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COMPARATIVE LIFE CYCLE ASSESSMENT OF ENERGY AND MATERIAL RECOVERY OF CARDBOARD IN MUNICIPAL SOLID WASTE

Examiners: Professor, D.Sc. (Tech.) Mika Horttanainen
M. Sc. (Tech) Ivan Deviatkin

ABSTRACT

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Cardboard contributes a large proportion in total MSW and mixed MSW. Recovery of cardboard, either as material or energy, is believed to reduce the impacts on the environment from the global warming point of view. European Union has been promoting recycling which resulted in recycling of the majority of well-separated cardboard. Published life cycle assessment studies show that recycling can provide the best benefits to the environment. However, some other studies argue that incineration with energy recovery would bring more credits. The technological data and system boundaries of the studies were proved to affect the outcome of the recovery methods studied.

The present thesis was carried out assuming high technology data for both recycling and incineration with energy recovery. The main focus was on global warming potential (GWP), but also acidification (AP) and eutrophication potentials (EP) were taken into consideration. Results of all three impact categories supported the option of energy recovery had higher benefits compared to material recovery. Even though recycling could reduce the environmental burdens in GWP, this method resulted in additional impacts on AP and EP. Full replacement of virgin fibers could offer better results than partial substitution for GWP but it was opposite for AP and EP.

Sensitivity analysis supported the superiority of energy recovery as the recovery method always reduced GWP, AP and EP. Performance of the recycling was not as steady as energy recovery. When electricity from natural gas or grid mix was substituted, energy recovery provides lower savings than in the baseline scenario.

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Tu Duong
Lappeenranta, May 2017

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LIST OF ABBREVIATIONS

ACE	The Alliance for Beverage Cartons and The Environment
AOX	Adsorbable Organic Halogen
AP	Acidification Potential
AR5	Fifth Assessment Report
BOD	Biochemical Oxygen Demand
CEPI	Confederation of European Paper Industries
CEWEP	Confederation of European Waste-to-Energy Plants
CHP	Combined Heat and Power
COD	Chemical Oxygen Demand
CPA	Corrugated Packaging Alliance
EC JRC	European Commission Joint Research Venture
EIA	U.S. Energy Information Administration
EP	Eutrophication Potential
EPA	Environmental Protection Agency
ERPC	European Recovered Paper Council
ETS	Emission Trading System
EU	European Union

FEFCO	European Federation of Corrugated Board Manufacturers
GHG	Greenhouse Gas
GWP	Global Warming Potential
GWP100	Global Warming Potential over 100-year time horizon
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LHV	Low Heating Value
MSW	Municipal Solid Waste
NEA	National Environment Agency
OECD	Organisation for Economic Co-operation and Development
RDF	Refuse-Derived Fuel
TDS	Total Dissolved Solids
TOC	Total Organic Carbon
TRS	Total Reduced Sulfur
TSS	Total Suspended Solids
WtE	Waste-to-Energy

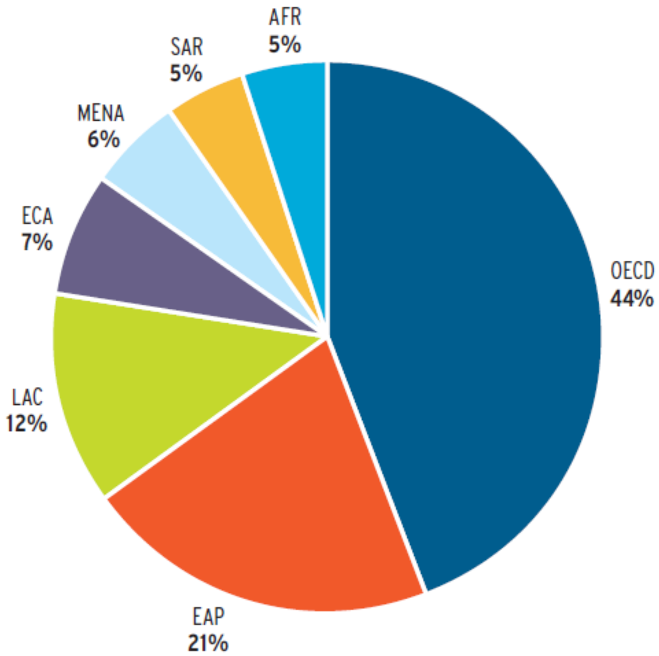
LIST OF SYMBOLS

CO_2	Carbon dioxide
NO_x	Nitrogen oxides
SO_2	Sulfur dioxide
SO_x	Sulfur oxides

1. INTRODUCTION

1.1. Background and motivations

The amount of solid waste generated has been rising significantly in recent decades because of the population explosion and improved living standard. A study from Hoornweg and Bhada-Tata executed for World Bank (2012) estimated that, generation of municipal solid waste (MSW) was about 1.2 kg per capita per day in 2012 in urban area, while that was only 0.64 kg ten years before. The study also projected that the mass of MSW generated would increase to 1.42 kg per capita per day by 2025. Regions with higher income produce greater amount of MSW compared to countries in developing state and low income (Figure 1). For instance, 29 member-countries of OECD (Organisation for Economic Co-operation and Development) accounted for 44% of the global solid waste generated with the highest average waste generation per capita of 2.2 kg/capita/day, nearly double the world's average of the same year. Whereas, the most populated region, East Asia and Pacific (EAP), accounted for only 21% of the global waste generated, two times less than OECD countries. (Hoornweg and Bhada-Tata, 2012)



OECD: Organisation for Economic Co-operation and Development

EAP: East Asia and Pacific

LAC: Latin America and the Caribbean

ECA: Eastern and Central Asia

MENA: Middle East and North Africa

SAR: South Asia

AFR: Africa

Figure 1: Waste generation by regions (Hoornweg and Bhada-Tata, 2012).

As a member of OECD, waste generation rate in Finland is at a high level. In addition to that, there is rising trend in the total waste generated annually. This is also the current trend in European Union (EU), where Finland is also a member (Eurostat, 2016). Waste generated per capita per day in Finland grew by nearly 20% from 1.13 kg in 1995 to 1.32 kg in 2014 (Eurostat, 2016). Furthermore, the number is much higher in urban area. According to Hoornweg and Bhada-Tata (2012), average waste generated per capita per day in Finnish urban area was 2.13 kg at the time. It was about the same rate of OECD's figure. More detailed information of EU waste statistics by country is provided in Appendix 1.

MSW consists of many different fractions such as bio-waste, paper, cardboard, glass, metal and others (Liikanen et al., 2016). Hoornweg and Bhada-Tata (2012) shows that paper and board product waste account for the second largest proportion of global solid waste, at 17%, after organic fraction. The composition of MSW varies widely on the region, however, organic and paper-related waste are always the two largest fractions in all areas. Paper and board waste occupies the largest share (32%) in OECD and organic waste stands second (27%) while it is opposite in the rest areas. Finland, as a member country of OECD, also has a high rate of paper and board waste. (Hoornweg and Bhada-Tata, 2012) Accounting for 30-40% of the country's MSW generation, fiber waste is the biggest proportion in Finnish waste (Hoornweg and Bhada-Tata, 2012; Statistics Finland, 2012; 2013; 2014; 2015; 2016).

It is due to the fact that almost every product requires a packaging, and the evolution of ready-to-go food, the demand for primary packaging is surging. In addition to this, international trading has become more popular, which requires secondary packaging for shipping activities. Confederation of European Paper Industries (CEPI) accounts for 95 % of European paper production. Figure 1 indicates that packaging products obtain for about half of both fiber production (Figure 2a) and consumption (Figure 2b) in CEPI member states. Both production and consumption of fiber packaging surged until a significant decrease, which occurred during the world economic crisis in 2007. In 2009, the production and consumption climbed up again but started to flatten a year after that.

Despite the dramatic decrease in 2007, the production and consumption of fiber packaging has notably increased compared to 1991. (CEPI, 2016)

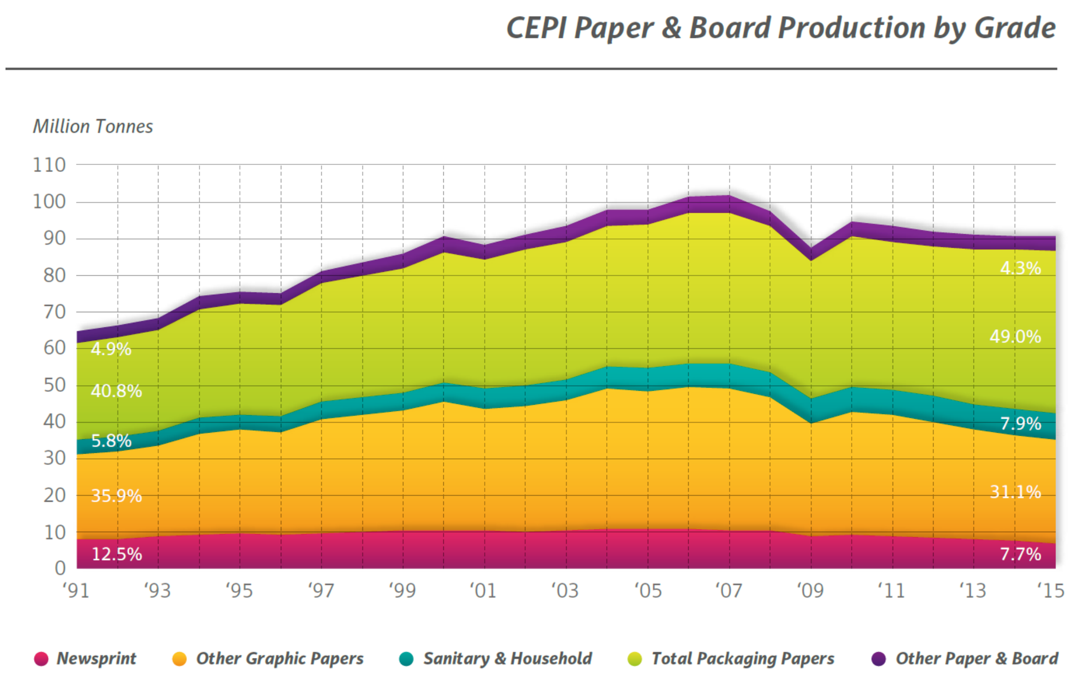


Figure 2a

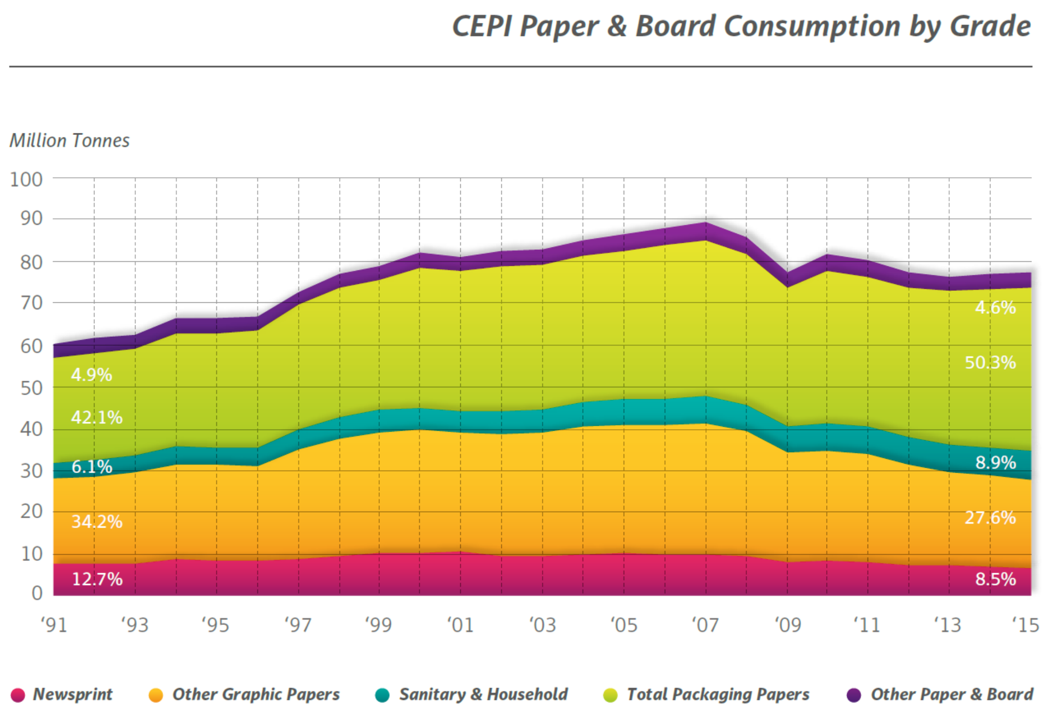


Figure 2b

Figure 2: CEPI Paper & Board Production (2a) and Consumption (2b) (CEPI, 2016).

As a result of escalating consumption of packaging paper and cardboard, increase in generation of fiber packaging waste is inevitable. Eurostat (2016) claimed that the packaging waste accounted for about 27% of MSW over the period of 2005-2014 in Finland. Moreover, approximately 41% of the packaging waste was fiber packaging. Appendices 2, 3 and 4 cover the entire information regarding the packaging waste in general and fiber packaging in particular in EU countries. (Eurostat, 2016)

It should be noted that most of the reports on packaging waste are based on the decision 2005/270/EC from the European Commission, which states, ‘packaging waste generated in a Member State may be deemed to be equal to the amount of packaging placed on the market in the same year within that Member State’.

The amount of waste is continuously expanding while landfill capacity is limited. In other words, space for disposal becomes scarce. This leads to the question of proper waste management in the future when currently exploited landfills are closed and construction of the new ones is legally banned. Furthermore, waste landfilling has many tremendous impacts on the environment. Decomposition of organic matters in disposed waste leads to generation of multiple gaseous pollutants such as methane and carbon dioxide – heavily contributing to climate change, whereas precipitation penetrating through the landfills results in leachate generation and pollution of groundwater. Even though advanced technologies are currently applied at engineered landfills to prevent leachate generation and emissions releases, landfilling should be the last choice for waste management in compliance with recent legislation **(**Directive 2008/98/EC**)**.

The effects of greenhouse gas (GHG) emissions on the environment have been noticed. GHGs have negative effects on the environment and continuous emissions of the large amounts of GHGs threatens health of the planet with climate change. In recent years, the GHG emissions have increased remarkably and according to Rockström et al. (2009), we already exceeded the boundary of ecosystem’s resilience for climate change and we are under pressure to reduce the greenhouse gas emissions in order to help minimizing the effects on environment. Making a move, EU aims to reduce 20%, 40% and 80% of the GHG emissions by 2020, 2030 and 2050, respectively compared to 1990 levels (European

Commission, 2016a; Ministry of Environment, 2016). As a member of the EU, Finland has approved its goal for 2020 together with the country's own individual targets: 16% emission reduction in non-ETS (Emission Trading System) sectors such as construction, building heating, transportation and waste management; and increasing the share of renewable energy to 38% in total final energy consumption. In addition to this, the target set for corporations under EU-wide ETS by 2020 is 21% carbon dioxide emission reduction of 2005 level. The country has not decided on its national targets for the further period. (European Commission, 2016a; Ministry of Environment, 2016)

In addition to that, it is widely known that ecosystems have limited capacity. However, it is clear that consumption of natural resources has been rising dramatically to meet the growing demands. Therefore, the natural capacity will definitely become exhausted under continuing excessive consumption. Thus, we need to use the resources efficiently while searching for alternatives to the conventional fossil materials. Certain fractions of MSW, such as bio-waste, paper and cardboard, plastics, metals and glass are technologically recyclable which can save the raw materials. Organic waste with sufficiently high calorific value can be incinerated to produce energy.

