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Greenhouse gas emissions and material flows

PART III: Materials used for packaging and building: plastics, paper and cardboard, and aluminium

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This report is a result of the research project *Greenhouse gas emissions and material flows*, a joint project of Institut Wallon, Institut pour un Développement Durable and Vito, co-ordinated by Institut Wallon. The project was financed by the Federal Office of Scientific, Technical and Cultural Affairs as a part of its research program on *Global Change and Sustainable Development - Sub-program 2*.

The approach, results and conclusions of the entire project can be found in the summary report *Greenhouse gas emission reduction and material flows. Final report*, edited by Institut Wallon.

The detailed results of the research of Vito are written down in three reports:

- *Greenhouse gas emissions and material flows. Part I: Analysis of the literature.*
- *Greenhouse gas emissions and material flows. Part II: Production and use of beverage packaging.*
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EXECUTIVE SUMMARY

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This report gives an overview of the flows (production, intermediate and final consumption, imports, exports) and the production and waste treatment processes of some of the materials used for the production of beverage packaging or, in some cases, construction of single family houses: plastics, paper and cardboard and aluminium. Technological improvements resulting in reductions in greenhouse gas emissions are discussed.

The purpose is not to present a detailed and exhaustive analysis of the concerned sectors, but to analyse the features and developments related to the production and the waste treatment of these materials, that might have an important influence on the life cycle greenhouse gas emissions related to the final products that are studied in this project.

For each of the materials quantitative data on the production, import, export and consumption at the different levels in the production and consumption chain have been collected and compared.
Then standard technologies for the production of the materials have been described briefly and opportunities for technological improvements resulting in reductions of greenhouse gas emissions have been identified. Major sources of information were the EIPPCB BREF documents, and the process descriptions and data that were used in the Dutch MATTER project.

Care has to be taken when interpreting production and consumption data. Production data for the production of the primary materials and the corresponding consumption data (refering to the consumption of materials by primary processors) can be derived quite easily from official production and foreign trade statistics. However, most often different processing steps still have to be carried out before these (transformed) materials reach the final consumer. At each of these intermediate production steps often quite important imports and exports occur. Hence, the consumption of the base material by the Belgian transformer is quite different from the consumption of the transformed material by the

Belgian final consumer. This is illustrated for plastics, for paper and cardboard and for aluminium.

A specific difficulty in tracing the material flows up to the level of the final consumer is the quantification of materials used for packaging or for components. Packaging and components are imported and exported as parts of products, and do not appear as such in the foreign trade statistics.

Important cross-boundary flows also exist for selectively collected waste materials, that have been sorted according to grades and qualities and that are internationally traded as secondary raw materials. E.g. the export of waste paper from Belgium more than doubles the use of recovered paper pulp for paper and board production in Belgium.

Plastics

The analysis of the actual flows of plastics and of intermediate organic chemicals in Belgium shows that both availability and reliability of statistics are problematic. Inconsistencies in the quantities reported make any analysis of actual flows of plastics and intermediates for plastics production tedious.

It also shows that no clear link can be established between the Belgian petrochemical production and the final use of plastics in Belgium. At all levels of the production chain of plastic products important import and export streams exist.

The production of plastics, and of the necessary intermediate organic chemicals, is a part of the much larger, highly integrated petrochemical complex. Crucial petrochemical processes, such as the production of ethylene or aromatics, have multiple inputs and outputs. Decisions on which inputs to use and which outputs to produce are based on the complex interactions between supply and demand for inputs and outputs.

Hence, life cycle greenhouse emission factors related to the production of plastics for packaging or for building materials will depend on the evolution of the total petrochemical complex. The MATTER analysis shows that with moderate greenhouse gas emission taxes energy related greenhouse gas emissions from the petrochemical sector can be reduced by about 20%. With drastic greenhouse gas emission taxes major changes in feedstock and products may occur.

Due to the complexity of the petrochemical processes calculating greenhouse gas emission factors for plastics is tedious. This is clearly shown by the striking differences in the older and the more recent versions of the APME ecoprofiles, which in their turn differ quite a lot from other detailed studies.

The quantity of plastics recycled in Belgium is small compared to the total processors' consumption of plastics.
Technologies for recycling waste plastics are in full development. Mechanical recycling of unmixed plastics wastes seems to offer the largest potential environmental benefits. Especially in the case of plastic beverage packaging mono-plastic waste streams can be separated, and regranulated plastics can enter into competition with virgin polymers.

Feedstock recycling techniques have not yet proven to be economically and environmentally reliable. Incineration with a highly efficient recovery of energy might be a valuable alternative. However, this requires integration in a well-developed heat net.

Paper and cardboard

As for the production and consumption of plastics there is a very weak link between the consumption of final paper and cardboard products on one hand and the production of the base materials on the other hand (pulp, base paper and cardboard). There is also a very weak link between the total recovery of waste paper in Belgium on one hand and the use of recovered paper pulp by Belgian paper and cardboard producers on the other hand.

The production of paper and cardboard for packaging production makes out only 15 % of the total paper and board production in Belgium. Import of paper and cardboard for packaging production exceeds the own production by a factor 5. 75 % of the paper and cardboard converting industry converts (mainly imported) paper and cardboard into packaging products. Most of the waste paper that is collected in Belgium is exported.

Energy use is the basic issue to address when considering reductions in greenhouse gas emissions in pulp and papermaking. Both process energy use and energetic recovery can be addressed. For energetic recovery it seems that a major breakthrough might be the IGCC technology for gasification of black liquor. However, major application of this technology is not expected before 2010.
There is quite some potential for CHP. However, it is hard to quantify the potential based on the existing data. The same applies for energy use as such and the other energy saving measures: data are poorly provided and it is difficult to come to quantified conclusions.

The use of recycled paper pulp provides an important potential for reducing energy use. However, the choice of system boundaries is essential for the evaluation of greenhouse gas emissions. The final greenhouse gas emission balance depends on the possible alternative uses for the biomass used for papermaking.

Aluminium

Belgium is a net importer of rough aluminium and a net exporter of intermediates and end products. The exports of intermediates are considerably larger than the exports of end products. The trade in Al waste also exceeds the trade in end products.

The use of aluminium for beverage packaging and for construction of single family houses is limited compared to other materials used. Therefore the overview of aluminium production processes and related greenhouse gas emissions has been kept rather superficial.

Most of the energy-related greenhouse gas emissions are produced during the production of primary aluminium.
40 % of all greenhouse gas emissions in the production of primary aluminium are specific process emissions. More than half of these process emissions are emissions of PCF.

Although PCF emissions have already been reduced by 60 % between 1990 and 2000, they can be further reduced to 20% of the actual level.
Process emissions related to the oxidation of the C anode can be avoided through the use of inert anodes. This technology is actually in the pilot phase.

Greenhouse gas emissions related to the production of secondary aluminium are only 3% of those related to the production of primary aluminium. Thus, recycling offers obvious reductions in greenhouse gas emissions.

A PLASTICS

A.1 Plastics flows

A.1.1 Introduction

When interpreting data on consumption of plastics it has to be checked carefully which definition of consumption is used, e.g. the consumption of primary plastics by plastics processors is not equal to the final consumption of plastics.

The same applies to plastic products. In statistics different types of plastic products are reported:

- intermediates (sheets, plates, tubes, …) that have to be transformed further into final products;
- intermediates / products that will be used as parts for assembling (e.g. cars, furniture, …);
- products for final use.

It is obvious that no statistics are available for the foreign trade of plastics in final products. Patel *et al* and Joosten *et al* have elaborated methodologies to account for this foreign trade[i,ii] (see also *Greenhouse gas emissions and material flows. Part I)*. Patel *et al* also developed a model to account for increasing stocks and the delayed release of waste plastics in long life applications.

However, in the context of this study we will start with a rough analysis based upon existing statistics and show that already at that level a lot of uncertainty exists.

A.1.2 Major plastics and their production routes

The petrochemical industry converts oil products and gas into petrochemicals. The most important groups of petrochemicals on a mass basis are plastics, solvents, fibres, resins and detergents. According to Gielen[iii], in 1994 the production of plastics and elastomers represented 72 % (on a mass basis) of the total petrochemical production in Western Europe.

Three groups of synthetic organic polymers can be distinguished:

- thermosets
- thermoplastics
- synthetic rubbers

Thermosets are heated to mould them in the desired shape. Once hardened the reaction is irreversible. Examples are phenol formaldehydes (phenoplasts), aminoplasts, some polyesters, epoxy resins and polyurethanes.

Thermoplastics can be processed and reprocessed after heating. Examples are polyolefins, vinyl polymers, polyamides, polycarbonates, thermoplastic polyesters, cellulose-derived plastics, …

The plastics that will be studied here are those that play a major role in packaging and in construction (see § A.1.3.5): polyethylene (PE) (low density polyethylene (LDPE), linear low density polyethylene (LLDPE) and high density polyethylene (HDPE)), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS) and expandable polystyrene (EPS), and polyethylene terephthalate (PET).[1]

Plastics are the result of a polymerisation of basic monomers. These monomers are all organic chemicals, most of them derived from fossil carbon feedstock, via the production of lower olefins (ethylene, propylene and butadiene) mainly through steam cracking, and via the production of benzene and xylene, as products of the refineries or as by-products of the steam cracking process.
Production of monomers for the production of primary plastics passes in some cases via several intermediates. Many of these intermediates have several applications next to production of monomers for primary plastics production.

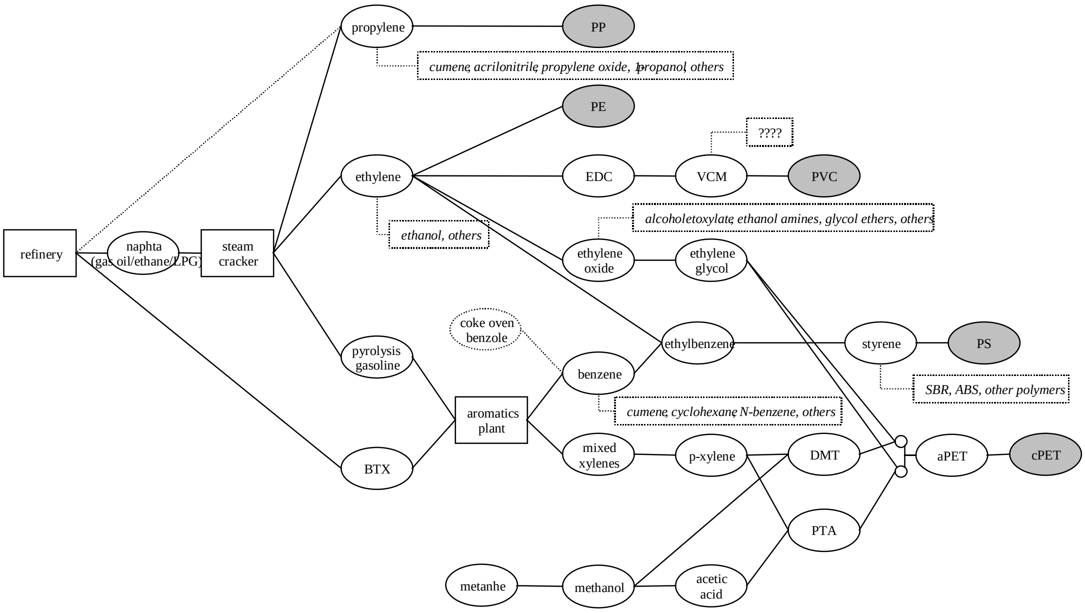

Figure 1 Production routes for the major thermoplastics

Figure 1 shows the production routes for the major thermoplastics, the intermediates in the production process and the alternative applications for these intermediates.

