Plastic Waste Recycling and Greenhouse Gas Reduction

Taking Copenhagen as an example from life cycle assessment perspective

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Master Thesis

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Acronyms

BTF	Back-to-feedstock
BTM	Back-to-monomer
CHP	Combined-heat-power plant
FU	Functional unit
GHG emission	Greenhouse gas emission
GWP	Global warming potential
LCA	Life cycle assessment
MPW	Mixed plastic waste
MSW	Municipal solid waste
NIR	Near infrared
PA	Polyamide
PE	Polyethylene
PE-HD	High density polyethylene
PE-LD	Low density polyethylene
PE-LLD	Linear low density polyethylene
PET	Polyethylene terephthalate
PP	Polypropylene
PS	Polystyrene
PU	Polyurethane
PVC	Polyvinyl chloride

Abstract

The production of plastics has reached about 300 million tons globally each year. The use of energy resources, the health problem and the impacts on the environment from its disposal phase trigger overriding concerns on plastic recycling which can both save energy consumption in production phase and achieve green end-of-life approach for plastics. With the concept of seeing waste as a valued resource, plastic waste ended up in recycling and energy recovery has reached 57.9% of plastic in EU each year.

In Denmark, the total recovery rate for all plastics in 2010 has reached 95%, in which recycling performance has reached almost 25% and energy recovery level is around 70%. Nevertheless, the recycling rate is mainly contributed by commercial plastic waste. The plastic waste mixed in MSW, presented as packaging, films, covers, bags, containers and other plastic products which are widely used in our daily life is still a "savage and desolate" area away from recycling. Copenhagen municipality is starting to explore this area by setting a target to reduce the amount of plastic mixed in municipal waste for incineration (40,000 tonnes) by 15,000 tonnes. Therefore, the LCA carried out in this study is to look at the climate change impact of different options for the treatment of plastics mixed in household waste. From the perspective of how to sort plastic out of household waste, a comparison has been made between REnescience sorting and kerbside sorting. From technology perspective, a comparison has been made among incineration with energy recovery, mechanical recycling and feedstock recycling. The successful practice of mechanical recycling with kerbside sorting will not only reduce the impact on global warming, but also realize a shift from “waste to energy” to “waste to material” in household plastic waste.

Key Words: Household Plastic Waste, Life Cycle Assessment, Greenhouse Gas Emission, Plastic Recycling

1. Introduction

The industrial scale production of plastics since the 1940s has transformed our everyday life (Al-Salem, Lettieri and Baeyens 2009). Given the versatile properties of plastics, such as it being inexpensive, lightweight, durable and strong, the production and usage of plastics has increased sharply ever since 1950 (Thompson, et al. 2009). In 2007, the production of plastics had reached 260 million tonnes per year all over the world and the turnover of European plastic industry had been in excess of 300 million euros with employment of 1.6 million people (PlasticsEurope 2008). During the *"plastic age",* plastics have been substantially involved in all aspects of daily life and have been considerably spreading their application potentials in scientific and medical advances (Thompson, et al. 2009) (Figure 1.1).

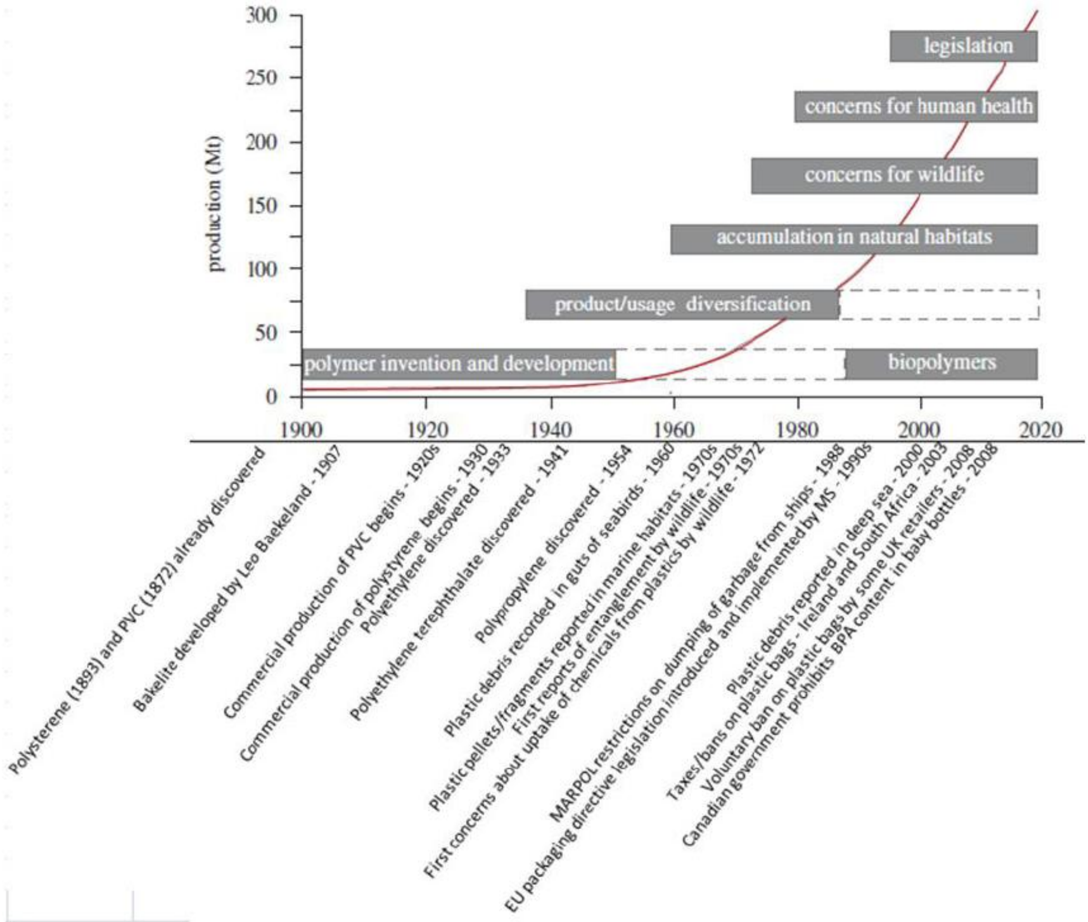


Figure 1.1: Global plastic production (Mt) with historical stages in the development, production and use of plastics, and associated concerns and legislative measures (European Commission DG ENV 2011)

However, plastics, as materials, are generating environmental and health problems considerably. One disadvantage is that plastic production relies heavily on the use of finite resources—fossil fuels. With the increasing demand of plastics around the world, huge amount of finite energy resources will be used up rapidly in current linear consumption of fossil fuels, *"from oil to waste via plastics"* (Thompson, et al. 2009). In addition, additives used to mix polymer resins and optimize the performance of materials are the cause of concerns on health issues. On the one side, the toxicity of some additive chemicals may have negative effects in animal or human populations; on the other side, mixed polymers are much more difficult and complicated to recycle than products made of a single polymer (Hopewell, Dvorak and Kosior 2009).

Another crucial problem comes from the end-of–life phase of plastic materials. Considerable accumulation of plastic wastes in the natural environment and in landfills *"contaminates a wide range of natural terrestrial, freshwater and marine habitats, with newspaper accounts of plastic debris on even some of the highest mountains"* (Thompson, et al. 2009). In terms of marine environment, the buoyant nature of plastics makes substantial quantities of cartons, bottles and bags floating on the sea surface. In addition to the visual disturbance, it also causes extremely high incidence of ingestion and entanglement by marine life (R. Thompson, et al. 2005, Cole, et al. 2011). To step further, there is speculation on the transferable potential of toxic chemicals from plastics in the food chain (Holmes, Turner, and Thompson 2012). Secondly, Landfill of plastic waste also attracts most attention. On the one side, landfill requires large area of land and causes aesthetic problems. On the other side, it is also under the risk that leachate of hazardous chemicals may lead to inadvertent soils contamination and be carried into streams, rivers and ultimately the sea (European Commission DG ENV 2011).

As a consequence, both of the use of resources and the impacts on the environment and health trigger overriding concerns about how to find and build a sustainable way which can both save energy consumption in production phase and achieve green end-of-life approach for plastics in face of the increasing demanding on plastics. Hence, considerable concern has been focused on plastic waste management. It ranges from evolution of broadly strategic frameworks to more detailed perspectives of behavioural guidance, from basic landfill treatment to energy recovery, recycling and environmental footprint of plastics, and prevention.

Prevention, advocated in the new Waste Framework Directive (WFD-2008/98/EC), is the best option to prevent waste generation in the first place; while recycling is positioned as the second priority. Specifically on plastic waste, in some cases the negative impacts brought by plastics can be alleviated or even eliminated if we are to simply reduce the production of plastics or substitute them by alternative materials. For example, in 1994, Denmark started to impose a tax on plastic bags for retailers to advocate reusable bags (CleanUp Australia 2010). This tax reduced plastic bag use by one-third (CleanUp Australia 2010). However, in some other fields the markets of plastic products are in expansion, such as in medical, wind power and construction industries (Pilz, Brandt and Fehringer 2010, R. C. Thompson, et al. 2009). In these cases, recycling can be regard as another way to achieve prevention. By transforming wastes into resources, huge amount of plastic waste find its outlet, at the same time, virginal plastic production will be reduced as certain amount of virginal plastic can be substituted by recovered materials correspondingly.

Therefore, this study is going to focus on carbon footprint analysis of plastic waste recycling and take Copenhagen municipality as an example. Before venturing to that, the next parts will present an overview of the history development of plastic treatment in EU countries and in Copenhagen, Denmark.

1.1 Plastic waste management in EU

In the EU scope, up to 3 billion tonnes of waste is produced every year, which imposes huge impact on the environment bringing about pollution and greenhouse gas (GHG) emissions that contribute to climate change, as well as significant losses of raw materials and energy (European Commission 2010). Plastic waste has been involved in the municipal solid waste (MSW) considerably, concentrated in packaging, films, covers, bags, containers and so on with widely used in our daily life (Al-Salem, Lettieri and Baeyens 2009). Over the past 30 years, MSW management has been driven by European waste policy which has evolved through "*environmental action plans and a framework of legislation*" (European Commission 2010) with the awareness of importance of reducing waste negative impacts. In 2005, a long-term strategy on waste brought a modernised approach to waste management which started a new era of EU waste policy. The new strategy originated from the EU's Sixth Environment Action Programme has been reflected in the Waste Framework Directive (WFD-2008/98/EC). With a focus on waste prevention, it marks *"a shift away from thinking about waste as an unwanted burden to seeing it as a valued resource"* (European Commission 2010). The new Waste Framework Directive

(WFD-2008/98/EC) aims to help EU move towards a recycling society with the targets for "EU Member States to recycle 50% of their municipal waste and 70% of construction waste by 2020" (Vasiljevic, et al. 2011). The Directive (WFD-2008/98/EC) also put forward a five-step waste hierarchy for waste management (see Figure 2.1b). This hierarchy establishes an order of priorities of varies waste treatment approaches, in which prevention is the best option with landfill as the last resort measured by the impact on the environment. The aim is to move waste management as high up as possible in the hierarchy. Plastic waste as one of the important parts in waste management has undoubtedly raised much attention.

Compared with the oldest form of waste treatment—landfill and the modern waste incineration with energy recovery, recycling has its unique advantage in saving energy needed to make new products as well as the amount of material needed from the natural environment. This is important due to the situation that Europe relies upon imports of scarce raw materials and recycling can provide EU industries with essential supplies recovered from waste in which plastic is one of the categories (European Commission 2010). Meanwhile, with more waste going to recycling, less amount of waste will end up in landfill sites and incineration plants.

Relating to plastic recycling specifically, a more detailed classification among different options has been described as Table 1.1. The primary recycling often refers to closed loop recycling using mechanical reprocessing and the new products have equivalent properties with the former ones (Hopewell, Dvorak and Kosior 2009). This technique has been mostly applied in the recycling of process scrap from industry. According to Parfitt (2002), 95% of process scrap representing 237,500 tonnes of the plastic waste is primary recycled in UK (cited in Al-Salem, Lettieri and Baeyens 2009). However, primary recycling has its limitation to involve post-consumer plastics. This kind of recycling requires highly on the range of polymer grades in plastic waste. However, plastic packaging or products usually consist of different polymers and other materials which make them difficult to end up with the primary recycling. It is because of this, at present, the only part of the post-consumer plastic waste stream that has been recycled in the primary recycling is the deposited PET bottles which are made from similar grades of PET. While under certain circumstances, recovered plastic has to be put into other applications because of the downgrading of properties, this is secondary recycling which also belongs to mechanical recycling. Mechanical recycling reprocesses plastic waste without breaking the material's chemical structure by physical means of grinding, shredding or melting (IPTS 2011). It is mainly applied on thermoplastic recycling, namely the five predominant plastic families (see Table 1.2).

Tertiary recycling is also called chemical or feedstock recycling and refers to the recovery of the petrochemical constituents of the polymer by cracking plastics into its monomers or into its oil and gas components (Hopewell, Dvorak and Kosior 2009, IPTS 2011). Therefore, chemical recycling can be distinguished in back-to-monomer (BTM) and back-to-feedstock (BTF) Recycling. The products from BTM processing can be used as raw chemicals and the products from BTF can be used as fuels (Broek 1997). The main advantage of chemical recycling is its lower requirement for the input quality of waste plastic, especially treating heterogeneous and contaminated polymers and higher quality of output compared with mechanical recycling (Al-Salem, Lettieri and Baeyens 2009). However, plastic recycling has still been dominated by mechanical recycling so far. Chemical recycling only takes place to a very small extent processing only 0.3% (0.07Mt) of the total plastic waste in Europe (EU-27 plus Norway and Switzerland) in the year 2008, while mechanical recycling representing 21.3% (5.3 Mt) (European Commission DG ENV 2011). The application limitation of chemical recycling mainly exists in both technical reasons and economic concerns. For example, BTM recycling (also called chemical depolymerisation) is *"very sensitive to the presence of impurities in raw plastics"* (Aguado, Serrano and Miguel 2006), it is so far only operational for certain types of polymers (PU, PA and PET) and cannot be used with the polymers like polyethylene, polypropylene or polyvinyl chloride (Wollny and Schmie 2000, IPTS 2011). This study focuses on both mechanical and feedstock recycling for the five predominant plastic families (see Table 1.2).

Quaternary recycling means energy recovery, which is not generally considered recycling in the EU context (European Commission DG ENV 2011). In Denmark, energy recovery has been widely employed in the form of incineration with heat and power generation.

Table 1.1: Plastic recycling 'cascade' terminology
(Hopewell, Dvorak and Kosior 2009, European Commission DG ENV 2011)

ASTM D7209 – 06 standard definitions	**Equivalent ISO 15270 standard definitions**	**Other equivalent terms**
Primary recycling	Mechanical recycling	Closed-loop recycling
Secondary recycling	Mechanical recycling	Downgrading
Tertiary recycling	Chemical recycling	Feedstock recycling
Quaternary recycling	Energy recovery	Valorisation

Currently, the best practice of waste plastic management in European countries is a combination of both recycling and energy recovery. The latest statistics published by PlaticsEurope shows that plastic waste reached 24.7 million tonnes in EU27+ Norway and Switzerland in 2010, in which

57.9% of plastic ended up in recycling and energy recovery (PlasticsEurope 2011). From the year 2006 to 2010, the total plastic waste generation had fluctuated slightly in EU27+ Norway and Switzerland, but there is an obvious trend in increasing recycling and energy recovery with annual growth rate of 4.3%, 4.1%, 3.1%, and 9.2% in 2007, 2008, 2009 and 2010 respectively as well as a total growth rate of 22.22% during 5years (calculated based on the data in Figure 1.2).

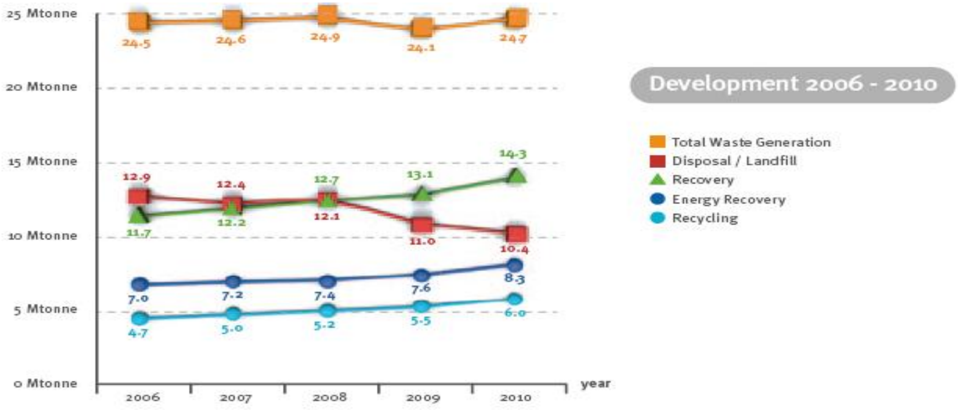


Figure 1.2: Total plastics waste recycling and recovery 2006 – 2010 (PlasticsEurope 2011)

There are various types of plastics, in which the five predominant plastic families account for the major market share among the total waste plastic. They are listed as follows (PlasticsEurope 2011):

Table 1.2: Plastic consumption in Europe by resin type in 2007 and 2010 (after PlasticsEurope 2008, PlasticsEurope 2011)

Plastic types	**Abbreviations**	**Distribution (%)**	
		In 2007	**In 2010**
polyethylene	low density (PE-LD), linear low density (PE-LLD), high density (PE-HD)	29%	29%
Polypropylene	PP	18%	19%
Polyvinyl chloride	PVC	12%	12%
Polystyrene	PS and EPS	8%	8%
Polyethylene terephthalate	PET	7%	6%
Others		26%	26%

Statistics shows that LDPE/LLDPE and HDPE constituted 29% of the plastics consumed in Europe (EU-27 plus Norway and Switzerland) in 2010, while PP and PVC account for 19% and 12% respectively, making them the first three most applied plastic types (PlasticsEurope 2011). And the distribution stays almost the same compared with that of in 2007 (PlasticsEurope 2008). The rest types of plastics together account for 26%, and each type of plastics in this category only contributes a small proportion. This study will focus on the five main types of plastic to look at their GHG emission from different treatment options individually.

1.2 Research question

The research question of the report is:

How is the global warming potential from possible technical options of household plastic waste treatment in Copenhagen?