Regarding the management of MSW, European countries have currently been aiming at strengthening of recycling. European governments have taken actions to prevent the landfilling of recoverable waste, such as introduction of bans and new taxes on landfilling of combustible and organic waste. Sweden has banned the landfilling of sorted combustible waste from 2002 and organic waste since 2005 (Söderman, 2002; CEWEP, 2016a). According to Confederation of European Waste-to-Energy Plants (CEWEP) (2016a), disposal of MSW in Switzerland is not permitted since 2005. Organic waste is no longer allowed for landfilling in Finland from 2016 (CEWEP, 2016a; Liikanen et al., 2016). Many other EU countries, such as Luxemburg and Slovenia, also adopt the landfill ban on organic waste. (CEWEP, 2016a)

Cardboard is a waste fraction which can either be used for material recovery or energy recovery. Due to the fact of high fibre content in cardboard, recycling with production of a new product or partial replacement of virgin materials is possible. On the other hand, cardboard also has high energy content, thus, it can be used as an alternative fuel. With material recovery, consumption of wood for pulp and paper production can be avoided, whereas fossil fuels or other fuels generally used in specific regions can be saved during energy recovery of cardboard.

Despite the encouragement to re-use cardboard, a significant amount of fibers is currently lost to landfills in some countries. For instances, National Environment Agency of Singapore (NEA) (2017) claimed that only 51% of paper and cardboard was recycled in their country in 2015 while the rest was disposed. Whereas, reports from the Environment Protection Department of the Government of Hong Kong (2016) stated that, 65% of generated MSW in Hong Kong was sent to landfills in 2015, and paper constituted 20% of the landfilled waste. In Finland, only about half of MSW were segregated in 2015 and approximately 23% of the mixed waste was landfilled. Paper and carboard constituted 11-17% and 7-10% of the mixed MSW respectively (Horttanainen et al., 2013; Finnish Solid Waste Association, 2016; Liikanen et al., 2016). According to studies from Irish Environmental Protection Agency (EPA) (2014), Ireland reported to landfill 8.5% of fiber packaging waste in 2012.

1.2. Objectives

Strictly directed by the EU government, landfilling is restricted in the member states in order to achieve the EU's targets of reducing waste. Thus, MSW management faces many challenges as the costs will increase. Recycling is strongly preferred in EU but energy recovery has its own benefits. However, MSW fractions have not been studied separately a lot; hence, it is useful to study the environmental impacts of different fractions separately and comprehensively when different recovery options are applied. In order to figure out the better environmentally friendly recovery method for cardboard, the advantages and drawbacks of each method are compared performing a life cycle assessment (LCA) study. The study will focus on the possible reduction of GHG emission in each option as climate change is amongst of the top essential areas of environmental concern at the moment. Eutrophication (EP) and acidification potentials (AP) are also taken into consideration.

2. OVERVIEW OF CARDBOARD

Cardboard refers to a certain type of paper usually used for packaging purposes. Cardboard is generally thicker and heavier than printing and graphic paper due to packaging requirements of durability and rigidity. (CEPI, 2014)

Cardboard found in MSW would include rinsed liquid packages, corrugated board box, paperboard for ready meals and dry products – such as cereal and pizza boxes, and paper bags (Etelä-Karjalan Jätehuolto Oy, 2016; L&T, 2014; Finnish Packaging Recycling Rinki, 2016a). Some examples of cardboards are shown in Figure 3.

Figure 3: Waste cardboard (Etelä-Karjalan Jätehuolto Oy, 2016).

In general, cardboard can be divided into two major groups: corrugated and non-corrugated cardboard.

2.1. Corrugated cardboard

Corrugated cardboard (Figure 4) consists of two main parts: the corrugated medium called fluting and the flat paper sheet called liner. As stated by the European Federation of Corrugated Board Manufacturers (FEFCO) and Corrugated Packaging Alliance (CPA) (2016), these two parts combined together improve the overall strength of the structure compared to each distinct segment. Corrugated board has extreme durability, considerable rigidity and resistance, which make the products good for packaging. In addition to that, corrugated products are versatile and lightweight with high strength-to-weight ratio. Those are the reasons that make corrugated a popular packaging material. Corrugated cardboards are frequently used as secondary packaging for transportation and delivery processes. (FEFCO, 2016; CPA, 2016)

Figure 4: Corrugated cardboard (CEPI, 2016).

The most commonly used corrugated cardboard is single wall type, which has one fluting layer between two liner boards. However, there are many different types of corrugated board available, depending on the needs of consumers as demonstrated in Figure 5. Single face corrugated cardboard consists of one fluting layer attached to a single liner board. Double wall and triple wall are made up with two and three arching layers between three and four liner layers, respectively.

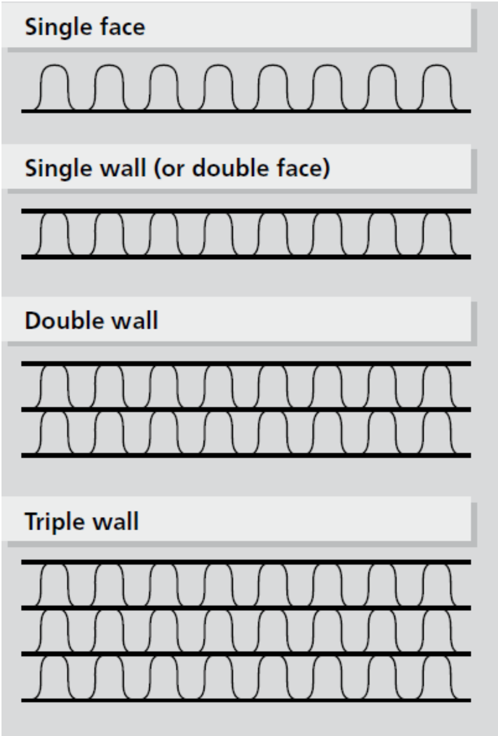


Figure 5: Available types of corrugated cardboard (CEPI, 2012).

2.2. Non-corrugated cardboard

Non-corrugated cardboard comprises all cardboards without the corrugated fluting medium. This type of cardboard is sometimes referred as linerboard or container board and mainly used for food packaging. Non-corrugated boards are mainly used as product packaging, which is to protect the goods. (Brogaard, et al, 2014)

The packaging for fresh drinks such as milk and juices is a special type of non-corrugated cardboard due to the special dominating structure of multilayers of different materials including polymers and aluminum, referred as beverage cartons in this thesis. According to the Alliance of Beverage Cartons and The Environment (ACE) (2016), the function of the multilayer structure is not only to prevent leakage but also to ensure the freshness, flavors and nutrition qualities of the liquids by protecting the liquids from light and oxygen, consequently to assure the optimal shelf-life of the products. (Figure 6).

Figure 6: Beverage cartons (ACE, 2016).

On average, beverage cartons contain 75% of cardboard, 21 % of polymers and about 4% of aluminum by weight (Mourad et al., 2008; ACE, 2016). The general structure of beverage cartons is shown in Figure 7.

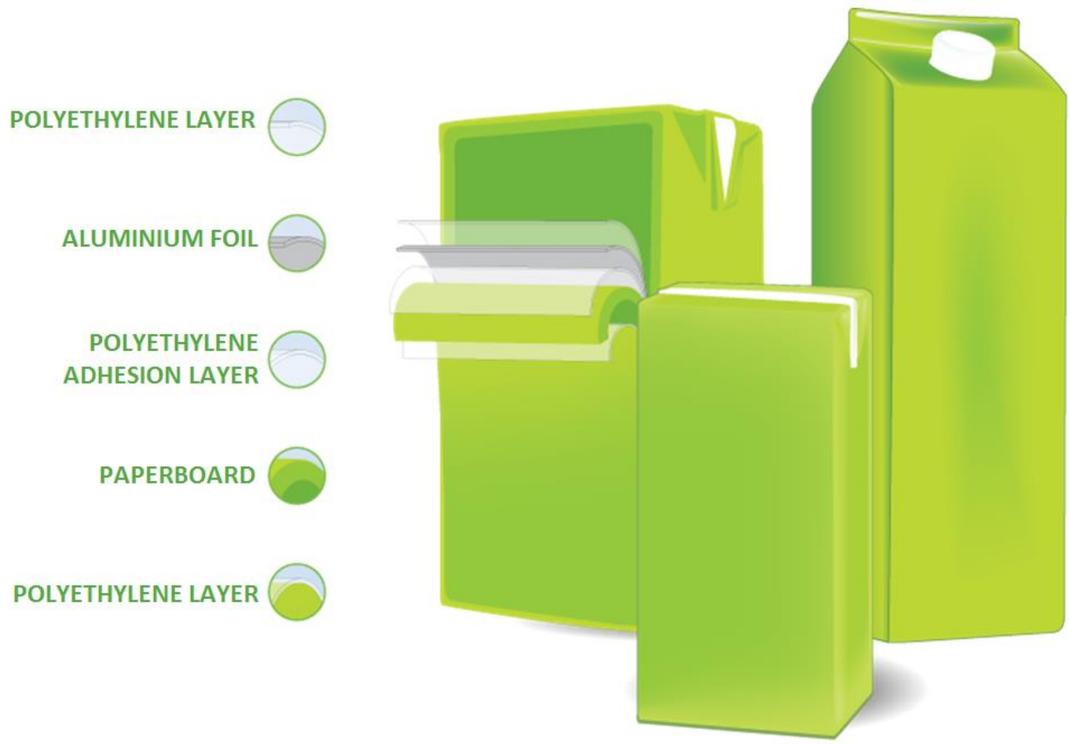


Figure 7: General structure of beverage cartons (ACE, 2016).

3. MATERIAL RECOVERY - RECYCLING

3.1. Cardboard production and recycling procedure

In general, paper and cardboard production starts with raw material processing. Raw materials after being delivered to the pulp and paper mill are forwarded to the pulping and stock preparation processes before entering dewatering and board production processes as shown in Figure 8 (FEFCO and Cepi Container Board, 2012).

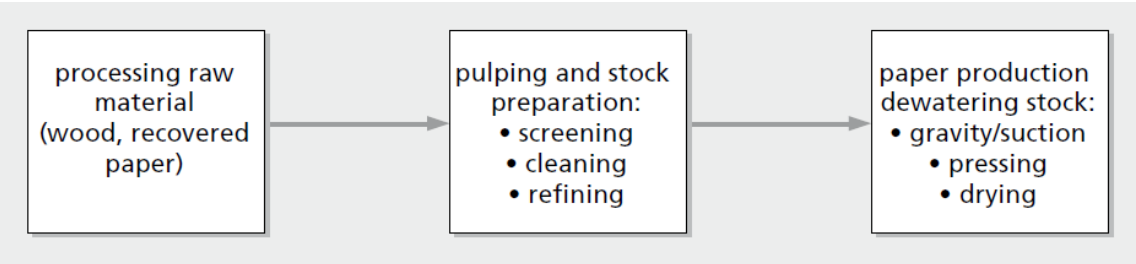


Figure 8: Outline of paper production (FEFCO and Cepi Container Board, 2012).

Figure 9 describes the paper and board manufacturing process. The primary raw material, wood, is debarked and chipped. Wood chips are sent to the pulping process to remove lignin and other organic compounds contained in wood from celluloses. When recovered paper or cardboard are used in a process of high quality paper production, de-inking process should be applied. Whereas, as stated by FEFCO and Cepi Container Board (2012), de-inking is not generally required for the packaging cardboard production. Primary fibers will be mixed together with the secondary fibers during blending. The mixing ratio depends on the quality requirements of the new products. Remaining undesirable contaminants will be eliminated in refining, screening and cleaning processes. After that, fiber slurry will go for paper making process. (FEFCO and Cepi Container Board, 2012; EU JRC, 2015)

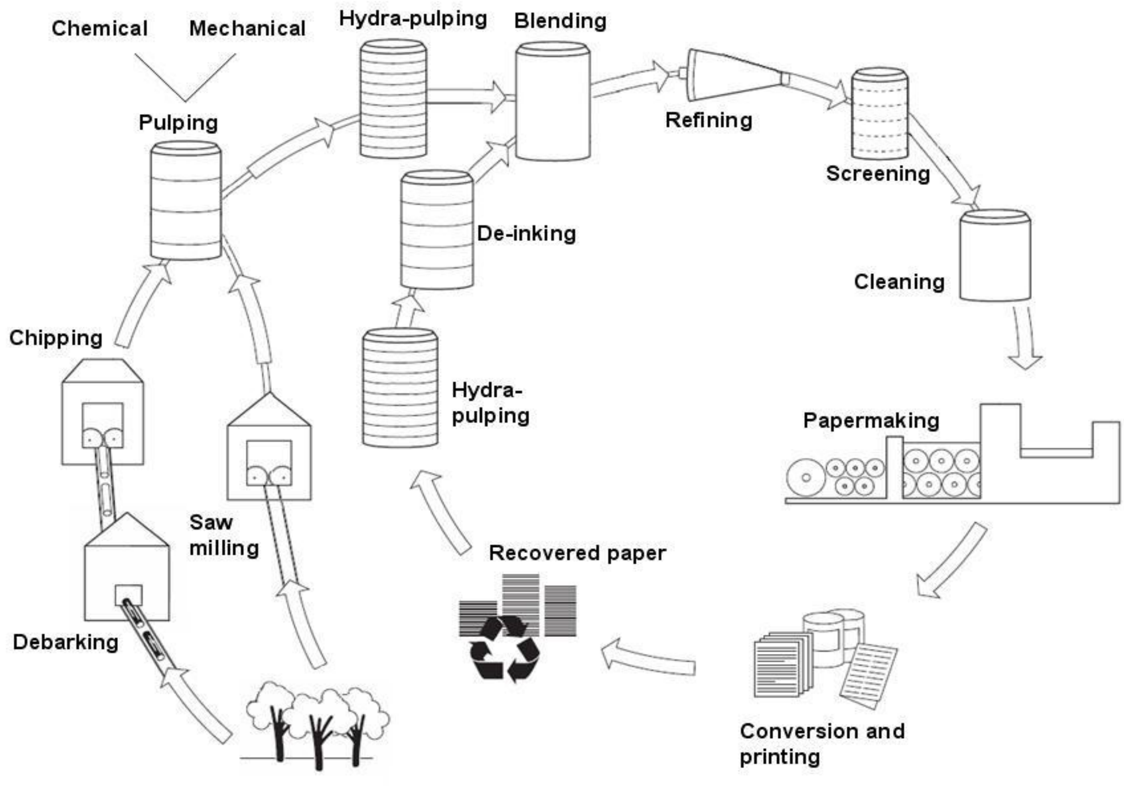


Figure 9: Paper and cardboard making process (EC JRC, 2015).

3.2. Environmental studies on cardboard recycling

Paper and cardboard recycling has clearly shown to be better option compared to landfilling with less environmental impacts while giving a solution to exhaustion of landfill capacity (Björklund and Finnveden, 2005; Villanueva and Wenzel, 2007).

Recycling paper and cardboard can probably avoid consumption of remarkable amounts of various natural resources other than just the principle material – wood (Mourad et al., 2008). Recovery of cardboard is energy intensive; however, reprocessing practice consumes less energy, produces less emissions and consequently produces less environmental burdens than primary production (Morris, 2005; Schmidt et al., 2007; Merrild et al., 2008; Brogaard et al., 2014). Recycled pulping process consumes about 9% of total energy required in virgin pulp production, and consequently, total energy requirement in overall production halves (Morris, 2005; Schmidt et al., 2007).