Biopolymers use sugars and starches as basic monomers. They are not considered further.

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[1] The use of polyurethanes (PUR) in building and packaging applications accounts for only 3 % of the total use of plastics for building and packaging.

A.1.3 Production and consumption of primary plastics in Belgium

A.1.3.1 Data sources

Next to the production data from the National Statistics Institute (NSI) and the foreign trade data of the National Bank of Belgium (NBB) the following data sources were used.

APME[2] gives an overview of the plastics consumption in Western Europe in 1998.[iv] This overview is based on detailed data per country, e.g. for Belgium.[v] The data refer to total plastics processors' consumption (processing of primary plastics into plastic products). They may include recycled polymers. A distinction is made for plastics and non-plastics applications[3]. They do not take into account the import/export flows of empty and filled packaging.

Two Belgian industrial federations were contacted: Fedichem[4] and Fechiplast[5].

A.1.3.2 Production of primary plastics in Belgium

According to the 1999 Annual Report of Fechiplast[viii], the production of plastics per inhabitant in Belgium is the highest in the world. In 1998 about 440 kg/inhabitant was produced, equivalent to a total production of about 4500 kton.
Fechiplast also gives figures for the production capacity of the most important plastics.[viii,vi,vii]

NIS provides statistical data on the production of polyethylene, polystyrene, polypropylene, polyvinyl chloride (Table 2). (PET is part of the category "other polyesters". No specific production figures for PET are available, but normally they should be zero, because there is no production capacity for PET in Belgium.)

For the plastics mentioned only the production figures from polyethylene and polypropylene seem to be compatible with the production capacities mentioned by Fechiplast. Production of PVC and of polystyrene exceeds the production capacity, in the case of PVC even with more than 100 %. Probably, some double counting occurs (maybe before and after compounding).

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[2] Association of Plastics Manufacturers in Europe

[3] Fibres, strappings, coatings, woodbondings, elastomers and composite packaging, such as LDPE film in cartons for liquid food are considered as non-plastic applications.

[4] Fedichem : Federation of the Chemical industry of Belgium

[5] Fechiplast : Association of plastics processors, part of Fedichem (Next to Fechiplast a second professional association exists, named Fabriplast. Together Fechiplast and Fabriplast represent about 90 % of the turn over and the employment of the plastics processing sector, of which Fechiplast has a share of roughly 2/3, Fabriplast 1/3, *Personal communication G. Scheys, Fechiplast*)

Table 1: Production capacities in Belgium for the major polymers

	1997 [kton]	1998 [kton]	1999 [kton]
LDPE	770	780	770
LLDPE	0	0	0
HDPE	770	840	910
PVC	345	345	325
PP	1490	1580	1560
PS (including EPS)	585	590	630
PET	0	0	0
ABS	?	?	100
PA	?	130	130
PC	?	130	130
Total		*4395*	*4555*

Table 2: Production of polyethylene, polystyrene, polypropylene and polyvinyl chloride

kton	1996	1997	1998
PE	1645	1701	1591
PS	773	778	789
PVC	757	825	769
PP			1317
total primary plastics	5619	6101	6195

The total production of primary plastics exceeds the production figure given by Fechiplast by 1,5 million tonnes. The figure of Fechiplast is in line with the total production capacity for the major plastics.

Next to the production of virgin polymer a small part of plastics (less than 40 kton) is produced through recycling of waste plastics (see § A.1.4).

A.1.3.3 Import and export of primary plastics

Foreign trade statistics from NBB for 1998 are given in Table 3.

PE, PP, PVC and PS show large net exports. Statistics for 1998 (and 1997) show PE exports exceeding production. This is equally so for PET (no PET production in Belgium) (and for PVC if we compare the export figures with the production capacity for PVC). This would mean that imported products are exported again.

Exports of PP equal 70 % of the production in 1998 and 80 % in 1997. Exports of PS equal 80 % of the production in 1998. Imports equal 55, 41 and 71 % of production for PE, PP and PVC respectively[6]. Only for PS import is comparatively less important (19 % of production).

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[6] In the case of PVC production capacity has been used in stead of NIS production figures

Table 3: Foreign trade statistics 1998

	import [ton]	export [ton]	net import [ton]
PE	882	1842	-960
LDPE (density < 0,94)	519	860	-341
HDPE (density ≥ 0,94)	363	982	-619
PP	541	1143	-602
PS	147	638	-491
EPS	51	225	-174
Other PS	96	413	-317
PET	210	73	137
PVC not mixed with other entities	234	426	-192
PVC mixed with other entities	31	56	-25

From the Fechiplast data and the foreign trade statistics it can be concluded that for plastics large export flows and important imports exist.
However, further examples will show that these statistics sometimes have to be taken with care.

A.1.3.4 Consumption of primary plastics

Plastics consumption in this paragraph is the consumption of primary plastics by plastics processors. The APME data will be compared to a calculation of the apparent consumption from the statistical data (NIS and NBB).

Table 4: Total consumption of plastics in Belgium in 1998[v]

kton/year	Plastics	non-plastics	recycled[a]	total
Thermoplastics	1204	254		1458
Thermosets	99	52		151
			29	29
Total	1303	306	29	1638
[a] *recycled resin from post-user plastic waste*				

Thermoplastics account for 89 % of all plastics consumption (plastics and non-plastics applications) and 92 % of all plastics applications. Thermoplastics used for non-plastics applications are mainly PET (more than 50 % of PET consumption consists of fibres) and PP.
One third of all thermosets are used in non-plastics applications.

With 130 kg/inhabitant (160 kg/inhabitant, when including non-plastics applications), primary plastics consumption is almost double of the average for Western Europe (76 kg/inhabitant)[iv]. Fechiplast gives a figure for plastics consumption of about 175 kg/inhabitant (1785 kton), which is slightly higher. Differences are probably due to differences in the definition of consumption.

Figures for production and consumption in some neighbouring countries are given in Table 5.

Comparing these consumption figures with the production figure of 440 kg/inhabitant (§ A.1.3.2) shows clearly that the production of primary plastics in Belgium is strongly export-oriented (net exports of 265 - 300 kg/inhabitant or 60-70 % of the production).

Table 5: Production and consumption of plastics in some European countries[vi]

kg/inhab.	production	transformation
Belgium	440	175
Germany	155	140
France	100	82
UK	45	77

The first column of Table 6 gives an overview of the consumption of plastics in Belgium per polymer type (for plastics applications only) for the most important polymers. The most used plastics are polyethylene (PE), polypropylene (PP) and polyvinyl chloride (PVC). Of all the other thermoplastics only polyamides consumption comes near to 50 kton. However, more than 60 % of it is for non-plastics applications. All the others are used in quantities of less than 25 kton/year.

Among the thermosets only PUR is used in large quantities for plastics applications.

Table 6: Consumption of plastics in Belgium and Western Europe in 1998 per polymer type (plastics applications only) (Source: APME/TN Sofres[v,iv]*)*

	Belgium		Western Europe	
	kton/year	%	Kton/year	%
LDPE/LLDPE	359	28	6526	21
HDPE	178	14	4473	15
PP	164	13	5003	16
PVC	199	15	5119	17
PS	130	10	2087	7
EPS	28	2	767	3
PET	79	6	1305	4
PUR	50	4	1412	5
Others	116	9	3729	12
Total	*1303*		*30421*	

Except for the higher proportion of PE in the total consumption the shares for the different polymers in Belgium are roughly the same as the West-European averages.

Table 7 shows the apparent consumption of the major polymers calculated from foreign trade data and from production capacities. Production was assumed to equal 95 % of production capacity.

Table 7: Apparent consumption of the major primary plastics (1998) (calculated from NIS and NBB data)

	apparent consumption [kton]
PE	636
LDPE	391
HDPE	245
PP	918
PET	136
PVC	92
PS	258
PC	-
total plastics	*2040*

The total plastics consumption exceeds the figures given by Fechiplast and APME by 250 to 600 kton. Data differ considerably for PP (+3500%), PS (+100%), HDPE (+33%) and PVC (-50%).

Table 8 shows the growth of the most used thermoplastics in Western Europe between 1994 and 1999.[viii] The consumption of polyethylene terephthalate (PET) has more than doubled in 5 years time (because of the increased use of PET in packaging applications).

Table 8: Growth of the most used thermoplastics in Western Europe[viii]

	growth 1998-1999 %	growth 1994-1999 %
LDPE	+ 0,7	+ 3,2
LLDPE	+ 8,5	+ 57,1
HDPE	+ 5,6	+ 23,3
PVC	+ 1,2	+ 6,8
PP	+ 8,2	+ 35,1
PS	+ 2,7	+ 13,9
EPS	+ 1,5	+ 28,5
PET	+ 20,4	+ 123,1
ABS	+ 0,9	+ 15,2
PA	+ 5,6	+40,5
PC	+ 10,0	+38,7

A.1.3.5 Major applications

General

APME also gives a breakdown of plastics consumption by industry sector (Table 9, Figure 2). Packaging accounts for 40 % of total plastics consumption. For Belgium this share even goes up to 50 %.
Although the use of plastics in building and construction is small compared to the total use of building materials (only 0,7 wt%)[ix], the amount of building materials is so large that the building and construction sector in Western Europe consumes about 20 % of total plastics.

Table 9: Consumption of plastics in Western Europe in 1998 per sector (plastics applications only)[iv]

	building[a]		packaging		other	total
	kt/year	%	kt/year	%	kt/year	kt/year
LDPE/LLDPE	302	5	4210	65	2014	6526
HDPE	422	9	2826	63	1225	4473
PP	150	3	2389	48	2464	5003
PVC	3342	65	769	15	1008	5119
EPS	544	71	210	27	13	767
PS	531	25	959	46	597	2087
PET		0	1229	94	76	1305
PU	574	41		0	838	1412
Others	349	9		0	3380	3729
Total	5746	19	12592	41	12083	30421
[a] building: extrapolation of data of 1995 proportional to growth of total plastics use						

Other important applications are found in the household/domestic sector (17 %), the electrical and electronics sector (8 %) and the automotive sector (7 %).

For PET and EPS the packaging and the building and construction sectors cover almost all consumption; for PVC, PE and PS they cover about 70 %. PP and PUR have important applications in other sectors. The category 'other plastics' is mainly used for other applications.