The research focuses on the different outlets of plastic waste and tries to look at their influence on climate change. Based on the research question, three working steps are formulated with specific working questions as following:

Research steps	**Sub-working questions**	**Outcomes**
System description	What is the current scheme for plastic waste treatment?	• Understanding of current plastic waste treatment situation in Denmark; • Regulations about plastic waste;
	What are the possible end-of-life methods for plastic waste?	• Operational or most realistic technologies regarding to energy recovery, mechanical recycling, chemical recycling; • Establishing scenario models
Data collection	What is the amount of household plastic waste generated in Copenhagen and its composition?	• Fraction composition and the amount of household plastic waste in Copenhagen;
	What's the data required for computing GHG emission	• Estimation on transport, substitution ratio, etc. for calculation
Software application (Sima pro)	How to model in Sima Pro	• Assessment results

2. Plastic waste management in Copenhagen

Facts about City of Copenhagen:

Area: 89.8 sq.km (Environmental Protection Agency 2006)

Inhabitants: 549050 (Copenhagen Municipality 2012)

Households: 336390 (Copenhagen Municipality 2011)

Workplaces: 355257 (Copenhagen Municipality 2009)

Waste treatment sites (Environmental Protection Agency 2006):

- Vestforbrænding Incineration plant (Glostrup, 10 km away from City Hall)
- Amagerforbrænding Incineration plant (4km east away from City Hall)
- Composting plant (5km south away from City Hall)
- Construction & Demolition waste recycling (5km south away from City Hall)
- Contamin. Soil landfill (5km south away from City Hall)
- Controlled landfill (10km southwest away from City Hall)

2.1 Regulation on plastic waste

Under the framework of EU regulations on waste and the new targets for recycling and incineration with energy recovery setting up in EU waste directive, Copenhagen has been committed to treating the waste correctly to reduce environmental impacts as much as possible and takes these developments in the waste management filed into consideration, which is shown in Copenhagen Waste Management Plan 2012. Copenhagen waste management system builds on a five-step waste hierarchy (see Figure 2.1a) in accordance with the EU Waste Framework Directive mentioned above (see Figure 2.1b). From figure 2.1a, it is obvious that in Copenhagen waste management system, more than half of the waste is recycled, and the second major part of waste ends up in recovery for heat and power (Technical and Environmental Administration 2008). Besides, the Copenhagen Carbon Neutral

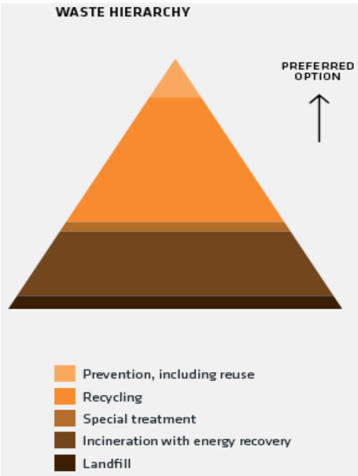


Figure 2.1a: Copenhagen waste hierarchy (Technical and Environmental Administration 2008)

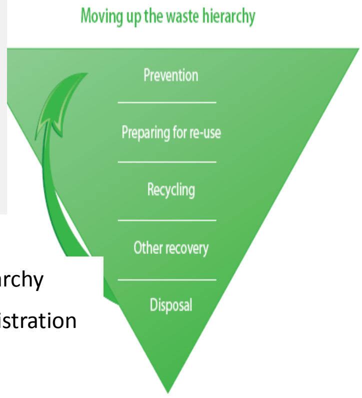


Figure 2.1b: Waste hierarchy in WFD-2008/98/EC (European Commission 2010)

Plan by 2025 (2009) describes an initiative aiming at separation of plastic from the waste stream and minimization of waste generation (City of Copenhagen—the Technical and Environmental Administration 2009). A target has been set up to reduce the amount of waste plastic mixed in municipal waste for incineration (40,000 tonnes) by 15,000 tonnes (Skovgaard 2012).

In order to regulate the handling of municipal waste from all citizens and businesses, Copenhagen municipal waste regulation was formulated in line with applicable environmental legislation, namely Environmental Protection Act, Waste Order, WEEE Order, Battery Order and Packaging Order. It consists of the rules for both households and commercial waste.

In commercial waste regulation, plastic waste is only mentioned in terms of handling non-recyclable PVC (polyvinyl chloride) waste. Specifically, it clarifies what types of products are to be attributed to non-recyclable PVC waste, such as discarded office equipment and furniture, discarded building materials which cannot be recycled at the plant and so on. And the scheme is to assign these non-recyclable PVC waste to landfilling. (Regulative for erhvervsaffald 2012).

There are two main rules regarding plastic waste mentioned in households' waste regulation, one is for PVC waste, the other is for recyclable plastic packaging waste. Firstly, PVC waste should be sorted from other waste and must be submitted separately from other bulky waste. The regulation also provides the defined types of PVC products ending up with recycling and landfill respectively. The products made of PVC going to recycling include: sewer pipes including joints and bends, water pipes and indoor drain systems, electric wires and cable trays, other products made of hard PVC and so on. PVC to landfill includes products like: soft panels and baseboards, blinds, ventilation tubes, suitcases, backpacks and bags, cables and wires, and so on. As for recyclable plastic packaging waste, the scheme mainly applies to multi-storey buildings in the municipality. It is required that all types of packaging of hard plastic that appear in households shall be collected in the

Figure 2.2 Different qualities of waste (Sartorius and Wuttke 2010)

designated containers emptied after fixed intervals or delivered to recycling sites (bulky ones). (Regulative for husholdningsaffald 2012). This new kerbside collection scheme will start in late 2012 (Larsen and Skovgaard 2012).

PVC has received much attention in Danish waste stream ever since 1991 when a voluntary agreement was made by Ministry of Environment, the Danish plastics industry and other trade organisations with one of the goals to *"keep PVC away from ordinary waste incineration, where technically and economically justifiable"*. Later, a mandatory PVC strategy has taken the place of the voluntary agreement aiming at *"keeping PVC wastes out of waste incineration plants, where possible as well as collecting and recycling recyclable PVC".* In the governmental waste management plan 1998-2004 it is stated that PVC waste has been required to be separated from other kinds of waste in order to be recycled or landfilled. (Pllinke, et al. 2000)

2.2 Current plastic waste stream figures

According to the latest report of PlasticsEurope, from the year 2006 to 2010, Denmark's improvement in recovery rate has been less than 5% but there is a change from energy recovery to recycling in Denmark with the recycling rate of total plastic waste improved by nearly 10% (PlasticsEurope 2011). In the year 2010, Denmark's recycling performance has reached almost 25% and energy recovery level is around 70%. As a result, the total recovery rate for all plastics in Denmark in 2010 reached 95% which is ranked 5th in EU27+N/CH (see Figure 2.2). Statistics from Danish EPA shows that from 2004 to 2009, Denmark's recycling rate of plastic packaging waste has been steadily increasing, and exceeded the target of 22.5% (European Commission 2011) indicated in EU Packaging Directive since 2008 (see Table 2.1).

Table 2.1: Plastic packaging and collection for recycling in Denmark (Tonnes) (Kaysen and Tønning 2010, Kaysen and Tønning 2011)

	2004	**2005**	**2006**	**2007**	**2008**	**2009**
Potential	174,273	182,789	190,792	191,978	164,838	165,449
Collection	28,439	34,863	38,695	41,787	41,951	43,681
Collection percentage	16.3	19.1	20.3	21.8	25.4	26.4
Export of plastic packaging waste	17,131	26,274	28,948	42,309	44,050	43,860

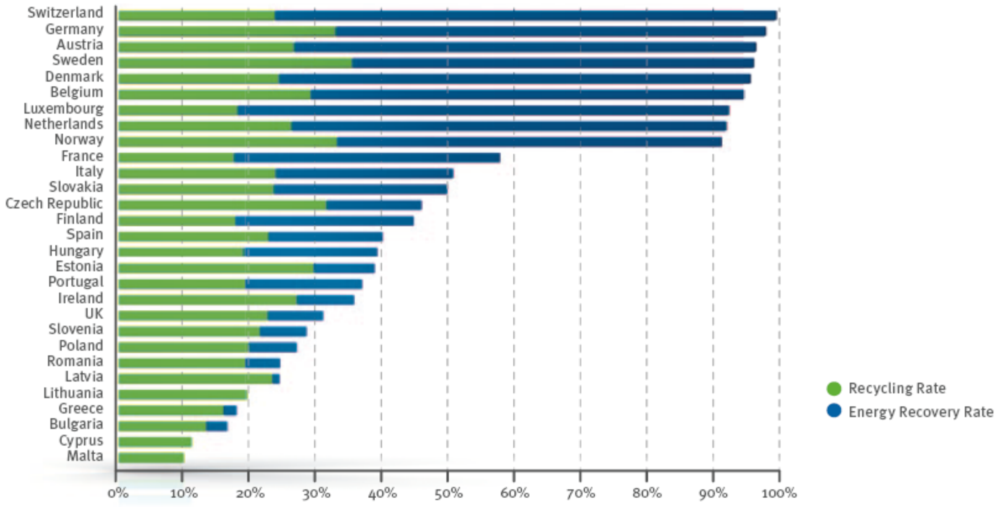


Figure 2.2: Total Recovery Rate for all plastics by Country 2010 (PlasticsEurope 2011)

At present, the best practice relating plastic waste disposal lies in the following two aspects. Firstly, from the Copenhagen municipal waste regulation mentioned above we can see that the collection and recycling of PVC has received much attention in both commercial and household waste. For instance, rigid PVC wastes are delivered to "WUPPI scheme" for recycling which is not only for private persons but also for municipality and waste companies. The scheme focuses on collection and recycling for construction waste of hard PVC (WUPPI A/S n.d.). WUPPI gets PVC from the recycling station where PVC waste has been sorted exclusively based on certain categories. Then the materials are transported for further processing that grind and wash PVC. After that, the materials are returned to WUPPI again for making new products (WUPPI A/S n.d.). In 2007, 3500 tonnes of hard PVC construction waste were gathered and recycled in new building products by the 'WUPPI scheme'.

Another part of plastic reuse has taken place mainly in (1) refillable PET-bottles (estimate of 1126 tonnes in 2009); (2) plastic pallets (estimates of 960 tonnes in 2009) and plastic crates (estimate of 7500 tonnes in 2009) used for transport or containing of food products (such as milk, bread, fish and beer). (Larsen and Skovgaard 2012)

In Copenhagen, municipal wastes are collected by both kerbside collection schemes and bring systems (Larsen and Skovgaard 2012) Households waste is equivalent to 25% of total waste, corresponding to 209,432 tonnes in 2009 (Veksebo 2010, cited in Larsen and Skovgaard 2012). So far, compared with the figure existing in recycling fraction, the majority of plastic waste ends up in the incineration furnace in the city of Copenhagen (see Table 2.2). Around 73%-74% of all household rubbish is incinerated, which involves a large amount of plastics that could be recycled (Buley 2011). According to an estimation on the composition from the Plastic Zero project team based on a range of surveys, the potential amount of plastic waste is estimated around 39,000 tonnes, wherein approximately 4000 tonnes of plastics are recycled, leaving 35,000 tonnes plastics in the combustible waste which account for 10% of total waste incinerated in Copenhagen in 2009 (Larsen and Skovgaard 2012) (see Figure 2.3). As a result, it is not only a loss of resources but also a contribution to large CO2 emissions (Technical and Environmental Administration 2008). If more plastics are put into appropriate recycling procedures they will become more raw materials entering a new production cycle and thus reducing resource use.

Table 2.2: Data on plastic waste in the city of Copenhagen (Larsen and Skovgaard 2012)

Data category	**Waste quantity (tonnes)**
Total amounts of household waste (in 2009)	**209,432**
Households waste Collected for recycling	
Drop-off containers, commingled glass packaging, plastic, metal	Plastic: 27
Bulky waste collection	PVC:9
Recycling stations	Plastic:26 PVC: 73 WEEE: 1914 Clothing: 145
Collection of clothing, bring banks	Clothing:124
Collection of WEEE	WEEE-collection: 2437

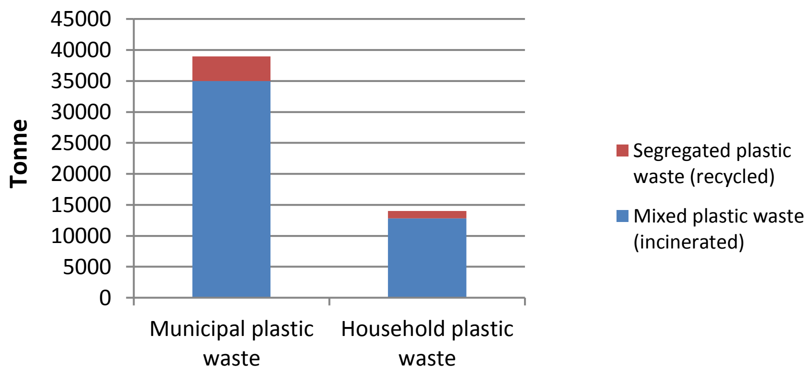


Figure 2.3: plastic waste in municipal waste and household waste in Copenhagen (Data source: (Larsen and Skovgaard 2012, Skovgaard 2012))

Particularly on plastic packaging waste, according to the statistics from Danish EPA (Miljøstyrelsen), polyethylene (PE) makes up the main part of the consumption of plastic packaging. Consequently, this type of plastic accounts for the largest part of the collected plastic material. Currently, it is the collection from commercial enterprises that contributes a very large part of the collection instead of households' part. (Kaysen and Tønning 2010). Table 2.3 shows the amount of different types of plastics generated and collected in packaging waste stream in Denmark. The data related with Copenhagen are estimated by the population ratio.

Table 2.3 Total supply of plastic packaging and PVC in Denmark in 2009. Tonnes.

Plastic types	**Potential supply**[1]	**Proportion** [1]	**Collection**[1]	**Collection rate** [1]	**Potential supply**[3] **(Copenhagen)**	**Collection**[3] **(Copenhagen)**
PE	115503	69,80%	24189	20,9%	10868	2276
PP	17708	10,70%	4216	23,8%	1666	397
PS (EPS)	12774	7,70%	1541	12,1%	1202	145
PET	10590	6,40%	10719	101,2%	996	1009
PVC[2]						Households:82; Commercial:228
Other plastics	8874	5,40%	5272	59,4%	835	
Total	165449	100%	45937	27,8%	15567	4328

Data source: [1] (Kaysen and Tønning 2011) [2] (Larsen and Skovgaard 2012) [3] Estimation based on the population ratio in 2009. According to the official publication by Copenhagen Municipality, there are 518,574 inhabitants in Copenhagen city while 5,511,451 in Denmark in 2009 (Copenhagen Municipality 2012).

3. Literature review

Chapter 1.1 has provided a review of the approaches for plastic waste treatment on different level—landfill, energy recovery, mechanical recycling, chemical recycling. It shows that the combination of recycling and energy recovery is the most prevailing option in European countries with even an increasing trend in recent years. In this chapter, the review mainly focuses on:

1. The development of application of LCA in plastic waste management research;

2. Different options for plastic waste recycling;

3. Mixed plastic sorting method

The researches and studies mentioned here are on the basis of relevant literature searched mainly from "Scopus" database provided by Aalborg University library. The searching fields include both "plastic recycling" and "LCA". Some other fields have been tried as well, such as "plastic waste mechanical recycling", "plastic waste chemical recycling" and so on. In order to get an overall view of the development in plastic waste recycling from life cycle perspective, the reviewed literature are selected to cover the last two decades, that is starting from 1990s.

3.1 Development of LCA in plastic waste management

Starting in the 1980s, life cycle perspective became a new approach applied in waste management (Christensen 2010). Within the past decades, life cycle assessment (LCA) has been applied widely in examination of the environmental burden of various disposal methods for different wastes. Particularly in the issue of plastic waste, plenty of studies focus on the comparison of different methods for disposal of plastic waste. Singer (1994) pointed out in his article that (1) recycling post-consumption plastic waste can significantly contribute to energy saving; (2) thermoplastics are preferable for recycling compared with the other type—thermosetting plastics which are molecular structured. It is because thermoplastics (including polyethylene, polyethylene terephthalate, polypropylene, polystyrene and polyvinyl chloride) break down when they are heated; (3) materials recycling would be some sort of optimal option but should be combined with social economic factors. Hunt (1995) made an LCA study for paper and plastics waste disposal based on different alternatives—combustion, landfill or compost. The result showed that significant CO2 equivalents emissions can be made by incineration of plastics, while composting and landfilling only create negligible global warming.

Further, the comparisons among plastic recycling approaches specifically break down to chemical recycling and mechanical recycling. Patel et al. (1999) compared the plastic waste disposal methods in Germany (including landfill, incineration, mechanical recycling and chemical recycling) in environmental terms. The result showed that (1) recycling clearly contributes to energy reduction and curbing CO2 emission, in which mechanical recycling yields higher environmental benefit than feedstock recycling technologies for bulk waste plastics. (2) Feedstock recycling is preferable to an average waste incinerator in Germany in the mid-1990s. More specifically, Wollny, et al. (2001) examined the potential environmental impacts (mainly on climate change) of several chemical recycling approaches—reducing agent in blast furnace, BASF pyrolysis process and SVZ gasification process respectively, and made a comparison with that of energy recovery. They also pointed out that due to the situation of immature sorting and recycling technology and lack of developed markets for secondary materials, chemical recycling held a dominant position in 1990s in Germany.

Within recent decade, studies have been emerged with focusing on particular type of plastic waste. For example, a LCA on polyethylene (PE)/ expanded polystyrene (EPS) packaging recycling in Australia was conducted by Ross and Evans (2003) and the result showed that recycling can largely reduce the environmental burden of plastic packaging and "the energy consumption by transportation is negligible when compared to the overall energy consumption of the system". Lindahl and Winsnes (2005) carried out LCA calculation on recycling of cable plastics (mainly PE and PVC) where Vinyloop process and Stigsnaes process have been applied as mechanical recycling and Chemical recycling respectively based in Sweden. The comparison showed that the Vinyloop process is preferable to the Stigsnaes process, but the later has priority in its location (in Denmark) than Vinyloop plant in Italy. Perugini, Mastellone and Arena (2005) carried out LCA for mechanical and feedstock recycling of PE and PP in Italy, the feedstock recycyling focuses on BP pyrolysis process and Veba Oel hydrocracking process. The result showed that mechanical reycyling option presented as the most envrionemtnlly preferable one and the feed stock recycling had some valuable environemtal indices. Dodbiba, et al. (2007) calculated global warming potential by LCA for energy recovery and mechanical recycling of plastic waste from discarded television sets (mainly PE, PVC, PS). The result verified again that mechanical recycling saves resources utilization and reduces greenhouse gases emission in comparison with energy recovery. Lazarevic, et al. (2010) reviewed extensive LCA of plastic waste and sorted out the key parameters and assumptions for the final selected studies (see Table 3.1).

3.2 Different options for plastic waste recycling

Singer (1994), Tukker, et al. (1999), Al-Salem, Lettieri and Baeyens (2009) and IPTS (2011) systematically introduced the recycling schemes for plastic waste and the corresponding technologies. Figure 3.1 builds an overall recycling structure on the basis of summarizing the processes and main technologies mentioned in the literatures. The LCA carried out in the current study only focus on the options in the real-line boxes. The BTM recycling (also called chemical depolymerisation) is exclude because it is only operational for certain types of polymers (PU, PA and PET) and cannot be used with the polymers like polyethylene, polypropylene or polyvinyl chloride (Wollny and Schmie 2000, IPTS 2011) due to its high sensitivity to the presence of impurities in raw plastics (Aguado, Serrano and Miguel 2006).

Regarding the chemical recycling technologies, the development of BTM and BTF recycling technologies during the 1990s has not resulted in any major applications (Gielen, Bennaceur and Tam 2006). Plenty of initiatives launched or stopped in the past decades. This study firstly selected several processes as the most realistic ones shown in Figure 3.1. The background, inputs, outputs of these chemical processes are described in AppendixⅢ. After further selection based on the consideration of transport distance, three best known processes are selected to be assessed in the scenarios of current project which are regarded as the most realistic ones for Copenhagen. These concerns:

1. Pyrolysis (BP polymer cracking process), in UK
2. Gasification (SVZ), in Germany
3. Hydrogenation (Veba Oel), in Germany

3.3 Mixed plastic sorting method

Compared with chemical processes mechanical path is only viable for single polymer recycling (Singer 1994). In this situation, proper sorting technologies should not be neglected when it comes to mechanical recycling. Broek (1997), with an overview of existing separation technoogies and identification technologies for mixed waste based on the properties of various type plastic, pointed out that the mostly applied separation technology was based on density differences which can be used for the separation of plastic from non-plastics and sink-float method can be further applied to separte PE and PP from other plastics. Dodbiba and Fujita (2004) reviewed various techniques for separating mixed plastic waste (MPW) in terms of wet and dry separating approaches. The available techniques were presented in the perspective of the operation rationale with the purity of sorted single plastic and the schematic design of each machine was showed. Among these approaches, near-infrared (NIR) sorting approach is common used in automatic plastics sorting system. As a conventional approach, sink-float princple of densisty sepoaration in water has proved effective in separating some type of plastics (Plastics Technology 2005). The advantage exists in its low cost as the separation tanks were simple and inexpensive to build. However, the disadvatage of wet separation technology is that drying the mixture after separation cannot be avoided and the waste water increases the loads to wate treametn plants, thus increasing electricity demand and related enviroenmtnal impacts (Dodbiba and Fujita 2004).

Besides the contents discussed above, there are also theoretical discussions on methodological aspect of LCA system, for example, the issues on LCA application in solid waste management, including system boundaries, multi-input allocation, time horizon (Finnveden 1999), the variations between original LCA system boundary on a product and on waste management system (Schmidt 2005) and so on. Because these issues are related with practical application of LCA method in this study, chapter 4.1—LCA in waste management provides more specific description and explanation.