Mourad et al. (2008) studied environmental effects regarding recycling rate of cardboard in aseptic packaging for milk. By increasing the recycling rate from 2% to 22%, the production could reduce 6% of the total energy consumption and significant amount of natural resources: 8% of water, 7% of coal, 11% of wood and 10% of land use. Furthermore, reductions in air and water emissions were also acknowledged. As a consequence of decrease in GHG emissions, 100-year-horizon global warming potential (GWP) was reduced by 9.7%. In addition, sulfur oxides (SO_x) emissions reduced by 6%, nitrogen oxides (NO_x) emissions by 8% and particulates by 10%. Water emissions were reduced in most indexes: 10% COD (Chemical Oxygen Demand), 9% BOD (Biochemical Oxygen Demand) and 6% TSS (Total Suspended Solids). However, the study also showed there was significant increase of TDS (Total Dissolved Solids) emissions by 57% (Mourad et al., 2008).

While reviewing available LCA studies on primary and secondary cardboard production, Björklund and Finnveden (2005), Merrild et al. (2008) and Brogaard et al. (2014) found out that there were some cases that recycling produced more impacts on the environment. These results stemmed from technological data applied, especially energy source used in the cases studied (Merrild et al., 2008; Brogaard et al., 2014). Production in countries less dependent on fossil fuels, for instance Norway, Sweden, released less CO_2 emission (Brogaard et al., 2014).

During recycling process, cellulose fibers shorten and, thus, their strength is reduced (material quality loss) (Brogaard et al., 2014). Furthermore, loss of fibers (material loss) is unavoidable. Owing to these factors, primary fibers need to be mixed with recycled fibers when required to ensure the paper specifications. In other words, substitution ratio of recycled fibers to virgin fibers is usually less than 1:1 and it depends on the reprocessing technology as well as the requirement of new products (Merrild et al., 2008; Merrild et al., 2012; Wang et al.,2012; Brogaard et al., 2014; Ferreira et al., 2015).

Cardboard is usually collected as a source-separated fraction. Cardboard boxes should be flattened when left at the collection points and beverage cartons need rinsing to clean the remaining liquids inside, as recommended by waste management operators (Etelä-

Karjalan Jätehuolto Oy, 2016; L&T, 2014; Finnish Packaging Recycling Rinki, 2016a). Well-sorted cardboard will be transported to recycling center from collecting points. Collection and transportation of cardboard also create impacts on the environment. Nevertheless, the impacts are much less compared to production practice and does not compromise the benefits from recycling (Merrild et al., 2012).

It should be noted that cardboard in contact with biowaste, especially soiled with greasy and oily food, is microbe contaminated and not feasible for use in some application of recycling as grease and oil could not be cleaned during the process (Finnish Packaging Recycling Rinki, 2016a; Havukainen et al., 2016).

In brief, environmental effects brought by paper and cardboard recycling are linked to technological data, especially the energy utilizing condition, of both recycling technologies and virgin technologies substituted (Merrild et al., 2008).

3.3. Current recycling practices

CEPI countries account for 23% of the global and 95% of the European paper production. Finland is the second largest pulp producer (after Sweden), as well as the second largest paper manufacturer (after Germany) in CEPI (CEPI, 2016).

Acknowledging the need to reduce impacts on environment from waste management activities, the EU plans to phase out landfilling of recyclable waste, including paper and cardboard, by 2025 (European Commission, 2016b). EU has been promoting recycling in member countries and encourages them to improve recycling rate of recycle fractions. EU has targeted to recycling 75% of paper and cardboard packaging by end of 2025 and 85% by end of 2030 (Directive 94/62/EC).

As stated by CEPI (2013), paper recycling rate in Europe is rising since 1991 (Figure 10). Before 2000, less than 50% of paper was recycled but the recycling rate has been rising since this year. The European Recovered Paper Council (ERPC) announced in 2013 that the figure has reached 72% in 2012, which is a world record. (CEPI, 2013; ERPC, 2013;

EC JRC, 2015). In Finland, about 93% of sorted paper-based fraction are recycled in 2015 (Eurostat, 2016; Statistics Finland, 2016).

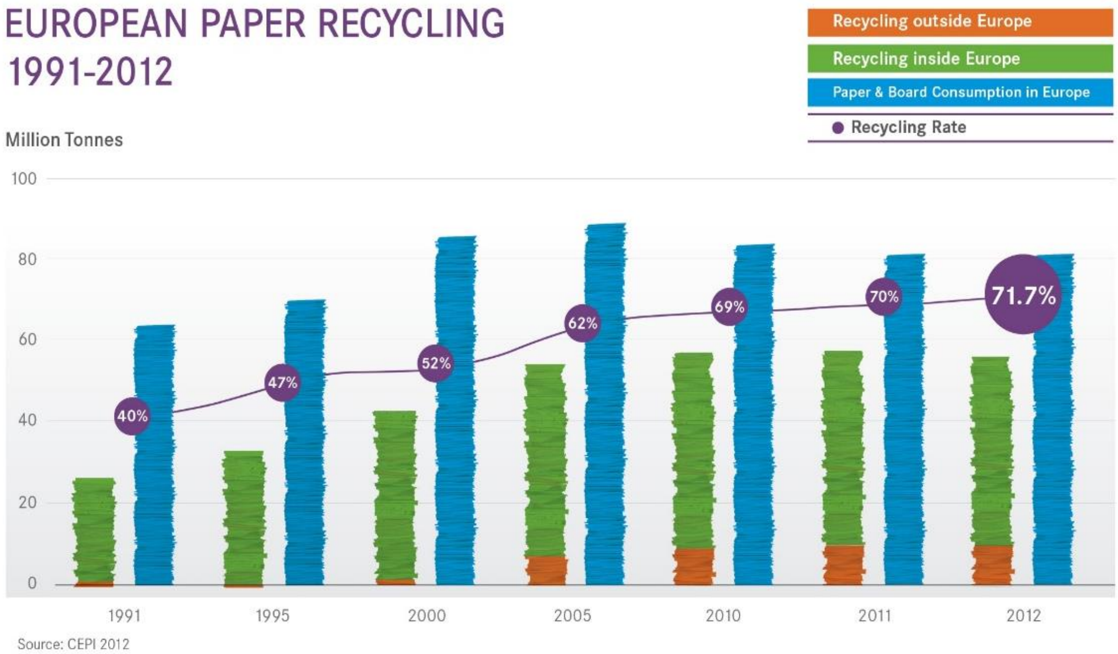


Figure 10: European paper recycling (CEPI, 2013).

Statistics from Finnish Packaging Recycling Rinki (2016b) show that the recycling rate of fiber packaging in Finland has been over 50% and always exceeded the recycling target since 1998. Since 2008, more than 90% of separately collected cardboard packages was recycled. By 2014, the recycling rate reached 101%, due to the fact that some cardboard was re-used as storage after first intention and only ended up in waste collection system after re-usage.

Research of Havukainen et al. (2016) has shown that source separation of cardboard was improved in households by 2012, compared to figures of 2006. 80% of households separated packaging cardboard in 2012; however, only 61% sorted milk containers and other cardboard accordingly. By 2013, only 58% of all paper and cardboard fractions was well-separated (Havukainen et al., 2016). This might restrain the available stocks of cardboard for material recovery.

4. ENERGY RECOVERY (WASTE TO ENERGY)

4.1. Waste to energy overview

Cardboard used for energy recovery is mostly delivered to Waste-to-Energy (WtE) plants as part of mixed MSW or part of refuse-derived fuel (RDF) prepared from mixed waste since EU is promoting recycling and most of the sorted waste are recycled (VTT, 2012). Mixed MSW will be directly delivered for mass burning without pretreatment whilst RDF requires mechanically refined before entering combustion stage. The incineration process produces heat which is used to generate steam. The steam produced can be used for heating and/or to produce electricity by utilizing steam turbines (Figure 11). Flue gas from the incineration process is treated prior to being released into environment to meet the emissions standards.

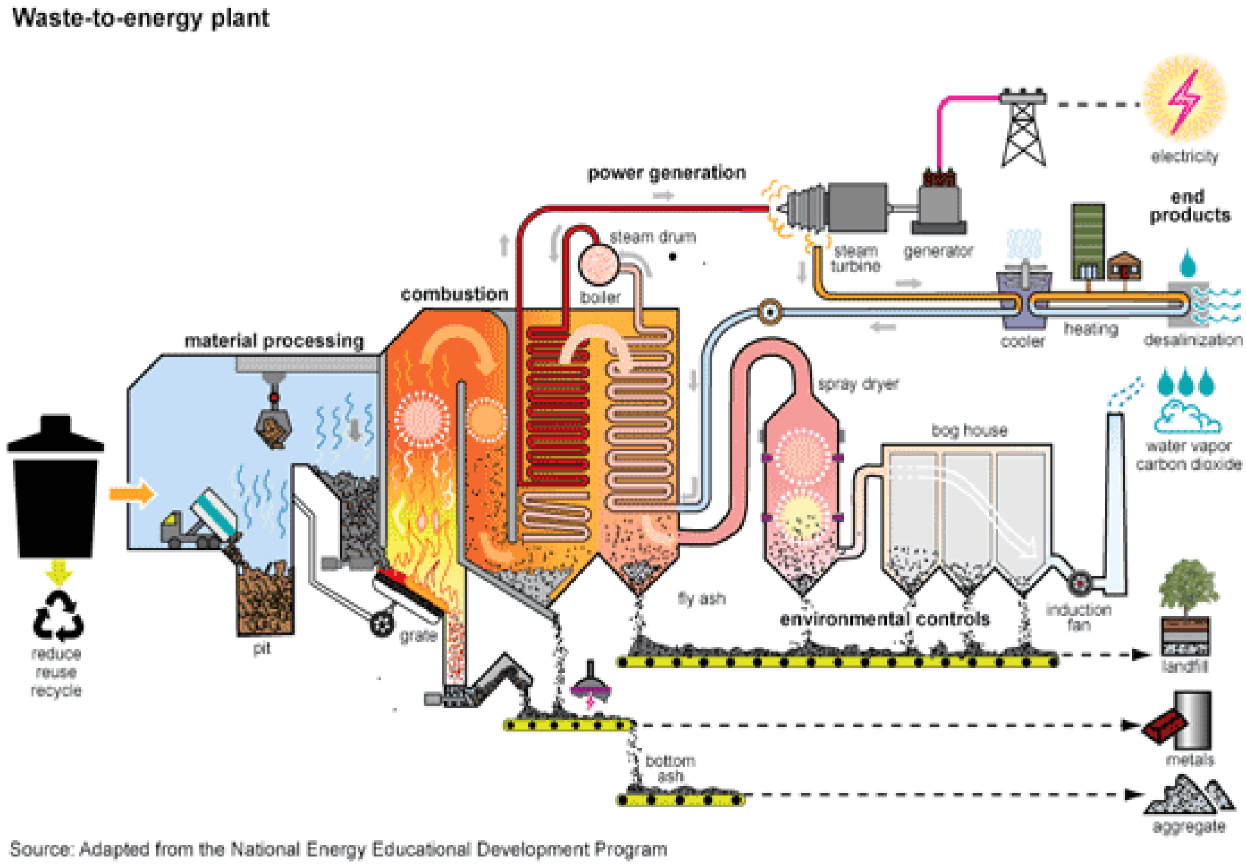


Figure 11: Waste-to-Energy plant (U.S. Energy Information Administration - EIA, 2016).

Incineration with energy recovery of MSW in general and cardboard in particular, cannot only reduce the pressure on management of solid waste but also provide substantial amount of energy. For instance, one ton of MSW, consisting of 26.6% fiber waste, could generate 481kWh of electricity, equivalent to one-day consumption of 16 US households in 2013 (EIA, 2016). The energy recovered depends on the energy content of the delivered fuels, which is resultant from their composition. MSW with high share of non-recyclables has lower energy content than MSW with large share of high-energy-density fractions such as plastics and papers.

The share between electricity and heat generation from the incineration of MSW depends on the local demand. In Northern European countries such as Finland and other Nordic countries, district heat demand is probably much higher than in southern countries, which leads to more energy to be recovered in form of heat.

In EU, 44% of MSW was either recycled or composted while only 27% was incinerated in 2014. It was in contrast in Finland, where half of MSW produced was incinerated and material recovery accounted for only 33% in 2014. (CEWEP, 2016d) As EU is promoting recycling, cardboard is recommended to be sorted accordingly and most of them to be used for reprocessing (VTT, 2012; Havukainen et al., 2016). A small part of separated cardboard might not be appropriate for recycling due to poor purity rate, being spoiled or small quantity batch collection and thus, go to incineration instead (Havukainen et al., 2016). On the other hand, as source separation is normally lower than 100%, cardboard still sometimes may show up in mixed MSW. For instances, in Finland, only half of MSW generated was separated accordingly (Statistics Finland, 2012; 2013; 2014; 2015; 2016). Previous studies of Horttanainen et al. (2013), Finnish Solid Waste Association (2016) and Liikanen et al. (2016) found that even though the rate varied among areas analyzed, cardboard still accounted for about 7-10% of mixed MSW (approximately 100 000 tonnes annually) in Finland. Most of mixed MSW used to be landfilled in Finland (approximately 70% in 2011). However, as landfill taxes and bans have been applied to avoid landfilling, energy recovery has become more popular, and consequently it reduced landfilling share of total mixed MSW to 23% in 2015 (Statistics Finland, 2012; 2013; 2014; 2015; 2016).

4.2. Cardboard and MSW characterization

Paper and cardboard are combustible fractions with relatively high energy among other fractions in MSW. The low heating value (LHV) of cardboard in arrival condition varies according to the places studied and usually ranges between 13-16 MJ/kg, which is lower only than average LHV of plastics (Giugliano et al., 2008; Merrild et al., 2012; Habib et al., 2013; Horttanainen, 2013; Ferreira et al., 2015; Boumanchar et al., 2016; Naroznova et al., 2016). However, Chang et al. (2007) found out that LHV of cardboard in Taiwan was 9 MJ/kg while study of Montejo et al. (2011) claimed that the value was only 5 MJ/kg.

Share of cardboard in MSW is a variation of geographical and seasonal conditions of the studied areas (Niessen, 2010). Utilizing rate of paper-based products in high-income countries tends to be higher than in lower-income countries. However, this fraction is always among the two biggest contributors in MSW, varying from 13% up to 40% (Chang et al., 2008; Giugliano et.al., 2008; Montejo et al., 2011; Hoornweg and Bhada-Tata, 2012). Besides consuming habits, sorting practices of local citizens also effect the share of cardboard in mixed MSW of the area. For instance, Havukainen et al. (2016) estimated that paper and cardboard constituted 26% of total MSW but only 18% in mixed MSW, due to source separation. Horttanainen et al. (2013) studied the composition of mixed MSW in South-Karelia while reviewed previous studies in different parts of Finland and found out that share of paper and cardboard varied from 11% to 17%. In the case of South-Karelia, paper accounted for 4.9% and cardboard accounted for 10%, which together contributed 14.9% of the mixed waste (Horttanainen et al., 2013). The contribution may depend also on season as Niessen (2010) claimed that paper and carboard may make up a larger portion in mixed MSW in autumn and winter. In overall, statistics from Finnish Solid Waste Association (2016) showed that cardboard constituted about 8.2% of mixed MSW on average.

LHV of mixed MSW in different regions of Finland ranged from 9 to 16 MJ/kg as reviewed by Horttanainen et al. (2013). The paper also studied the LHV of mixed MSW in different areas of South-Karelia region. The results show that LHV in this region was relatively higher than in previous published measurements and varied according to population density and season. LHV fluctuated about 15 MJ/kg mixed MSW and in sparsely populated area, it went up to around 20 MJ/kg in autumn winter. This was because of differences in each fraction's characteristics and their contribution in the MSW. Horttanainen et al. (2013) also analyzed the share of energy by fraction in Lappeenranta, a city in South-Karelia. LHV of cardboard was measured around 16-17 MJ/kg and cardboard shared 14% of the energy content in mixed MSW (Horttanainen et al., 2013).