In its annual reports Fechiplast indicates that almost 80 % of the total turn over of its members (plastics processors) is exported. This explains the high primary plastics consumption figure mentioned previously (§ A.1.3.4).

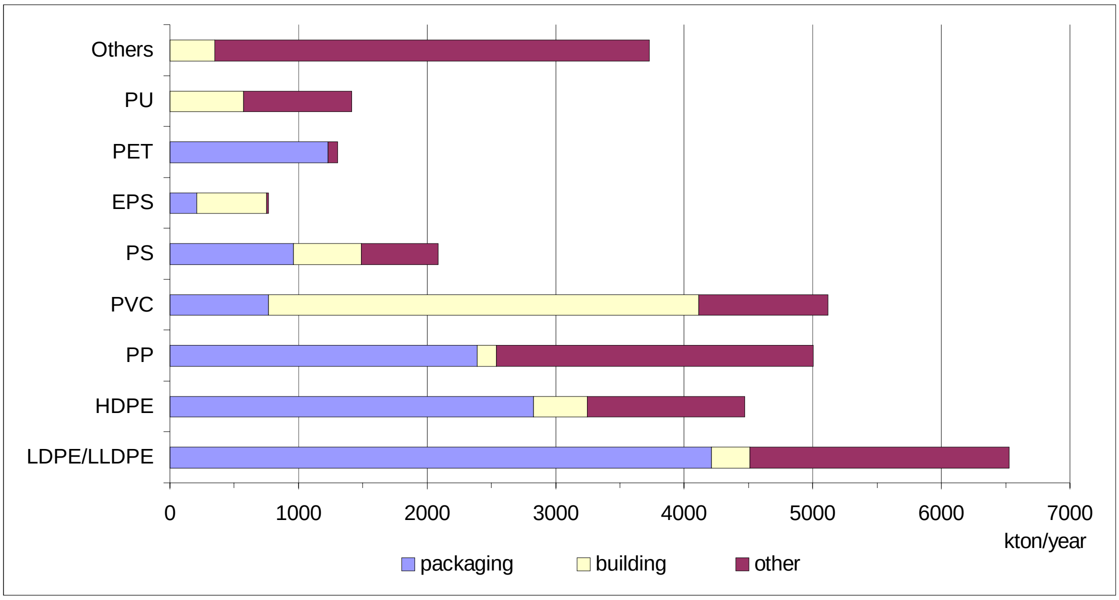

Figure 2: Consumption of plastics in Western Europe in 1998 per sector (plastics applications only)[iv]

Packaging

PE accounts for more than 50 % of plastics use for packaging. PP accounts for about 20 %, followed in decreasing order of use by PET and PS (including EPS) (both about 10 %) and PVC (about 5 %). The use of PET has increased strongly. Excluding use for fibres, which is considered non-plastics use, PET is almost exclusively used for packaging (93 %, of which 88 % bottles)[x].

Polycarbonate (PC) can also be used for bottles and films, but is at present not very important.
Some plastics are used as co-polymers or as a barrier or sealing layer: polyvinylidene chloride (PVDC), ethylene vinyl alcohol (EVOH), polyethylene naphthalate (PEN) and polyamides. The quantities involved are however much lower than for the previously mentioned main plastics.
Polyurethanes (PU) can be used for shaped foam parts. However, their use seems to be negligible.

Finally, two biopolymers can be used for the production of films, foils, bags and bottles: polyhydroxy butyric acid and polyhydroxy butyrate/valerate.

Construction

PVC accounts for 55 % of plastics use for construction (for pipes and ducts, floor and wall coverings, window frames and profiles). PS, EPS and PUR (used for insulation) together make up 21 %. HDPE and LDPE (mainly for pipes and ducts) make up 12 %.[ix]

A.1.3.6 Final consumer consumption of plastics

For estimating the final consumer consumption of plastics we are faced with some difficulties: no statistical data exist on the use of plastics in final products or for the foreign trade of plastics in final products that are not entirely made out of plastics (components, packaging).

In a report on packaging[xi] APME estimates the final consumer consumption of plastic packaging in Belgium in 1997 at 395 kton, of which 288 kton is domestic packaging and 107 kton is distribution or industrial packaging. This figure differs quite a lot from the estimate (138 kton and 90 kton respectively in 1999) based on figures of FOST Plus and Val-I-Pac, which are based on declarations by the affiliated companies and market studies (see *Greenhouse gas emissions and material flows, Part II*).

A.1.4 Plastics waste

A.1.4.1 Plastics waste in Belgium: actual situation

TN Sofres estimated the total amount of post-consumer plastic waste in Belgium in 1998 at 506 kton[v] (Table 10, Figure 3) and at 525 kton in 1999[xii]. Almost 60 % of it is plastic packaging waste.
No figures were found on the amount of plastic waste from plastics production and processing. A German study estimated that both quantities in Germany are roughly equal.[xiii]

Table 10: Post-user plastic waste in Belgium in 1998[v]

	packaging		non-packaging		total	
	kton	%	kton	%	kton	%
landfilling and storage	75	26	172	80	247	49
Incineration	35	12	8	4	43	8
energy recovery	124	42	31	14	155	31
mechanical recycling of local waste	24	8	2	1	26	5
feedstock recycling						
export of waste to be recycled	34	12	1	0	35	7
Total	292	100	214	100	506	100
mechanical recycling of imported waste	*11*				*11*	

Half of all the post-consumer plastic waste is landfilled. However, there is a large difference between the non-packaging waste and the packaging waste. 80 % of all the non-packaging plastic waste and more than 90 % of the plastic waste from building, agriculture and the automotive sector is landfilled. For packaging this is only 26 %. Recycling is for more than 90 % related to plastic packaging.

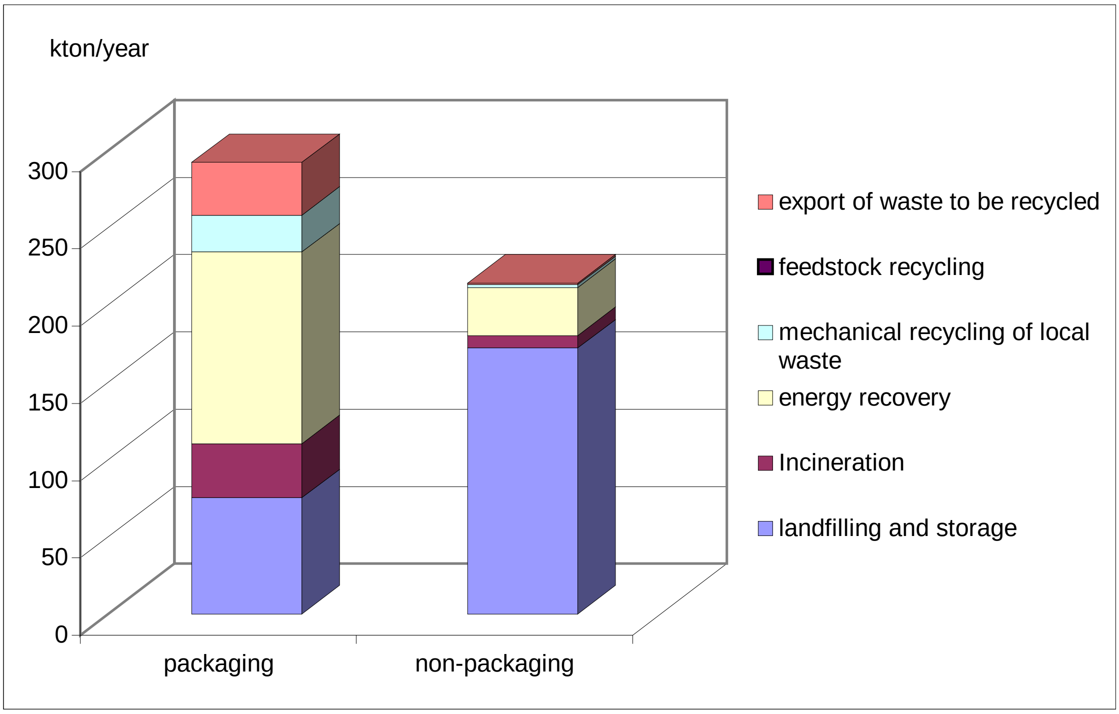

Figure 3: Post-user plastic waste in Belgium in 1998[v]

In 1998 recycling in Belgium (exclusively mechanical recycling) accounted for only 5 % of the total waste stream. For plastic packaging waste this figure rises to 8 %. About 7 % of post-consumer plastic waste is exported to be recycled. On the other hand a small quantity of plastic waste is imported for recycling in Belgium.
According to 1999 data local mechanical recycling has diminished (to 17 kton), and more waste is exported to be mechanically recycled (50 kton).
In 1999 energy recovery was for 97 % related to incineration of mixed waste. 2% was incinerated in cement kilns.

Feedstock recycling of European post-user plastic waste (346 kton) is an almost exclusively German affair (341 kton). 320 kton is recycled in Germany. The remaining 26 kton is exported from Germany to Japan.

These percentages for recycling and recovery are higher than estimates for Western Europe in 1995 (energy recovery: 17 %; mechanical recycling: 7,6 %; feedstock recycling: 0,6 %; export for recycling: 1 %)[xiv]

The quantity of plastics recycled in Belgium in 1998 (37 kton, including import of waste plastics for recycling) is small compared to the total processors' consumption of plastics (1458 kton, thermoplastics only).

Figures from TN Sofres can be compared to FOST Plus and Val-I-Pac data for plastic packaging waste. TN Sofres estimates the plastic packaging waste in municipal solid waste at 200 kton. After correction of FOST Plus data for the market share covered (see *Greenhouse gas emissions and material flows. Part II*) the amount of domestic plastic packaging brought on the Belgian market in 1999 can be estimated at 138 kton. The reason why these figures differ so strongly is not clear. The FOST Plus figure is based on direct declarations of the companies. The TN Sofres figures are based on interviews with waste management organisations and recyclers.

According to FOST Plus 24 kton of the waste of its affiliated companies was recycled in 1998[xv]. The figure given by TN Sofres (based on Belvaplast data) is higher (mechanical recycling of local waste + export of waste to be recycled: 29 kton). In 1999 the quantity recycled through the mediation of FOST Plus has risen to 35 kton (which is still lower than the total amount of plastics waste that was selectively collected by FOST Plus: 47 kton).[xvi]
Use of (corrected) FOST Plus data leads to a recycling percentage of domestic plastic packaging waste of 25 %. Based on TN Sofres data the recycling percentage is only 15 %.

TN Sofres estimates the packaging waste of distribution and industry at 92 kton, of which 23 kton has been recycled. Similar figures can be extrapolated from the Val-I-Pac figures for 1999[xvii] (respectively 90 and 22 kton[7]).

A.1.4.2 Types of plastics waste[xviii]

Packaging waste

Short life products; most of it ends up in the waste stream within one year after production.

Domestic plastic packaging waste

- Plastic bottles and flasks are separately collected in the PMD[8] fraction, of which monoplastic streams of PET, HDPE and PVC are separated.
- The other domestic plastic packaging waste ends up in the rest fraction of the domestic solid waste.

