000155082	0.59%	0.000335229	1.27%	-0.003774455	-14.2%	0.0001659	0.63%
Terrestrial eutrophication (molc N eq)	0.038284472	0.042328477	95.9%	0.000615883	1.40%	0.000742701	1.68%	-0.005858903	-13.3%	0.0004563	1.03%
Freshwater eutrophication (kg P eq)	0.00204536	0.002167745	95.4%	3.73755E-06	0.16%	7.1473E-05	3.14%	-0.000227286	-10.0%	2.969E-05	1.31%
Marine eutrophication (kg N eq)	0.003863201	0.00425585	96.0%	5.62878E-05	1.27%	7.42455E-05	1.67%	-0.000570385	-12.9%	4.72E-05	1.06%
Freshwater ecotoxicity CTUe	42.47213583	38.63153555	80.7%	0.099695211	0.21%	1.714267707	3.58%	-5.425129467	-11.3%	7.4517668	15.56%
Land use (kg C deficit)	5.444093491	5.704916501	95.3%	0.053653635	0.90%	0.156802573	2.62%	-0.53980899	-9.0%	0.0685298	1.15%
Water resource depletion (m3 water eq)	0.018089387	0.016447685	90.9%	0.000166318	0.92%	0.00064567	3.57%	0.000591759	3.4%	0.000238	1.36%
Mineral, fossil & ren resource depletion (kg Sb eq)	0.000201109	0.000235204	98.1%	4.41469E-07	0.18%	2.22984E-06	0.93%	-3.86945E-05	-16.1%	1.928E-06	0.80%
average value			**94.8%**		**0.6%**		**2.0%**		**-11.0%**		**2.4%**

Annex -12 – Results of LCIA for I kg of PET bottles recycled into bottles (B2B scenarios) in the context of Denmark.

B2B(CFF(Econ)) method

B2B_DK_CFF(R1,R2=N Loops)										
Impact category	Total	1.Bottles production		2.Collection&sorting		3.Recycling		4.Secondary bottles		5.Disposal	
	Value	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.
Climate change (kg CO2 eq)	4.053779329	2.460600038	*55.4%*	0.020152614	*0.40%*	0.045669167	*1.03%*	-0.388517521	*-8.7%*	0.3618131	*8.14%*
Ozone depletionkg (CFC-11 eq)	3.29324E-07	1.99096E-07	*57.3%*	3.17652E-09	*0.91%*	2.83322E-09	*0.82%*	-1.82604E-08	*-5.3%*	6.852E-09	*1.97%*
Human toxicity, non-cancer effects (CTUh)	1.21689E-06	6.73029E-07	*50.8%*	3.3117E-09	*0.25%*	1.56599E-08	*1.18%*	-1.06994E-07	*-8.1%*	2.074E-07	*15.66%*
Human toxicity, cancer effects (CTUh)	2.54656E-07	1.60403E-07	*57.2%*	5.83608E-10	*0.21%*	3.14437E-09	*1.12%*	-2.60076E-08	*-9.3%*	1.574E-08	*5.61%*
Particulate matter kg (PM2.5 eq)	0.002257083	0.001542035	*60.6%*	1.1716E-05	*0.46%*	1.5036E-05	*0.59%*	-0.000288972	*-11.3%*	3.747E-05	*1.47%*
Ionizing radiation HH (kBq U235 eq)	0.785472082	0.462026329	*57.1%*	0.003504729	*0.43%*	0.005109507	*0.63%*	-0.024240097	*-3.0%*	0.0107319	*1.33%*
Ionizing radiation E (interim) (CTUe)	2.21622E-06	1.30753E-06	*57.0%*	1.33969E-08	*0.58%*	1.62367E-08	*0.71%*	-7.81079E-08	*-3.4%*	3.51E-08	*1.53%*
Photochemical ozone formation (kg NMVOC eq)	0.010982755	0.007198866	*59.1%*	0.000159554	*1.31%*	7.33391E-05	*0.60%*	-0.001197241	*-9.8%*	0.000247	*2.03%*
Acidification (molc H+ eq)	0.020410819	0.013380172	*59.4%*	0.000155082	*0.69%*	0.000145395	*0.65%*	-0.002105043	*-9.3%*	0.0003789	*1.68%*
Terrestrial eutrophication (molc N eq)	0.034616225	0.021916616	*57.9%*	0.000615883	*1.63%*	0.000322122	*0.85%*	-0.003267556	*-8.6%*	0.0010424	*2.75%*
Freshwater eutrophication (kg P eq)	0.001844935	0.001122403	*56.9%*	3.73755E-06	*0.19%*	3.09991E-05	*1.57%*	-0.000126759	*-6.4%*	6.782E-05	*3.44%*
Marine eutrophication (kg N eq)	0.003495878	0.002203572	*57.8%*	5.62878E-05	*1.48%*	3.22016E-05	*0.84%*	-0.000318108	*-8.3%*	0.0001078	*2.83%*
Freshwater ecotoxicity CTUe	47.5747692	20.0024327	*39.5%*	0.099695211	*0.20%*	0.74350804	*1.47%*	-3.025636886	*-6.0%*	17.022173	*33.64%*
Land use (kg C deficit)	4.920615495	2.953861574	*56.6%*	0.053653635	*1.03%*	0.068008032	*1.30%*	-0.301055671	*-5.8%*	0.1565435	*3.00%*
Water resource depletion (m3 water eq)	0.016470813	0.008516195	*86.6%*	0.000166318	*1.69%*	0.000280039	*2.85%*	0.000330028	*3.5%*	0.0005436	*5.72%*
Mineral, fossil & ren resource depletion (kg Sb eq)	0.000181167	0.000121783	*60.1%*	4.41469E-07	*0.22%*	9.67121E-07	*0.48%*	-2.15802E-05	*-10.6%*	4.404E-06	*2.17%*
average value			**58.1%**		**0.7%**		**1.0%**		**-6.9%**		**5.8%**