Since EU is promoting recycling with ambitious target, cardboard is encouraged to be well sorted so that source separation efficiency could be maximized. The practices might increase the LHV of mixed MSW due to increase in share of fraction with higher LHV such as plastics; however, it might reduce the renewable share of energy in mixed MSW, as a consequence of reduction in mass share (Horttanainen et al, 2013).

4.3. Environmental impacts of cardboard incineration with energy recovery

EIA (2016) considers waste incineration with energy recovery a good waste management means as it does not only help to reduce the amount of waste to be landfilled but also works as an alternative fuel to avoid consumption of fossil fuels (Figure 12). In addition to that, this method would bring environmental benefits as it generally produces less CO_2 emissions compared to conventional fuels, especially fossil CO_2 thanks to the share of renewable fractions (CEWEP, 2016b and 2016c; Profu, 2004; EIA, 2016).

As a part of renewable share of MSW, incineration of cardboard with energy recovery has been studied to figure out the benefits of it. Reports of Schmidt et al. (2007) and Naroznova et al. (2016) found that the method could bring credits in GWP, AP and EP. When being compared to landfilling, this means of cardboard recovery showed markedly better performance in GWP, AP and EP perspectives (Profu, 2004; Björklund and Finnveden, 2005; Cherubini et al., 2009; Hupponen et al., 2015).

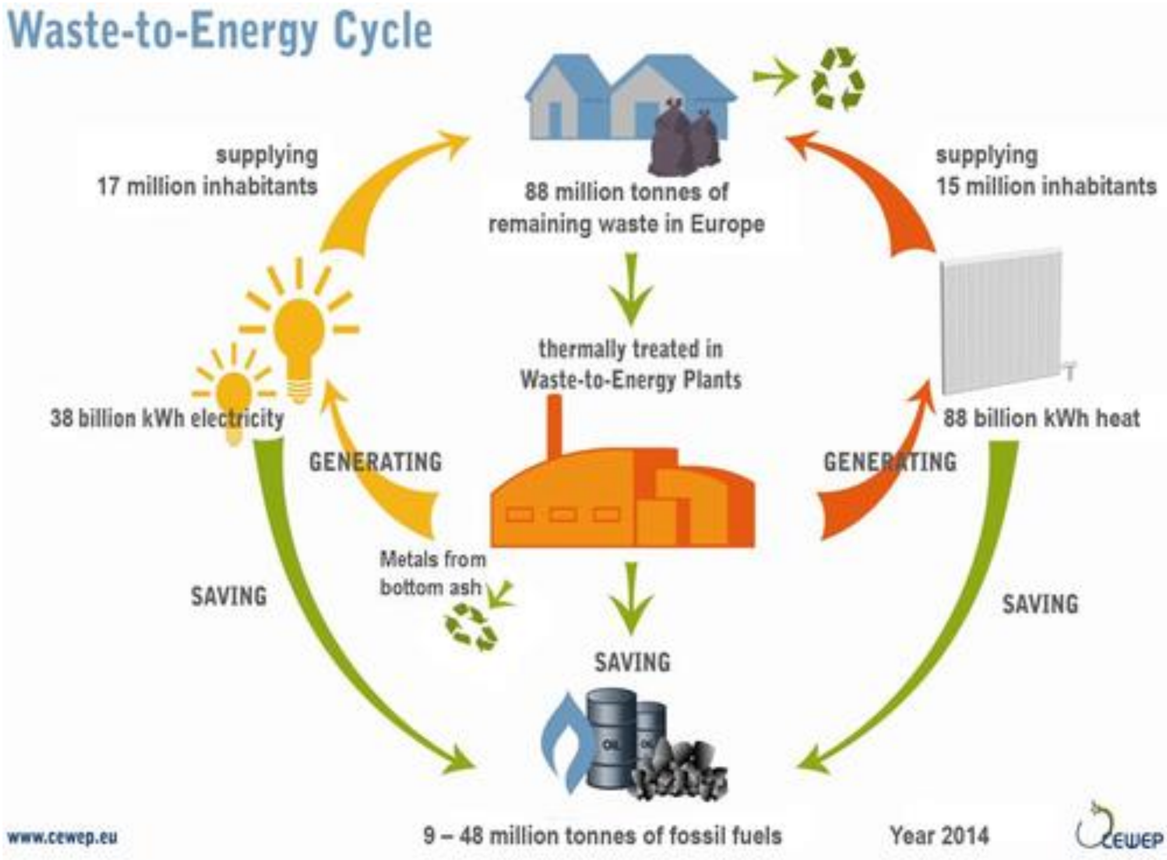


Figure 12: Waste-to-Energy Cycle (CEWEP, 2016b).

Published LCA studies of Merrild et al., (2008), Profu (2004), Merrild et al. (2012) claimed that the choice of technologies applied for both incineration and avoided energy generation, especially the choice of marginal energy source substituted, were factors that determine the benefits that energy recovery can provide. In their study, Profu (2004) and Habib et al. (2013) have pointed that when energy recovery from waste incineration substituted other renewable energy source such as biomass and wind, the savings are less than when comparing to substitution of coal and other fossil fuels, especially in GWP point of view. The reason behind this was because combustion of fossil fuels, especially coals, normally produce large amount of CO_2 emissions per energy unit generated. The data of emission factors in a Finnish power plant provided in GaBi Professional database (Thinkstep, 2016) are presented in Table 1. It can be seen that these factors differ for each fuel type; thus, it strongly affects the results when a particular choice is made. Substitution of high emission fuels such as coal would clearly bring more benefits than replacing natural gas. Even though biogas and biomass seems to have higher emission rate than coal, this source of energy fully comprises of biogenic carbon, which is considered as a part of natural cycle while coal contains only fossil (non-biogenic) carbon. This makes a big difference when evaluation without biogenic carbon is carried out.

Table 1: Cradle-to-gate emission factors for Finnish power plants with capacity over 50 MW (GaBi, 2016).

Energy carrier specific power plant	Natural gas	Biogas	Heavy fuel oil	Hard coal	Biomass
CO_2 [kg/TJ fuel input]	55 040	101 137	77 590	94 806	101 450
CO [kg/TJ fuel input]	21.3	150.0	24.8	8.1	149.5
SO_2 [kg/TJ fuel input]	0.4	75.5	319.3	111.0	25.8
NO_x [kg/TJ fuel input]	51.1	100.0	261.3	159.3	99.7

Development of energy technology would improve the utilization efficiency of energy resources as well as reduce the emissions per energy unit produced. However, this would have diverse effects on the overall results when applied to energy production from conventional fuels and from waste. Reduction in avoided emissions would deduct the net savings of the study while in the opposite, less emissions from WtE would lead to more savings in total. (Merrild et al., 2008; Wang et al., 2012; Habib et al., 2013) Merrild (2008), Damgaard and Christensen (2008) and Wang et al. (2012) noticed that the total efficiency of energy recovery was higher while both heat and electricity were recovered. Electricity recovery alone would only bring fairly low or medium recovery level. This makes the option preferable to cold countries which has high demands for heating than warmer countries such as southern European countries (Wang et al., 2012).

5. LIFE CYCLE ASSESSMENT (LCA) OF CARDBOARD

Both recycling and incineration with energy recovery of cardboard were proved to bring more environmental benefits than landfilling (Profu, 2004; Björklund and Finnveden, 2005; Morris, 2005; Schmidt et al., 2007; Villanueva and Wenzel, 2007; Merrild et al., 2008; Cherubini et al., 2009; Habib et al., 2013). Nevertheless, it is unfeasible to conclude which method is environmentally better between material and energy recovery; results were ambiguous as either of the managements showed consistent advantage over the other in previous LCA studies. Reports of Profu (2004) and Luoranen et al. (2009) showed that energy recovery would cause lower impacts, such as GWP and AP, on the environment. However, other publications generally preferred recycling since this option, though not always but more often, consumed less energy and caused less impacts (Morris, 1996; Profu, 2004; Morris, 2005; Villanueva and Wenzel, 2007; Schmidt et al., 2007; Wang et al., 2012). In addition to that, Morris (1996) and Björklund and Finnveden (2005) compared the two methods in terms of energy conservation and found out that recycling was superior in this point of view as the saved energy from recycling was more than energy generated by WtE.

As discussed in Chapters 3 and 4, benefits brought by either recycling or incineration with energy recovery are strongly dependent on the technological data. In other words, it could also affect the comparison outcome. Merrild et al. (2008) claimed that at low recycling performance, incineration with energy recovery was always preferable, whereas it was in contrast when high recycling technologies were applied. Merrild et al. (2008) later expanded the system to include the forestry activities, the results were slightly changed but it did not affect the overall outcome of the comparison. However, when the system boundaries were expanded to include fossil fuel substituted energy production from saved biomass from the reprocessing, material recycling always provided better environmental benefits compared to incineration with energy recovery (Merrild et al., 2008). This came to a conclusion that system boundaries are essential in LCA performance.

Recycling prevents the benefits from incineration with energy recovery and vice versa. If cardboard is recycled, it cannot be combusted, consequently, there are no alternative fuels to substitute traditional fuels. This study would like to take turn to evaluate the benefits obtained by an option, together with losses for not utilizing the other choice, in environmental point of view, so that it can be used to support the improvement of the processes. We will focus mainly on the GWP resulted from the activities. In addition, AP and EP will also be under consideration.

5.1. Goal and Scope

The function of the study was to recover cardboard with two possible options: (i) as a raw material in a cardboard production process, and (ii) as a fuel to produce energy in forms of heat and electricity. The amount of cardboard waste generated in Finland in 2014, which was 253 019 tonnes (Joint website of Finland's environmental administration, 2016; Eurostat, 2016), was set as the functional unit of the study.

The study initiated with delivery of generated cardboard to the recovery facilities. In the first scenario, cardboard would be transported to the recycling center to produce secondary cardboards substituting same amount of products from virgin materials. Alternatively, in the second scenario, waste cardboard would be sent to a combined heat and power (CHP) plant for incineration to generate heat and electricity. In this study, energy generated from cardboard combustion would substitute the same amount of heat and electricity provided from hard coal, which is a marginal fuel in Finland. Furthermore, hard coal has to be imported from Russia and Finland aims to get rid of hard coal utilization to reduce the dependence on energy imports (Ministry of Economic Affairs and Employment, 2016). We assumed that the differences in collection and transportation of cardboard did not affect the results significantly based on the studies by Merrild et al. (2012) and Hupponen et al. (2015). System boundaries are outlined in Figure 13 and detailed model is represented in Annex V.

Since there is also a small amount of plastics and aluminum in beverage cartons, we would also consider the recycling of aluminum and incineration of plastics when cardboard is recycled. These parts are separated from fibers in shredders and rejected in material recovery option, while no separation was required for incineration. Both parts were collected as residues of the separation process. Aluminum would be recycled to replace primary aluminum with lower substitution ratio due to degradation of the metal during recycling process, or so called downcycling (Koffler and Florin, 2013). On the other hand, because the amount of plastics was small and they were obviously contaminated with fibers, this fraction was assumed to be incinerated at the same CHP plant used in energy recovery. Heat and electricity produced from the combustion of plastics would be used as substitution the same amount of heat and electricity generation from hard coal, similar to the scenario when cardboard was utilized for energy recovery (as seen in Figure 13). Aluminum recycling was not feasible when cardboard was incinerated as it was combusted into fine particles found in bottom ash. Flow of each component are shown in Figure 13 and briefly summarized in Table 2.

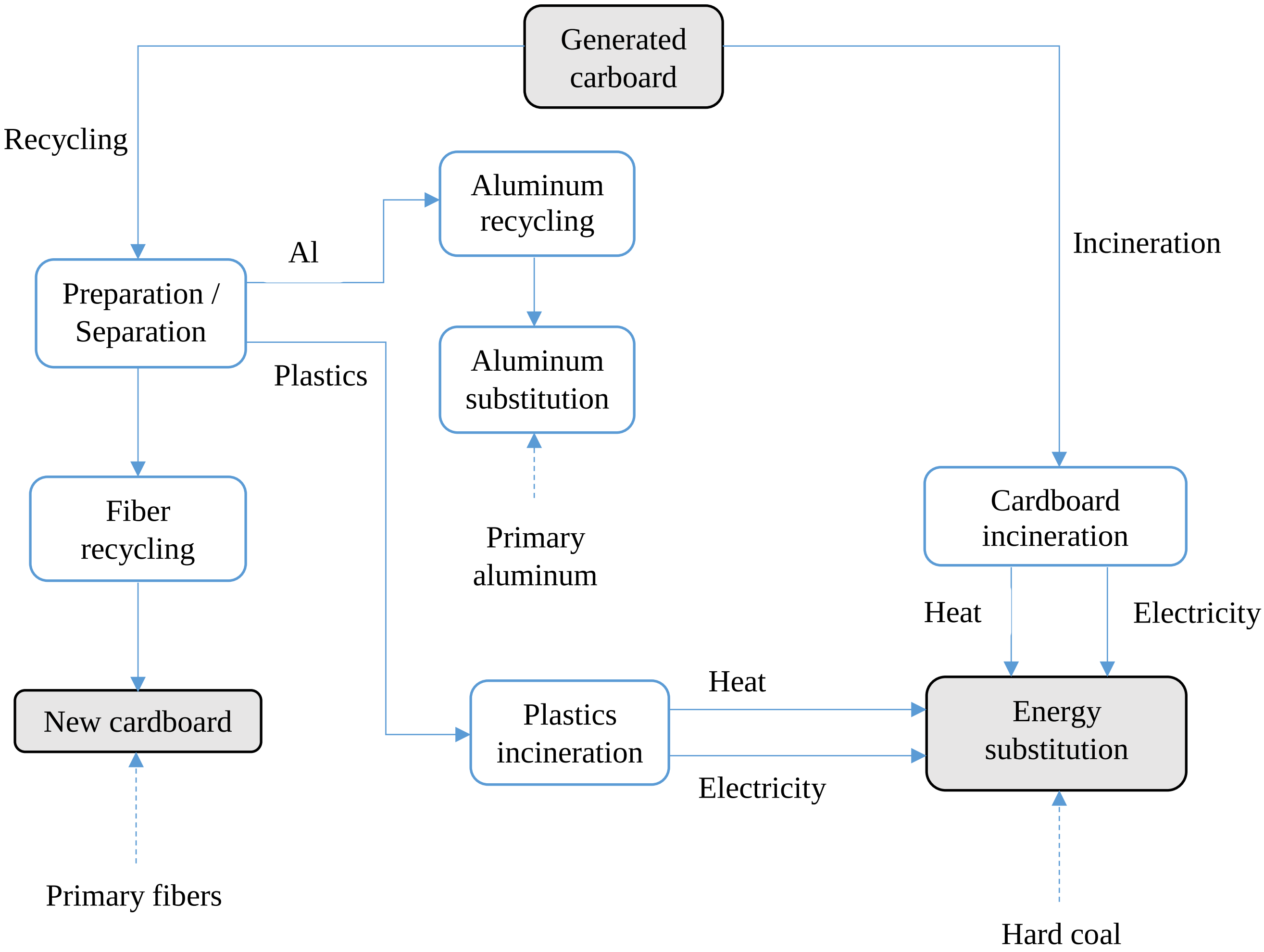


Figure 13: System outline

Table 2: Brief summary of component treatment

Scenario	Fiber	Aluminum	Plastics
Cardboard recycling	Recycled	Recycled	Incinerated
Cardboard incineration	Incinerated	Disposed*	Incinerated

*: disposed together with ash

5.2. Life cycle inventory analysis

The system was modelled using GaBi 6.0 Professional (http://www.gabi-software.com/international/software/) and based on data retrieved from the program databases (Thinkstep, 2016).