Industrial and distribution plastic packaging waste

- mainly consists of the same material; in many cases they may be of single grade; in most cases they can be reclaimed at modest expenses;
- vessels, pallets, pallet boxes, foils, bags and trays or bins made of PE (HDPE, LDPE, LLDPE); Big Bags or FIBC's (Flexible Intermediate Bulk Containers) made of PP, sometimes with a PE liner; shock absorbing material in packaging made of PUR, expanded polystyrene or other materials

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[7] Total declared packaging quantity 445000 ton , representing 64 % of the total market; 13 % is plastic packaging. Recycling rate for plastic packaging was about 37 %.
[8] PMD : plastic bottles and flasks, metal packaging, beverage cartons

Building and construction

- small percentage of all building and construction waste
- heavily contaminated (stone, glass, …)
- long living applications: 5 to 20 years for furniture, floor covering, …, more than 40 years for conduits, windows, isolation, …

Automotive

- pure plastic streams after selective dismantling of large components: 30 % of all plastics used in a car (about 9 kton)
- a heavily mixed, heavily contaminated stream of shredder residue: 25 % of the total weight of the car; 30-40 wt% plastics (tendency in Europe to energetic valorisation) (9-12 kton)
- future: increasing use of plastics; increasing number of disposed cars with a high plastics content

Electrical/electronical

- increasing proportion
- problems for recycling and valorisation:
  - bromine and chlorine containing fire retardants: risk for dioxin-emissions
  - use of fillers hampers identification and separation

A.1.4.3 Future evolution of plastics waste

An increase of plastic waste is to be expected. The use of plastics has increased dramatically in recent years. Many of these products have a long lifetime and will only end up in the waste stream after several years.

Patel *et al.* estimated that on average 14 years pass until plastic products end up as waste, but there is a wide range, from a few months (e.g. packaging) to 50 years or more (e.g. building materials). Depending on the future development of consumption, they expect plastics waste in Germany to increase by 35-55 % between 1995 and 2005 (average annual growth rate of 3 to 4,5 %). Plastics stocks in the economy will increase from roughly 70 Mt today to a steady-state value of 125 Mt (+79 %, stagnation scenario) up to more than 270 Mt (+ 285 %, high growth scenario).[xiii,i]

APME expects an annual growth rate of approximately 4 % for plastics consumption in Western Europe. Post-use plastics waste, however, is expected to increase by 6,6 % per annum in the same period (with annual increases of 12 and 14 % respectively for PP and PET).[xiv]

Based on these estimates, estimates for post-consumer plastic waste in Belgium in 2005 range from 620-690 kton (Patel *et al*) to 800 kton (APME).

A.1.5 Production and consumption of intermediates for plastics production

A.1.5.1 Production of intermediates for plastics production

Of all the organic chemicals used in the production of the above-mentioned plastics detailed production statistics are only available for ethylene, benzene and xylenes. The other chemicals are reported under aggregated entries.

Table 11: Production statistics for ethylene and benzene (1995 - 1998) (source: NIS)

kton	1995	1996	1997	1998
Ethylene	701	741	851	948
Benzene		204	168	177

For the other chemicals only production capacities are available. These have been compiled from literature data sources and own enquiries (Table 12).

Table 12: Production capacity, foreign trade and apparent consumption for intermediates for plastics production in 1998

	Import[a]	export[a]	net import[b]	Production[c]	production capacity[d]	apparent consumption[b]
Ethylene	1094	226	868	948	1980	2749
Propylene	590	415	175		1610	1704
Benzene	800	102	698	177	540	1211
m-xylene and mixed xylenes				13		
mixed xylenes	1	7.3	-6.4		25	17
p-xylene	not available	0.05			0	-
Ethylbenzene	4.7	15.4	-11		530	493
Styrene	554	345	208		500	683
Chlorine					610	
Dichloroethane	0.7	102	-101		1935	1737
vinyl chloride	34	84	-50		975	877
terephthalic acid	184	not available			920	-
dimethyl terephthalate	1.5	0.1	1.4		0	1.4

sources:
[a] NBB
[b] calculated
[c] NIS
[d] compiled from literature data sources and own enquiries

Both for ethylene and benzene the production figure from NIS is less than half the installed capacity. This raises serious doubts if all the production has been declared. An explanation for the large differences might be that companies do not declare the quantities that are used internally for further transformation (e.g. ethylene and benzene transformed into ethyl benzene, ethylene transformed into ethylene oxide or polyethylene, …).

A.1.5.2 Import and export of intermediates for plastics production

Table 12 also gives the reported import and export figures for these intermediates.
Some import or export data are not available because of confidentiality reasons. This is e.g. the case for the import of p-xylene and the export of purified terephthalic acid (PTA), because there is only one producer of PTA in Belgium.[9]

The apparent consumption of these organic chemicals was calculated from the foreign trade data and from the production capacities. Production was assumed to equal 95 % of production capacity.

An inconsistency appears when comparing import and export figures with production capacities for the production of vinyl chloride monomer (VCM). VCM is almost exclusively used for the production of PVC. However, the consumption figure for VCM in 1998 calculated on the basis of the import and export statistics and the production capacity for VCM do not match with the production capacity for PVC. Considerable exports (up to 500.000 tons) are not reported (as confirmed in this case by Fechiplast and by one company).

These inconsistencies show that these production and foreign trade statistics have to be taken with care.

A.1.5.3 Conclusions on the availability and use of statistical data

To make a full analysis of the actual flows of plastics and intermediates for plastics both availability and reliability of statistics are problematic.

Inconsistencies in the quantities reported, as well for the production statistics as for the foreign trade statistics, make any analysis of actual flows of plastics and intermediates for plastics production and consumption tedious or even impossible.

No other data than those reported here could be found (no additional data available at Fedichem or Fechiplast). Some companies gave figures on their actual production. However these data are not complete.

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[9] Production capacity for PTA was at about 450.000 ton in 1998. 500.000 tons of additional capacity was installed in 1998. 180.000 tons of PTA were reported to be imported.. PTA is used almost exclusively for the production of PET and there is no PET production in Belgium. Hence, the bulk of the PTA production has to be exported. However, this is not reported in the export statistics.
On the other side of the production chain p-xylene is used for the production of PTA. Up to 2000 the production capacity for p-xylene in Belgium was very low compared to the needs for the production of PTA. However, no imports of p-xylene are reported.

A.1.6 Link between consumption and production of plastic products in Belgium

In order to gain more insight in the links between the Belgian consumption of plastic products and the Belgian production system two complementary analyses have been made:

1. an analysis of the material flows in the production system for polyethylene bottles;
2. an analysis of the origin and of the consumption of plastic products based on the input-output table for the Belgian economy in 1990.

A.1.6.1 Material flow for PE from ethylene production to end use of PE bottles

Figure 4 shows the material flows, starting from the calculated consumption of ethylene to the final use of PE in packaging or building materials. Some assumptions had to be made to complete the picture[10]. The lines are proportional to the magnitude of the flow (in kton).

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[10] % use of PE for packaging, building was based on European averages : see Table 9
PE use for bottle production was estimated at 1/5 of total PE use for packaging

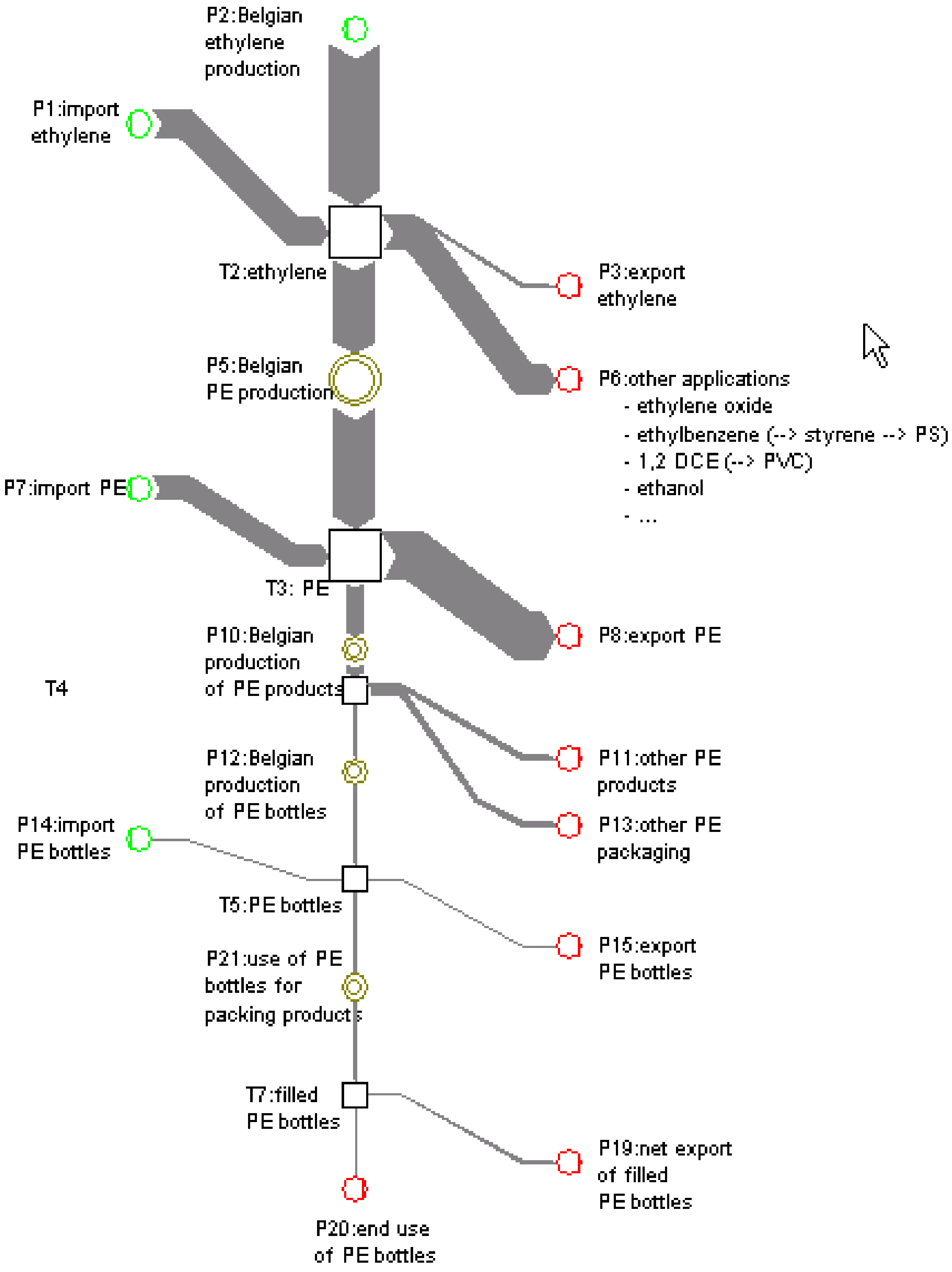

Figure 4: Polyethylene flows and end uses

Ethylene consumption

Table 13 shows estimates for the consumption of ethylene for different applications.
About 55 % of the ethylene consumption is used for polyethylene production. This figure matches with European estimates of 59 %[iii]. Which part of it is local production and which part of it is imported is difficult to say.
Ethyl benzene is almost entirely used for styrene production. Styrene is used for polymer production: PS, SBR, ABS, … VCM is mainly used for the production of PVC.