Annex -13 – Results of LCIA for I kg of PET bottles recycled into bottles (B2B scenarios) in the context of Denmark. B2B(CFF(R1,R2=N loops)) method

B2F_DK_SES									
Impact category	Total	1.Bottles production		2.Collection&sorting		3.Recycling		4.Secondary bottles	
	Value	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.
Climate change (kg CO2 eq)	4.425004845	4.752259837	*88.2%*	0.113702024	*2.11%*	0.520329172	*9.7%*	-0.961286188	*-17.8%*
Ozone depletionkg (CFC-11 eq)	3.83291E-09	3.84523E-07	*94.4%*	3.44946E-09	*0.85%*	1.94581E-08	*4.8%*	-4.03598E-07	*-99.1%*
Human toxicity, non-cancer effects (CTUh)	4.54827E-07	1.29985E-06	*80.7%*	6.4394E-08	*4.00%*	2.45662E-07	*15.3%*	-1.15508E-06	*-71.7%*
Human toxicity, cancer effects (CTUh)	2.43998E-07	3.09792E-07	*90.5%*	3.92562E-09	*1.15%*	2.86408E-08	*8.4%*	-9.83602E-08	*-28.7%*
Particulate matter kg (PM2.5 eq)	-0.00109615	0.002978198	*71.0%*	1.39581E-05	*0.33%*	0.000105105	*2.5%*	-0.004193411	*-100.0%*
Ionizing radiation HH (kBq U235 eq)	0.828627481	0.892330775	*95.9%*	0.003614836	*0.39%*	0.034205478	*3.7%*	-0.101523608	*-10.9%*
Ionizing radiation E (interim) (CTUe)	2.14729E-06	2.52529E-06	*95.4%*	1.39111E-08	*0.53%*	1.09077E-07	*4.1%*	-5.00987E-07	*-18.9%*
Photochemical ozone formation (kg NMVOC eq)	0.007219347	0.01390347	*95.0%*	0.000184451	*1.26%*	0.000545023	*3.7%*	-0.007413597	*-50.7%*
Acidification (molc H+ eq)	0.004034507	0.025841686	*95.6%*	0.000179121	*0.66%*	0.001021809	*3.8%*	-0.02300811	*-85.1%*
Terrestrial eutrophication (molc N eq)	0.020551323	0.042328477	*93.2%*	0.000717342	*1.58%*	0.002375563	*5.2%*	-0.02487006	*-54.8%*
Freshwater eutrophication (kg P eq)	0.001568958	0.002167745	*90.8%*	6.74216E-06	*0.28%*	0.00021294	*8.9%*	-0.000818469	*-34.3%*
Marine eutrophication (kg N eq)	0.002051395	0.00425585	*93.2%*	6.81027E-05	*1.49%*	0.000241355	*5.3%*	-0.002513913	*-55.1%*
Freshwater ecotoxicity CTUe	48.96881678	38.63153552	*62.8%*	5.478890325	*8.91%*	17.41106881	*28.3%*	-12.55267787	*-20.4%*
Land use (kg C deficit)	-3.032398368	5.704916494	*61.6%*	0.059282233	*0.64%*	0.464929628	*5.0%*	-9.261526723	*-100.0%*
Water resource depletion (m3 water eq)	0.01743049	0.016447685	*89.1%*	0.000159029	*0.86%*	0.001843823	*10.0%*	-0.001020047	*-5.5%*
Mineral, fossil & ren resource depletion (kg Sb eq)	8.68031E-05	0.000235204	*96.0%*	1.29813E-06	*0.53%*	8.41208E-06	*3.4%*	-0.000158111	*-64.6%*
average value			**87.1%**		**1.6%**		**7.6%**		**-51.1%**

Annex -14 – Results of LCIA for I kg of PET bottles recycled into fibres (B2F scenarios) in the context of Denmark.