Composition of cardboard was modelled using the findings of Jokela (2016), who claimed that 6.6% is liquid packages, 26.9% is carton packages, 41.1% is corrugated board packages and 5.4% is other types of cardboard. Quantity of each type of cardboard was determined by multiplying their proportion to the functional unit of the study. The amounts of aluminum and plastics were calculated by multiplying the average share of each element in beverage cartons: 75% cardboard, 21% plastics and 4% aluminum (Mourad et al., 2008; ACE, 2016), with the amount of this cardboard type. Aluminum and plastics accounted for 0.26% and 1.4% of the total mass of cardboard, respectively.

Both the recycling and incineration with energy recovery technologies considered in this report were relatively high efficiency, which represented the average EU level. Virgin cardboard production and energy generation from alternated sources were also assumed to be technologically advanced with latest available data. These assumptions were made in order to strive for the most practical results since all related technologies have been under continuous research for improvement. Detailed information of the processes will be introduced in the sub-chapters about each option.

5.2.1. Recycling

Fibers need to be cleaned from other substances before being used in the production process. During the preparation process, fiber loss is unavoidable. According to Merrild et al. (2008) and Wang et al. (2012), the loss ranges between 10-17%, depending on the technology applied. In this report, we would like to assume high recycling efficiency, thus, 10% of fiber loss was applied in the modelling.

We used the recycling processes available in GaBi 6.0 Professional database, which were built based on report of FEFCO and Cepi Container Board and represent EU average production. In the study, recovered fibers were utilized to either partly or fully substitute the virgin materials. Different types of cardboard were taken into account with different consuming rate of recycled fibers as below. All these types of cardboard were produced as parts of corrugated board production. (FEFCO and Cepi Container Board, 2012; Thinkstep, 2016)

- 'Semichemical fluting (2012)': This is a single-ply board produced with mixed fiber inputs. The fresh fiber rate is 91% of total fibers utilization.
- 'Kraftliner (2012)': Higher rate of recycled fiber usage is adopted in this two-ply board production. About 80% of utilized fibers are virgin fibers.
- 'Wellenstoff / Fluting (2012)': Approximately 1.07 kg of recycling cardboard are needed to produce 1 kg of this medium, without using primary fibers. The products can have either one or two plies.
- 'Testliner (2012)': It usually consists of two plies and is totally produced from recovered fibers. 1.08 kg of waste fiber to produce 1 kg of new board.

The modelling of cardboard production from virgin materials was built based on the paperboard production at Skoghall Mill of Stora Enso, which provided one sixth of the beverage cartons on the global market (Stora Enso, 2015). Apart from the waste cardboard, the input materials of the mill included wood and pulp purchased. The upstream processes for these inputs were taken into account in the whole system. Pulp production was modelled based on UPM pulp production, one of largest pulp supplier in Europe and the world. The parameters represented all UPM pulp mills (UPM, 2016). Detailed inputs and outputs of these two processes are presented in Table 3. For wood production, approximately 10.2kg CO_2/m^3 wood is released during forest activities (Karjalainen et al., 2001). Waste from the production (such as sludges, ash and other residues) was sent for disposal at a landfill, presented by unit process 'Landfill for municipal solid waste', which represented the situation in Finland and other countries such as France, Great Britain, Ireland and Norway. Crude oil and electricity required for the production were supplied from unit processes 'Crude oil mix' and 'Electricity from hard coal', respectively. Both the data sets were built to represent average national situation in Finland.

Energy (electricity and heat) generated during virgin board production was utilized to substitute the equivalent amount of electricity and heat generated from hard coal.

Plastics and aluminum components were collected for recovery after being separated from fibers. Unit process 'Waste incineration of plastics (unspecified) fraction in municipal solid waste (MSW)' available in GaBi 6.0 Professional database, representing typical EU circumstances, was applied for combustion of plastics at a CHP plant to produce energy in forms of heat and electricity. The total efficiency of the plant was 82% (GaBi, 2016). Recovery of aluminum was presented by unit process 'Aluminium recycling (2010)' also available in GaBi. It should be noted that during recycling, the inherent properties of aluminum are changed in a sense of downcycling. Thus, the corrected credit named 'Paperbacked aluminium foil - scrap credit (open loop)' available in GaBi was used to present replacement of primary aluminum. This data set represented average EU level defined for aluminum laminated to paper, which was appropriate for our study case (GaBi, 2016). However, about 21% of material loss in the recycling procedures of aluminum is considered according to findings of Merrild et al. (2012); as a consequence, the credit process was modified by including consideration of material loss mentioned. Data set 'Aluminum ingot mix' for EU was chosen for the alternated primary aluminum.

Table 3: Inputs and outputs of the virgin board and pulp production (per one tonne board or pulp produced) (Stora Enso, 2015; UPM, 2016).

		Paperboard production[a]	**Pulp production**[b]
	Unit	**Quantity**	**Quantity**
Inputs			
Crude oil	GJ	0.94	-
Electricity supply	kWh	882.0	580*
Steam	kWh	-	2 800*
Water	m^3	51.7	61.0
Wood	m^3	3.0	4.0
Pulp	kg	154	-
Outputs			
Cardboard	tonnes	1.0	-
Pulp	tonnes	-	1.0
Electricity	kWh	11.4	-
Steam for district heating	kWh	4.5	-
Tall oil	kg	11.4	-
Waste for disposal	kg	8.6	50.0
Hazardous waste	kg	-	0.1
Emissions to air			
Carbon dioxide (fossil)	kg	70.8	82.0
Nitrogen dioxide	g	0.57	1.0
Sulfur	kg	0.09	-
Sulfur dioxide	kg	-	0.1
Particulates	kg	-	0.2
Total reduced sulfur (TRS)	kg	-	0.03
Emissions to water			
Nitrogen (as total N)	kg	0.09	-
Phosphorous	kg	0.01	-
Total suspended solids (TSS)	kg	1.06	0.4
Total Organic Carbon (TOC)	kg	3.6	-
Adsorbable Organic Halogen (AOX)	kg	0.02	0.1
Chemical Oxygen Demand (COD)	kg	-	10.0
Waste water	m^3	31.3	35.0

a: Stora Enso (2015)

b: UPM (2016)

*: self-sufficient

5.2.2. Incineration

Incineration of cardboard with energy recovery after arriving at the CHP plant was modelled with two separate datasets in GaBi database: ‘Paper/Cardboard’ and ‘Waste incineration of plastics (unspecified) fraction in municipal solid waste (MSW)’ (same unit process as in recycling option), considering the difference in energy content of the two components. The LHV of plastics was assumed to be 30 MJ/kg whereas cardboard’s value was 15 MJ/kg (GaBi, 2016). The datasets represented EU average level with the overall efficiency of the plant was 82% (27% of total energy output was electricity and 73% was steam) (GaBi, 2016), which was appropriate for Finland with high demand of heating due to cold weather. The flow mass was calculated based on the share of beverage cartons in cardboard waste as well as the constitution of cardboard, as mentioned above.

The energy, in forms of heat and electricity, produced would substitute the same amount generated from hard coal, which were modelled with unit processes ‘Thermal energy from hard coal’ and ‘Electricity from hard coal’ available in GaBi. Both data sets were built to represent Finnish average.

5.3. Life cycle impact assessment (LCIA)

Global warming is an essential issue globally at the moment so it is chosen as the main impact category in the study. Time horizon of 100 years is most commonly used for global warming potential (GWP) and according to European Commission Joint Research Venture (EC JRC) (2010), Intergovernmental Panel on Climate Change (IPCC) would be the best option for this impact category; thus, we would like to use IPCC AR5 (fifth assessment report) global warming potential in 100 years (GWP 100) excluding biogenic carbon as an LCIA method in this study. In addition to GWP, AP and EP are also considered in this study. There is no evaluation method recommended with satisfactory level by EC JRC for AP and EP; hence, we would like to choose CML2001 as the assessment methods for these two categories as this method has been used with high frequency in previous LCA studies and it could provide robust results (Martínez et al., 2015).

6. LCA RESULTS

6.1. LCIA results

LCIA results of the modelling showed that energy recovery provided credits in all impact categories (GWP100, AP and EP) while the results for the recycling scenario were more diverse as seen from Table 4. Replacement of virgin fibers seemed to bring benefits in GWP100; however, the savings reduced when the substitution ratio increased. This was because of the high energy consumption during production process of fluting and testliner (100% recycled fiber products) in the inventory data (FEFCO and Cepi Container Board, 2012). These two processes were estimated to consume 30-35% more energy per tonne of product compared to production of semichemical fluting and kraftliner (partial recycled fiber). On the other hand, the results were less promising from the AP and EP points of view as it showed that recycling did not always bring benefits. Only full substitution would bring benefits while partial substitution only created additional burdens on the environment. The main reason seemed to be the utilization of additives in the production. Most of additives (such as Alum - $Al_2(SO_4)_3$, peroxide, H_2SO_4 and biocides) were either not added or required in small amount in the full replacement processes compared to a partial replacement. As a consequence, production of semichemical fluting and kraftliner produced more emissions to the air (NO_x, SO_x, Total Reduced Sulfur - TRS) and to the water (Total Nitrogen, Total Phosphorus) (FEFCO and Cepi Container Board, 2012). In general, assessment results indicated that incineration with energy recovery was more environmentally beneficial than recycling in all three perspectives. The actual saved emissions by incineration were approximately the same level or even much less compared to recycling; but as it caused less burdens, energy recovery made a better performance with lower level of net impacts. Results of GWP and AP were in a good agreement with the previous study of Luoranen et al. (2009). However, Luoranen et al. (2009) found energy recovery was not a better option in the EP perspective, which was in contrast with the results of this report. This was because of the differences in the system boundaries of the studies.

Shares of emissions in each unit process calculated based on the total actual release in incineration and recycling options are presented in Table 5 and 6. It can be seen from the tables that the contribution of each unit processes varies a lot. For the incineration scenario, most of the released emissions were from the combustion of fiber and plastics. Because of its small share in total mass of cardboard, combustion of plastics components made modest contribution in AP and EP. However, in GWP, release from combustion of plastics accounted the largest proportion. This was because this fraction mostly contained non-biogenic carbons while cardboard comprises mostly biogenic carbons. Recycling process and energy required for stock preparation in material recovery contributed most of the burdens in the whole process. These two unit processes accounted more than 80% of the total release in all three impact assessments. Avoidance of virgin cardboard production, including electricity required, chiefly created environmental credits in the recycling option. These unit processes with large shares were considered for sensitivity analysis to check the robustness of the results.

Table 4: GWP, AP and EP of the scenarios studied.

	GWP [tonnes CO2-Equiv.]			AP [tonnes SO2-Equiv.]			EP [tonnes PO4-Equiv.]		
	Emitted	**Saved**	**Net**	**Emitted**	**Saved**	**Net**	**Emitted**	**Saved**	**Net**
Incineration	4.18E+04	-2.55E+05	-2.13E+05	8.56E+01	-6.40E+02	-5.55E+02	1.54E+01	-6.95E+01	-5.41E+01
Recycling									
Semichemical fluting	1.83E+06	-2.03E+06	-1.98E+05	6.67E+03	-4.63E+03	2.05E+03	1.92E+03	-1.13E+03	7.85E+02
Kraftliner	5.15E+05	-6.65E+05	-1.50E+05	1.79E+03	-1.52E+03	2.67E+02	5.38E+02	-3.66E+02	1.72E+02
Fluting	1.94E+05	-2.18E+05	-2.43E+04	2.06E+02	-5.08E+02	-3.02E+02	8.03E+01	-1.14E+02	-3.36E+01
Testliner	1.94E+05	-2.17E+05	-2.29E+04	2.07E+02	-5.04E+02	-2.97E+02	8.08E+01	-1.13E+02	-3.21E+01

Table 5: Contribution of each stage to GWP, AP and EP compared with the total produced emissions of the incineration scenario.

	GWP	**AP**	**EP**
Diesel mix at refinery (EU-27)	0.51 %	1.55 %	1.87 %
Cardboard incineration	19.4 %	89.0 %	86.4 %
Plastics incineration	77.0 %	6.57 %	7.56 %
Substituted electricity from hard coal	-298 %	-366 %	-222 %
Substituted thermal energy from hard coal	-311 %	-382 %	-228 %
Truck for transportation	3.00 %	2.83 %	4.12 %
Total	**-509 %**	**-648 %**	**-350 %**

Table 6: Contribution of each stage to GWP, AP and EP compared with the total produced emissions of the multiple recycling options.

	GWP				AP				EP			
	Semi-chemical Fluting	**Kraftliner**	**Fluting**	**Testliner**	**Semi-chemical Fluting**	**Kraftliner**	**Fluting**	**Testliner**	**Semi-chemical Fluting**	**Kraftliner**	**Fluting**	**Testliner**
Pulp production	-2.8%	-3.2%	-2.5%	-2.5%	-3.1%	-3.7%	-9.4%	-9.3%	-6.6%	-7.5%	-14.7%	-14.5%
Primary aluminium production	-0.1%	-0.3%	-0.9%	-0.9%	-0.1%	-0.4%	-3.7%	-3.6%	-0.02%	-0.1%	-0.6%	-0.6%
Aluminum recycling	0.1%	0.2%	0.6%	0.6%	0.03%	0.1%	0.9%	0.9%	0.01%	0.03%	0.2%	0.2%
Landfill	-0.7%	-0.8%	-0.6%	-0.6%	-0.1%	-0.1%	-0.2%	-0.2%	-0.7%	-0.8%	-1.5%	-1.5%
Fiber recycling process	95.8%	86.8%	64.9%	64.8%	98.2%	94.7%	53.8%	54.0%	99.3%	98.0%	86.4%	86.5%
Plastics incineration	1.8%	6.3%	16.6%	16.6%	0.1%	0.3%	2.7%	2.7%	0.1%	0.2%	1.5%	1.4%
Crude oil mix	-0.6%	-0.7%	-0.6%	-0.5%	-0.7%	-0.8%	-2.1%	-2.1%	-0.2%	-0.2%	-0.4%	-0.4%
Electricity to consumers	0.5%	-1.2%	-5.6%	-5.7%	0.3%	-0.8%	-13.4%	-13.3%	0.1%	-0.3%	-3.8%	-3.7%
Electricity for paper production	-94.0%	-106.4%	-82.8%	-82.2%	-64.8%	-76.9%	-196.5%	-193.6%	-24.6%	-28.0%	-55.1%	-54.2%
Electricity for stock preparation	1.9%	6.8%	17.9%	18.0%	1.3%	4.9%	42.6%	42.3%	0.5%	1.8%	11.9%	11.8%
Thermal energy from hard coal	-1%	-3%	-9%	-9%	-0.5%	-2.4%	-21.5%	-21.4%	-0.2%	-0.8%	-5.9%	-5.9%
Forest activities	-4%	-4%	-3%	-3%	-	-	-	-	-	-	-	-
Paperboard production	-8%	-9%	-7%	-7%	-0.01%	-0.01%	-0.03%	-0.03%	-26.8%	-30.4%	-59.9%	-58.9%
Total	**-10.8%**	**-29.2%**	**-12.5%**	**-11.8%**	**30.7%**	**14.9%**	**-146.9%**	**-143.5%**	**40.9%**	**31.9%**	**-41.8%**	**-39.7%**

6.2. Sensitivity analysis

In this part, sensitivity analysis was carried to check the consistency of the study. The focus was on the unit processes with the high contribution to the overall system from LCIA results. Parameters with high potential to affect the outcome would be adjusted to figure their influences on the systems.