Table 13: Estimates of ethylene consumption according to application

	production capacity [kton]	ethylene consumption [kton]	[%]
Polyethylene	1620	1539	55,0
Ethyl benzene	535	134	4,8
VCM	975	415	14,8
ethylene oxide	500	302	10,8
residual ethylene consumption		410	14,6
Total		2749	

Assumptions :
- *no losses in production; all ethylene is transformed into the final product*
- *95 % of production capacity used*

Polyethylene consumption (= production of polyethylene products)

PE exports are higher than local production. This means that some of the imported PE is exported again (see higher).
PE use for production of packaging is calculated at 20 % of total Belgian PE production. PE use for production of building and construction materials is calculated at 2 % of total Belgian polyethylene production. However, the import of PE is larger than the use for production of packaging or building and construction materials, which means that theoretically all PE for packaging and for building and construction materials can have been imported. Probably in reality part will have been imported and part will have been produced in Belgium. The I/O table does not provide enough detail to trace the origins of the PE.[11]

Consumption of polyethylene bottles

Consumption of polyethylene products was calculated for the case of PE bottles. No direct information on the import or export of PE bottles is available. Data are available on

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[11] If we assume that PE consumption is proportionally distributed over Belgian and foreign production, Belgian PE production for Belgian consumption equals about 25 % of total Belgian PE production. In this case we also assume that 75 % of the imported PE is exported again. However, it would seem logic to assume that most of the imported PE would be transformed into products. In that case the share of Belgian PE production for Belgian consumption would be lower.

the foreign trade of plastic bottles in general. Of these, 33 % are assumed to be PE bottles.

End use of HDPE bottles accounts for only 1,1 % of total Belgian PE production. Tracing back the production location of the PE used for these bottles is impossible. All of it can have been produced in Belgium or it can have been imported at different levels in the production chain, even all of it. Even tracing back if the bottles themselves have been produced in Belgium seems hardly possible.

A.1.6.2 Analysis of production and consumption of plastic products using the I/O table

In the following analysis of the share, the Input/Output table of 1990[xix] (the most recent one available) was used to calculate the share of the domestic production in the domestic consumption of plastics. All production, deliveries, imports and exports are expressed in monetary terms.

Import, export, production and consumption of plastic products

Belgium is a net exporter of plastic products. Imports, exports and production are of the same magnitude.

Table 14: Import, export, production and consumption of plastic products

million BEF	Belgian (intermediate and final) consumption					export	total
	Food	beverages	construction	others	total		
Belgian production	3392	82	2544	20193	26211	101714	127925
Import	4778	112	12575	63153	80618	3138	83756
Total	8170	194	15119	83346	106829	104852	211681

Table 14 clearly shows the dominance of foreign trade flows of plastic products (import for Belgian consumption, Belgian production for export) compared to Belgian production for Belgian consumption.

Of all intermediate and final domestic consumption of plastic products only 25 % is Belgian production. 75 % is imported.

Of the total Belgian production of plastic products only 20 % is consumed in Belgium. 80 % is exported. (The same figure was already cited from the Fechiplast annual reports, § A.1.3.5).

Consumption of plastic products in the packaging and the building sector

The input-output tables do not give specific data on packaging. We can assume that a large part of the plastic products delivered to the beverage and food sectors consists of packaging materials. Of these, 40 % is produced in Belgium. 60 % is imported.

Only 17 % of the plastic products consumed in the construction sector are produced in Belgium. 83 % is imported.
Belgian production of plastic products for consumption in the food, beverages and construction sectors is marginal compared to total Belgian production of plastic products. (This does not include non-food packaging.)

Inputs for the production of plastics products

About 55 % of all the inputs for the production of plastic products come from the chemical sector (Table 15). These inputs include primary polymers. Only 10 % of these chemical products are of Belgian origin. 90 % is imported. This is consistent with the large import and export flows for individual polymers that were already cited from the foreign trade statistics.

Table 15: Origin of inputs for production of plastic products

million BEF	chemical sector	total
Belgian production	4909	26568
Import	43263	61548
Total	48171	88116

A.1.6.3 Conclusions

Production of plastic products in general, and plastic packaging or building materials more specifically, is strongly export-oriented. 80 % is exported. On the other hand, of all plastic products consumed in Belgium, only 25 % is of Belgian origin.

Already at the level of the intermediate consumption of PE the link with the Belgian production system for PE (PE production, ethylene production) is very weak. The origin of the PE used by the Belgian plastics' processors cannot be traced easily.
This is confirmed by the analysis of the input data for plastic products. Only 10 % of the chemical intermediates (among which primary plastics) used in the production of plastic products (expressed in monetary terms) are produced in Belgium.

The link between the final consumption of plastic packaging (or even more detailed, plastic beverage packaging) and plastic building materials, and the production system for PE is as good as non-existent.
Residual demand[12] (Belgian and export) for ethylene and for PE at the different levels largely outweighs the intermediate demand for primary PE for the production of packaging or building materials, and even for the production of PE products as a whole.[13]

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[12] residual demand : demand not covered by the considered end uses

[13] Part of the ethylene for other applications will also end up in packaging or building applications. This is the case for PVC or PS products (and much less for PET products) of which almost 80 % are used for packaging or building applications. Nevertheless, these plastics, as well as the intermediates in their production system, are also traded in

Another (methodological) difficulty in linking Belgian consumption to Belgian production can be demonstrated with the case of PET. There is no PET production at all in Belgium, although there is a significant production of terephthalic acid, one of the intermediates in PET production.

It can be concluded that the link between the Belgian production system for plastics and plastic products and the final (or even intermediate) consumption of plastic products in Belgium is very weak and seems hard to quantify. Changes in the final domestic consumption of plastic products will not influence the Belgian production system significantly, and if they do, the effect of these changes seems hard to quantify with the available data.

A.2 Plastics production processes

A.2.1 Relevant processes

This part will give a short overview of the production methods for the main plastics mentioned above, focussing specifically on existing options for greenhouse gas emission reduction.

However, considering the very weak link between the final consumption of plastic packaging or building materials and the Belgian production of basic organic chemicals, there is no reason to analyse the Belgian production system for basic organic chemicals to assess the impact of (changes in) the considered final consumption on GHG emissions. Hence, the following analysis will draw on European state-of-the-art technology.[14]
For the same reason an optimisation of the production system based on the considered final consumption does not make sense. Changes in the Belgian final consumption will not have significant effects on the production system. Hence, we will look for possible evolutions in the "cradle-to-factory gate" GHG emission factors for the considered plastics.

In the MATTER MARKAL model[xx] alternative options exist for the following petrochemical processes (including plastics production):

- for the production of ethylene, propylene and aromatics different options exist:
    - cracker feedstock options: gas oil, LPG, ethane, naphtha
    - 0recovery of propylene, benzene, xylene from refineries
    - ethylene, propylene recovery from off gases from fluid catalytic cracking (FCC)

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large volumes (VCM, intermediate between ethylene and PVC, is exported in large quantities; considerable trade also exists in styrene; both for PS and PVC local production is to a large extent export-oriented), which means that the same observations as those made for PE are valid.

[14] Patel *et al*[i,xiii] also refer to state-of-the-art technology to "reflect the German situation" (*"In terms of technology, production is modelled in Western Europe in the mid 1990s."*). Reasons for this are that the state-of-the-art technology is very similar for the whole of Western Europe (and even of the whole of the industrialized countries) and that specific data are hard to get.

  - alternative technologies:
    - oxidative coupling (output mainly ethylene)
    - MTO (methanol-to-olefins) (output ethylene, propylene, C4)
    - flash pyrolysis wood (output ethylene, BTX)
- for the other petrochemical processes:
  - caprolactam production (3 alternatives, 2 of them directed at N_2O emissions mitigation)
  - adipic acid production (2 alternatives, one directed at N_2O emissions mitigation)
  - PUR production (2 alternatives: standard and using lignin)
  - biomass options for butadiene, butanol, ethanol, methanol, acetic acid, acetone, 1-propanol
- waste treatment options (recycling, energy recovery)

For our purpose only the production of ethylene, propylene and aromatics, and the waste treatment options are relevant.

A.2.2 Primary plastics

A.2.2.1 Polymerisation

Polymerisation is the coupling of monomers to macromolecules. According to the chemical process a distinction is made between:

- radical polymerisation of unsaturated hydrocarbon monomers (e.g. PE, PP, PS);
- polycondensation of bifunctional monomer molecules with the release of water (e.g. PET); these polymers can be hydrolysed again when water is added to the melt;
- polyaddition in which monomers are coupled through a kind of intramolecular isomerisation; no reaction product is split off (e.g. di- or tri-isocyanates and diols or polyols reacting to form polyurethanes); these molecules are also sensitive to water.

Polymers can be amorphous or semi-crystalline. They can be linear or more or less branched. The properties of the polymer are highly dependent on the number and the length of the side branches. Linear chains, chains with few side branches and chains with very short side branches allow the polymer to pack in a regular structure in the solid state, producing a high-density crystalline structure with superior mechanical properties.

If two or more different monomers polymerise together the resulting polymer is called a co-polymer (e.g. ethylene vinyl acetate, styrene butadiene rubber (SBR)).

In most cases additives are used: pigments and colouring agents, stabilisers (to protect for degradation caused by temperature, UV radiation or light), plastifiers and fillers. For some applications flame retardants are added (e.g. plastics used for electrical and electronic appliances). Some of these additives can contain heavy metals (pigments, stabilisers), chlorinated or brominated organics (flame retardants). Some plastifiers (e.g. phthalates) are suspected to be carcinogenous.

Different polymerisation processes can be distinguished:

- without a solvent:

  - liquid phase polymerisation (bulk polymerisation or high-pressure polymerisation): a liquid monomer phase
  - gas phase polymerisation (low-pressure polymerisation): a gas phase and a solid phase in a fluidised bed reactor, low pressure (7-20 bar) and a temperature of 70-100 °C
- with a solvent:
  - solution polymerisation: uses a solvent in which both the monomer and the polymer dissolve, pressure 30-100 bar, temperature 150-250 °C
  - suspension or slurry polymerisation: only the monomer is soluble in the solvent; the polymer precipitates; during polymerisation the reaction mixture is stirred heavily, stabilizers are added to prevent coagulation; the catalyst is soluble in the monomer, pressure beneath 40 bar, temperature beneath 110°C
  - emulsion polymerisation: the monomer and the polymer are emulsified in water; the catalyst is water-soluble.
    The advantage of the emulsion process is that it is a continuous process. On the other hand the presence of emulsifier or catalyst residues in the final polymer can influence its quality (e.g. less transparency in the case of PVC).