Table3.1 Overview of LCA studies in Europe (Lazarevic, et al. 2010)

Reference	Waste stream	Polymers	Treatment technologies	Avoided material	Virgin material substitution ratio considered	Avoided electricity	Avoided heat	Transport	Geographical scope
Carlsson (2002)	Household plastic packaging waste	HDPE, LDPE	MR MSWI	Virgin PE, PET	1:1 1:0.8 for HDPE 1:0.7 for LDPE	n.a.	Biomass coal	Collection excluded	Sweden (National)
Eriksson and Finnveden (2009)	(1) Non-recyclable plastic (2) Mixed plastic	Not clear	MSWI LF	n.a.	n.a.	Wind coal	Oil Biomass CHP	Collection excluded	Sweden and European (n.a.)
Frees (2002)	(1) Transport packaging (2) plastic bottles and cans from households and businesses	HDPE, LDPE, PP	MR MSWI	Virgin HDPE, LDPE, PP	1:0.9	Danish average natural gas	Danish average (natural gas) (oil and gas)	Collection included	Denmark (National)
Jenseit et al. (2003)	ELV plastic components	PP, PE, PC, PU, ABS, PA	MR MSWI SRF in a cement kiln FR-gasification FR-reduction agent in a blast furnace LF	Virgin PP	1:1	n.a.	Not clear coal: SRF – cement kiln	Collection excluded	European (Data: DE)
Kreißig et al. (2003)	PVC cable waste	PVC	MR– Vinyloop FR – Stigsneas FR–Watech PVC MSWI LF	Virgin PVC	1:1	n.a.	n.a.	Collection excluded	European (Data: DE/DK)
Perugini et al. (2005)	Household plastic packaging waste	PET, PE	MR MSWI LF FR–low temp. pyrolysis &MR FR-hydrocracking &	Virgin PET, PE	1:1	n.a.	n.a.	Collection included	Italy (National)

			MR						
Raadal et al.(2008)	Household plastic packaging waste	HDPE, LDPE, PP, PET, PS	MR MSWI LF	Virgin HDPE,LDPE, PP, PET,PS	1:0.95	n.a.	Oil and electricity	Collection included	Norway (National)
RDC and Coopers& Lybrand (1997)	Plastic packaging waste	PET, PVC, HDPE, LPDE	MR MSWI	Virgin PET, PVC,HDPE, LPDE	1:1 1:0.5	n.a.	n.a.	Collection included	European (Data: CH/DE)
Shonfield (2008)	Mixed post-consumer plastic waste	HDPE, LDPE, PP, PET, PVC, PS	MR MSWI SRF in cement a kiln FR– pyrolysis FR–reduction agent in a blast furnace LF	Virgin HDPE,LDPE, PP, PET,PVC, PS (wood) (concrete)	1:1	Natural gas	Coal: SRF-cement kiln	Collection excluded	UK (National)
Von Krogh et al. (2001)	Plastic bottles for foodstuffs	HDPE	MR MSWI LF	HDPE	1:1	n.a.	Oil	Collection included	Norway (Regional)

MR – mechanical, FR – feedstock recycling, MSWI – municipal solid waste incineration, SRF – incinerated as a solid recovered fuel, LF – landfill

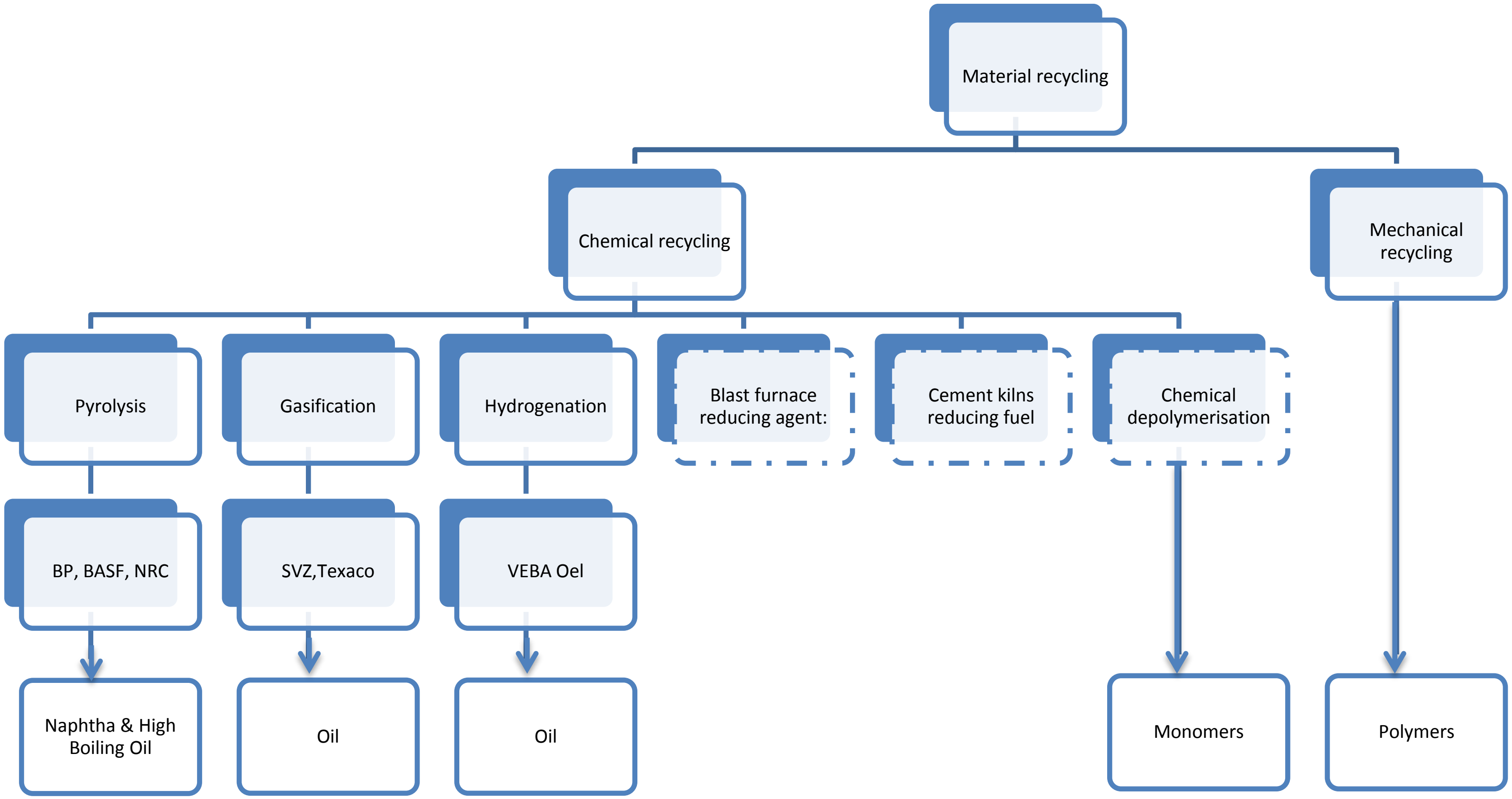


Figure 3.1: Different recycling schemes with reference to the main technologies (after Singer 1994, Tukker, et al. 1999, Al-Salem, Lettieri and Baeyens 2009 and IPTS 2011)

Note: the processes represented in solid blocks will be assessed in this report while the ones in dashed boxes will not.

4. Methodology

4.1 Life cycle assessment in waste management

Life cycle assessment (LCA) is the concept that considers all processes from raw material extraction (*"cradle"*) to final use and disposal phase (*"grave"*) (ISO 14040 2006). LCA studies started in the late 1960s and early 1970s, when Coca Cola Company used environmental assessments to estimate the environmental pollution from beverage containers (Curran 2006). The long-anticipated LCA standards were developed in International Standards Organization (ISO) 14000 series from 1997 to 2002. These standards were further revised in 2006 putting forward two documents ISO 14040 describing the principles for LCA and ISO 14044 describing requirements and guidelines for LCA.

LCA approach began to emerge in solid waste management since 1988 (Christensen 2010). Waste management system is largely contingent on the local conditions, criteria and preferences of approaches applied by decision makers (Christensen 2010). Christensen (2010) classified five main types of approaches have been used extensively or emerging on the scene in waste management, therein Life cycle assessment, as a comprehensive accounting system, is a common tool used to evaluate the environmental impact of products by computing the emissions and resources used and aggregating them into agreed impact categories, such as global warming. The EU waste directive, (cited in Christensen 2010) suggests that *"life cycle thinking should be introduced in all waste management decision-making, and derogation from the waste hierarchy should be based on life cycle thinking"*.

Nowadays, LCA has been increasingly applied in the field of waste management. However, there are two differences between a traditional LCA of products and an LCA of a waste system (Schmidt 2005):

- Functional unit formulation
- System description

The following figure illustrates the comparison of a product-oriented LCA system and a waste system's LCA (cited in Schmidt 2005). Therefore, the waste management system usually includes four steps: waste collection, sorting, recycling, incineration and landfilling.

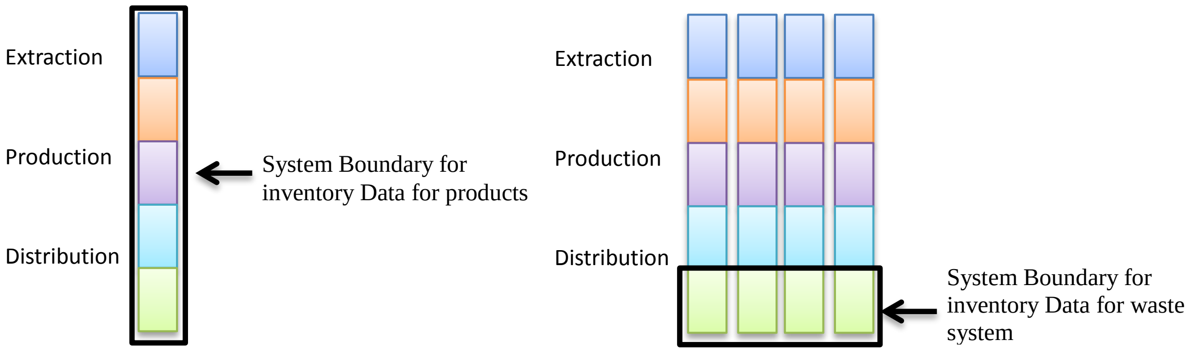


Figure 4.1: Difference in limits for calculation of data for a product-LCA and LCA of waste management systems. (Translated from Coleman et al, 2003 p. 178, cited in Schmidt 2005)

This study complies with the ISO 14040 and ISO 14044 of standards governing the use of LCA and follows four phases as suggested by the standards. Those phases are: Goal and scope definition, Life cycle inventory, Life cycle impact assessment and Interpretation (specific analyses on the four phases see Chapter 5).

4.2 Consequential LCA

Consequential LCA and Attributional LCA are two approaches which can be used for defining system boundaries. The attributional approach strives to identify the processes that are involved in the physical flows and allocate the environmental impacts to the primary and secondary services by allocation factors (Thrane and Schmidt 2007, Wenzel, Wesnæs and Dall 2009). While in consequential modelling, the marginal concept is widely used to predict the change in supply responding to a change in demand. Wenzel, Wesnæs and Dall (2009) gives a definition of marginal supply as the following:

Marginal supply = the response to a marginal change in demand on the market in question

By using concequential approach, there is no considertion needed on the cut of criteria anymore as the co-product allocation is avoided by system expansion. The comparision between the two methods are shown in Table 4.1

In the current study, consequential LCA method has been applied. The system boundary shows in Figure 5.1. As the most important products, the marginal energy supply has been discussed in Chapter 5.2.1. For other products, the marginal supply has been considered as the same products themselves. For example, the output of methanol in SVZ gasification put on the market may lead to reduce the production of methanol industry. That is to say it is affected by the market change. Therefore the marginal methanol is still considered as the methanol from plant. Other marginal products are also considered in the same way.

Table 4.1: Main characteristics of and differences between consequential and attributional modelling in life cycle inventory (based on Weidema 2003; Schmidt and Weidema 2007, cited in Schmidt 2007)

Feature	Consequential modelling	Attributional modelling
Nature	Attempts to predict to responses to a change in demand	Describes how existing production is taking place
Included processes/suppliers	Marginal	Average
Co-product allocation	Co-product allocation is avoided by system expansion	Co-product allocation is treated by using allocation factors

4.3 Tool—Sima Pro 7.3

SimaPro is a software tool for Life Cycle Assessments that calculates environmental impacts associated to a product or services. It follows the ISO standards 14040 and 14044 (Goedkoop, et al. 2010). SimaPro was developed by the Dutch consultancy company Pré. As the most widely used LCA software, it is used in more than 80 countries by industries, consultancies and universities worldwide (PRé Consultants n.d.).

When applying SimaPro into assessing the environmental impact of described systems or scenarios, it is important to choose appropriate method and database. In this study ReCiPe Midpoint method is employed to quantitatively analyse the life cycle of households' plastic waste treatment (mainly on recycling and incineration). ReCiPe method, as an advanced version of widely-used Ecoindicator 99 method, consists of 18 impact categories at the midpoint level (Goedkoop, Oele, et al. 2010). Although global warming (expressed by CO2-eq) is the only one impact category assessed in this study, the result of other impact categories can also be reflected by this method, which provides a chance to have an overview of total impacts. Besides, Ecoinvent unit process is chosen as the database here.

5. LCA on Plastic Waste treatment

5.1 Goal and Scope

5.1.1 Goal

The purpose of the study is to identify the amount of climate change contribution from plastic waste treatment options in Copenhagen municipality, Denmark. Through the comparison of possible recovery schemes (incineration, recycling on different levels), this study tries to figure out a better solution for plastic waste treatment. The plastic waste mentioned in the study mainly refers to the amount of plastics which exists in and could be extracted from household waste. Household refuse together with the similar waste from businesses or industry constitute the concept of “municipal waste”, which includes kitchen waste (biomass), paper, plastics, metals, and glass (Doka 2009). Compared with the long history of paper and glass specifications for recycling, plastic waste collection for recycling are of more recent date and almost all of the collected plastics are from businesses (Kaysen and Tønning 2011). Therefore, by assessing the impacts from different schemes of households’ plastic waste treatment, it is possible to locate the hotspot(s) and investigate scheme(s) of great advantage with GHG reduction potential in order to facilitate the Copenhagen “Plastic Zero” project aiming at reducing the amount of plastic waste (Københavns kommune–Teknik og Miljøforvaltningen n.d.).

5.1.2 Functional unit (FU)

In order to compare the various outlets of household plastic waste, the same amount of waste is considered in all analysed scenarios. The functional unit is defined as incinerating or recycling of the potential plastic waste (12,460tonne) from Copenhagen households. This includes:

Table 5.1: Potential plastic waste and its composition

Fraction	Potential in Copenhagen (tonne)
PE	2100
PP	5600
PS (EPS)	840
PET	2380
Other plastics	1540
Total	12,460

Note: 1) composition is estimated based on Shonfield (2008); 2)PVC content in the household waste is assumed to be negligible and kept in allowable range for incineration and other recycling operations due to Danish long history practice of keeping PVC waste out of household waste (detailed description see Chapter 2.1 and 2.2). Thus, the total amount is 14,000t (Larsen and Skovgaard 2012) minus the amount of PVC (1540t).

5.1.3 System boundary

Plastic waste is widespread on various fields of our daily life, it can be found from private households, industrial and commercial packaging, WEEE, agriculture, automotive to construction and demolition (Goodship 2007, IPTS 2011). But typically the main sources of post-consumer waste plastic are municipal solid waste, construction and demolition waste, automotive waste, and waste from electric and electronic equipment (IPTS 2011). The assessing scope of this study specifically focuses on the energy recovery and recycling of potential plastic waste from household waste.

There are other categories of waste that may also involve with plastic waste (Christensen 2010) but usually are unstable and difficult to track and not dealt with in this report:

- Commercial waste
- Construction and demolition waste
- Agricultural waste
- Waste from warfare
- Waste from natural disasters

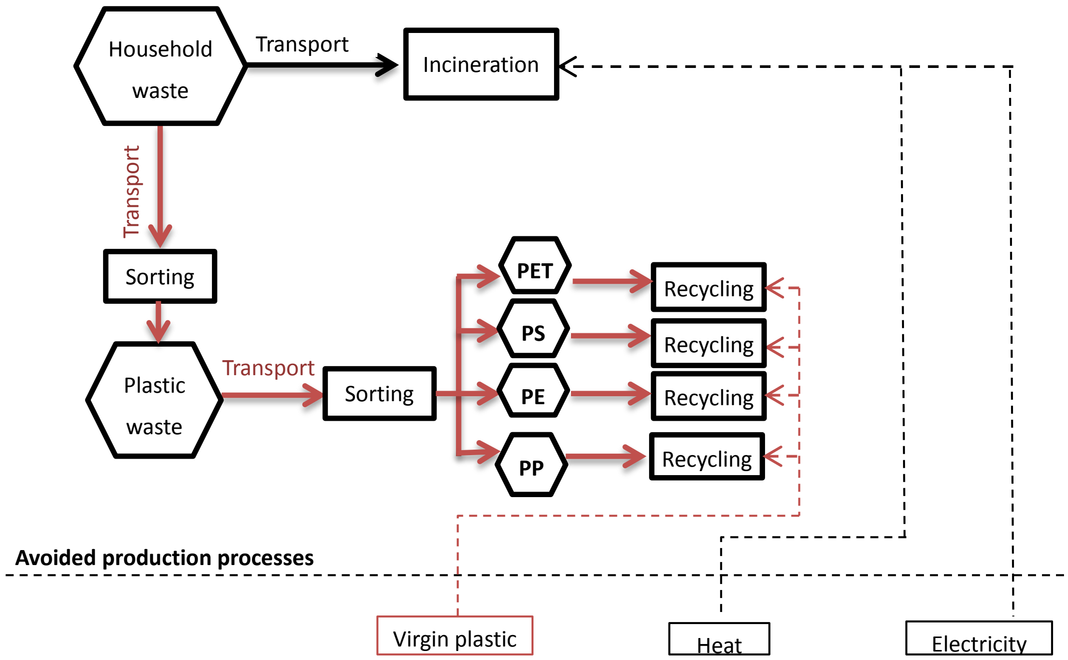


Figure 5.1: A general system scenarios description

Generally speaking, the life-cycle of plastics starts with the energy consumption needed for production of plastics. Then, the plastics enter into use stage as products or part of the products. The end-of –life issues arise when plastic products reaching to the end of their life span. As illustrated in Figure 5.1, the processes covered by LCA of the waste management system in this study will only include disposal phase starting from household waste, including transportation factor. The modelled schemes shown in Figure5.1 indicate the system boundary and describe the simplified relation between processes. Two main possible outlets for plastic waste are presented in the model represented by the scenarios (see detailed scenarios in next section 5.1.4).

One option describes more or less the current situation in Copenhagen, which shows that most plastic wastes are mixed with other residues in household waste and then end up in incineration for energy recovery to produce district heating or power.

The other option is recycling, which are further divided into 2 possible routes. One way is that household waste goes into REnescience and NIR sorting for separation of individual type of plastic waste and then enters into mechanical or chemical recycling. The second route is to collect well-separated plastic waste directly from houses under the assumption that plastic waste could be segregated by household in a designated trash bin when discarding. As such, the mixed plastic waste could be transported directly to NIR sorting and enter into different recycling processes with less washing compared with that of in the first path..

Regarding to recycling scenarios, the consumption of a certain amount and types of virginal plastic can be avoided by using recovered materials. Here, in the detailed scenarios, the recycling can be further divided into mechanical and chemical recycling focus on major plastic families (PE, PP, PS, and PET) respectively. PVC is out of assessment in this study as PVC content in the household waste is assumed to be negligible and kept in allowable range for incineration and other recycling operations due to Danish long history practice of keeping PVC waste out of household waste since 1991 (detailed description see Chapter 2.1 and 2.2). Currently, mechanical recycling is significantly used to treat plastic packaging waste. The mechanical recycling includes serious of operations. Briefly, the plastics are first shipped to reprocessors to chop into flakes and remove contaminants, and then the washed flakes is further extruded into strands and cut into pellets. Finally, the pellets come to the market again to substitute virgin plastics used for new polymer products manufacturing. The main processes—shredding and extrusion are involved in the calculation.