In LCIA part, it can be seen that the electricity and heat production which are substituted play an important role on the environmental benefits, especially electricity production as it also holds big shares in recycling scenario as well. In the current modelling, cardboard was used as a fuel to substitute hard coal. During the sensitivity analysis, cardboard was used to substitute other types of electricity such as Finnish mix grid and the one from natural gas, which also contribute big part in energy production and consumption in Finland. The processes used in modelling were available in GaBi and named ‘Electricity grid mix’ and ‘Electricity from natural gas’, both of which represent Finnish average conditions. Finnish electricity grid mix by fuel types is presented in Figure 14 (GaBi, 2016).

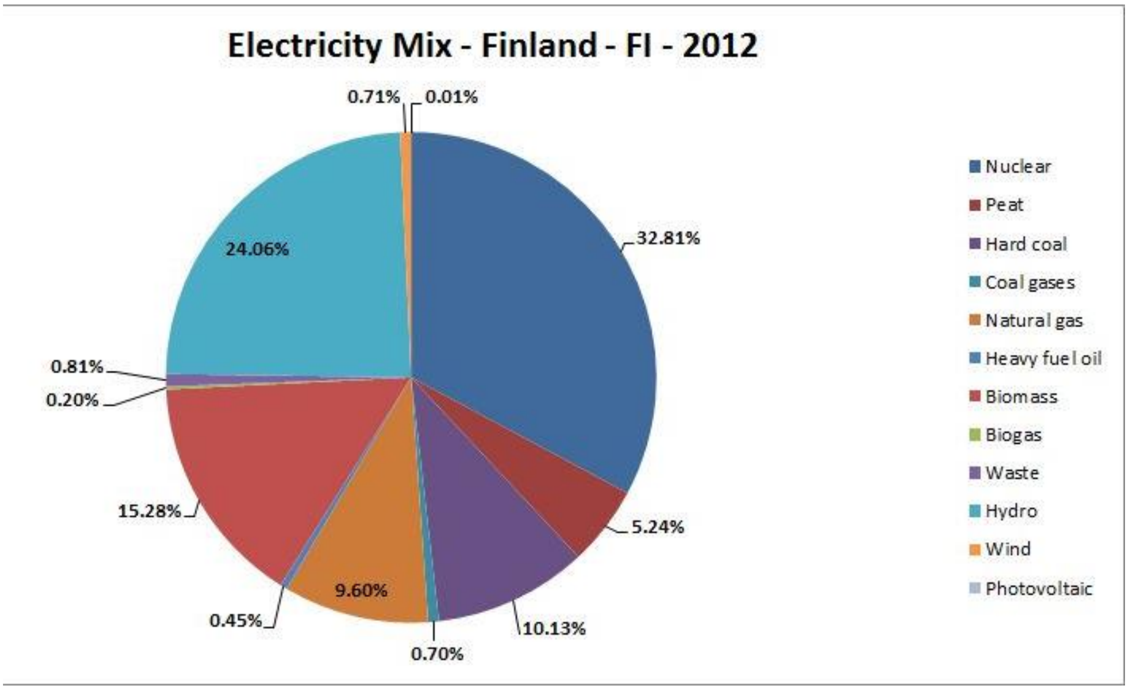


Figure 14: Finnish electricity grid mix by fuel types in 2012 (GaBi, 2016).

When natural gas and Finnish grid mix were chosen as substituted electricity generation, the savings from both incineration and recycling were reduced, as seen in Figure 15.

With the same amount of recycled fibers, the number of new products from partial replacement processes were higher than from full replacement processes. This resulted in higher amounts of products from virgin fibers, and consequently, more environmental burdens, were avoided in partial replacement production. When natural gas was used instead of hard coal, the avoided emissions declined almost by half as the average CO_2 emissions per energy unit generated of natural gas are about 40% lower than of hard coal, 55 tonne/TJ fuel input for natural gas and 95 tonne/TJ fuel input for hard coal (Thinkstep, 2016) (see Table 1). The additional impact from the recovery activities remained the same, but the avoided impact almost halved with the change of the replaced fuel, semichemical fluting and kraftliner with tremendous impacts were affected more severely.

There was a remarkable contribution of renewable energy (biomass, biogas, waste, hydro, wind and photovoltaic) in the grid and renewable energy was expected to release less CO_2 than fossil fuels such as hard coal, which lowered the overall avoided GHG per energy unit in the system. The situation was similar to the case of natural gas.

In both new energy choices, incineration with energy recovery still showed better performance over recycling in this analysis in all three impact categories. The choices led to drastic changes in semichemical fluting and kraftliner scenarios as they reversed the performance of these processes in GWP and multiplied the burdens in AP and EP. Results of fluting and testliner were not affected much in AP and EP but still reversed in GWP.

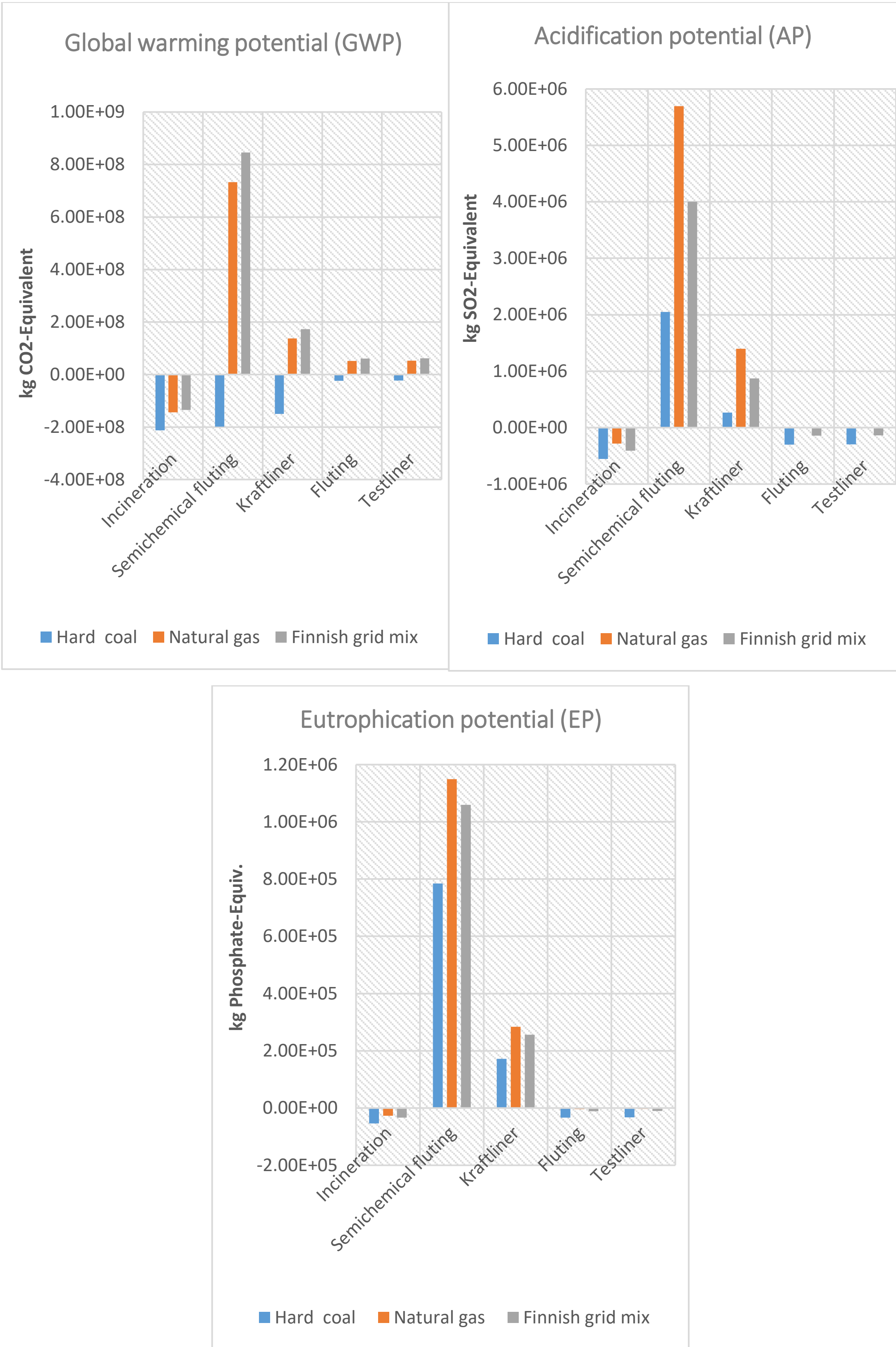


Figure 15: GWP, AP and EP of different electricity production sources.

Regarding heat production, the process ‘Thermal energy from hard coal’ currently used to represent avoided heat production has the energy efficiency of 100%. In the sensitivity analysis, this process was replaced by similar processes with lower energy efficiency available in GaBi database. Three processes ‘Process steam from hard coal 95%’, ‘Process steam from hard coal 90%’ and ‘Process steam from hard coal 85%’ with thermal efficiency of 95%, 90% and 85% respectively were used to model the substituted heat generation from hard coal. The impact assessment results are shown in Figure 16. It can be seen that the energy efficiency did not notably affect the overall results of all scenarios in all three impact assessments, except noticeable improve in benefits of incineration with energy recovery.

The lower efficiency of the avoided technology was, the higher were the credits of energy recovery. When the energy efficiency was low, more resources were required to meet the demands. Increase of consumption resulted in more emissions to be released to the environments. In other words, avoided release was increased.

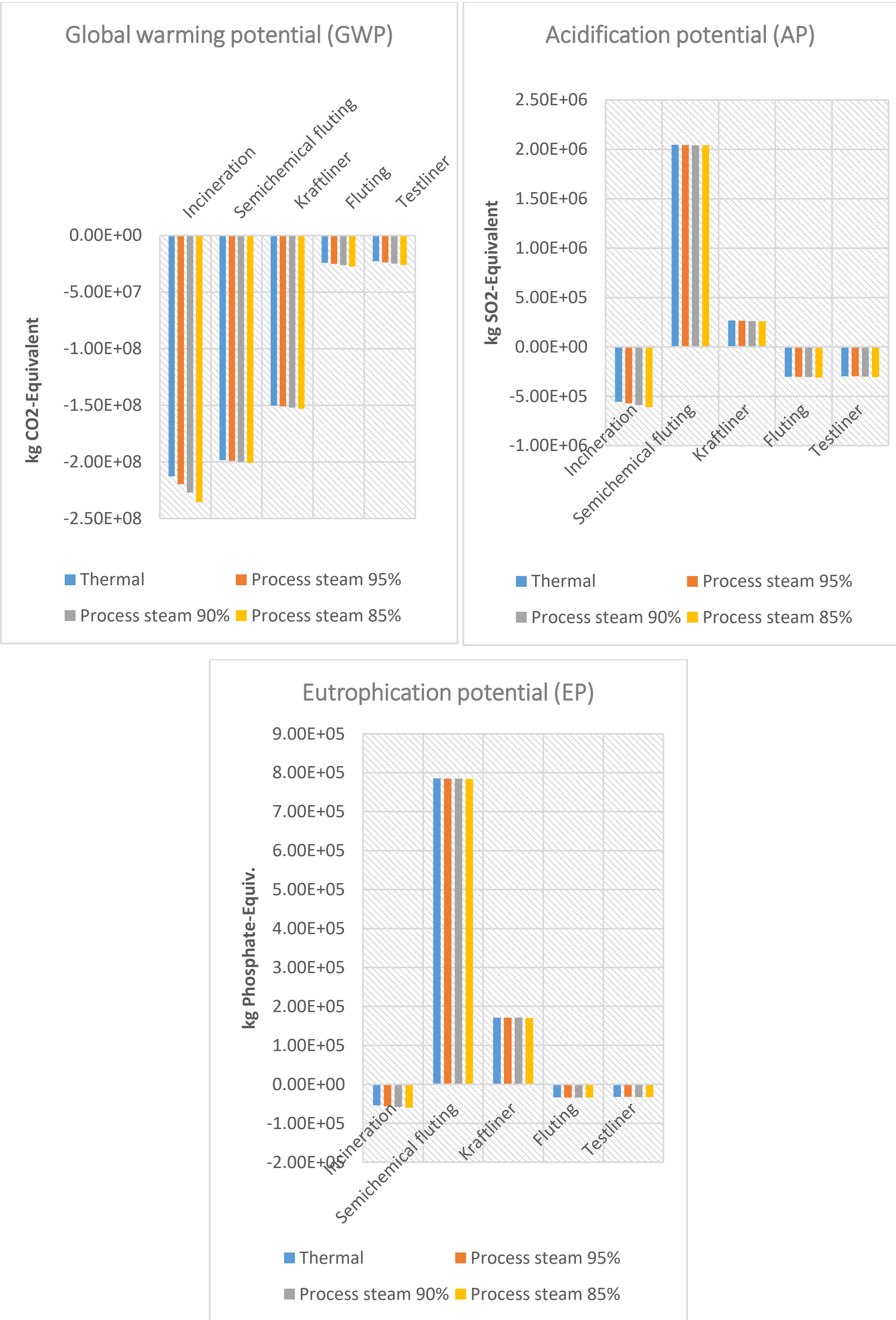


Figure 16: GWP, AP and EP of different heat production.

We suppose that the change of energy efficiency in paper production may affect the outcome significantly. As stated in the Skoghall Mill environmental statement (2013, 2016), the board production was slightly higher but the total electricity consumption was vaguely lower in the 2015. The electricity consumption per tonne of board produced in 2015 reduced 5% compared to 2012. Lower in-house electricity production rate in 2015, approximately 31% and 34% respectively was the reason for only 1.5% decrease in bought electricity. (Stora Enso, 2013 and 2016) We would assume that the in-house electricity was unchanged, and only adjust the utilization rate of electricity bought from supplier. The electricity consumption per tonne paperboard manufactured would be changed to the value of 2012 (1.5% higher than the default value). In addition to that, we would assume that electricity consumption efficiency was improved by reducing the consumption per tonne of board produced by 2% and 5%. Results of this adjustment are demonstrated in Figure 17. This unit process represented the substituted production; hence, when better technologies were applied in production from virgin fibers, there was less avoided impacts, and consequently, reduction in the net outcome. The adjustment seemed to mostly affect the results semichemical fluting, especially in GWP. When the electricity utilizing rate was higher, semichemical fluting could provide the most savings in GWP. The savings diminished when the efficiency was improved. It can be seen that the savings was only half of the current situation when electricity utilizing efficiency was improved by 5%. Slight changes were noticed for semichemial fluting in EP and kraftliner in GWP and AP. For the rests, the adjustment seemed to have subtle effects. Generally, despite the fluctuation in values, the overall outcome was the same with incineration remaining a better choice across three impact categories and both energy and material recovery could bring benefits to the environment in GWP aspect.