Polycondensation takes place at high temperatures and with long reaction times. Unlike the polymerisation processes, the polycondensation process is endothermic.

Table 16 summarises the processes that can be applied for the production of the major plastics.

Table 16: Polymerisation processes for different polymers

	temperat. °C	pressure bar	HD PE	LD PE	LLD PE	PP	PS	PVC	PET
Liquid phase	< 100	high/low		■	■	■	■		■
gas phase	70-100	7-20	■		■	■			
solution	150-250	30-100	■		■	■	■		
suspension emulsion	< 110	< 40	■	■	■	■	■	■	
Polycon-densation	230-285								■

grey boxes indicate which processes can be applied

A.2.2.2 Main production routes

Polyethylene

Depending on the reaction conditions the polyethylene polymer chains may be highly linear or side-branched. Three main groups are distinguished (Table 17): high-density polyethylene (HDPE), low-density polyethylene (LDPE) and linear low-density polyethylene (LLDPE).

- LDPE is produced at a temperature of about 200 °C (cooling is used to keep temperature below 350 °C at which ethylene might decompose) and at a very high pressure (1500 atm / 2000 - 3000 bar) in a tubular or autoclave reactor. The resulting polymer contains a lot of long side branches.
- HDPE is produced at lower temperature and pressure (25-50 bar) in a reactor containing a liquid hydrocarbon diluent and Ziegler Natta catalysts, or by gas phase polymerisation. The molecules are less branched and can be packed more tightly, leading to a higher degree of crystallisation, a higher rigidity and a higher melting temperature.
- LLDPE contains short side branches. It is actually produced at low pressure through co-polymerisation (slurry or gas phase polymerisation) of ethylene with 1-alkenes (mainly 1-butene, also 1-hexene, 1-octene).

Metallocene catalysts that are claimed to give improved properties, have joined the traditional Ziegler-Natta and chromium catalysts. Metallocenes also allow slurry loop operators to enter the LLDPE market. Bimodal processes, using twin slurry or gas phase polymerisation or a combination of reactors, claim to produce resins competitive with those from metallocenes.

Table 17: Types of polyethylene

	Density	melting temperature	branching
LLDPE	0,910-0,925		high short branches
LDPE	0,910-0,925	110 °C	high long branches
HDPE	0,940 - 0,965	130 °C	Low

Polypropylene

Polypropylene is made from propylene monomers using a Ziegler Natta type catalyst. The three main types of commercial processes are:

- suspension polymerisation (solvent: propylene or hexane/heptane)
- liquid phase polymerisation
- gas phase polymerisation.

In the continuous polymerisation process liquid propylene is dissolved under low pressure at a temperature of 40-90 °C in an inert hydrocarbon solvent (heptane, nonane) in which Ziegler Natta catalysts are dispersed.

The difference with polyethylene is that alternate carbon atoms are attached to a -CH3 group rather than to a hydrogen atom.
PP typically has a density of 0,905 and a melting temperature around 165 °C.

Polyvinyl chloride

PVC is produced from vinyl chloride monomer (VCM, see), using a suspension, an emulsion or a bulk process. The suspension process is the one most extensively used (average European market shares: suspension PVC: 80 %, emulsion PVC: 13 %, bulk PVC: 5 %[xxi]). The emulsion process requires considerably more energy than the suspension process. It leads to polymers with a high molecular weight, but the emulsifiers are difficult to eliminate, which can be a problem for some applications[xxiii]. The bulk process uses still less energy. However, it leads to PVC of inferior quality.

The PVC separated from the polymerisation process is a powder. Additives are added afterwards to form granulated compounds or powder pre-mixes.

In comparison with other thermoplastics PVC can be used with a large range of additives (Table 18). Thanks to these additives PVC with very high molecular weight can be processed. Combination of plastifiers with PVC with a very high molecular weight has allowed developing flexible products with elastomer properties with exceptionally high resistance against abrasion. In the case of rigid PVC the number and quantity of additives is low. In other cases the total quantity of additives can go up to more than 50 % of the total product.

Table 18: PVC composition for different applications[xxii]

	PVC resin %	fillers %	phthalates etc. %
Wiring	42	36	22
Foils	32	50	18
Carpets	28	57	15
Pipes	93	5	2
window frames	78	18	4

The total PVC market in Western Europe roughly consists of 2/3 rigid applications and 1/3 flexible applications. 61 % of all PVC is used in the building and construction sector, 18 % for packaging[xxiii].

Polyethylene terephthalate

PET is a thermoplastic polyester resulting from a condensation reaction. Two production routes are used in the production of PET:

- terephthalic acid (TPA) route: p-xylene is oxidised to TPA which, after purification (selective catalytic dehydrogenation), reacts with ethylene glycol to form bishydroxyethyl terephthalate (BHET).
- dimethyl terephthalate (DMT) route: p-xylene is oxidised and reacts immediately with methanol, producing DMT. When the DMT reacts with ethylene glycol again BHET is formed. The methanol is liberated and can be recovered and re-used.

Polymerisation of BHET in the liquid phase yields amorphous PET (APET) used for the production of fibres and films. A second polymerisation in the solid state increases the molecular weight and produces partially crystalline PET (CPET) used for production of bottles via injection moulding and stretch blow moulding.

Polystyrene

PS is a versatile polymer resin used in a wide range of applications - especially in the packaging industry. It is sold in three main forms: crystal or general purpose polystyrene (GPPS), high impact polystyrene (HIPS) and expandable polystyrene (EPS).

The crystal form is pure PS with few additives and is used when clarity is required even though it is very brittle. The high impact form is translucent or opaque because of rubber compounds (e.g. polybutadiene) added to the reaction and incorporated into the resin to inhibit crack propagation and hence reduce brittleness. The expandable form is the same as the crystal form except that low molecular mass hydrocarbons, usually pentane, are incorporated into the finished resin. These additives vaporise during subsequent processing to produce a foam.

PS is formed through polymerisation of styrene (see §   ).

- bulk polymerisation: the formed PS is highly transparent, but the length of the macromolecules is too divers to use it for injection moulding. This method has been replaced by suspension polymerisation;
- suspension polymerisation: better controlled molecular weight but less transparent;
- emulsion polymerisation: used for high impact polystyrene (HIPS).

In modern processes the polymerisation takes place in solution in the styrene monomer, at high temperature, but without addition of solvents or catalysts.

A.2.3 Intermediates for plastics production

A.2.3.1 Lower olefins production

Applications of lower olefins

Ethylene is mainly used in the production of:

- polyethylene
- 1-2 dichloroethane → vinylchloride monomer (VCM) → PVC
- ethylene oxide → polyol, glycol (→ PET)
- ethylbenzene → styrene (→ PS)
- acetaldehyde → acetic acid → vinyl acetate
- ethanol

59 % of ethylene is used for polyethylene production. 17 % is used for the production of VCM. [xxv]

Propylene is mainly used in the production of:

- polypropylene
- acrylic acid → acrylic esters
- cumene→ phenol, acetone
- acrylonitrile → fibers
- butyraldehyde → butanol, ethylhexanol
- propylene oxide → polyol, glycol, …
- 1-propanol
- other

More than 50 % of propylene is used for polypropylene production. [xxiv]

Over the next five years, ethylene is forecast to grow at around 2,4 % per year. Propylene demand is predicted to increase at 3,9 % per year.[xxiv]

Main production routes

Ethylene, propylene and butadiene are mainly produced by the steam cracking process. In Western Europe this process accounts for 98 % of all ethylene and butadiene produced, and for 75 % of all propylene[xxiv].
Propylene is also recovered from off-gas from Fluid Catalytic Cracking of primary distillate in refineries. Finally, it can also be produced through dehydrogenation of propane, but this is only economic when propane prices are low.

Steam cracking

- General description[15]

In a steam cracker hydrocarbons from the feedstock are cracked into smaller molecules. The cracking reaction is highly endothermic. The hydrocarbon stream is preheated and mixed with steam. It is then fed to a tubular fired reactor where it is heated to 750 - 875 °C for 0,1 to 0,5 seconds under controlled residence time, temperature profile and partial pressure.
Separation of cracked products can only be achieved under cryogenic conditions, at temperatures as low as -150 °C. By their very nature therefore, steam crackers are highly energy-integrated units. As much energy as possible is recovered immediately downstream of the pyrolysis furnaces, principally through the generation of high-pressure steam, which is then generally used to drive turbo-compressors for both the charge gas and refrigeration systems.

After the cracking furnace the resultant gas is cooled in steam-generating facilities. The primary fractionator is used to condense out and fractionate fuel oil streams produced from naphtha and gas oil fed crackers. Further cooling of the gases takes place in the

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[15] A detailed description of the process can be found in the EIPPCB BREF document[xxiv].

quench tower by a circulating oil or water stream (used as medium level heat source for the rest of the plant).

The remaining gases are further separated in the product fractionation section. This section consists of a chilling train, various fractionation towers and C2/C3-hydrogenation units. (cryogenic distillation of gaseous compounds in several sequential steps).

Ethane and propane are recycled to the reaction furnace feed. Methane is used as fuel gas. Hydrogen is used for hydrogenation of acetylene (removal of acetylene from the ethylene stream).

The debutaniser overhead product contains an appreciable quantity of butadiene. The raw C4 stream can be:
- selectively hydrogenated to butanes
- fully hydrogenated to butanes for recycle cracking or LPG sales
- sent to a butadiene extraction unit, where it is separated into butadiene, butane and butenes through solvent extraction and extractive distillation.

The quantity of cracked gasoline produced in a naphtha cracker (25-40 wt% benzene, 10-15 wt% toluene) usually justifies a hydrogenation unit to remove diolefins for preparing as feedstock for aromatic extraction units (aromatics plant, see § A.2.3.2).
Pygas may also be fractionated to recover C5 molecules for specialist applications or heat soaked to produce a stable stream that can be blended into motor gasoline.

Whilst the steam cracking process employed on the more than 50 plants in Europe is broadly similar, each plant is virtually unique in terms of the parameters, which determine its economic optimum configuration for the producer.

- Feedstock

In Western Europe naphtha accounts for more than 70 % of the feedstock for steam cracking. Alternative fossil feedstocks are gas oil, butane, ethane, propane and other sources (Table 19). Gas feedstocks are less used in Europe because they are rarely economically available.[16]

Flexible crackers can run on different feedstocks. They are more expensive but they have the opportunity to use the fossil feedstocks which is cheapest at the moment, or which produces the currently most valuable products.

In Europe, few plants are able to take advantage of the availability of gas feedstocks, although many do have limited flexibility to process some LPGs. The characteristics of a "gas" feedstock steam cracker are somewhat different from one designed for "liquid" feeds. Consequently, the degree of flexibility for feedstock selection is limited.

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[16] There are few locations where sufficient gas is concentrated to allow economic recovery of ethane from natural gas. Cracking of fairly significant quantities of liquefied petroleum gas (propane and butane) occurs during the summer months when seasonal effects reduce the cost of LPG relative to naphtha.