B2B(CFF(Econ)) method

B2F_DK_CFF(IV)										
Impact category	Total	1.Bottles production		2.Collection&sorting		3.Recycling		4.Secondary bottles		5.Disposal	
	Value	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.
Climate change (kg CO2 eq)	4.600922924	4.752259849	*94.4%*	0.020152614	*0.40%*	0.105297015	*2.09%*	-0.435176859	*-8.6%*	0.158390304	*3.15%*
Ozone depletionkg (CFC-11 eq)	2.14522E-07	3.84523E-07	*96.8%*	3.17652E-09	*0.80%*	6.5324E-09	*1.64%*	-1.8271E-07	*-46.0%*	2.99938E-09	*0.76%*
Human toxicity, non-cancer effects (CTUh)	9.07134E-07	1.29985E-06	*90.9%*	3.3117E-09	*0.23%*	3.61063E-08	*2.52%*	-5.22908E-07	*-36.6%*	9.07741E-08	*6.35%*
Human toxicity, cancer effects (CTUh)	2.79987E-07	3.09792E-07	*95.5%*	5.83608E-10	*0.18%*	7.24982E-09	*2.23%*	-4.45279E-08	*-13.7%*	6.88882E-09	*2.12%*
Particulate matter kg (PM2.5 eq)	0.001142616	0.002978198	*97.9%*	1.1716E-05	*0.39%*	3.46678E-05	*1.14%*	-0.001898369	*-62.4%*	1.64033E-05	*0.54%*
Ionizing radiation HH (kBq U235 eq)	0.866354327	0.892330785	*97.8%*	0.003504729	*0.38%*	0.011780723	*1.29%*	-0.045960012	*-5.0%*	0.004698103	*0.51%*
Ionizing radiation E (interim) (CTUe)	2.36469E-06	2.52529E-06	*97.4%*	1.33969E-08	*0.52%*	3.7436E-08	*1.44%*	-2.26798E-07	*-8.8%*	1.53675E-08	*0.59%*
Photochemical ozone formation (kg NMVOC eq)	0.0109841	0.01390347	*97.0%*	0.000159554	*1.11%*	0.000169094	*1.18%*	-0.003356156	*-23.4%*	0.000108137	*0.75%*
Acidification (molc H+ eq)	0.016082019	0.025841686	*97.5%*	0.000155082	*0.59%*	0.000335229	*1.27%*	-0.010415833	*-39.3%*	0.000165856	*0.63%*
Terrestrial eutrophication (molc N eq)	0.032884632	0.042328477	*95.9%*	0.000615883	*1.40%*	0.000742701	*1.68%*	-0.011258743	*-25.5%*	0.000456314	*1.03%*
Freshwater eutrophication (kg P eq)	0.001902122	0.002167745	*95.4%*	3.73755E-06	*0.16%*	7.1473E-05	*3.14%*	-0.000370523	*-16.3%*	2.96898E-05	*1.31%*
Marine eutrophication (kg N eq)	0.003295532	0.00425585	*96.0%*	5.62878E-05	*1.27%*	7.42455E-05	*1.67%*	-0.001138055	*-25.7%*	4.72034E-05	*1.06%*
Freshwater ecotoxicity CTUe	42.21463432	38.63153572	*80.7%*	0.099695211	*0.21%*	1.714267707	*3.58%*	-5.682631212	*-11.9%*	7.451766892	*15.56%*
Land use (kg C deficit)	1.791184318	5.704916527	*95.3%*	0.053653635	*0.90%*	0.156802573	*2.62%*	-4.192718187	*-70.1%*	0.068529771	*1.15%*
Water resource depletion (m3 water eq)	0.01703585	0.016447685	*96.5%*	0.000166318	*0.98%*	0.00064567	*3.79%*	-0.000461778	*-2.6%*	0.000237956	*1.36%*
Mineral, fossil & ren resource depletion (kg Sb eq)	0.000168226	0.000235204	*98.1%*	4.41469E-07	*0.18%*	2.22984E-06	*0.93%*	-7.15774E-05	*-29.8%*	1.92798E-06	*0.80%*
average value			**95.2%**		**0.6%**		**2.0%**		**-26.6%**		**2.4%**

Annex -15 – Results of LCIA for I kg of PET bottles recycled into fibres (B2F scenarios) in the context of Denmark.