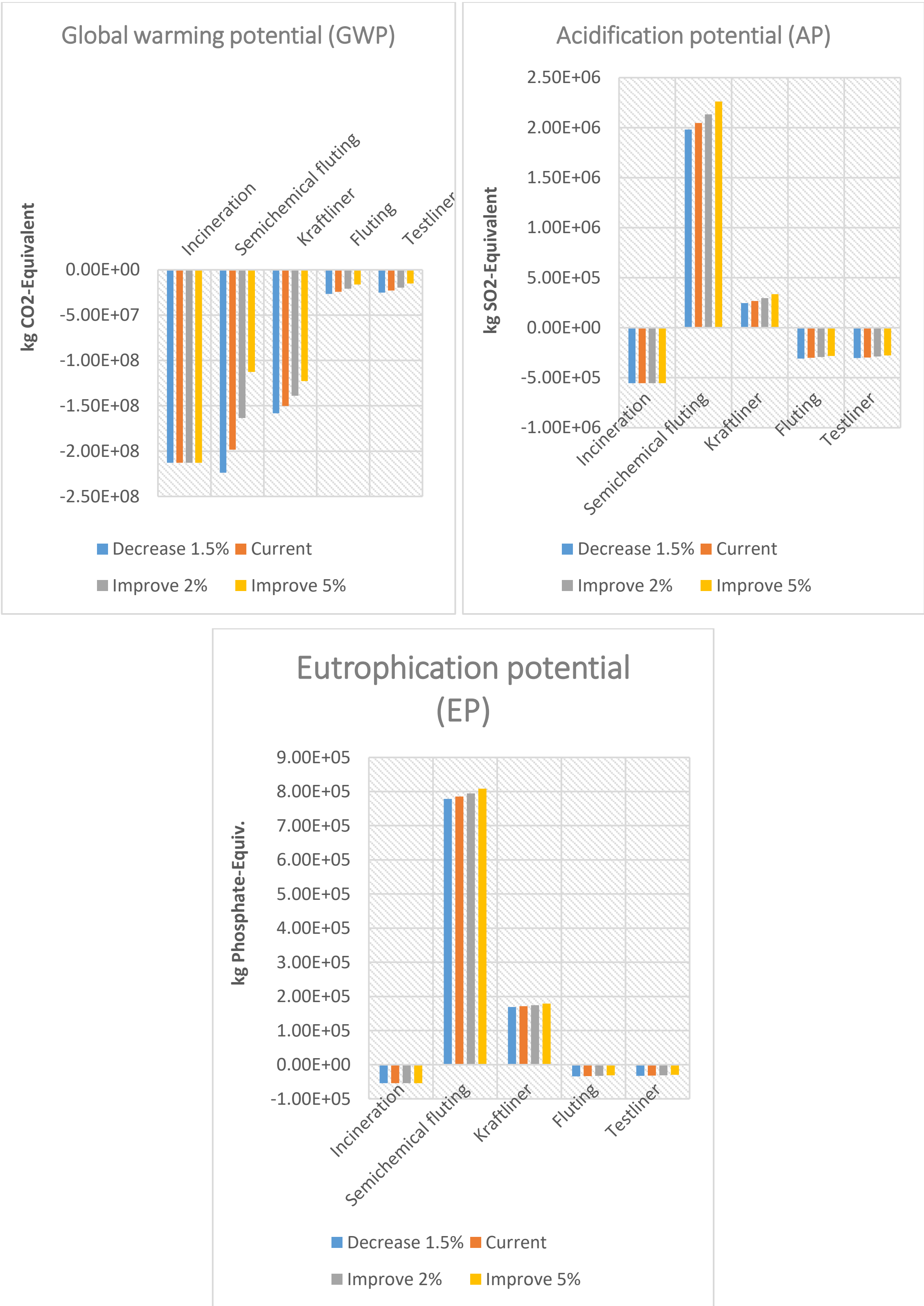


Figure 17: GWP, AP and EP results when energy efficiency is adjusted.

In the recycling scenario, the recycling practices of fibers always dominated most of the GHG emissions in the whole system. AP and EP results also remarked the activity as the main contributor. Owing to this, we would expect that improvement of the recycling technology would bring more environmental benefits. The fiber loss was chosen as the adjusted parameter for analysis as it would affect the amount of cardboard produced. Thus, it will affect the emissions released as well. Fiber loss would be adjusted to 20%, 15% and 5%, to compare with current loss of 10%. The results are indicated in Figure 18. As expected, while limiting the loss of fiber, the benefits that recycling could bring improved significantly in GWP. When fiber loss was controlled at 5%, recycling of cardboard into semichemical fluting could provide almost the same benefits as energy recovery. However, there were noticeable increases of burdens in AP and EP for semichemical fluting and kraftliner. The reasons seemed to relate to the utilization of additives during the production. More fibers recycled meant that more board produced together with higher level of additives consumption.

In brief, incineration with energy recovery of cardboard remained the best choice throughout the analysis with consistent emission savings in all three impact categories: GWP, AP and EP. Recycling with partial substitution would not be a good option in AP and EP points of view as they created environmental burdens instead of savings in most cases studied. On the contrary, recycling with full substitution would provide emission savings according to AP and EP results, thanks to the avoidance of additives consumption. It was noticed that recycling of fibers could bring benefits only when fuels with high emission factors such as coal were used as consumed energy of the avoided technology.

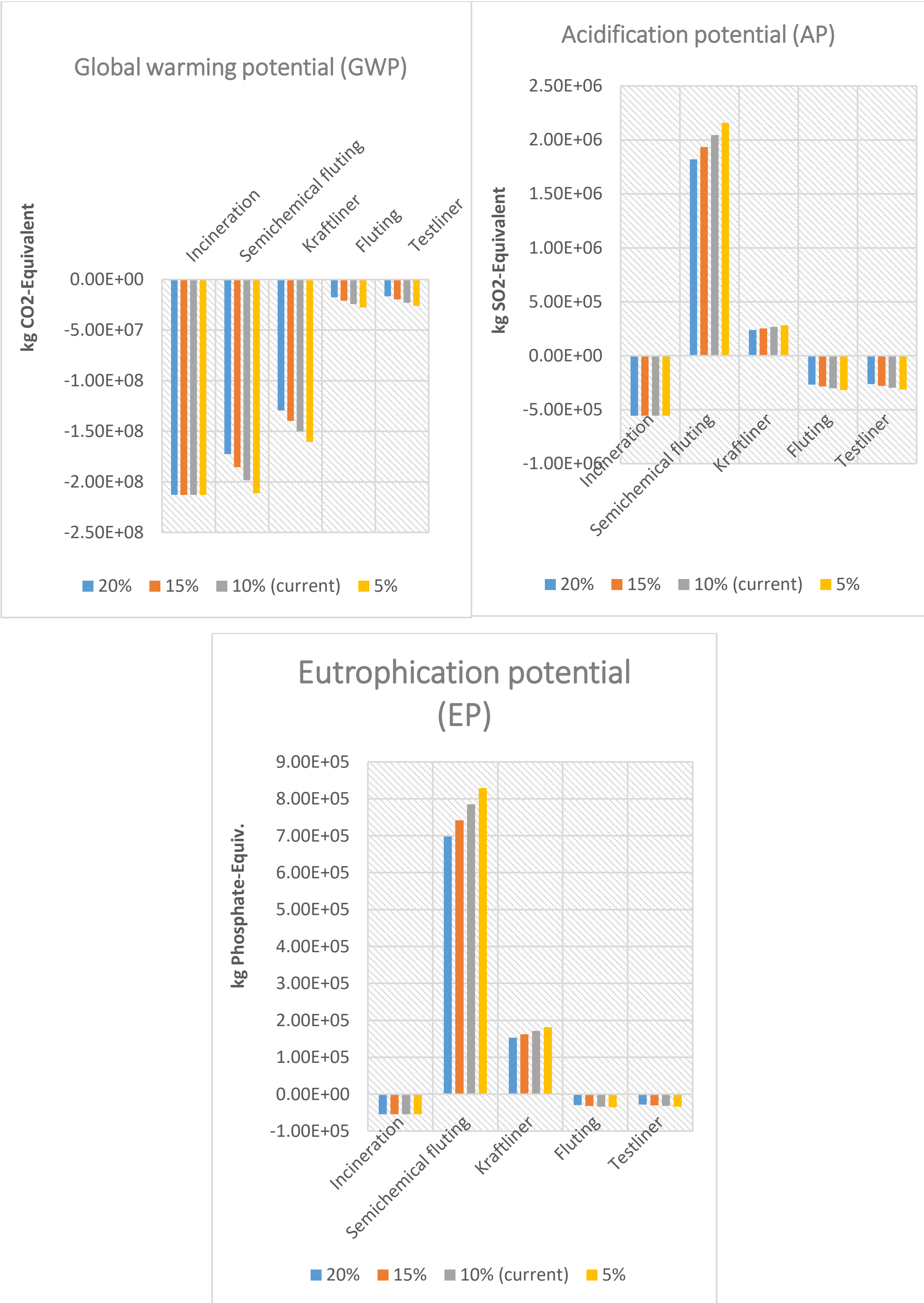


Figure 18: GWP, AP and EP results with different fiber loss.

7. DISCUSSION AND CONCLUSIONS

The results of the impact assessment showed that both incineration with energy recovery and recycling could reduce the environmental effects in GHG points of view. However, the first choice seemed to be able to provide better results than the latter option as the emissions was seen lower. The values of acidification and eutrophication potential impact also indicated that combustion of cardboard was more advantageous as recycling sometimes created environmental burdens instead of benefits as expected.

A partial replacement of virgin fibers seemed to have more benefits than a full replacement in GWP impact. Recycling of the cardboard waste into semichemical fluting, which had the highest fresh fiber rate, was slightly less beneficial than energy recovery, while benefits provided by the products fully produced from recycled fibers were about ten time less. The reason was because of the high consumption of fossil fuels in modellings of full substitution products (fluting and testliner). However, when energy consumption in the system was provided from natural gas and gird mix – instead of hard coal as in original assumption, the results showed that full replacement was preferable. The partial substitution of cardboard had higher avoided emissions than the full substitution products. Both natural gas and grid mix had lower emission rate per energy unit, resulted in enormous decrease in avoided emissions while actual release maintained the same. These factors reversed the impact results of the recycling methods.

Unlike GWP, the results in AP and EP always showed that incineration was a better choice than recycling and the full substitution was always better than the partial replacement. However, it demonstrated that partial replacement did not provide better environmental effects. It can be seen from the results that the production of semichemical fluting, utilizing 9% of recycled fibers, resulted in higher impacts than production of fluting and testliner.

All the sensitivity analysis results indicated that the changes of the parameters in the unit processes would not affect the order of the environmental importance of the recycling methods studied. The analysis of energy resource in primary production affected recycling the most, especially in GWP as it reversed the performance. No significant changes occurred when adjusting other parameters, except the case of energy efficiency and fiber loss on semichemical fluting and kraftliner as remarkable changes were acknowledged. It demonstrated that a higher energy efficiency in primary production resulted in lower saved benefits from the recovery. It is in contrast as development in recovery technologies would bring more environmental benefits. These factors determined the outcome of the recovery noticeably.

The thesis incorporates certain limitations. To begin with, the recycling processes in the modelling were built based on the life cycle assessment database of cardboard by FEFCO and Cepi Container Board (2012); however, the report stated that the research was not carried out for comparison purpose between primary production and recovered fiber based manufacture; and thus, might not completely be applicable for the purpose of the study performed. Next, there were some limitations in the modelling of the study. Firstly, due to lack of practical information, four substitution rates had not been represented by one same product with just different rates but by four similar types of cardboard which still had some distinct properties from each other. For instances, semichemical fluting (9% recycled fibers) was a one-ply product while kraftliner (10% recycled fibers) and testliner (full replacement) were normally a two-ply board; surface treatment should be applied for fluting and testliner to ensure the stiffness and strength as required. These specific requirements for each types of cardboard might lead to slight differences in the production line, and consequently, energy consumption and emissions. Being compared to one same virgin production might affect the precision of the comparison. Secondly, reprocessing processes were assumed to utilizing mixed types of paper and board. Even though paper and carboard have similar properties but there are still some differences such as fiber quality. Paper normally has higher quality with better fiber strength, which resulted in less material loss and quality loss during recycling processes; thus, recycling of paper is expected to have higher efficiency. Last, FEFCO and Cepi report (2012) was based on weighted average data collected from interested parties. There were some missing data for several production sites and assumption needed to be made. Different habits in practices at production sites might affect the precision of the comparison. For instances, renewable fuels contributed significantly in fuels consumption in partial substitution production while production of full substitution products chiefly utilized fossil fuels. As a result, fossil CO_2 emissions from semichemical fluting and kraftliner were considerately lower. Lastly, the study only took into account three impact categories: GWP, AP and EP while other impact categories such as abiotic depletion, ozone layer depletion potential, photochemical ozone creation potentials and radioactive radiation should also be considered to obtain a full picture of the study.

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APPENDICES

APPENDIX I. Municipal waste generated in European Union countries from 1995 to 2014. (Eurostat, 2016)

Municipal waste generation
kg per capita
Waste generated

geo \ time	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
EU (28 countries)	:	:	496 (s)	:	:	520 (s)	:	:	:	511 (s)	515 (s)	521 (s)	523 (s)	520 (s)	511 (s)	503 (s)	498 (s)	487 (s)	478 (s)	474 (s)
EU (27 countries)	473 (s)	484 (s)	498 (s)	496 (s)	510 (s)	523 (s)	521 (s)	527 (s)	515 (s)	513 (s)	516 (s)	522 (s)	524 (s)	521 (s)	512 (s)	504 (s)	499 (s)	488 (s)	479 (s)	475 (s)
Belgium	455	450	457	451	460	471	467	482	465	485	482	485	493	479	467	456	456	447	437	436
Bulgaria	694	618	579	591	598	612	596	602	603	599	588	577	553	599	598	554	508	460	432	442
Czech Republic	302	310	318	293	327	335	274	279	280	279	289	297	294	306	317	318	320	308	307	310
Denmark	521	577	543	545	577	610	606	616	598	620	662	666	707	741	693	673 (e)	781	750	752	758
Germany	623 (s)	641 (s)	658 (s)	647 (s)	638 (s)	642 (s)	632 (s)	640	601	587	565	564	582	589	592	602	626	619	615	618 (e)
Estonia	371	399	424	402	409	453	366	401	414	445	433	398	449	392	339	305	301	280	293	357
Ireland	512	522	544	554	577	599	699	692	730	737	731	792	772	718	651	624	617	587	586 (s)	:
Greece	:	339	366	381	396	412	420	426	431	436	442	447	453	458	464	532	503	506	509 (s)	:
Spain	505	530	554	557	606	653	652	637	646	600	588	590	578	551	542	510	485	468	454	435 (e)
France	475	486	496	507	507	514	526	530	506	519	530	536	543	541	535	533	538	538	517	509
Croatia	:	:	224 (e)	:	:	262 (e)	:	:	:	304 (e)	336 (e)	384	399	415	405	379	384	391	404	387
Italy	454	457	468	472	498	509	516	523	524	540	546	559	557	552	543	547	529	504	491	488
Cyprus	595	605	612	616	620	628	650	655	670	684	688	694	704	728	729	689	672	657	618	617 (e)
Latvia	264 (e)	265 (e)	255 (e)	248 (e)	256 (e)	271 (e)	305 (e)	343	304	318	320	343	391	345	352	324	350	301	312	325
Lithuania	426	401	422	445	351	365	378	405	389	373	387	405	419	428	381	404	442	445	433	433
Luxembourg	587	585	604	625	646	654	646	653	678	679	672	683	695	697	679	679	666	652	616	616 (e)
Hungary	460	469	487	485	483	446	452	457	464	454	461	468	457	454	430	403	382	402	378	385
Malta	395 (e)	420 (e)	444 (e)	469 (e)	476	546	540	541	580	623	623	624	654	674	649	601	589	588	582	600
Netherlands	539	551	576	577	582	598	595	600	586	599	599	597	606	600	589	571	568	549	526	527
Austria	437	516	532	532	563	580	576	608	607	574	575	597	597	600	590	562	573	579	578	566
Poland	285	301	315	306	319	320	290	275	260	256	319 (e)	321 (e)	322 (e)	320 (e)	316 (e)	316 (e)	319 (e)	317 (e)	297 (e)	272 (e)
Portugal	352	372	397	413	433	457	454	441	449	445	452	465	471	518	520	516	490	453	440	453
Romania	342	326	326	278	314	355 (e)	341 (e)	385 (e)	353 (e)	349 (e)	383 (e)	396 (e)	391 (e)	411 (e)	381 (e)	313	259	251	254	249
Slovenia	596	591 (e)	589 (e)	585	550 (e)	513 (e)	478	407	418	485	494	516	525	542	524	490	415	362	414	432
Slovakia	295	275	274	259	261	254	239	270	281	261	273	284	294	313	307	319	311	306	304	321
Finland	413	410	447	466	484	502	465	458	466	469	478	494	506	521	480	470	505	506	493	482
Sweden	386	391	416	437	428	428	439	465	464	460	477	490	486	483	470	439	449	450	451	438
United Kingdom	498	511	532	542	569	577	591	598	591	602	581	583	567	541	522	509	491	477	482	482
Iceland	426	435	443	449	454	462	467	476	484	503	516	563	558	495	355	306	320	338	345	:
Norway	624	630	618	645	594	613	361	392	402	414	426	459	491	487	470	469	485	477	496	423
Switzerland	600	603	603	612	635	656	660	674	667	660	661	709	720	736	702	708	689	694	702	730
Montenegro	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	544	514	508	551
Former Yugoslav Republic of Macedonia, the	:	:	:	:	:	:	:	:	:	:	:	:	:	349 (e)	354	351 (e)	357	381	384	370
Serbia	:	:	:	:	:	:	:	:	:	:	:	233	280	347	360	363	375	364	336	302
Turkey	441	466	499	506	459 (e)	465 (e)	476	470	465	440	458 (e)	434	433 (e)	400	419 (e)	407	416 (e)	410	406 (e)	405 (e)
Bosnia and Herzegovina	:	:	:	:	:	:	:	:	:	:	:	:	:	356	354	332	340	340	311	:
Kosovo (under United Nations Security Council Resolution 1244/99)	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	417 (e)	:	:

:=not available s=Eurostat estimate (phased out) e=estimated

Source of Data: Eurostat
Last update: 30.11.2016
Date of extraction: 09 Dec 2016 13:46:37 CET
Hyperlink to the table: http://ec.europa.eu/eurostat/tgm/table.do?tab=table&init=1&plugin=1&language=en&pcode=tsdpc240
General Disclaimer of the EC website: http://ec.europa.eu/geninfo/legal_notices_en.htm
Short Description: Municipal waste consists to a large extent of waste generated by households, but may also include similar wastes generated by small businesses and public institutions and collected by the municipality; this part of municipal waste may vary from municipality to municipality and from country to country, depending on the local waste management system. For areas not covered by a municipal waste collection scheme the amount of waste generated is estimated.
Code: tsdpc240

APPENDIX II. Packing waste generated in EU countries in tons from 2005 to 2014. (Eurostat, 2016)

GEO/TIME	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
European Union (28 countries)	:	:	:	:	:	:	:	79,132,289	79,586,793	:
European Union (27 countries)	78,966,076	80,545,969	81,311,912	81,513,668	76,592,661	78,808,985	80,169,054	78,933,683	79,388,223	:
European Union (15 countries)	70,749,779	72,075,345	73,158,020	72,401,789	68,296,662	70,006,710	70,985,742	69,409,125	69,572,312	:
Belgium	1,659,443	1,665,533	1,669,002	1,690,170	1,642,275	1,685,954	1,702,505	1,715,569	1,738,288	:
Bulgaria	520,192	368,943	318,328	302,208	303,883	321,197	314,639	328,797	350,043	378,668
Czech Republic	847,445	898,668	962,682	967,626	894,353	922,726	945,316	962,346	1,005,749	1,019,805
Denmark	983,011	970,890	978,960	902,156	693,950	693,950	883,096	894,913	893,073	923,026
Germany	15,470,500	16,132,765	16,112,500	16,044,800	15,052,100	16,002,600	16,486,200	16,586,600	17,126,900	17,777,700
Estonia	137,189	152,135	162,245	214,470	161,579	157,907	193,029	197,286	223,928	227,808
Ireland	925,222	1,028,472	1,055,951	1,026,759	972,430	863,714	863,596	809,501	870,109	:
Greece	1,061,005	1,056,000	1,050,000	1,050,000	1,008,000	927,400	870,420	773,370	749,300	:
Spain	7,798,421	8,006,787	8,419,900	8,006,123	7,424,350	7,389,590	7,146,841	6,722,712	6,695,844	6,862,569
France	12,360,928	12,667,985	12,797,250	12,828,115	12,277,691	12,515,928	12,810,715	12,256,790	12,130,056	12,473,429
Croatia	:	:	:	:	:	:	:	198,606	198,570	204,708
Italy	11,952,800	12,219,550	12,540,928	12,169,000	10,862,000	11,411,000	11,637,700	11,345,342	11,462,983	:
Cyprus	123,066	63,065	78,298	87,466	79,758	79,528	75,554	74,945	78,703	:
Latvia	263,833	306,838	323,123	263,933	186,223	213,905	216,089	213,877	229,318	221,614
Lithuania	264,016	283,672	342,374	329,685	260,704	272,478	292,348	302,137	319,744	344,726
Luxembourg	98,832	105,070	102,041	104,186	91,260	102,489	104,679	107,607	112,007	108,576
Hungary	853,044	884,957	968,067	1,004,580	977,814	880,773	838,449	1,012,824	1,022,362	1,012,087
Malta	42,333	43,568	48,191	49,287	50,542	45,747	53,253	52,553	57,032	58,128
Netherlands	3,349,000	2,755,000	2,785,000	2,780,000	2,528,500	2,724,000	2,748,000	2,749,000	2,814,000	2,788,000
Austria	1,111,400	1,166,352	1,184,550	1,180,134	1,163,931	1,230,852	1,232,059	1,253,574	1,271,696	1,303,528
Poland	3,509,005	3,654,700	3,133,718	4,181,889	3,780,155	4,292,969	4,611,056	4,669,892	4,826,420	4,845,959
Portugal	1,498,121	1,732,815	1,713,272	1,784,849	1,719,274	1,664,296	1,565,838	1,528,181	1,559,170	1,575,304
Romania	1,140,844	1,309,381	1,287,019	1,170,700	998,690	974,940	992,510	1,059,557	:	:
Slovenia	168,630	204,182	212,085	215,110	206,994	203,763	207,396	202,021	200,396	209,704
Slovakia	346,700	300,515	317,762	324,925	395,304	436,342	443,673	448,323	442,659	463,613
Finland	688,820	677,000	695,715	700,799	653,796	708,241	709,643	715,744	716,686	731,893
Sweden	1,512,080	1,419,862	1,442,951	1,410,248	1,420,278	1,261,876	1,294,793	1,294,883	1,048,053	1,097,884
United Kingdom	10,280,196	10,471,264	10,610,000	10,724,450	10,786,827	10,824,820	10,929,657	10,655,339	10,384,147	11,436,361
Iceland	:	:	:	:	:	43,593	43,662	45,123	:	:
Liechtenstein	:	5,562	5,897	5,911	5,999	5,950	5,724	5,195	5,632	5,779
Norway	:	489,243	505,895	708,786	705,215	722,024	726,557	696,396	740,015	763,024

Special value: ‘:’ not available

APPENDIX III. Fiber packaging waste generated in EU countries in tons. (Eurostat, 2016)

GEO/TIME	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
European Union (28 countries)	:	:	:	:	:	:	:	31,527,252	32,316,785	:
European Union (27 countries)	30,362,659	31,301,231	31,591,388	31,259,904	29,783,190	31,220,830	31,779,682	31,462,347	32,247,655	:
European Union (15 countries)	27,654,406	28,254,288	28,908,546	28,353,129	27,090,752	28,352,461	28,785,396	28,231,305	28,918,760	:
Belgium	636,671	635,316	639,798	643,154	628,410	648,075	656,019	659,323	674,821	:
Bulgaria	149,319	127,041	106,653	87,077	97,015	138,716	110,270	122,270	134,270	129,580
Czech Republic	306,346	335,365	357,671	373,685	337,799	353,413	374,591	379,627	398,846	410,675
Denmark	516,341	528,282	518,622	509,395	381,347	381,347	397,273	367,733	374,713	372,984
Germany	6,896,300	7,104,100	7,148,400	6,939,500	6,634,100	7,196,200	7,346,900	7,272,400	7,838,900	8,148,800
Estonia	59,111	63,741	68,591	68,605	57,263	54,154	60,283	66,345	76,743	73,804
Ireland	325,888	398,681	408,871	406,468	370,194	325,874	334,354	358,923	380,191	:
Greece	400,000	400,000	400,000	440,000	430,000	392,900	378,750	337,100	325,200	:
Spain	3,133,368	3,295,700	3,625,270	3,546,684	3,280,086	3,460,628	3,411,000	3,240,570	3,352,539	3,356,000
France	4,295,497	4,419,169	4,471,656	4,283,537	4,378,975	4,672,591	4,881,558	4,806,565	4,701,892	4,793,755
Croatia	:	:	:	:	:	:	:	64,905	69,130	73,205
Italy	4,315,000	4,399,668	4,619,078	4,501,000	4,092,000	4,338,000	4,436,203	4,255,404	4,171,145	:
Cyprus	39,155	19,645	25,485	27,477	25,408	25,373	24,865	24,619	23,755	:
Latvia	66,775	82,140	115,065	83,204	57,979	63,824	64,009	61,433	67,889	64,602
Lithuania	72,587	85,706	102,063	103,013	82,009	82,360	88,589	85,615	91,598	95,931
Luxembourg	31,881	32,005	30,081	37,077	31,174	29,998	32,700	30,110	31,260	31,125
Hungary	296,017	304,369	348,349	348,286	320,884	312,054	276,533	409,208	388,618	454,506
Malta	15,253	15,728	18,029	16,384	16,616	16,544	22,209	22,032	26,455	27,053
Netherlands	1,465,000	1,055,000	1,080,000	1,079,000	1,026,500	1,163,000	1,144,000	1,129,000	1,200,000	1,167,000
Austria	495,000	523,206	517,150	503,572	481,084	505,275	501,978	516,420	518,101	542,419
Poland	1,253,300	1,420,700	959,082	1,237,032	1,192,868	1,322,984	1,419,869	1,493,336	1,556,345	1,567,972
Portugal	525,108	762,000	697,227	717,700	710,695	703,725	687,267	646,701	700,941	712,631
Romania	270,260	411,848	386,855	352,100	271,560	265,982	293,100	303,108	:	:
Slovenia	56,030	70,416	76,268	80,331	82,312	80,904	82,226	79,305	79,125	84,730
Slovakia	124,100	110,244	118,731	129,581	150,725	152,061	177,742	184,144	182,143	191,914
Finland	247,700	261,900	265,393	256,074	241,978	251,748	255,051	253,446	258,674	253,019
Sweden	645,000	676,352	686,000	650,968	646,709	495,540	504,483	509,207	522,738	531,391
United Kingdom	3,725,652	3,762,909	3,801,000	3,839,000	3,757,500	3,787,560	3,817,860	3,848,403	3,867,645	4,748,900
Iceland	:	:	:	:	:	14,359	14,668	15,686	:	:
Liechtenstein	:	2,150	2,267	2,231	2,400	2,171	2,142	1,618	2,246	2,251
Norway	:	281,503	283,011	312,728	307,000	309,866	314,393	293,606	301,625	322,588

Special value: ‘:’ not available

APPENDIX IV. Fiber packaging waste generated in EU countries by kilograms per capita. (Eurostat, 2016)

GEO/TIME	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
European Union (28 countries)	:	:	:	:	:	:	:	62.48	63.86	:
European Union (27 countries)	61.81	63.48	63.82	62.91	59.76	62.5	63.66	62.88	64.26	:
European Union (15 countries)	:	:	:	:	:	:	:	:	:	:
Belgium	60.76	60.23	60.21	60.05	58.21	59.48	59.38	59.25	60.34	60.64
Bulgaria	19.5	16.71	14.13	11.62	13.03	18.76	15.01	16.74	18.48	17.94
Czech Republic	30	32.75	34.73	35.98	32.34	33.74	35.69	36.12	37.93	39.02
Denmark	95.28	97.16	94.96	92.72	69.05	68.74	71.32	65.77	66.74	66.09
Germany	83.62	86.24	86.89	84.51	81	88	91.52	90.42	97.2	100.62
Estonia	43.63	47.33	51.16	51.31	42.91	40.67	45.41	50.16	58.23	56.14
Ireland	78.34	93.29	92.95	90.54	81.62	71.46	73.05	78.25	82.68	:
Greece	36.41	36.3	36.2	39.72	38.71	35.33	34.11	30.52	29.66	:
Spain	71.78	74.23	80.16	77.18	70.75	74.3	72.97	69.28	71.91	72.2
France	68.18	69.66	70.06	66.74	67.89	72.09	74.95	73.45	71.52	72.59
Croatia	:	:	:	:	:	:	:	15.2	16.25	17.28
Italy	74.44	75.67	79.04	76.51	69.24	73.18	74.71	71.47	69.25	72.73
Cyprus	53.02	26.16	33.22	34.93	31.44	30.59	29.22	28.5	27.56	:
Latvia	29.83	37.03	52.29	38.21	27.07	30.43	31.08	30.2	33.73	32.4
Lithuania	21.85	26.21	31.59	32.21	25.93	26.59	29.26	28.66	30.97	32.71
Luxembourg	68.54	67.72	62.67	75.88	62.63	59.17	63.09	56.71	57.53	55.95
Hungary	29.35	30.22	34.64	34.7	32.02	31.21	27.73	41.25	39.28	46.07
Malta	37.77	38.81	44.33	40.02	40.28	39.91	53.35	52.53	62.49	63.3
Netherlands	89.77	64.54	65.93	65.61	62.1	70	68.53	67.38	71.41	69.2
Austria	60.16	63.28	62.34	60.51	57.66	60.41	59.82	61.26	61.1	63.5
Poland	32.84	37.25	25.16	32.45	31.27	34.78	37.3	39.23	40.91	41.25
Portugal	49.99	72.42	66.13	67.98	67.25	66.56	65.1	61.5	67.03	68.52
Romania	12.68	19.43	18.52	17.14	13.33	13.14	14.55	15.11	:	:
Slovenia	28.01	35.09	37.79	39.74	40.36	39.49	40.05	38.55	38.41	41.09
Slovakia	23.1	20.52	22.09	24.09	27.98	28.2	32.93	34.05	33.65	35.42
Finland	47.22	49.73	50.18	48.19	45.32	46.94	47.33	46.81	47.56	46.33
Sweden	71.43	74.48	74.99	70.61	69.55	52.84	53.39	53.49	54.45	54.8
United Kingdom	61.68	61.84	61.98	62.11	60.34	60.34	60.35	60.41	60.31	73.5
Iceland	:	:	:	:	:	45.15	45.98	48.91	:	:
Liechtenstein	:	61.38	64.28	62.89	67.14	60.27	58.99	44.14	60.73	60.43
Norway	:	60.4	60.1	65.59	63.58	63.38	63.47	58.5	59.38	62.79

Special value: ‘:’ not available

APPENDIX V. System modelling in recycling option with Semichemical fluting production