5.1.4 Scenarios

The following table shows the key processes included in the modelled scenarios. The process diagram, specific description and assessment result for each scenario are presented in Chapter 5.3.

Table5.2: Key processes included in the scenarios

Scenario	Key processes
Scenario 1	Municipal incineration with energy recovery (all plastic waste from household waste)
Scenario 2	REnescience sorting (to get plastic waste); Pre-treatment Washing Near infra-red (NIR) sorting (to get individual type of plastic); Mechanical recycling of PVC, PET, PE, PP, PS fractions
Scenario 3	REnescience sorting (to get plastic waste); Pre-treatment Washing Near infra-red (NIR) sorting to get PET fraction Mechanical recycling of PET fractions; Pre-treatment shredding Pyrolysis of PP, PE, PS fractions (BP polymer cracking process)
Scenario 4a	REnescience sorting (to get plastic waste); Pre-treatment Washing Pre-treatment shredding Gasification of plastics (mainly PET, PP, PE, PS fractions) (SVZ)
Scenario 4b	REnescience sorting (to get plastic waste); Pre-treatment Washing Near infra-red (NIR) sorting to get PET fraction Mechanical recycling of PET fraction; Pre-treatment shredding Gasification of PP, PE, PS fractions (SVZ)
Scenario 5a	REnescience sorting (to get plastic waste); Pre-treatment Washing Pre-treatment shredding Hydrogenation of plastics (mainly PET, PP, PE, PS fractions) (VEBA Oel)
Scenario 5b	REnescience sorting (to get plastic waste); Pre-treatment Washing Near infra-red (NIR) sorting to get PET fraction Mechanical recycling of PET fraction; Pre-treatment shredding Hydrogenation of PP, PE, PS fractions (VEBA Oel)
Scenario 6	Near infra-red (NIR) sorting (to get individual type of plastic); Mechanical recycling of PET, PE, PP, PS fractions

Note: Transport consideration is also included in the assessment

5.1.5 Impact categories and method for impact assessment

Method for impact assessment used in Life Cycle Impact Assessment (LCIA) is important as it transforms the input data into environmental output as impact potentials. ReCiPe is one of the important methods in SimaPro. ReCiPe 2008 method consists of two sets of impact categories related to midpoint and endpoint level. Climate change as one of the eighteen impact categories is addressed at midpoint level (Goedkoop, Oele, et al. 2010). The purpose of present study is to identify the possible treatment methods of household plastic waste in term of global warming potentials. Thus, the method of ReCiPe Midpoint (H) has been selected with a focus on climate change.

5.1.6 Data quality requirement

Geographical scope and technological scope

This LCA study aims to present different schemes and technologies for household plastic waste treatment in terms of global warming potential. The geographical scope of household waste is confined in Copenhagen municipality, Denmark. The analysed system includes waste collection, sorting and incineration/recycling.

Collection process takes place in Copenhagen without question. Separation of plastic from household waste either by REnescience (scenario 2-5) or households themselves (scenario 6) also happens in Copenhagen. It should be mentioned that REnescience is still a trial plant rather than a mature technology, so the LCA study uses the current performance data provided by DONG Energy. Mechanical recycling and various chemical recycling of plastic waste are located in other European countries (Germany, UK), which is shown in Table 5.4. It is expected that the Near infra-red (NIR) sorting for individual type of plastic and pre-treatment processes before recycling are located near the recycling facility.

Temporal scope and data sources

The research and practice of chemical recycling for plastic waste had boomed in 1990s but without resulting in many applications up to now. This LCA study chooses 3 most realistic technologies for Copenhagen municipality based on current conditions. Besides, the impact assessment of climate change expressed by CO2-eq is assessed in 100-year time horizon in ReCiPe Midpoint (H) method.

The amount of households plastic waste employed in current study is estimated by Plastic Zero project team in Copenhagen based on preliminary surveys. The composition ratio from a UK report is employed here to estimate different plastic fractions in household waste, where the Danish data is not available. Thus, the effect of a different composition in mixed plastics will be illustrated in a sensitivity analysis. Data regarding to REnescience sorting and NIR sorting as well as alternative disposal options are taken either from published literature or from Ecoinvent database.

5.1.7 Key assumptions and uncertainties

Composition of household plastic waste

As stated in the above section, due to the lack of composition of household plastic waste in Copenhagen, the following composition ratio is applied in this study to estimate the amount of plastic waste in different types in household plastic. However, the proportion of PP and PE fractions in plastic packaging waste from Danish household, illustrated in Table 2.3, shows a significant difference compared with the composition employed here. Although the differences may be caused by the existence of other plastic products with longer life-span than packaging in household waste and different packaging waste in commercial waste, the assumption might risk the calculation result if the real situation altered. Therefore, sensitivity analysis will be carried out examining the effect of variation in the composition with higher level of PE fraction and lower level of PP and PET fraction (sensitivity analysis see chapter 5.4.1).

Table 5.3: Default composition of input plastic waste (Shonfield 2008)

Material type	Default composition, %
PE	15
PP	40
PET	17
PS	6
PVC	11
Others	11

Another important assumption related with the composition is that PVC content in the collected household waste in Copenhagen is negligible and kept in allowable range for incineration and other recycling operations due to Danish long history practice of keeping PVC waste out of household waste since 1991 (detailed description see Chapter 2.1 and 2.2).

REnescience sorting

This study only focuses on taking plastics out by using REnescience technology. For that reason the consumption of water, enzymes and heat for processing organic fraction is not included in the calculation (Schmidt and Løkke 2012). Similarly, the energy consumption for the separation of recyclable materials is divided and allocated on plastic segregation by weight. Chapter 5.2.1 provides detailed description about REnescience and the calculation.

Besides, prior to NIR sorting, the mixed plastic as one of the outputs from REnescience machine is assumed to be washed in consideration of the acceptance of NIR sorting machine (Løkke 2012). The electricity utilization is estimated about 0.5 kwh/tonne (Løkke 2012).The water and energy consumption associated with washing is estimated based on the figure in a project report from Danish EPA (Frees 2002). The report offers consumption of water and energy (for warming the water) in washing plastic package of various kinds of products by warm water (40 °C). And a medium figure of 78L/kg and 10.9MJ/kg has been used in the LCA models. To examine the effect of variation in the consumption two alternatives with lower and higher consumption will be assessed in the sensitivity analysis (see chapter 5.4.2).

Substitution ratio from mechanical recycling

It is assumed that recycled plastic obtained from the mechanical recycling processes is of high quality and substitutes directly for virginal plastic on a 1:1 basis.

Transport

In this study, the consideration for transport can be divided into two processes—one for municipal collection system, the other for overseas recycling. Therefore, transport in the former process is assumed to be by 21-tonne lorries with outward and return trip; while the later one is assumed to be by >32 tonne lorries. For the recycling scenarios, it is assumed that NIR sorting and all required pre-treatment processes are co-located with the recycling facilities so there is no need to consider the transport between process stages. The distance for municipal collection and transporting to recycling are estimated by using Google map (see Table 5.4).

Table 5.4: Transport distance

Route	Distance, km
Collection from households to incinerator (energy recovery facility)	9
From sorting to mechanical recycling, Hamburg, Germany	393
From sorting to pyrolysis facility (BP process), Grangemouth, United Kingdom	1932
From sorting to gasification facility (SVZ), Saxony, Germany	656
From sorting to hydrogenation facility (VEBA Oel), Gelsenkirchen, Germany	678

Market condition

A further important assumption in this study is that markets exist for the products derived from recycling. In mechanical recycling processes, it is assumed that markets exist for recycled plastics that are produced– PP, PE, PET, and PS. And markets also exist for recovered fuel in chemical recycling processes. Otherwise, the credits received from substituting avoided products will be reduced which will result in an increase in environmental impact.

5.2 Life Cycle Inventory

5.2.1 Data collection

The technical data for REnescience and NIR sorting as well as chemical/mechanical recycling processes are collected from various literatures. While the background data on incineration, transport are sourced from Ecoinvent database. Appendix Ⅰ shows the detailed figures and sources.

REnescience

A pilot REnescience plant developed by DONG energy has been established since 2009 in Copenhagen (DONG Energy n.d.). Currently, it is operating for municipal waste refinery by using enzymes to separate the biodegradable material from recyclables such as metals, glass and plastics (DONG Energy n.d.). The sorting process can be understood simply as two steps: (1) the mixed waste is firstly heated and then reacts with enzymes to take organic materials away in the form of liquid fraction; (2) then the solid fraction of remains mainly consists of glass, metals, plastics, textiles are exposed to further sorting to get recyclables.

This study only focuses on taking plastics out by using REnescience technology. For that reason the consumption of water, enzymes and heat for processing organic fraction is not included in the calculation (Schmidt and Løkke 2012). Similarly, the energy consumption for the separation of recyclable materials is divided and allocated on plastic segregation by weight. According to Riber et al. (2009) cited by Tonini and Astrup (2012), the proportions of plastic, glass, metal and textile in average Danish residual waste are 9.2%, 2.9%, 3.5% and 1.9% respectively. While the electricity consumed to separate recyclables was estimated at 18kwh/tonne waste treated (Tonini and Astrup 2012). Therefore, the energy allocation for plastic treatment is 9.5 kwh/tonne plastic treated.

Besides, prior to NIR sorting, the mixed plastic as one of the outputs from REnescience machine is assumed to be washed in consideration of the acceptance of NIR sorting machine (Løkke 2012). The water and energy consumption associated with washing is estimated based on the figure in a project report from Danish EPA (Frees 2002). A medium figure of 78L/kg and 10.9MJ/kg has been used in the LCA models. The electricity utilization is estimated by personal experience about 0.5 kwh/tonne (Løkke 2012). Finally, it is estimated that there is 10% material loss in REnescience (Tonini and Astrup 2012).

NIR sorting and mechanical recycling

Near infra-red sorting (NIR) is commonly used in the automatic plastic sorting (Dodbiba and Fujita 2004). The data used for NIR (Titech) sorting process is based on Shonfield (2008). Appendix Ⅰ illustrates the separaion effiencecy of different plastics and energy consumption.

The mechanical recycling process was considered mainly including shredding and extrusion in LCA models. The estimations of energy consumption in shredding (to cut the product less than 80 mm in diameter) and extrusion are 24kwh/tonne and 270kwh/tonne respectively with 2% material loss during this process based on Shonfield (2008).

Pyrolysis (BP), gasification (SVZ) and hydrogenation (Veba Oel) recycling

Before entering into feedstock recycling, a treatment of size reduction is needed for the sorted plastic mixture. The data for pre-shredding treatment is estimated based on the same process in mechanical recycling (24kwh/tonne).

The inventory data related to the pyrolysis (BP) recycling and hydrogenation (Veba Oel) recycling are collected from their official documents (Bez and Nürrenbach 2001, Dijkema and Stougie 1994), cited in Perugini, Mastellone and Arena (2005). The inventory data describing gasification (SVZ) recycling is collected from Tukker, et al. (1999). Appendix Ⅰ gives the original data and the corresponding equivalent products used in LCA. The description on different technologies is shown in AppendixⅢ.

Incineration

Incineration process happens in Copenhagen, Denmark. The environmental benefits accrues from incineration with energy recovery, which in Copenhagen avoid the requirement to obtain electricity and heating from other sources. According to Schmidt (2005), the electricity and heating efficiency for waste incineration in Copenhagen is 14% and 71% respectively. Data regarding to the energy which can be recovered from different types of plastic waste is based on Ecoinvent datasets in Sima Pro: 42.74 MJ/kg for PE, 32.78 MJ/kg for PP, 22.95 MJ/kg for PET and 38.67 MJ/kg for PS.

Table 5.5: Applied efficiencies for waste incineration Copenhagen (Schmidt 2005)

Power efficiency	14%
Heating Efficiency	71%
Total efficiency	85%

Marginal energy production

The energy recovery derived from incineration has potential effect on the energy supply system in the future. It is necessary to identify the energy suppliers that are actually affected by the system changes, so that the input and output/avoided energy can be presented by the mixture of these suppliers which is the so-called marginal energy supply (Chapter 4.2 gives the explanation of marginal concept).

The marginal electricity production used here is based on the LCA inventory study of electricity in Demark by Merciai, Schmidt and Dalgaard (2011). Except for incineration senario, the marginal electricity production on european average is used in other scenarios where the proceses happen in Germany or UK. Appendix Ⅰ shows the detailed data and processes used in Ecoinvent.

The district heating in Copenhagen is mainly supplied from waste incineration and the central combined-heat-power plant (CHPs) (Schmidt 2005). The heating supplied by waste generation depends on the amount of waste supply, that is to say, only the supply from CHPs will be affected by the changes in the system. Therefore, the marginal district heating supplier is only CHPs. Another factor needed to be involved in is that in Copenhagen heat generation in the warmest 3 months is enough (even excess) to cover the demand, so there is no marginal district heat production for 1/4 of a year. Therefore, the amount of marginal heat production needs to be modified by multiplying 3/4 (Schmidt 2005). The marginal heat is presented by a combination process made by the unit processes in Ecoinvent (see Table 5.6).

Table 5.6: Applied LCA data in marginal heat (Schmidt 2005)

Unit process in Ecoinvent (2003) Anvendt	Burned fuel
Natural gas, burned in boiler modulating >100kW	0,494 MJ
Light fuel oil, burned in boiler 100kW, non-modulating	0,515 MJ

Transport

In this study, two types of transport are considered. The first part transport (from household to collection spot such as incinerator, REnescience plant) has been expected to use municipal collection system. The distance is estimated as 9km based on Google map and personal experience (Løkke 2012). The second part refers to the transport for overseas recycling, due to the reason that the total amount of plastic waste in Denmark is not big enough to have its own recycling plants (Buch-Andersen 2005). Germany as one of the destinations shows its advantages on both geographical and technical factors for Denmark. Except for BP pyrolysis recycling in UK, all of the mechanical and chemical recycling assessed in this study located in Germany. The distance is estimated by Google map (See Table 5.4).

5.2.2 Relating data to functional unit

Some of the data collected above are expressed in different functional unit, therefore transformation of all the data into unified functional unit defined in this study is shown in the following tables. Table 5.7-5.10 show the data related with scenario1, 2, 6 respectively. Because of the several same processes possessed by scenario 3-5, the relevant data has been shown in table. The outputs in bold and italic form present the avoided products. The original data sources have been showed in Appendix Ⅰ.

Table 5.7: Inventory data related to scenario 1—incineration

Input		**Output**	
Collection (municipal collection system)			
Plastic waste (t)	1,25E+04	Plastic waste (t)	1,25E+04
Transport (km)	9,00E+00		
Incineration			
Plastic waste (t)	1,25E+04	***Electricity (14%) (MJ)***	5,05E+07
		Heating (71%*0,75) (MJ)	1,92E+08

Table 5.8: Inventory data related to scenario 2—mechanical recycling

Input			**Output**
		collection (municipal collection system)	
Plastic waste (t)	1,25E+04	Plastic waste (t)	1,25E+04
Transport (km)	9,00E+00		
		REnescience sorting	
Plastic waste (t)	1,25E+04	Plastic waste (t)	1,12E+04
Electricity energy (kwh)	1,18E+05		
		Pre-washing	
Plastic waste (t)	1,12E+04	Plastic waste (t)	1,12E+04
Electricity energy(kwh)	5,61E+03		
Cold water (t)	8,75E+05		
Heat energy (MJ)	1,22E+08		
		Transport：393km	
		NIR sorting (Titech)	
Plastic waste (t)	1,12E+04	PE (t)	1,48E+03
Electricity energy (kwh)	3,01E+05	PP (t)	4,44E+03
		PS (t)	4,59E+02
		PET (t)	1,65E+03
		Mechanical recycling	
Sorted PE (t)	1,48E+03	***Recycled PE (t)***	1,45E+03
Electricity energy (kwh)	4,36E+05		
Sorted PP (t)	4,44E+03	***Recycled PP (t)***	4,35E+03
Electricity energy (kwh)	1,31E+06		
Sorted PS (t)	4,59E+02	***Recycled PS (t)***	4,50E+02
Electricity energy(kwh)	1,35E+05		
Sorted PET (t)	1,65E+03	***Recycled PET (t)***	1,62E+03
Electricity energy (kwh)	4,86E+05		

Table 5.9: Inventory data related to scenario 3- 5—chemical recycling

Input			**Output**
	collection (municipal collection system)		
Plastic waste (t)	1,25E+04	Plastic waste (t)	1,25E+04
Transport (km)	9,00E+00		
	REnescience sorting		
Plastic waste (t)	1,25E+04	Plastic waste (t)	1,12E+04
Electricity energy (kwh)	1,18E+05		
	Pre-washing		
Plastic waste (t)	1,12E+04	Plastic waste (t)	1,12E+04
Electricity energy(kwh)	5,61E+03		
Cold water (t)	8,75E+05		
Heat energy (MJ)	1,22E+08		
Transport to pyrolysis:1932km; Transport to gasification: 656km; Transport to hydrogenation: 678km			
	NIR sorting (Titech)		
Plastic waste (t)	1,12E+04	Polyolefines fraction(t)	6,38E+03
Electricity energy (kwh)	3,01E+05	PET(t)	1,65E+03
	PET mechanical recycling		
Sorted PET(t)	1,65E+03	Recycled PET(t)	1,62E+03
Electricity energy (kwh)	4,86E+05		
	Pre-shredding		
Polyolefines fraction(t)	6,38E+03	Polyolefines fraction(t)	6,38E+03
Electricity energy (kwh)	1,53E+05		
	Pre-shredding (including PET)		
Polyolefines fraction (t)	8,03E+03	Polyolefines fraction(t)	8,03E+03
Electricity energy (kwh)	1,93E+05		
	Pyrolysis (BP process)		
Polyolefines fraction (t)	6,38E+03	***Paraffin production(t)***	2,86E+03
Naphtha (t)	3,80E+01[1]	***Naphtha production(t)***	1,69E+03
Electricity energy (MJ)	1,35E+06	***Refinery gas (t)***	9,38E+02
		CO_2(t)	2,20E+03
	Gasification (SVZ)		
Polyolefines fraction(t)	6,38E+03	***Methanol (t)***	5,96E+03
Waste oil (t)[2]	2,14E+03	***Natural gas (m3)***	2,50E+06[3]

[1] Unit conversion from 8.36E+05 (MJ) to 3.80E+01 (t) by energy value of naphtha: 22000MJ/t

[2] Replaced by crude oil process in Sima Pro calculation, specific discussion see Appendix Ⅰ

[3] Unit conversion from 1707 (t) to 2,50E+06 (m3) by energy content of natural gas: 53.2 MJ/kg , 38.2 MJ/m3

……table continued from previous page			
Lignite (t)	1,05E+04	***Electricity (MJ)***	1,91E+07
Natural gas (m3)	8.37E+05	CO2 (t)	5,29E+04
Fuel Oil (t)	3,34E+02		
Gasification (SVZ) (including PET)			
Polyolefines fraction	8,03E+03	***Methanol (t)***	7,51E+03
Waste oil (t)	2,70E+03	***Natural gas (m3)***	3,15E+06[4]
Lignite (t)	1,32E+04	***Electricity (MJ)***	2,40E+07
Natural gas (m3)	1,05E+06	CO2 (t)	6,66E+04
Fuel Oil (t)	4,21E+02		
Hydrogenation (Veba Oel)			
Polyolefines fraction(t)	6,38E+03	***Crude oil (t)***	5,25E+03
Natural gas (m3)	7,72E+05[5]	***Natural gas(m3)***	7,98E+05[6]
Electricity energy (MJ)	6,13E+06		
Steam (t)	2,65E+02[7]		
Hydrogenation (Veba Oel) (including PET)			
Polyolefines fraction (t)	8,03E+03	***Crude oil (t)***	6,61E+03
Natural gas(m3)	9,72E+05[8]	***Natural gas(m3)***	1,00E+06[9]
Electricity energy (MJ)	7,72E+06		
Steam (t)	3,34E+02[10]		

[4] Unit conversion same as the above

[5] Unit conversion from 2,95E+07 (MJ) to 7,72E+05 (m3) by energy value of natural gas: 38.2MJ/m3

[6] Unit conversion by using energy value of natural gas: 53.2 MJ/kg, 38.2MJ/m3

[7] Unit conversion from 7,15E+05 (MJ) to 2,65E+02 (t) by energy value of steam: 2700MJ/t

[8] Unit conversion by using energy value of natural gas: 38.2MJ/m3

[9] Unit conversion by using energy value of natural gas: 53.2 MJ/kg, 38.2MJ/m3

[10] Unit conversion by using energy value of steam: 2700MJ/t

Table 5.10: Inventory data related to scenario 6—mechanical recycling after household sorting

Input			**Output**
	collection (municipal collection system)		
Plastic waste (t)	1,25E+04	Plastic waste (t)	1,25E+04
Transport (km)	9,00E+00		
	Transport：393km		
	NIR sorting (Titech)		
Plastic waste (t)	1,25E+04	PE (t)	1,65E+03
Electricity energy (kwh)	3,33E+05	PP (t)	4,93E+03
		PS (t)	5,10E+02
		PET (t)	1,83E+03
	Mechanical recycling		
Sorted PE (t)	1,65E+03	***Recycled PE (t)***	1,62E+03
Electricity energy (kwh)	4,85E+05		
Sorted PP (t)	4,93E+03	***Recycled PP (t)***	4,83E+03
Electricity energy (kwh)	1,45E+06		
Sorted PS (t)	5,10E+02	***Recycled PS (t)***	5,00E+02
Electricity energy(kwh)	1,50E+05		
Sorted PET (t)	1,83E+03	***Recycled PET (t)***	1,80E+03
Electricity energy (kwh)	5,39E+05		

5.3 Life Cycle Impact Assessment

The main goal of this study is to, based on LCA methodology, calculate the GHG emissions from plastic waste treatment under current situation in Copenhagen city and give a comparison of potential recycling methods among four major plastic types from an environmental point of view. Therefore, the following scenarios have been defined to facilitate the achievement of the aims. In this step, the global warming potential of each scenario is calculated based on life cycle inventory presented in above section and the results are presented. Due to the reason that the current study only focuses on one impact category—“climate change”, normalisation and weighting are not used. As one of the characterisation factors in the midpoint categories in ReCiPe method, the global warming potential, abbreviated as GWP is assessed based on the IPCC report 2007 and its Hierarchist perspective uses 100 year timeframe (Goedkoop, Heijungs, et al. 2009).