B2B(CFF(IV)) method

B2F_DK_CFF(Econ)											
Impact category	Total	1.Bottles production		2.Collection&sorting		3.Recycling		4.Secondary bottles		5.Disposal	
	Value	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.	Value	Pct.
Climate change (kg CO2 eq)	4.746555748	4.752259849	*94.4%*	0.020152614	*0.40%*	0.105297015	*2.09%*	-0.289544035	*-5.7%*	0.158390304	*3.15%*
Ozone depletionkg (CFC-11 eq)	2.75666E-07	3.84523E-07	*96.8%*	3.17652E-09	*0.80%*	6.5324E-09	*1.64%*	-1.21566E-07	*-30.6%*	2.99938E-09	*0.76%*
Human toxicity, non-cancer effects (CTUh)	1.08213E-06	1.29985E-06	*90.9%*	3.3117E-09	*0.23%*	3.61063E-08	*2.52%*	-3.47916E-07	*-24.3%*	9.07741E-08	*6.35%*
Human toxicity, cancer effects (CTUh)	2.94888E-07	3.09792E-07	*95.5%*	5.83608E-10	*0.18%*	7.24982E-09	*2.23%*	-2.96266E-08	*-9.1%*	6.88882E-09	*2.12%*
Particulate matter kg (PM2.5 eq)	0.001777909	0.002978198	*97.9%*	1.1716E-05	*0.39%*	3.46678E-05	*1.14%*	-0.001263076	*-41.5%*	1.64033E-05	*0.54%*
Ionizing radiation HH (kBq U235 eq)	0.881734939	0.892330785	*97.8%*	0.003504729	*0.38%*	0.011780723	*1.29%*	-0.0305794	*-3.4%*	0.004698103	*0.51%*
Ionizing radiation E (interim) (CTUe)	2.44059E-06	2.52529E-06	*97.4%*	1.33969E-08	*0.52%*	3.7436E-08	*1.44%*	-1.509E-07	*-5.8%*	1.53675E-08	*0.59%*
Photochemical ozone formation (kg NMVOC eq)	0.012107244	0.01390347	*97.0%*	0.000159554	*1.11%*	0.000169094	*1.18%*	-0.002233011	*-15.6%*	0.000108137	*0.75%*
Acidification (molc H+ eq)	0.019567699	0.025841686	*97.5%*	0.000155082	*0.59%*	0.000335229	*1.27%*	-0.006930153	*-26.2%*	0.000165856	*0.63%*
Terrestrial eutrophication (molc N eq)	0.036652393	0.042328477	*95.9%*	0.000615883	*1.40%*	0.000742701	*1.68%*	-0.007490982	*-17.0%*	0.000456314	*1.03%*
Freshwater eutrophication (kg P eq)	0.002026118	0.002167745	*95.4%*	3.73755E-06	*0.16%*	7.1473E-05	*3.14%*	-0.000246527	*-10.8%*	2.96898E-05	*1.31%*
Marine eutrophication (kg N eq)	0.003676384	0.00425585	*96.0%*	5.62878E-05	*1.27%*	7.42455E-05	*1.67%*	-0.000757203	*-17.1%*	4.72034E-05	*1.06%*
Freshwater ecotoxicity CTUe	44.11633845	38.63153572	*80.7%*	0.099695211	*0.21%*	1.714267707	*3.58%*	-3.780927079	*-7.9%*	7.451766892	*15.56%*
Land use (kg C deficit)	3.194286017	5.704916527	*95.3%*	0.053653635	*0.90%*	0.156802573	*2.62%*	-2.789616488	*-46.6%*	0.068529771	*1.15%*
Water resource depletion (m3 water eq)	0.017190385	0.016447685	*95.7%*	0.000166318	*0.97%*	0.00064567	*3.76%*	-0.000307243	*-1.8%*	0.000237956	*1.36%*
Mineral, fossil & ren resource depletion (kg Sb eq)	0.00019218	0.000235204	*98.1%*	4.41469E-07	*0.18%*	2.22984E-06	*0.93%*	-4.76239E-05	*-19.9%*	1.92798E-06	*0.80%*
average value			**95.1%**		**0.6%**		**2.0%**		**-17.7%**		**2.4%**

Annex -16 – Results of LCIA for I kg of PET bottles recycled into fibres (B2F scenarios) in the context of Denmark.

B2B(CFF(Econ)) method