Table 19: Feedstocks for steam crackers in Western Europe

Feedstock	EIPPCB BREF[xxiv]	Groenendaal Gielen[xxv]	Joosten[x]
Naphtha	73 %	73 %	63 %
gas oil	10 %	16 %	15 %
Ethane	5 %	6 %	9 %
Butane	6 %	6 %	13 %
Propane	4 %		
Others	2 %		

- Outputs

The steam cracking process results in different output fractions (Table 20). Ethane and propane (and sometimes butane) are recycled to the reactor to increase ethylene and propylene yields.

Yields for ethylene and propylene depend on the feedstock, decreasing from ethane to LPG, naphtha and gas oil[17], and on the process adjustments. 'High severity cracking' at higher temperatures and shorter residence time needs more energy but it reduces the secondary reactions that promote coking. It yields more ethylene and less propylene than 'low severity cracking'.
Comparison of data on cracker yields for ethane, naphtha and gas oil from Patel[i], Groenendaal and Gielen[xxv], Joosten[x] and EIPPCB[xxiv] gives comparable figures (Table 20).

Table 20: Steam cracker yields for different feedstocks

	ethane	naphtha	gas oil
Ethylene	80 - 81 %	29 - 30 %	22 - 25 %
Propylene	1 - 2 %	16 - 17 %	14 - 15 %
C4	3 %	8 - 10 %	9 - 11 %
pyrolysis gasoline	1 - 3 %	21 - 24 %	20 - 22 %
Methane	6 - 7 %	13 - 15 %	8 - 12 %
Hydrogen	6 %	1 - 2 %	1 %
pyrolysis fuel oil	-	4 -5 %	15 - 22 %

Ethylene manufacture via the steam cracking process is a mature technology that has been the industry standard for almost 50 years. The process continues to be improved, notably in the development of furnace design where new materials and enhanced coil configuration has led to a significant improvement in conversion and selectivity to the

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[17] As a general rule, the conversion of hydrocarbons to lower olefins decreases as the molecular weight of the feedstock increases.

desired products. Improvements in the efficiency of machinery and distillation column internals have allowed greater throughput with the same major equipment items.

- Costs

For a plant of 600.000 t/year ethylene capacity, built on a greenfield site, typical European investment costs are given in Table 21.[xxiv]

Table 21: Ethylene plant investment costs for different feedstocks

Feedstock	total cost M euro	cost per ton ethylene capacity euro/t ethylene
Ethane	540-600	900-1000
Naphtha	660-780	1100-1300
Gasoil	720-850	1200-1400

CEFIC[18] concludes that at average cracker margins, investment in non-advantaged greenfield plant in Europe cannot return its cost of capital. This would only be possible if there is access to lower cost gas feedstocks, co-location with other production units (sharing common services) or investment in "brownfield" sites where infrastructure already exists.
The "core” cost of a cracker (inside battery limits) might be expected to account for around 60-65 % of the total greenfield plant cost.

The figures are much higher than those cited by Joosten[x]: 438, 691 and 802 ECU1994/t ethylene capacity for ethane, naphtha and gasoil respectively. These figures include ISBL, off-site costs and 15 % contingency. They are based on figures from a 1989 publication.

Investment in a new plant is normally justified over at least 20 years. In the cracking section, some components will require to be replaced several times in this period, because of severe operating regime, whereas much of the equipment in the recovery section has a life expectancy in excess of 50 years.
Some 75 % of new capacity brought on-stream in the last 10 years has been achieved through investment in expansion projects rather than in new facilities.

Recovery of olefins from fluid catalytic cracking (FCC) offgases

Because naphtha and gas oil are the predominant feedstocks in Europe, a large proportion of propylene demand (and the whole of the butadiene demand) can be satisfied by the steam cracking process. The balance of propylene demand is supplied from extraction of propylene from refinery FCC offgas and imports. Propylene recovery from FCC offgases accounts for about 25 % of total European propylene production.

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[18] Conseil Européen de l'Industrie Chimique (European Chemical Industry Council)

In Fluid Catalytic Cracking heavy (vacuum) gas oils from refineries are cracked into lighter fractions. The most important product is gasoline. Lighter fractions are by-products.

Per ton of feedstock only a small amount of olefins can be obtained (ethylene ± 0,7 %, propylene ± 0,5 %). Because of the high throughput of catalytic crackers (1000-3000 kton/year) reasonable olefin yields can be obtained.[x]

Other

There is one propane dehydrogenation plant in Europe (in Antwerp). Interest is growing in propane dehydrogenation in cases where LPGs are abundant and inexpensive.

There are other technologies for increasing the production of propylene relative to ethylene. However, none of them is expected to offer significant environmental performances, and they are only relevant for specific locations and commercial conditions.

Prices

The prices of products and feedstocks are highly cyclical. The price of naphtha has fluctuated by 93 % over the period 1993 -1998, and this has resulted in product price fluctuations ranging from 63 % (for butadiene) to 104 % (for propylene).

Table 22: Price ranges for naphtha, ethylene and propylene in the period 1993 - 1998[xxiv]

	price range (Euro/ton)
Naphtha	95 - 185
Ethylene	320 -520
Propylene	220 - 450

Technological and environmental perspectives[xxiv,x]

In the last decades there have been no major technological breakthroughs in steam cracking.

The EIPPCB BREF document lists a number of recent advances in conventional steam cracking. They are mainly focused on plant de-bottlenecking, operating costs reduction and environmental protection. In the immediate future it is expected that steam crackers will continue to dominate the production of ethylene and propylene. Expected developments are:

- continued de-bottlenecking;
- development of feedstock flexibility (including gas condensates and the less desirable refinery product streams, C4 and heavier);
- optimisation of selectivity towards the most valued products (i.e. for propylene); this may favour older crackers that are not yet modified to high severity.

In the longer term, other processes may challenge the dominance of steam cracking because they produce a more desirable balance of products (e.g. advanced FCC).

Steam cracking is very energy consuming. A process that enables the catalytic conversion of methane to lower olefins (also known as Gas to Olefins - GTO) has been patented, but there has been no commercial application.
There is also a methanol to olefins (MTO) process under development. Ethylene and propylene are formed through catalytic dehydration of methanol. A commercial process is available but no plants have been built yet.
So far there has been no substantial cost or technology breakthrough to differentiate GTO or MTO against the best of the existing steam cracking technologies.
In the MATTER model methanol and ethanol when produced from biomass are feedstock substitution options. It is concluded that the process only becomes competitive at very high GHG penalties.[xxv]

A process route is also being developed for the autothermal cracking of gas feeds. In this process the partial oxidation over a catalyst produces heat to sustain the reaction. However, the route produces large quantities of CO, acid gas and organic acids that require separation and treatment, and so the process has no obvious economic or environmental benefits over existing steam cracking technologies.

Groenendaal and Gielen also consider flash pyrolysis of biomass. Biomass is cracked into ethylene, BTX, CO and CO2. The process is only tested on a laboratory scale. It only becomes competitive at very high GHG penalties.[xxv]

Next to energy consumption and the related greenhouse gas emissions from combustion of fossil fuels other major environmental impacts are related to the flue gases from the combustion processes, VOC emissions, process water purge and the spent caustic stream. None of these would play an important role in a comparison of different technologies.

A.2.3.2 Aromatics production

Applications of benzene and xylenes

Aromatics that are used as intermediates for the production of the plastics considered in this document are benzene and p-xylene.

Benzene is an intermediate in the production of [xxiv]:
- styrene (50 %) → polystyrene, rubbers, ABS, …
- cumene (21 %) → phenol, acetone
- cyclohexane (13 %) → adipic acid, caprolactam

P-xylene is used for the production of terephthalic acid; terephthalic acid is used for the production of PET. Mixed xylenes are used for solvents. O-xylene is used for the production of phthalic anhydride, which is used for plasticisers and polyesters.

50 % of all toluene is converted into benzene. 12 % is used in the production of toluene diisocyanate (TDI), a precursor of polyurethane.

Main production routes[xxiv]

Aromatics are produced from three sources:
- refineries
- steam crackers
- coaltar processing.

Benzene can either be produced from the pyrolysis gasoline (BTX) fraction of steam crackers or via catalytic reforming of naphtha, which also runs via a BTX fraction, which has, however, a different composition. According to CEFIC, the pyrolysis gasoline treatment produces 55 % of the benzene. 20 % comes from the reformate and a few percents from coal tar. The balance is obtained through chemical treatment of other aromatics, by means of 2 basic processes:
- HDA (hydrodealkylation): C7 and C8 aromatics, such as toluene and xylenes are converted into benzene;
- TDP (toluene disproportionation): toluene is converted into benzene and xylenes.

The typical content of benzene in benzol, pyrolysis gasoline and reformates is 70, 30 and 8 % respectively.

Reformates are the main source of the xylenes (85 - 90 %).

Aromatics production from a petrochemical feedstock results from a set of closely connected and integrated unit processes allowing
- to separate the aromatics from the non-aromatics;
- to isolate the pure products;
- to convert some products: toluene to benzene (HDA), toluene to benzene and xylene (TDP), o-xylene and m-xylene to p-xylene (isomerisation).

The feedstock is never a pure substance but a cut. From this cut, one or more pure aromatics are extracted, while the rest can realise value in a gasoline pool of a refinery. The composition of the pyrolysis gasoline and reformate feedstocks can be influenced to a certain extent, acting on the operating conditions and feedstock quality of the steam crackers and reformer, keeping in mind that they are only secondary products of the olefins and gasoline production.

A large amount of aromatics are also present in gasoline. The EU Auto-Oil Directive requests that as of 1 January 2000 the benzene concentration in gasoline is reduced from a maximum of 5 % to a maximum of 1 %. This might lead to a benzene production excess. There is low forecasted growth of the EU benzene production capacity from 1998 to 2003 and it will mainly be driven by the need to recover benzene from upstream feedstocks in response to the Auto-Oil directive. The growth rates of other aromatics are very weak. Only p-xylene has shown significant increased demand due to the growing use of PET for packaging.[xxiv]

Prices and costs

For a process treating 540 kton/year pyrolysis gasoline and producing 160 kton/year benzene, 80 kton/year toluene and 300 kton/year raffinate the EIPPCB BREF study gives an investment cost of 80 MEuro (= 500 Euro/ton benzene capacity) and production costs of 30 Euro/ton.

Table 23: Price ranges for benzene and p-xylene in the period 1993 - 1998 (European spot prices)[xxiv]

	price range (US$/ton)
benzene	210 - 380
p-xylene	250 - 2000

Technological and environmental perspectives

The EIPPCB BREF document does not report any important technological perspectives. Emissions from aromatics plants are to a large extent due to the production of the utilities. Minor part of the emissions are related to the core process:

- emissions of CO, NOx, VOC and particulates from flaring in emergency conditions;
- flue gas from the heating furnaces;
- atmospheric emissions of VOCs;
- emission of aromatics to water.