Scenario 1

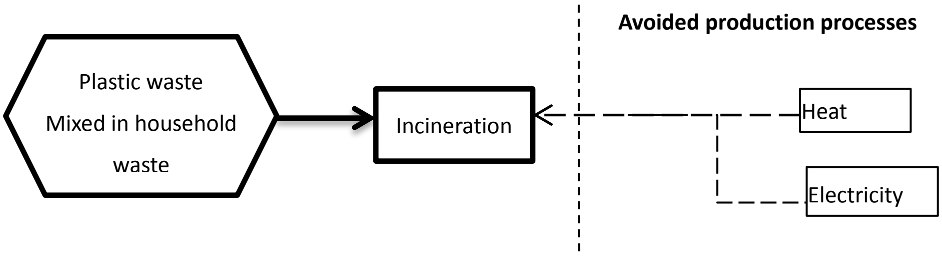


Figure 5.2 Scenario 1—mixed plastic waste end up with incineration with energy recovery

In this scenario, the system starts from the point that the municipal truck leaves for collection of households' wastes to the point at which wastes have been incinerated. During the whole procedure, plastic wastes are mixed with other residues in the households' waste and then transported by municipal collection system directly to incineration producing district heating and power in Copenhagen, Denmark (Figure 5.2).

It should be noted that the bulky PVC has been assumed to be kept away from the collected waste and the chlorine content is acceptable for municipal incineration (elaborated in chapter 5.1.7). Besides, the data collection and assumption on transport, energy recovery efficiency and the choice of marginal energy have been discussed in chapter 5.1.7 and 5.2.1.

Assessment results are shown in the following. Figure 5.3 reveals that the impact from transportation is negligible.

Table 5.11: Global warming contribution from different processes in Scenario 1 (kg CO2-eq/ FU)

Unit	Incineration	Transport	Total
kg CO2-eq	-1,75E7	1,47E5	-1,74E7

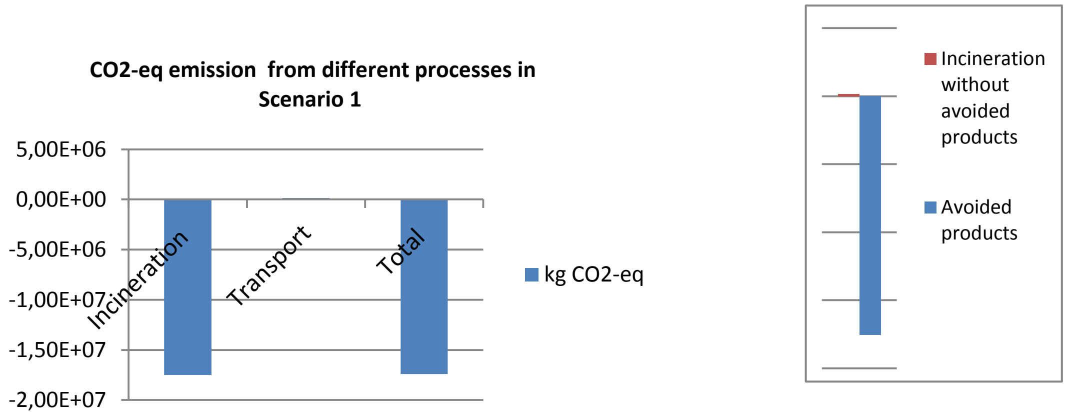


Figure 5.3: CO2-eq emission from different processes in Scenario 1 (kg CO2-eq/ FU)

Note: The avoided products have been included in the incineration process. The small chart on the right hand shows the separated impacts in incineration process

Scenario 2

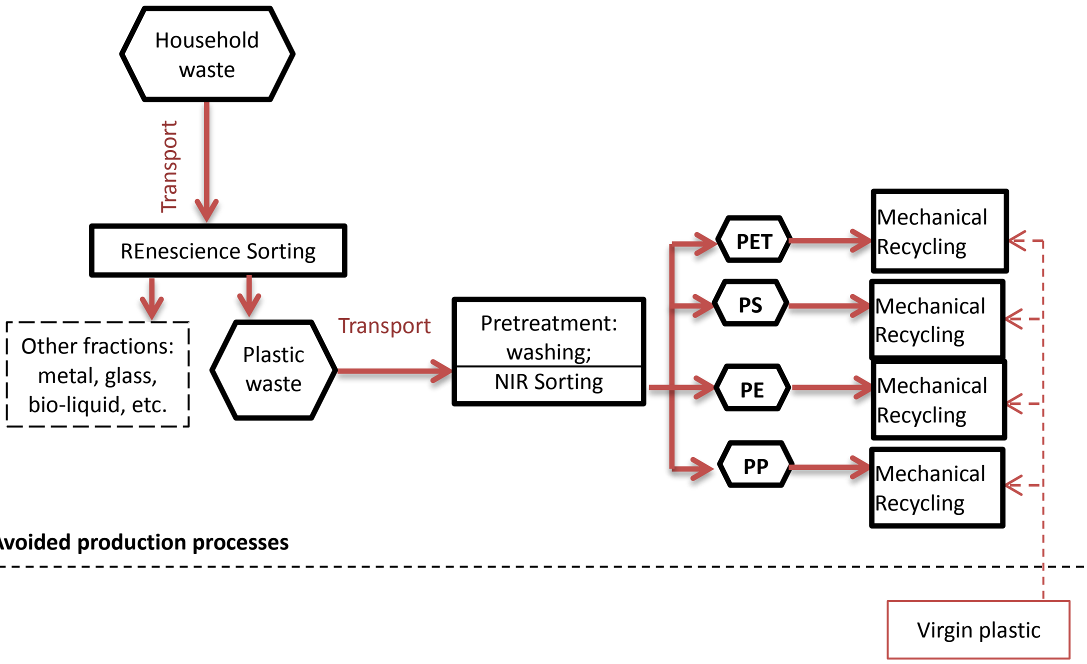


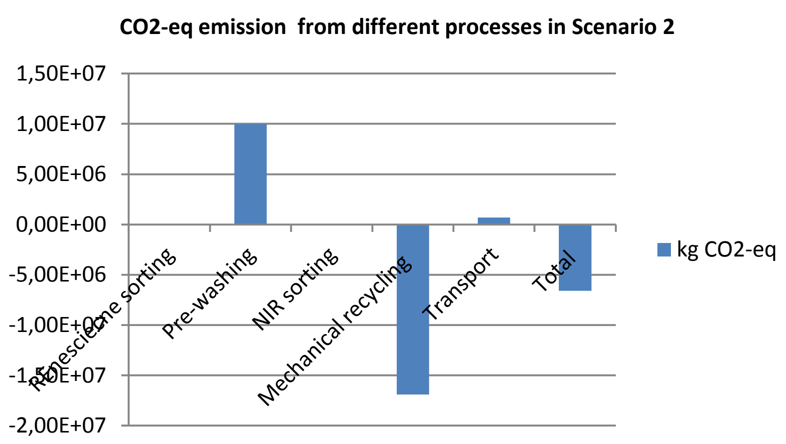
Figure 5.4 Scenario 2—PE, PP, PS, PET end up with mechanical recycling individually

This scenario describes that the plastic wastes are collected and sorted in succession and then end up with mechanical recycling in Hamburg, Germany. Mechanical recycling highly requires the purity of input materials. Therefore, REnescience sorter is firstly employed to separate mixed plastics from household waste, and then the mixed plastics experience NIR sorting after washing to obtain individual type of polymers prepared for mechanical recycling (Figure 5.4).

Assessment results reveal that the sorting processes as well as transportation contribute negligible impacts on climate change compared with pre-washing process. As a matter of fact, the medium level of resource and energy consumption (found in the reference document) is applied in the pre-washing process. It is possible that the impact from pre-washing may be lower or even higher when the energy consumption is altered. Due to the significance and uncertainty in the pre-washing process, higher and lower consumption alternatives are assessed in sensitivity analysis.

Table 5.12: Global warming contribution from different processes in Scenario 2 (kg CO2-eq/ FU)

Unit	REnesciecne sorting	Pre-washing	NIR sorting	Mechanical recycling	Transport	Total
kg CO2-eq	1,98E4	9,98E6	3,56E4	-1,69E7	6,78E5	-6,6E6



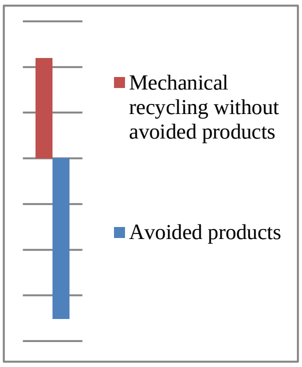


Figure 5.5: CO2-eq emission from different processes in Scenario 2 (kg CO2-eq/ FU)

Note: The avoided products have been included in mechanical recycling process. The small chart on the right hand shows the separated impacts in mechanical recycling process.

Scenario 3

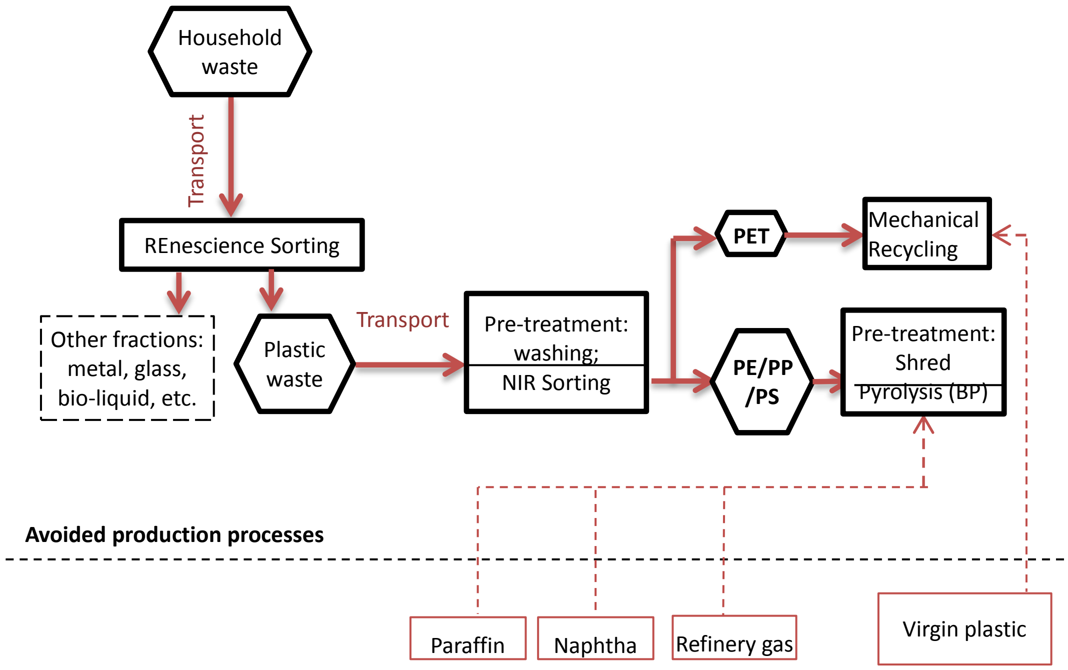


Figure 5.6: Scenario 3—mechanical recycling for PET, pyrolysis for polyolefins

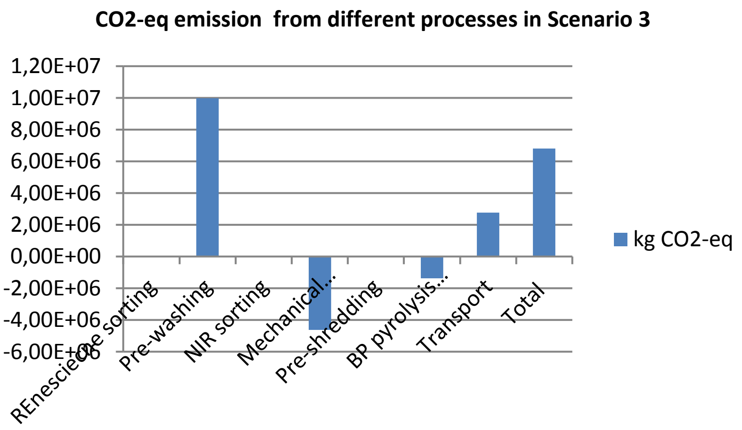
The overall flow in scenario 3 is the same as scenario 2 with only one change at the end of the scheme, that is, PE, PP and PS fractions go into chemical recycling—BP pyrolysis in Grangemouth, United Kingdom instead of mechanical recycling. The light fraction, heavy waxy fraction and gaseous fraction in the main products can substitute for naphtha, paraffin and refinery gas respectively (Shonfield 2008)(Figure 5.6).

In polymer cracking process, the acceptance criteria requires about 80% of the plastic that enters the process is polyolefin (PP/PE), and allows maximum 15% PS (Tukker, et al. 1999). In light of the situation that the fraction of PS only accounts for small proportion in packaging waste (see table 5), it is estimated here that the PS content in the plastic waste from household is within allowed limits for polymer cracking process. As such, this scenario assumes that the PE, PP and PS fractions are suited for pyrolysis technology; while PET is mechanically recycled as scenario 2.

As shown in Table 5.13, similar as scenario 2 the pre-washing process is still significant. However, the emission from transport becomes higher due to the recycling taken place in UK instead of Germany. Therefore, the potential savings derived from both mechanical and chemical recycling is offset by pre-washing and transport, mainly.

Table 5.13: Global warming contribution from different processes in Scenario 3 (kg CO2-eq/ FU)

Unit	REnesciecne sorting	Pre-washing	NIR sorting	Mechanical recycling (PET)	Pre-shredding	BP pyrolysis (PE,PP,PS)	Transport	Total
kg CO2-eq	1,98E4	9,98E6	3,56E4	-4,62E6	1,8E4	-1,37E6	2,76E6	6,82E6



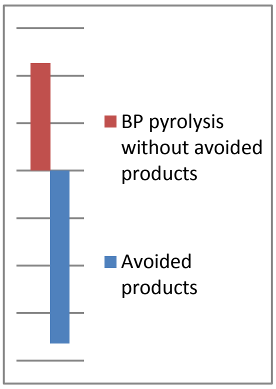


Figure 5.7: CO2-eq emission from different processes in Scenario 3 (kg CO2-eq/ FU)

Note: The avoided products have been included in mechanical recycling and BP pyrolysis processes. The small chart on the right hand shows the separated impacts in BP pyrolysis process.

Scenario 4a

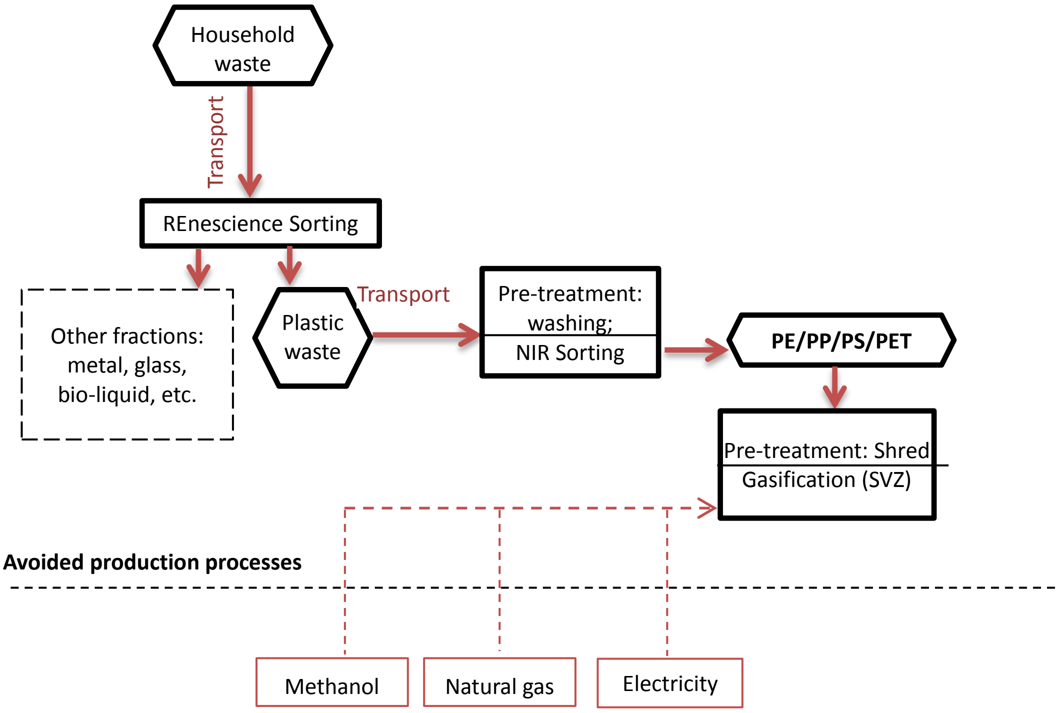


Figure 5.8: Scenario 4a—gasification process for mixed plastics

In this scenario, gasification technology has been assessed in other to compare with pyrolysis. The acceptance criteria of SVZ gasification process are more tolerance for various input materials than BP pyrolysis but the limitation on chlorine content still exist (2%-6%) (Tukker, et al. 1999). Therefore, Scenario 4 is the same as scenario 3 with only one change at the end of the scheme, that is, PE, PP, PET and PS fractions all go into chemical recycling—SVZ gasification process in Saxony, Germany (Figure 5.8).

Because of the large amount of CO2 emission generated in the gasification process itself along with the energy inputs, the emission saved by the avoided products seems to be far less the generation.

Table 5.14: Global warming contribution from different processes in Scenario 4a (kg CO2-eq/ FU)

Unit	REnescience sorting	Pre-washing	Pre-shredding	SVZ gasification	Transport	Total
kg CO2-eq	1,98E4	9,98E6	2,27E4	7,22E7	1,03E6	8,33E7

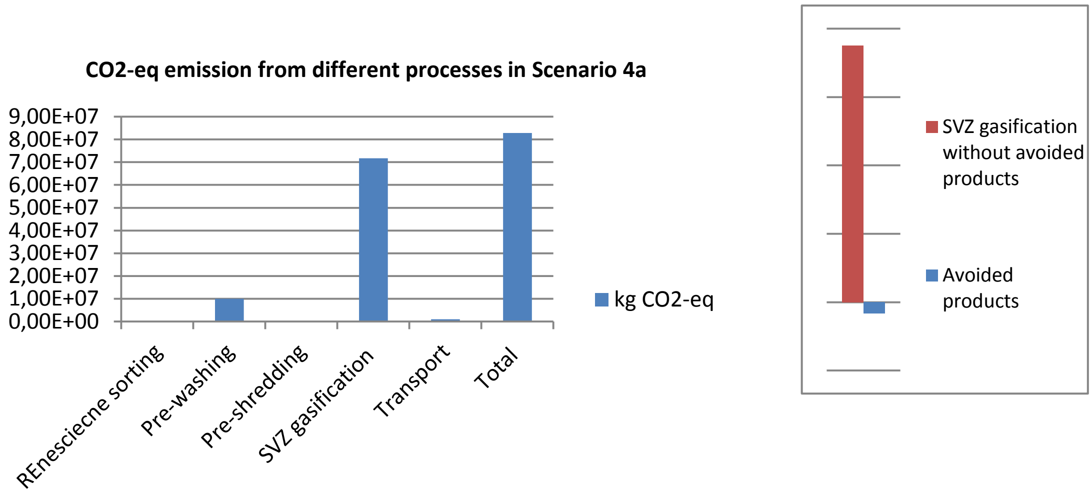


Figure 5.9: CO2-eq emission from different processes in Scenario 4a (kg CO2-eq/ FU)

Note: The avoided products have been included in SVZ gasification process. The small chart on the right hand shows the separated impacts in SVZ gasification process.

Scenario 4b

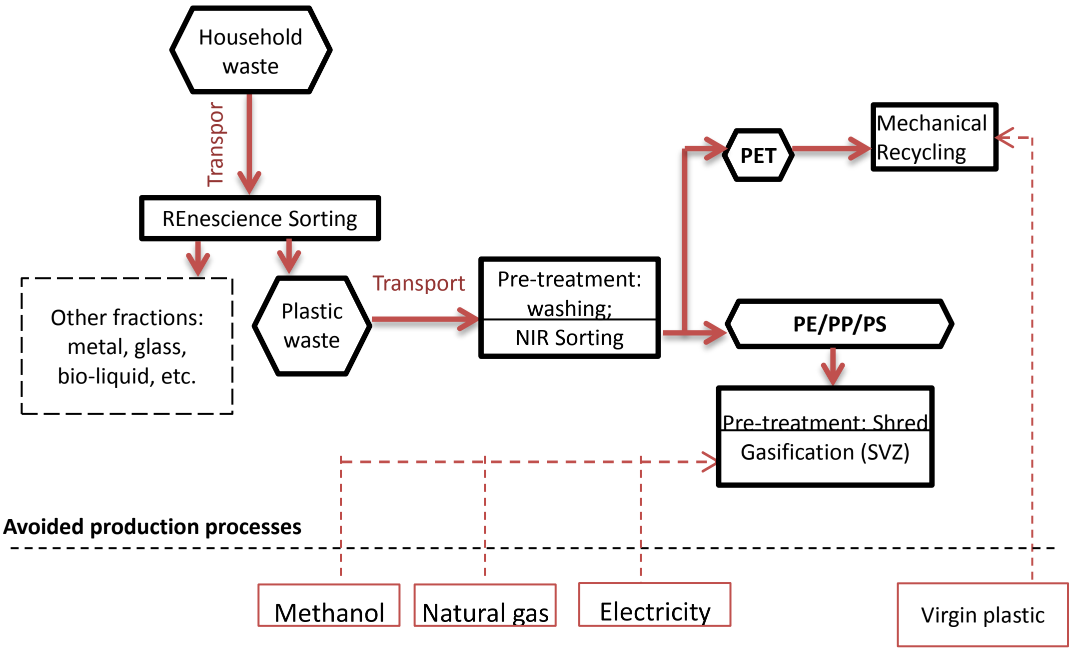


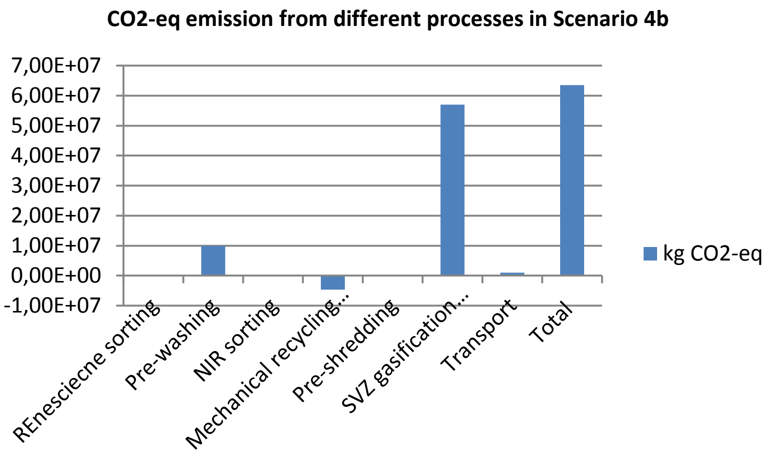
Figure 5.10 Scenario 4b—gasification for PE, PP, PS and mechanical recycling for PET

In order to enable a comparison with scenario 4a as well as scenario 3 on a fair basis, this scenario extracts PET from mixed plastic waste for mechanical recycling while leaves other fractions in SVZ gasification (Figure 5.10).

The assessment results reveal that even though the mechanical recycling of PET provided emission savings but the final result has been diverted by the emission contribution from SVZ gasification process.

Table 5.15: Global warming contribution from different processes in Scenario 4b (kg CO2-eq/ FU)

Unit	REnescience sorting	Pre-washing	NIR sorting	Mechanical recycling (PET)	Pre-shredding	SVZ gasification (PE,PP,PS)	Transport	Total
kg CO2-eq	1,98E4	9,98E6	3,56E4	-4,62E6	1,8E4	5,74E7	1,03E6	6,38E7



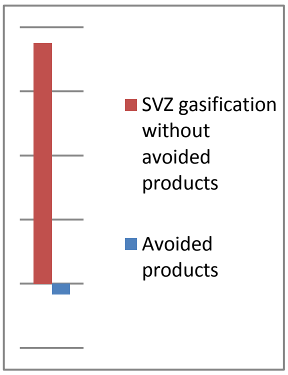


Figure 5.11: CO2-eq emission from different processes in Scenario 4b (kg CO2-eq/ FU)

Note: The avoided products have been included in mechanical recycling and SVZ gasification processes. The small chart on the right hand shows the separated impacts in SVZ gasification process.

Scenario 5a

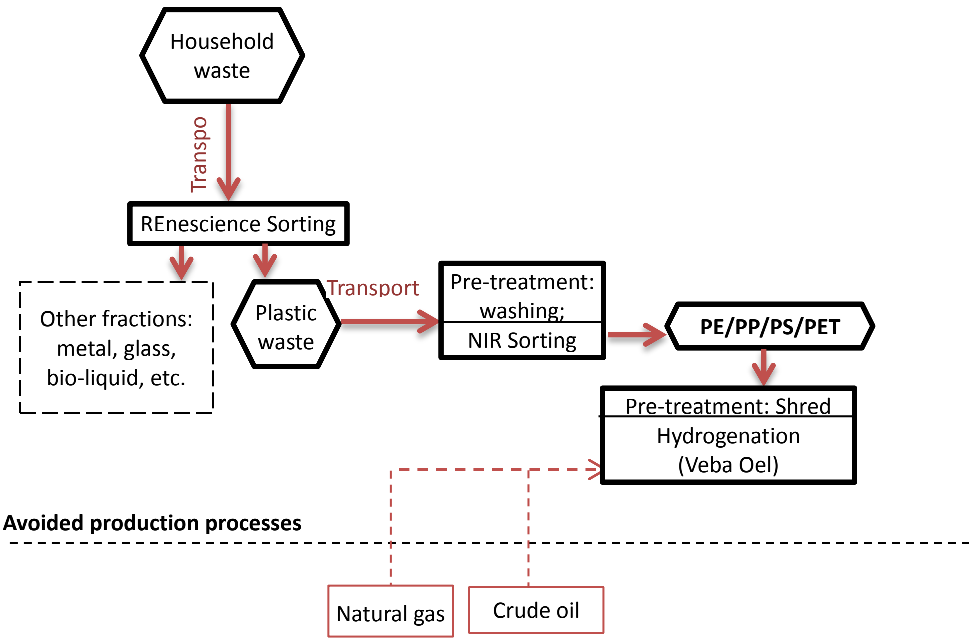


Figure 5.12: Scenario5a—hydrogenation for mixed plastic waste

Similar as scenario 4a, household wastes are sent to REnescience for separation of mixed plastic waste, and then transported to a plant installed in Bottrop, Germany to *"convert plastic waste in fragment of hydrocarbons, in appearance and composition similar to crude oil"* (Perugini, Mastellone and Arena 2005).

The only change between Scenario 4 and Scenario 5 is the technology employed for feedstock recycling. Besides the variation of recycling site stated above, the approach has also altered from gasification to hydrogenation. Compared with SVZ gasification process, hydrogenation shows more positive result on GHG emission. With the emission derived from recycling process declining, the impact of pre-washing process becomes significant again.

Table 5.16 Global warming contribution from different processes in Scenario 5a (kg CO2-eq/ FU)

Unit	REnescience sorting	Pre-washing	Pre-shredding	Veba Oel hydrogenation	Transport	Total
kg CO2-eq	1,98E4	9,98E6	2,27E4	-3,94E3	1,06E6	1,11E7

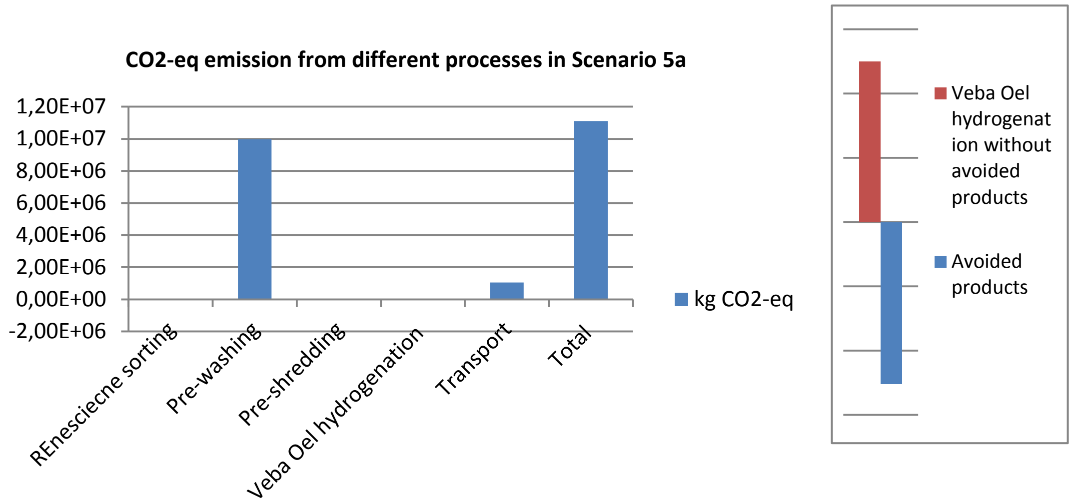


Figure 5.13: CO2-eq emission from different processes in Scenario 5a (kg CO2-eq/ FU)

Note: The avoided products have been included in Veba Oel hydrogenation process. The small chart on the right hand shows the separated impacts in Veba Oel process.

Scenario 5b

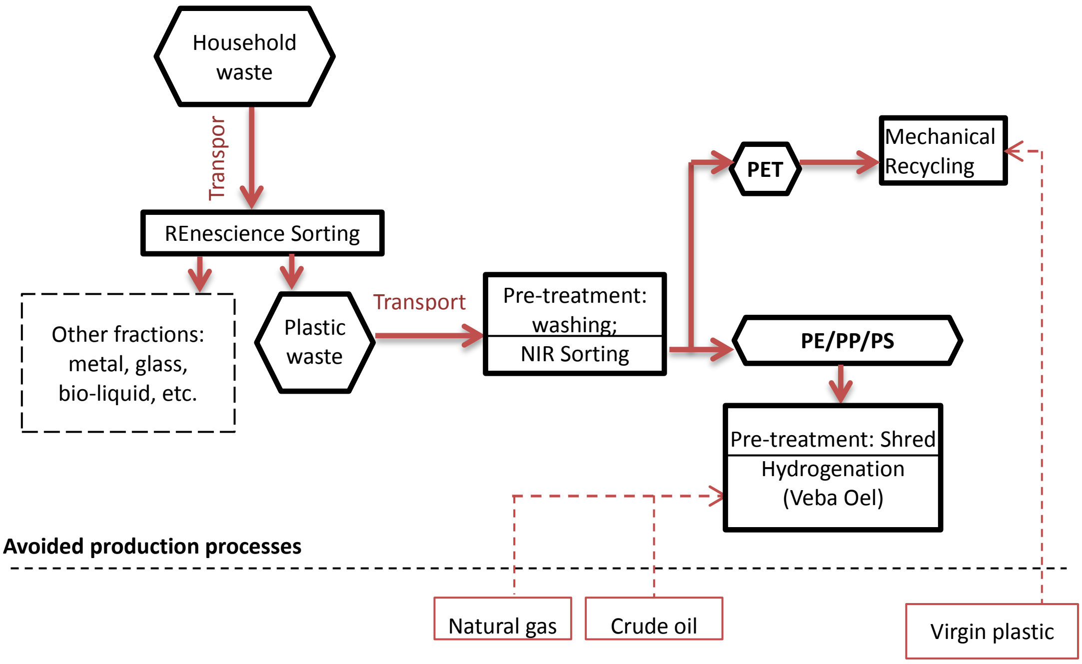
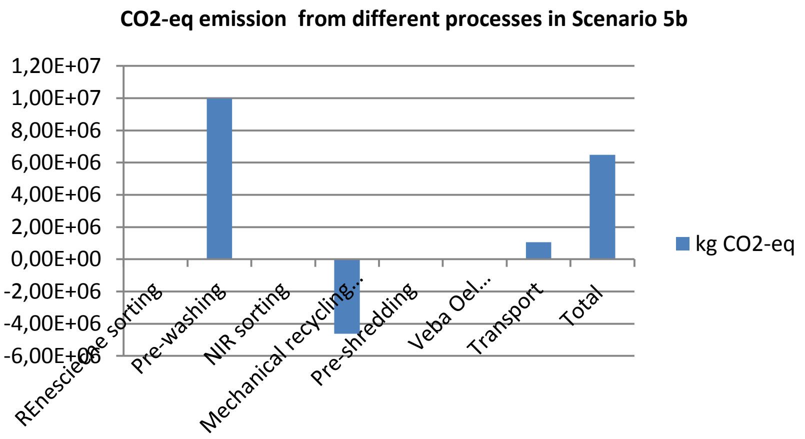


Figure 5.14: Scenario5b—hydrogenation for PE, PP, PS and mechanical recycling for PET

Scenario 5b plays the same role as scenario 4b, that is, to make a comparison among various treatment options on a same basis respectively. Compared with scenario 3, the only difference comes from the change between the process of BP pyrolysis and Veba Oel hydrogenation. The overall emissions of two scenarios are close. Although BP pyrolysis process shows greater advantage on emission saving than Veba Oel hydrogenation, the transport emission finally offsets and diverts the advantage since the transport distance triples. Compared with scenario 4b, it is clear that SVZ gasification contributes the highest GHG emission. Finally, when comparing with scenario 5a, we can see that mechanical recycling displays bigger advantage than hydrogenation. Of course, the conclusion is based on the assumption that the recycled plastics from mechanical approach can substitute virgin plastic on 1:1 basis and the market exists.

Table 5.17: Global warming contribution from different processes in Scenario 5b (kg CO2-eq/ FU)

Unit	REnescience sorting	Pre-washing	NIR sorting	Mechanical recycling (PET)	Pre-shredding	Veba Oel hydrogenation (PE,PP,PS)	Transport	Total
kg CO2-eq	1,98E4	9,98E6	3,56E4	-4,62E6	1,8E4	-3,13E3	1,06E6	6,49E6



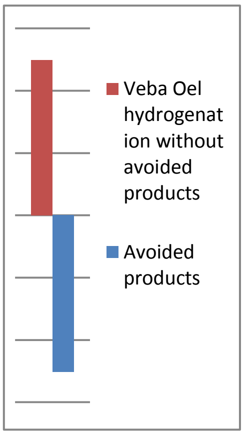


Figure 5.15: CO2-eq emission from different processes in Scenario 5b (kg CO2-eq/ FU)

Note: The avoided products have been included in mechanical recycling and Veba Oel hydrogenation processes. The small chart on the right hand shows the separated impacts in Veba Oel process.

Scenario 6

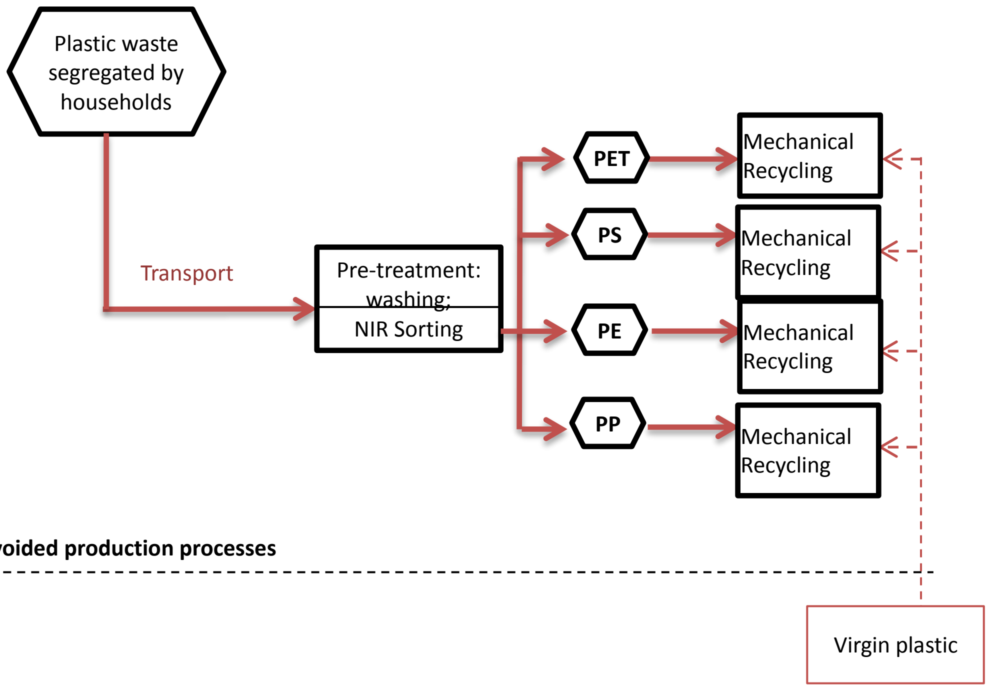


Figure5.16 Scenario 6—kerbside sorting for mechanical recycling

This scenario describes the situation under the assumption that the potential plastic waste could be well-separated by household in a designated trash bin when discarding. In fact, a new kerbside collection is going to be carried out from late 2012 in Copenhagen, aiming at collecting rigid plastic packaging separately from other household waste (Larsen and Skovgaard 2012).

In this way, the mixed plastic waste could be transported directly to NIR sorting and enter into different recycling processes afterwards (Figure 5.16). Therefore, this scenario can be roughly equal to scenario 2 with exclusion of REnescience sorting process. Actually, the result of the former one is more positive than that of the later one when including material losses in REnescience into consideration. Obviously, among all the scenarios, it represents the lowest emission option.

Table 5.18: Global warming contribution from different processes in Scenario 6 (kg CO2-eq/ FU)

Unit	NIR sorting	Mechanical recycling	Transport	Total
kg CO2-eq	3,96E4	-1,92E7	7,38E5	-1,84E7

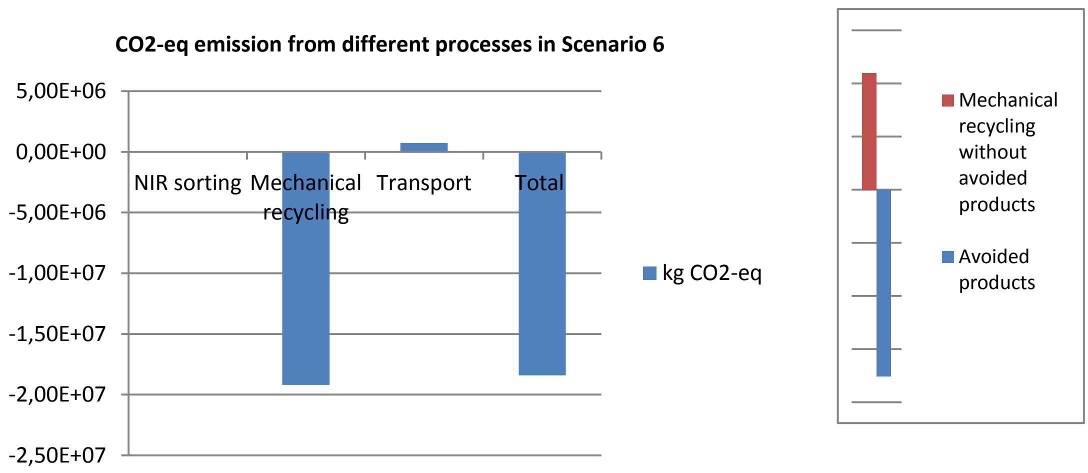


Figure 5.17: CO2-eq emission from different processes in Scenario 6 (kg CO2-eq/ FU)

Note: The avoided products have been included in mechanical recycling process. The small chart on the right hand shows the separated impacts in mechanical recycling process.

5.4 Interpretation

In the above section, the individual assessment result has been shown and the comparisons among mutual processes for each scenario have been also elaborated. The total emission from all scenarios is illustrated in Figure 5.18, where we can see that scenarios with SVZ gasification process contribute highest emission, followed by the other two feedstock recycling approaches—Veba Oel hydrogenation and BP pyrolysis. The largest emission saving occurs in scenario 6—mechanical recycling with new kerbside sorting system, while incineration with energy recovery presents the second largest saving.

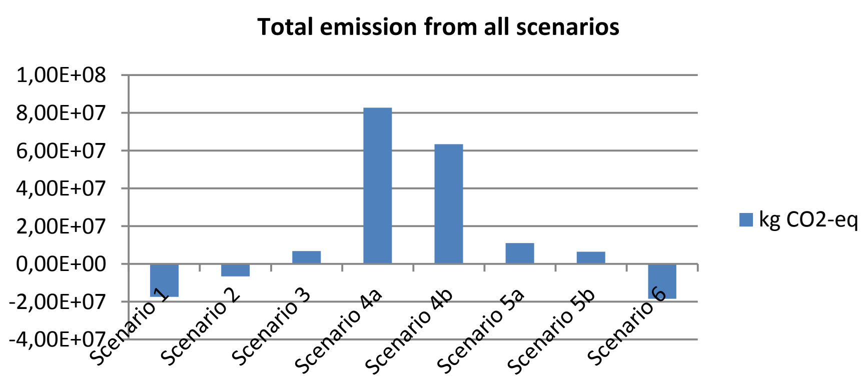


Figure 5.18: Total emission from all scenarios

However, the result may vary due to some uncertainties. For instance, a change in composition of plastic waste may result in a different outcome as the amount of plastics entering into different recycling processes will be changed. Another factor may influence the result is the pre-washing step. This step has significant affected the total emission of several scenarios, which has been clearly shown in chapter 5.3. In addition, in the assessment, a marginal power supply representing future changes has been employed in the situation of both Denmark and other European countries. However, the future marginal supply doesn't consider coal fired power supply at all which contributes high CO2 emission. For that reason, the result may vary if the marginal power supply is assumed as coal fired power supply.

Therefore, sensitivity check is undertaken in this section to provide a critical reflection of the presented result. As mentioned above, it is necessary to involve three major aspects into sensitivity analysis—the composition of plastic waste, the energy and resource consumption in pre-washing and marginal energy supply.

5.4.1 Sensitivity analyses—composition of household plastic waste

The reason to build up this sensitivity check is that a composition ratio based on UK situation has been applied due to the lack of composition of household plastic waste in Copenhagen. However, it shows significant differences with the figure collected about plastic packaging waste from Danish household, especially on the PP and PE fractions (elaborated in Chapter 5.1.7). Thus, it is necessary to have a look at what will happen when the composition changes (see Table 5.19). Most scenarios are supposed to be change in current sensitivity check due to the change of composition ratio in household plastic waste.

Table 5.19: Composition ratio of household plastic waste for sensitivity analysis

Material type	Default composition, %	Alternative composition, %
PE	15	56
PP	40	10
PET	17	6
PS	6	6
PVC	11	11
Others	11	11

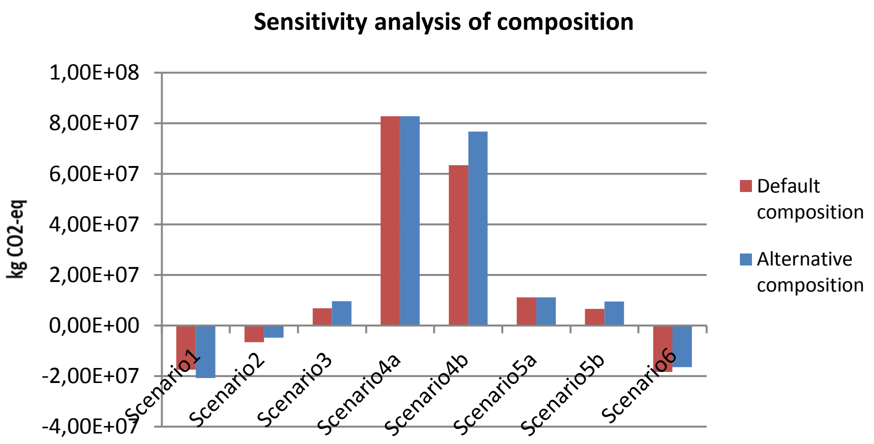


Figure 5.19: Sensitivity analysis of composition

As shown in Figure 5.19, the altering of composition ratio in household plastic waste does affect the total emission of most scenarios. However, the effect is not to an extent to trigger big changes in the rankings of the scenarios. The only alternation which affects the rankings occurs between scenario 1—incineration and scenario 6—mechanical recycling with kerbside sorting. The change can be attributed to the largely increased PE fraction and decreased PP fraction. Firstly, the energy value of PE (42.47 MJ/kg) is higher than PP (32.78 MJ/kg), which means that the energy that can be recovered from the waste stream will increase when the amount of PE increases and PP decreases. Thus, the emission saving becomes higher in scenario 1 as there is a potential for more energy recovery. Secondly, the separation efficiency of PE (78.5%) is lower than PP (88.1%) in NIR sorting facility. With the waste amount increasing in PE and decreasing in PP, the amount of plastic which can be sorted out from sorting facility for mechanical recycling will decline. Thus, the emission saving becomes lower in scenario 6 due to the decline of avoided products—recycled plastics.

5.4.2 Sensitivity analyses—pre-washing

Pre-washing process is built in order to ensure that plastic waste sorted out of municipal waste by REnescience can meet the input requirements of NIR sorting facility. A medium figure of energy and water consumption has been used in the LCA models. However, in some scenarios, pre-washing process shows a significant influence on the total emission. So it is necessary to make a sensitivity check on the situation with higher or lower consumption (see Table 5.20).

Table 5.20: Water and energy consumption in pre-washing for sensitivity analysis

Consumption	Default	Higher	Lower
Cold water (L/kg)	78	213	11
Energy for Warming water (MJ/kg)	10.9	29.8	0

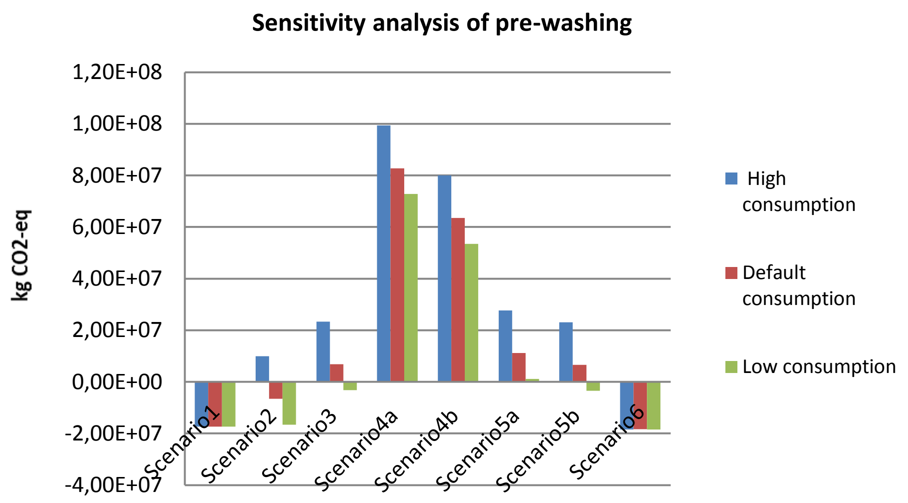


Figure 5.20: Sensitivity analysis of pre-washing

Except for Scenario1 and Scenario6, pre-washing process involves in all of the rest scenarios. Figure 5.20 illustrates the variation for each scenarios resulting from the consumption levels. Geranial speaking, pre-washing step has important influence on total emission of all scenarios with it. However, the original rankings remain the same without affected by the change of consumption levels in pre-washing. It should be noted that scenario 2 is significantly affected by pre-washing step, with the lowest consumption in pre-washing scenario 2 becomes very close to the most emission saving options—Scenario 1 and Scenario 6.

5.4.3 Sensitivity analyses—marginal power production

The applied electricity mix model based on consequential future described in the inventory reports of 2.0 LCA consultants (Merciai, Schmidt and Dalgaard 2011) has been employ as the marginal power production. It reflects the competitive suppliers which are likely to respond to a long-term change in demand (see Appendix Ⅰ). The coal fired power generation as a traditional option has not been considered in the future consequential model at all as it is regarded as being phased out and constrained in the future. However, from a short-term perspective, it is also reasonable to assume the marginal supply is coal as it is still has its competitiveness in energy supply in Denmark and Europe. The unit processes in Ecoinvent used to represent the new marginal supply in Denmark and OECD countries are “Electricity, hard coal, at power plant/NORDEL” and “Electricity, hard coal, at power plant/UCTE” respectively.

When the marginal electricity supply changes from “consequential future” to “consequential coal” the emission results of all scenarios will be changed correspondingly. Figure 5.21 shows the comparison between the default result and new variation resulting from the assumption of coal as the marginal electricity supply. The change in marginal supply results in more emission saving for Scenario 1 and Scenario 4 and higher emission for the rest scenarios. This is because electricity production exists in the avoided products/output of incineration with energy recovery (Scenario 1) and SVZ gasification process (Scenario 4a and 4b). More CO2 emission can be saved when the avoided electricity is generated based on coal than other clean energy (the consequential future model mainly consists of energy from biomass, wind, etc.). The overall rankings remain almost same except for a switch between Scenario1 and Scenario 6.

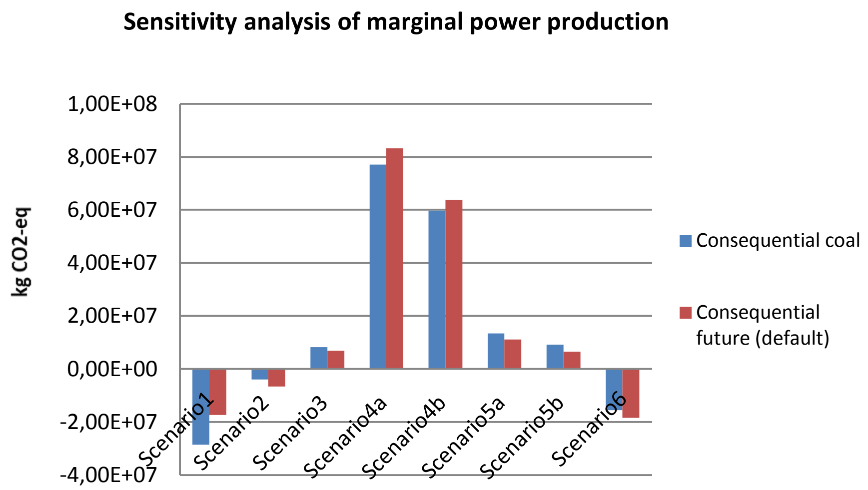


Figure 5.21: Sensitivity analysis of marginal power production

5.4.4 Completeness check

Completeness check is required in order to confirm all the data collection, assumption and life cycle stages are available and completed (Thrane and Schmidt 2007). In the current study, all the information about data type, system boundary, scenarios design and processes in waste treatment stages as well as assumptions have been presented in chapter 5.1—goal and scope. The inventory data collection and calculation have been shown in chapter 5.2—life cycle inventory and Appendix Ⅰ.

5.4.3 Consistency check

The purpose of consistency check is to ensure the data, assumptions and methods are consistent throughout the whole life cycle assessment (Thrane and Schmidt 2007). In the current study, chapter 5.2—life cycle inventory and Appendix Ⅰ provides detailed information on the data collection and calculation. The data with respect to specific country have been used when the processing steps which take place in the country (for instance, Denmark), while European average data have been applied when certain data are not available in specific countries (for instance, marginal electricity supply in UK and Germany). The assumptions and uncertainties which have or may have high influence on the results have been checked by sensitivity analysis in the above sections.

5.4.4 Other Impact Categories

Although this study only focuses on the impact of climate change, it is also possible to have a glance at several other impact categories for different scenarios. The impact categories such as depletion, human toxicity, acidification, eutrophication and eco-toxicity etc. are presented in Figure5.22. We can see from the figure that scenario 4a/4b with SVZ gasification process not only have strong impact on climate change but also has significant impact on human toxicity, fresh water eutrophication, fresh water eco-toxicity and marine eco-toxicity.

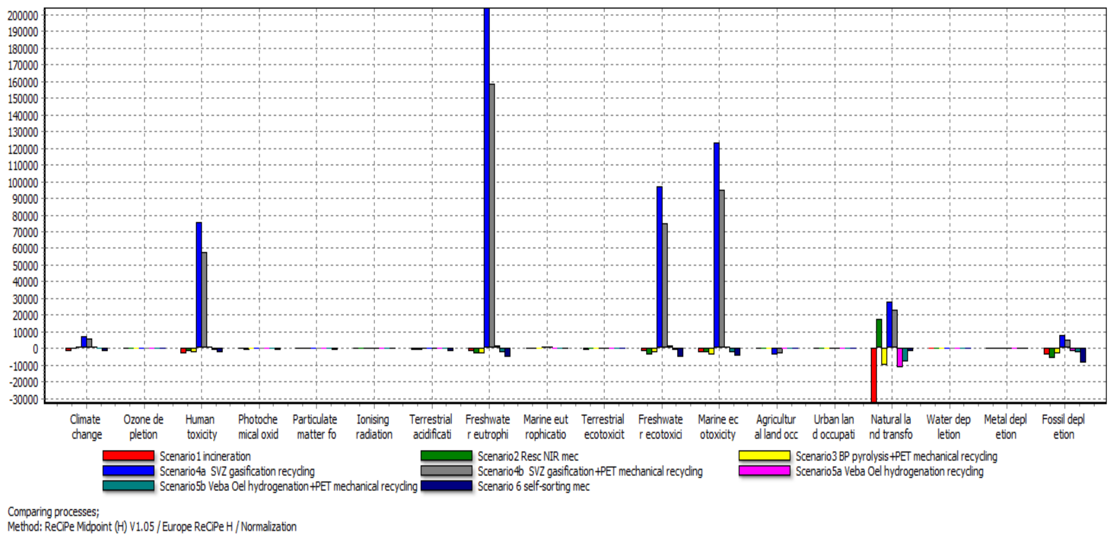


Figure 5.22 Environmental Impacts from different scenarios (after normalisation)

6. Conclusions

6.1 General conclusion

With a skyrocketed rise of plastic production ever since 1940s, plastics have been getting more and more attention due to its use of resources and its impacts on the environment and health. In face of the increasing demand on plastics as well as plastic waste generated correspondingly, European plastic waste management has experienced the evolution from basic landfill disposal to energy recovery and recycling with the ultimate goal of prevention. At present, the best practice of waste plastic management in European countries is a combination of both recycling and energy recovery. In the year 2010, 57.9% of plastic in EU (EU-27 plus Norway and Switzerland) ended up in recycling and energy recovery. Looking at recycling alone, mechanical recycling took place processing 21.3% (5.3 Mt) of the total plastic waste in Europe (EU-27 plus Norway and Switzerland), while Chemical recycling only representing 0.3% (0.07Mt).

At present, the majority of recycled plastics derive from commercial plastic waste, such as industrial packaging waste and process scrap. It should be noted that, besides the best practice in dealing with deposited PET bottles, considerable plastic wastes involved in household waste have not gotten well-extracted and recycled. These wastes consist of packaging, films, covers, bags, containers and other plastic products which are widely used in our daily life. In dealing with MSW, EU waste policy has been playing an important role over the past 30 years. The emphasis has been changed from reducing waste negative impacts to seeing waste as a valued resource. The new Waste Framework Directive (WFD-2008/98/EC) has set the targets for EU Member States to recycle 50% of their municipal waste and 70% of construction waste by 2020.

In Demark, incineration with energy recovery for MSW has been utilised as a strategic component of an integrated waste management policy (Gendebien, et al. 2003). The total recovery rate for all plastics in 2010 has reached 95%, in which recycling performance has reached almost 25% and energy recovery level is around 70%. The recycling rate of plastic packaging waste has been steadily increasing, and exceeded the target of 22.5% indicated in EU Packaging Directive since 2008. Nevertheless, the same as the situation in other countries, it is the collection from commercial enterprises that contributes a very large part of the recycling instead of households' part.

6.2 Conclusion on LCA study

Take Copenhagen municipality as an example, under the framework of EU regulations on waste and the new targets for recycling, Copenhagen Waste Management Plan 2012 and Copenhagen Carbon Neutral Plan by 2025 have been put into force. With respect to plastic waste, a new target has been set up to reduce the amount of waste plastic mixed in municipal waste for incineration (40,000 tonnes) by 15,000 tonnes. In Copenhagen municipal waste regulation, specific rules for PVC waste disposal have been already in place. And a new kerbside collection scheme which includes source separation of plastic waste will start in late 2012.

Based on this background, the current study focuses on different outlets of plastics mixed in household waste and tries to look at their contributions to climate change. From the perspective of how to sort plastic out of household waste, a comparison has been made between REnescience sorting and kerbside sorting. From technology perspective, a comparison has been made among incineration with energy recovery, mechanical recycling and feedstock recycling. In addition, it is not realistic for demark to have its own recycling plants due to the amount of plastic waste, the recycling plants selected in the study are mainly located in Germany (only one in UK) in consideration of distance. Finally, eight scenarios have been built up.

The total emission from all scenarios presents differently. Scenarios with SVZ gasification process contribute highest emission, followed by the other two feedstock recycling approaches—Veba Oel hydrogenation and BP pyrolysis. The largest emission saving occurs in Scenario 6—mechanical recycling with kerbside sorting, while incineration with energy recovery presents the second largest saving.

If we look at the individual process in each scenario, assessment results reveal that:

1. Although REnescience sorting affects the total emission very slightly, the cleaning of plastic waste after REnescience increased environmental impacts for recycling, especially in Scenario 2, Scenario 3 and Scenario 5. Therefore, kerbside sorting presents more advantage.

2. The emission saving rankings of different technologies is:

Mechanical recycling > BP pyrolysis > Veba Oel hydrogenation > SVZ gasification

However, this result should be considered seriously as the real situation on the market for recycled plastic from mechanical recycling is not clear. Some further discussion on this point has been made in Chapter 7. Besides, even though feedstock recycling methods showed lower advantage in emission saving, they are more tolerant in the input materials. Thus, they provide another outlet for (1) low-quality plastics which cannot be mechanically recycled or; (2) mechanically recycled plastic which cannot be used due to the quality or market restrictions.

3. Transportation contributes negligible impacts on climate change in all scenarios. One exception occurs in Scenario 3 where the recycling plant is located in UK.

Given the uncertainty and significance in the pre-washing process, higher and lower consumption alternatives are assessed in sensitivity analysis. Besides, sensitivity analysis has been also applied in composition of household plastic waste and alternative marginal electricity supply. The results reveal that the total emission of the scenarios changed to some extent, but the overall rankings remain almost the same except for a slight switch between Scenario1 and Scenario 6.

Limitations of LCA Study

1. The market capacity for the recycled plastic and the quality of recycled plastic decides whether or not the recycled plastic can substitute virgin plastic on 1:1 basis, which are not considered in this study and deserves further discussion.

2. The real effect of kerbside sorting in Copenhagen is unknown. Therefore, the loss is not considered in this study.

3. The losses and other residues from NIR sorting and recycling processes ending up with incineration or landfill is not analysed in this study.

7. Further considerations

The LCA on climate change impact provided in this study is based on different treatment schemes for household plastics waste from technology perspective. The scenario—Mechanical recycling with kerbside sorting shows the highest potential in GHG reduction. In reality, the result may also be affected by the factors like market, policy and citizen participation. Therefore, the integrated effects from these factors should be considered.

Market

In LCA studies, mechanical recycling shows a clear advantage compared with other options. However, its advantage in practice may be compromised due to the market condition. This is because the emission saving from mechanical recycling is largely derived from the avoided products which are accounted as virgin plastics with the substitution based on 1:1. Hereby, it is under the risk of saturated market. At present, the only part of the post-consumer plastic waste stream that has been recycled in the primary recycling is the deposited PET bottles which are made from similar grades of PET. The recycled plastics originated from packaging or other products have to be put into other applications because of the downgrading of properties. Some applications which can be found on the market are grocery bags, garden benches, marker posts, shutters and blinds, etc. It is possible that the increased amount of recycled plastics will affect the supply in the market and then replace more virgin plastic in the market as a competitive supplier. However, another possibility also exists where the demand of recycled plastics has been already saturated or nearly saturated due to the limited application of downgrading plastics. In this situation, the plastics come from mechanical recycling have no potential or very limited potential to substitute virgin plastics. It will result in a large decline in the benefits obtained from mechanical recycling by reducing avoided products and increasing the load of re-treatment for the recycled plastics (incineration, feedstock recycling or landfill).

Policy

In the face of the predicament mentioned above, the policy approach adopted by government may be of help in increasing the demand for recycled materials as the intervention from policy side can bring some stimulation on the market. For example, maintaining a stable price of recyclate after processing can be of great help for the development of markets for recycled plastics (Singer 1995). Besides, to create a framework to encourage a clear separation of plastic waste from other waste at low level of dirt is also a challenge job for local authorities.

Households

The households play two important roles in plastic recycling. For one thing, they are the consumers who can make a decision on whether to buy the products made by recycled plastics, and then affect the market demand on recycled plastics. For another, they are also the waste producers every day. The kerbside separation efficiency and the benefit obtained by it are largely rely on the households' disposal decisions on whether or not to clearly separate plastic out of other wastes.

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Appendix Ⅰ Data collection

NIR sorting (Titech)

Table 1: NIR sorting (Titech) data from Shonfield (2008)

Description	Unit	Value	Comment
Throughput	t/h	0.861	Based on run 1
Power consumption (per unit)-1000mm	KW	1.6	Suggested set-up uses 2 x 1000 mm sorters and 2 x 700 mm sorters - maximum capacity for this set-up is 2 t/h
Acceleration belt	KW	2.2	Requires 1 per sort unit
Conveyor	KW	1.5	Requires 2 per sort unit
Compressed air	KW	15	Centralised compressor serving all sorters
Separation efficiency			
PP	%	88.1	
PE	%	78.5	
PET	%	77.1	
PS	%	60.7	

Calculation on energy consumption:

11214/0.861*(1.6+2.2+1.5*2+15) = 3, 01E+05 (kWh)

12460/0.861* (1.6+2.2+1.5*2+15) = 3, 33E+05 (kWh)

Pyrolysis (BP)

Table 2: Inventory of pyrolysis (BP) recycling (Bez and Nürrenbach 2001), cited by Perugini, Mastellone and Arena (2005)

BP process

Input		Output	
Polyolefines fraction	1 kg	Products	
Auxiliary materials		Gas fraction	0.147 kg
Sand	0.0085 kg	Heavy fraction (waxes)	0.448 kg
CaO	0.046 kg	Light fraction (liquid)	0.265 kg
Water	0.002 m^3	$CaO/CaCl_2$	0.057 kg
Auxiliary energy		Sand	0.076 kg
Naphtha	0.131 MJ	Air Emissions	
Electric energy	0.212 MJ	CO_2	0.345 kg
		NO_x	0.0003 kg
		SO_2	0.002 kg
		Residues	
		Waxy filter to incineration	0.046 kg

Table 3: Products of the BP pyrolysis process and the equivalent avoided products (marginal)

BP pyrolysis process products	Equivalent products	Basis for Substitution
heavy fraction	Paraffin	1:1
light fraction	Naphtha	1:1
gas fraction	Refinery gas	1:1

Gasification (SVZ)

Table 4: Inventory of SVZ process (Tukker, et al. 1999)

Inputs		Outputs	
MPW-agglomerate	763 g	Methanol	712 g
Waste oil	256 g	Syngas	204 g
Lignite	1.25 kg	Electricity	2,28 MJ
Water	7.9 l	CO2	6,32 kg
Oxygen	1,47 kg	Water vapour	9,9 kg
Fuel oil	40 g	Effluent	9,9 kg
Natural gas	0,1 m2	Gypsum	0,1 kg
		Slag	0,9 g

Table 5: Products of the SVZ gasification process and the equivalent avoided products (marginal)

SVZ gasification process products	Equivalent products	Basis for Substitution
Methanol	Methanol	1:1
Syngas	Natural gas	1:1
Electricity	Electricity	1:1

As there is no relevant product to describe “Waste oil”, an LCA result from a Germany organization (Umweltvundesamt) cited by the report—“Critical Review of Existing Studies and Life Cycle Analysis on the Regeneration and Incineration of waste oil” from DG Environment, European Commission has been used here to estimate the GWP of waste oil as an input. The model of LCA conducted by Umweltvundesamt for calculating the environmental performance of refinery recycling of waste oil in SVZ is as follows:

Environmental performance = process impacts – saved impacts of primary input

“Process impacts” refers to the environmental impacts from consuming 1000kg waste oil (1431 kg CO2-eq); the “saved impacts of primary input” are the environmental benefit derived by substituting the 75% natural gas, 10% heavy oil and 15% lignite which are avoided by using waste oil (1366 kg CO2-eq). The result showed that the CO2-eq emission was 65kg for 1000kg waste oil.

(EUROPEAN COMMISSION 2001)

The result is closed to that of the crude oil process (50kg CO2-eq) in Ecoinvent—"Crude oil, production NL, at long distance transport/RER U", which includes both the extraction of crude oil and transportation from exploration site to refinery in Europe. Therefore, in order to simplify the calculation, this study decided to replace waste oil by using crude oil process from Ecoinvent in the process—"SVZ gasification recycling" . As a matter of fact, another way has been also tried in Sima Pro, that is, to directly add 65kg CO2-eq (per tonne of waste oil) emission in the process—"SVZ gasification recycling" instead of citing crude oil process. The result of GWP impact remains the same as that of the former one.

Hydrogenation (Veba Oel)

Table 6: Inventory of hydrogenation (Veba Oel) recycling (Dijkema and Stougie 1994) cited by Perugini, Mastellone and Arena (2005)

Veba process

Polyolefines fraction	1 kg	Products	
Auxiliary materials		Syncrude	0.822 kg
Hydrogen	0.011 kg	E-gas	0.09 kg
CaO	0.001 kg	HCl	0.005 kg
Auxiliary energy		$CaCl_2$	0.0041 kg
Natural gas	4.62 MJ	Air Emissions	
Electric energy	0.96 MJ	NH_3	0.006 g
Steam	0.112 MJ	Hydrocarbons	2.23 g
		Residues	
		Solid waste	0.05 kg
		Residue to incineration	0.066 kg

Table 7: Products of Veba Oel hydrogenation process and the equivalent avoided products (marginal)

Veba Oel hydrogenation process products	Equivalent products	Basis for Substitution
Syncrude	Crude oil	1:1
Gas fraction	Natural gas	1:1

Electricity

Table 8: Data for the consequential future scenario—Denmark (Merciai, Schmidt and Dalgaard 2011)

Flows	Consequen-tial future kWh	Consequen-tial historical kWh	Consequen-tial coal kWh	Attributional kWh	LCI data Ecoinvent (2010)
Outputs					
Electricity, at pp	1	1	1	1	Reference flow
Inputs					
Elec. coal	0.000	0.145	1.000	0.482	'Electricity, hard coal, at power plant/NORDEL'
Elec. oil	0.004	0.000	--	0.030	'Electricity, oil, at power plant/DK'
Elec. gas	0.197	0.000	--	0.190	'Electricity, natural gas, at power plant/NORDEL'
Elec. biomass	0.403	0.364	--	0.107	See **Table** 5
Elec. nuclear	0.000	0.000	--	0.000	--
Elec. hydro	0.003	0.000	--	0.000	'Electricity, hydropower, at run-of-river power plant/RER'
Elec. wind	0.393	0.491	--	0.190	'Electricity, at wind power plant 800kW/RER'
Elec. geoth.	0.000	0.000	--	0.000	--
Elec. solar	0.000	0.000	--	0.000	--
Elec. marine	0.000	0.000	--	0.000	--

Table 5: Applied LCI data for biomass. Data are obtained from Prapaspongsa et al. (2010).

Biomass	Amount	Efficiency	LCI data. Ecoinvent (2010)
Outputs			
Elec. biomass	1 kWh		Reference flow
Inputs			
Burning biomass	1/0.413= 2.42 kWh	41.3%	See the inventory of the burning of biomass in the methodology report of Schmidt et al. (2011).

Table 9: Data for the consequential future scenario—Europe (Merciai, Schmidt and Dalgaard, Inventory of country specific electricity in LCA-Europe 2011)

Flows	Consequen-tial future kWh	Consequen-tial historical kWh	Consequen-tial coal kWh	Attributional kWh	LCI data Ecoinvent (2010)
Outputs					
Electricity, at pp	1	1	1	1	Reference flow
Inputs					
Elec. coal	0.000	0.000	1.000	0.257	'Electricity, hard coal, at power plant/UCTE'
Elec. oil	0.000	0.000	--	0.029	'Electricity, oil, at power plant/UCTE'
Elec. gas	0.127	0.674	--	0.239	'Electricity, natural gas, at power plant/UCTE'
Elec. biomass	0.121	0.121	--	0.031	See **Table 5**
Elec. nuclear	0.000	0.000	--	0.254	'Electricity, nuclear, at power plant/UCTE'
Elec. hydro	0.067	0.000	--	0.153	50% 'Electricity, hydropower, at reservoir power plant, alpine region/RER' and 50% 'Electricity, hydropower, at reservoir power plant, non alpine regions/RER'
Elec. wind	0.580	0.185	--	0.033	'Electricity, at wind power plant 800kW/RER'
Elec. geoth.	0.011	0.007	--	0.003	'Electricity, production mix photovoltaic, at plant/DE'
Elec. solar	0.093	0.014	--	0.002	'Electricity, production mix photovoltaic, at plant/DE'
Elec. marine	0.003	0.000	--	0.000	'Electricity, production mix photovoltaic, at plant/DE'

Table 5: Applied LCI data for biomass based electricity. Data on efficiencies are derived from IEA (2011, p II.28) as the ratio between electricity generation from biomass electricity plants and use of biomass in electricity plants.

Biomass	Amount	Efficiency	LCI data. Ecoinvent (2010)
Outputs			
Elec. biomass	1 kWh		Reference flow
Inputs			
Burning biomass	1/0.262 = 3.82 kWh	26.2%	See the inventory of the burning of biomass in the methodology report of Schmidt et al. (2011).

Appendix Ⅱ Unit process used in Ecoinvent

Incineration

Process/product	Source
Disposal, polyethylene, 0.4% water, to municipal incineration/CH U	Ecoinvent 2.2, unit processes
Disposal, polypropylene, 15.9% water, to municipal incineration/CH U	Ecoinvent 2.2, unit processes
Disposal, polyethylene terephtalate, 0.2% water, to municipal incineration/CH U	Ecoinvent 2.2, unit processes
Disposal, polystyrene, 0.2% water, to municipal incineration/CH U	Ecoinvent 2.2, unit processes

Mechanical recycling

Process/product	Source
Polyethylene terephthalate, granulate, bottle grade, at plant/RER U	Ecoinvent 2.2, unit processes
Polyethylene, HDPE, granulate, at plant/RER U	Ecoinvent 2.2, unit processes
Polypropylene, granulate, at plant/RER U	Ecoinvent 2.2, unit processes
Polystyrene, expandable, at plant/RER U	Ecoinvent 2.2, unit processes

Electricity and heat in Denmark

Process/product	Source
Pellets, mixed, burned in furnace 50kW/CH U	Ecoinvent 2.2, unit processes
Electricity, oil, at power plant/DK U	Ecoinvent 2.2, unit processes
Electricity, natural gas, at power plant/NORDEL U	Ecoinvent 2.2, unit processes
Electricity, Biomass, DK	Ecoinvent 2.2, unit processes
Electricity, at wind power plant/RER U	Ecoinvent 2.2, unit processes
Electricity, hydropower, at power plant/DK U	Ecoinvent 2.2, unit processes
Electricity, hard coal, at power plant/NORDEL U	Ecoinvent 2.2, unit processes
Natural gas, burned in boiler modulating >100kW/RER U	Ecoinvent 2.2, unit processes
Light fuel oil, burned in boiler 100kW, non-modulating/CH U	Ecoinvent 2.2, unit processes

Electricity in Europe

Process/product	Source
Pellets, mixed, burned in furnace 50kW/CH U	Ecoinvent 2.2, unit processes
Electricity, natural gas, at power plant/UCTE U	Ecoinvent 2.2, unit processes
Electricity, at wind power plant 800kW/RER U	Ecoinvent 2.2, unit processes
Electricity, hydropower, at reservoir power plant, alpine region/RER U	Ecoinvent 2.2, unit processes
Electricity, hydropower, at reservoir power plant, nonalpine regions/RER U	Ecoinvent 2.2, unit processes
Electricity, production mix photovoltaic, at plant/DE U	Ecoinvent 2.2, unit processes
Electricity, production mix photovoltaic, at plant/DE U	Ecoinvent 2.2, unit processes
Electricity, production mix photovoltaic, at plant/DE U	Ecoinvent 2.2, unit processes
Electricity, hard coal, at power plant/UCTE U	Ecoinvent 2.2, unit processes

Transport

Process/product	Source
Transport, municipal waste collection, lorry 21t/CH U copy	Ecoinvent 2.2, unit processes
Transport lorry >32t, EURO3/RER U copy	Ecoinvent 2.2, unit processes

Others

Process/product	Source
Paraffin, at plant/RER U	Ecoinvent 2.2, unit processes
Naphtha, at refinery/RER U	Ecoinvent 2.2, unit processes
Refinery gas, at refinery/RER U	Ecoinvent 2.2, unit processes
Naphtha, at refinery/RER U	Ecoinvent 2.2, unit processes
Methanol, from synthetic gas, at plant/CH U	Ecoinvent 2.2, unit processes
Natural gas, production DE, at long-distance pipeline/RER U	Ecoinvent 2.2, unit processes
Lignite briquettes, at plant/DE U	Ecoinvent 2.2, unit processes
Heavy fuel oil, at regional storage/RER U	Ecoinvent 2.2, unit processes
Crude oil, production NL, at long distance transport/RER U	Ecoinvent 2.2, unit processes
Steam, for chemical processes, at plant/RER U	Ecoinvent 2.2, unit processes
Tap water, at user/RER U	Ecoinvent 2.2, unit processes

AppendixⅢ Chemical recycling technologies

Table 10: List of initiatives for chemical recycling (Tukker, et al. 1999)

Technology name	**Technology description**	**Input**	**Output**
Pyrolysis			
BP pyrolysis process	Cracking of plastic waste in a fluidized bed reactor of sand. The product (paraffinic wax) is cleaned from fine particles and HCl (amongst others) and fractionated. 80-90% of the plastic waste is recovered as liquid product. Ca. 20 ppm chlorine remains with an input containing 2% PVC. Process conditions: T = ca. 500ºC	MPW: clean plastic waste, incl. 2wt% PVC (max. 4%), minimum amount of plastics 90 wt%;	Main product is paraffinic wax to be used as a feed for refineries or steam crackers.
BASF pyrolysis process	Liquid phase thermal cracking (pyrolysis/ depolymerisation). The technology was developed to process DSD waste. Due to lack off waste no large scale plant was build and the pilot plant was shut down. 1994-1996 Process conditions: ca. 400 ºC	MPW: max. 8% PVC	HCl, petrochemical gaseous and liquid feedstock
NRC process (NKT Research Centre A/S, Denmark)	Pyrolysis with subsequent metal extraction. The aim is to produce purified calcium chloride instead of HCl. Pilot plant project started in September 1998 and will finish in August 2000. Process conditions: p= 2-3 bar, T= max. 375 ºC;	PVC waste (cables, flooring, profiles...): pre-treatment of mixed plastic waste: separation of PE, PP, wood etc., resulting in almost pure PVC waste;	Calcium chloride, coke, organic condensate (for use as fuels) and heavy metals for metal recycling.
Gasification			
Texaco	Gasification of pre-treated mixed plastic waste. The technology is based on heavy oil gasification and consists of two parts, a liquefaction step (pre-treatment) and an entrained bed gasifier. A pilot is available in the USA. A project to erect a large scale plant (40-50 kt/year of MPW) in Rotterdam (Pax project) ceased around 1997. This was due to lack of feedstock with the right specification. Process conditions: T steam = 1200-1500 ºC, p= 20 - 60 bar, O2, steam;	MPW: max. 10% PVC, plastics content > 90 wt%; Input quality: roughly cleaned and shredded plastic waste;	Synthesis gas (mainly CO and H2), slag, fines.

SVZ process	The MPW is fed into a reactor, together with lignite (in the form of briquettes) and waste oil. This reactor is a solid bed gasification kiln. Oxygen and steam are used as gasification media, and are supplied in counter flow with the input materials. The output synthesis gas is used for various purposes. The main part, around 70 %, is used for the production of methanol. About 20 % is used for electricity production	Chlorine content: 2% as default, though higher concentrations are tolerable	heat, ash, tar oil (ash and tar oil is gasified in an entrained-flow gasification process to produce synthesis gas)
Hydrogenation			
Veba combi cracking process	The plant configuration includes a depolymerisation (visbreaking) section and the VCC section. A plant has been realised in the KAB (Kohleölanlage Bottrop) site. Process conditions: Depolymerisation: T=350-400ºC Hydrogenation: 400-450 ºC, p= ca. 100 bar, CaO, H2;	MPW: max 4% PVC	syncrude (liquid product), gas, HCl, hydrogenation residue.
Blast furnace	Replacement of heavy oil or coal by mixed plastics waste as reduction agent in the pig iron production in a blast furnace.	MPW: chlorine content of up to 1, 5% (ca. 3% PVC) is permitted to be used. The chlorine content should be lower than 2% to avoid corrosion problems in the gas cleaning installations.	
Cement kilns	Cement kilns produce a clinker by sintering alkalic raw materials such as lime (CaCO3), clay (SiO2 and Al2O3) and gypsum (CaSO4) in a kiln at a very high temperature (1450°C in the solid fraction). Cement production demands major amounts of fuel; coal, oil or gas. The energy costs of cement kilns can be up to 25% of the turnover, and the financial benefits of using waste as a fuel are obvious.	The input material should be chipped or shredded. The PVC content is generally limited by licence obligations, 1-2% chlorine often being the maximum for individual waste streams	