A.2.3.3 Further transformation of lower olefins and aromatics

Ethyl benzene and styrene

99 % of ethyl benzene is used for styrene production. Nearly all ethyl benzene is manufactured from ethylene and benzene (for a detailed description[xxvi]).
Styrene is used for the production of PS (about two third), SBR, ABS and other polymers.
A number of different routes exist for the manufacture of styrene monomer, but currently the only two commercially used routes are:

1) dehydrogenation of ethyl benzene
2) air oxidation of ethyl benzene

Nearly all styrene is manufactured by direct dehydrogenation of ethyl benzene.[x]

1,2-DCE and VCM[xxiv]

VCM's main application is PVC that consumes 98 %, while the rest is used in polyvinylidene chloride and chlorinated solvents.
It is produced through hydrochlorination of acetylene (now not usually economic) or from ethylene and chlorine (production of 1,2-DCE). DCE is decomposed by heating in a

high temperature furnace and gives vinyl chloride and hydrogen chloride. The latter reacts further with ethene in the presence of oxygen (oxychlorination) to produce DCE.
VCM is stored as a liquid under pressure in spheres or tanks. PVC manufacturing plants remote from VCM production sites receive deliveries of liquid VCM by road or rail tankers, or ship.

Ethylene oxide and ethylene glycol[xxiv]

Ethylene oxide (EO) is formed through direct oxidation of ethylene. Ethylene glycol is formed as a by-product, and is fed directly into an ethylene glycol plant. About 40 % of European EO production is converted into glycols, although globally the figure is about 70 %.
Ethylene glycol is formed through hydration of ethylene oxide. Higher glycols are formed as by-products (the most significant is DEG (diethylene glycol)). 57 % of all MEG is used for polyester fibre. 18 % is used for PET for packaging.[xxvii]

TPA and DMT

see § A.2.2.2.

A.2.4 Plastics waste treatment

A.2.4.1 Plastics waste treatment options

A large range of possible treatment options for waste plastics exists:

- recycling technologies
  - mechanical recycling
    - re-extrusion of unmixed plastic waste
    - mechanical recycling of mixed plastics waste
  - feedstock recycling
    - back-to-feedstock recycling
    - back-to-monomer recycling
    - use of plastics as reducing agent in blast furnaces
- energy recovery technologies
  - mono-incineration of plastics waste
  - co-incineration of plastics waste
    - in domestic solid waste incinerators
    - in cement kilns
    - in coal fired electricity plants

The status of these technologies is quite different. Some are frequently used at industrial scale, some have been introduced recently and have good prospects, some are only in a pilot or a testing phase or have proven not (yet) to be economically viable.
Different technologies have different requirements for the feedstock they use: more or less contaminated mixed plastic waste, mono-plastic streams, … Hence, they are not all mutually exchangeable, or they are only so after some pre-treatment in order to separate contaminants, or to produce mono-plastic streams from mixed streams.

A detailed analysis of all technologies falls out of the scope of this report. While some general comments will be given on the treatment of plastics waste in general, the focus will be on options that are or will become available for the treatment of waste plastic bottles, and that are relevant for the assessment of actual and future greenhouse gas emissions related to beverage packaging.

A.2.4.2 Cleaning and sorting

Some of the technologies described below differ in the type of waste stream they can handle. Some can handle more or less contaminated plastics waste streams, other can handle mixed plastic streams (within specified ranges for specific plastics, i.e. Cl containing PVC); still other can only handle mono-plastic streams.

Various cleaning and sorting technologies have been developed to upgrade plastics waste streams. Especially for re-extrusion of plastic waste to regranulate that can replace virgin polymer, an unmixed plastic waste stream is crucial. Manual sorting of mixed plastic waste streams leads to relatively high sorting costs. However, recently there have been impressive developments for the sorting of plastic containers that can reduce sorting costs by up to 60% (see Part XX packaging).

A.2.4.3 Mechanical recycling

Mechanical recycling (or material recycling or back-to-polymer recycling) is the reuse of the plastics while maintaining the chemical structure of the polymers.

A first type of mechanical recycling processes recycles plastics to the re-extrusion process to replace virgin polymer. It is suited only for unmixed plastic waste types. It is used for industrial plastic waste from plastic processing and for specific separately collected products, e.g. separately collected plastic packaging, used building materials, …

In a second type of mechanical recycling ("downcycling") mixed plastics wastes are heated and cast into large moulds to make mainly thick-walled plastic products, that replace wood, concrete or metal products (e.g. garden or street furniture, sound damping walls, …).

The only material recycling option for thermosets (e.g. PUR) is grinding them and using them as fillers.

Mechanical recycling of unmixed plastic waste

- General aspects

Mechanical recycling to the re-extrusion process to replace virgin polymer is suited only for unmixed plastic waste types. It is suited for production waste and for selectively collected or sorted plastic wastes (e.g. plastic bottles).

A relatively new and promising technique is the use of compatibilisers in reusable plastics mixtures. The importance of polymer mixtures (blends) among plastics materials as a whole is increasing. The worldwide turnover of blends is growing at an annual rate of 9 to 10 %. The use of compatibilisers in reusable plastics will allow avoiding additional, cost-intensive separation processes, while producing plastics blends for an extremely diverse range of applications.[xxviii]

There are some important constraints to re-extrusion of plastics.
Most polymers degrade during use because of exposition to UV light or higher temperatures. Only single-type, unaged plastics, recycled through the melt, can reproduce the mechanical properties of virgin material. During the recycling process they are further degraded. The molecules have become shorter and the products from recycled material will be brittle. Hence, products from recycled polymer will never have the same qualities as those made out of virgin polymer, even if the recycled polymer is derived from unmixed homogenous polymer waste. Even single polymer waste streams may contain polymers of different qualities (molecular weight, weight distribution).
The mechanical qualities of the product can be improved by adding additives, by adding compatibilisers when processing mixed plastic waste or by mixing recycled polymer with virgin polymer. Virgin polymer can be mixed physically or a recycled inner layer can be co-extruded or co-injected with virgin polymer outer layers.

This quality differences can lead to the exclusion of the use of recycled plastics for specific applications. Standards, customer specifications and quality requirements limit their use in the food and in the health care sector, for pressure pipes, vehicle parts, …
Legislation is prohibiting contact between foods and recycled plastics.

Other specific constraints to mechanical recycling of plastics can be the fact that some polymers are hard to separate, e.g. PE and PP can not be separated entirely, or that specific additives (e.g. heavy metals) can be present in quantities that are no longer allowed (e.g. Cd based pigments in old beer crates, flame retardants containing polybrominated diphenyl ethers).

Finally, an imbalance between supply and market for recycled plastics may exist.

- Mechanical recycling of HDPE and PET bottles

Recycled HDPE can be used for trays, crates, racks, bins, pipes, cable conduits, pallets, …
In many flasks and other recipients (jars, bottles, waste bins, …) a minimum of 25 % recycled material can be used.

Prices for waste HDPE are very volatile, e.g. the price at which HDPE was purchased at the sorting centre in Belgium went down from more than 2500 BEF/T at the beginning of 1998 to -1500 BEF/T halfway 1999, to go up again to more than 4500 BEF/T at the end of 1999. The market for waste plastic becomes more and more international.[xv,xvi]
A clear potential for replacement of primary HDPE by secondary exists. The actual use depends on the relative prices of primary and secondary HDPE.

Recycled PET has many applications in the textile sector (fillings for coats, sleeping bags, …, clothes, carpets). Since PET for the bottle sector normally has a higher molecular weight than that required for textile applications, it is fairly easy to use in the textile sector. Other applications are films, jars, straps, bottles and flasks, packaging blisters, …

Three groups of PET bottles can be distinguished:

- transparent, colourless bottles: the largest fraction having also the largest market value; they can be used for replacing primary PET;
- clear blue bottles: the colouring agent can be a problem in certain applications; a small fraction of clear blue bottles does not pose a problem when mixed with colourless bottles; however, the share of blue bottles for packing water increases;
- coloured bottles (green, mixed or not with blue bottles) for the strapping market.

In 1999 in Europe 219.000 tonnes of PET bottles were recycled. Almost 75 % of European reclaimed PET is used in the production of polyester fibres for applications such as carpets and filling for winter jackets and sleeping bags. 12 % is used in new sheet packaging. 10 % is used in the manufacture of new PET bottles.[xxix]

The recycled PET market has seen a similar evolution as the HDPE market with prices fluctuating between -1000 to 700 BEF/T. Price increases for recycled PET in 1999 were caused by increasing prices of primary PET and by an increasing demand for secondary PET for wall-to-wall carpeting in the US, and for the fibre market in Asia.[xvi]

It can be concluded that the potential for replacement of primary PET by secondary exists. Actual use depends on the relative prices of primary and secondary PET. PETCORE estimates the market for recycled PET at 8,5% of total market in 2000 and at 25% in 2002.

Recently, some modifications have been made to the standard PET bottle to make them suitable to pack beverages such as beer, milk products or fruit juices. These modifications are generally incompatible with existing mechanical recycling processes.

Different data are found for the energy requirements of mechanical recycling of plastic bottles. The data used by Joosten[x] cover washing, ferro removal, grinding, hydrocycloning, centrifuging, thermic drying and non-ferro removal. In the case of HDPE bottles degassing, melting, extruding and granulation are included. In the case of PET bottles these last steps are not included. Approximately 90 % of the input plastic waste can be processed into the granulate. 10 % ends up as waste. For HDPE bottles 2,7 - 3,1 GJe per ton plastic waste input is needed. For PET bottles only 1,1 to 1,5 GJe per ton is needed.

Patel *et al*[xiii] give a figure of 1,75 GJe per ton of PET waste bottle to produce PET flakes that can be reused for bottle production.

It depends on the end product if the PET flakes are regranulated before further processing. For production of fibres PET flakes can be used directly. For production of bottles the flakes are in most cases first regranulated.

According to Heyde and Kremer[xxxi] 4,2 MJe and 0,11 MJ heat is needed to process 1,62 kg of DSD bottle fraction into 1 kg of recycled material for bottle production (grinding, washing, density separation, drying, extrusion and pelletisation).

For unmixed bottle fractions the data provided by Joosten can be used.

Patel *et al* also give a figure for recycling of old PET bottles into fibres: to process 1 ton of waste PET bottles into 0,89 ton of PET fibre 6 GJe is needed (4,8 GJe for the spinning process, 1,22 MJe for shredding).

A.2.4.4 Feedstock recycling

Back-to-feedstock recycling processes recycle (mixed) plastics wastes back to the level of the feedstock (cracking products, gases). These recycled feedstocks can be used again for the production of petrochemical products (not only plastics).

Back-to-monomer recycling processes recycle wastes of polycondensation or polyaddition polymers (PET, PA, PUR, …) back to the level of the individual monomers.

A special case is the injection of plastics in blast furnaces to replace heavy oil as reducing agent.

Back-to-feedstock recycling

In back-to-feedstock recycling processes the polymers are split in low molecular weight products that can be used as feedstock for chemical processes. Several feedstock-recycling processes have been developed (see Tukker *et al*[xxx] for an extensive list). Pyrolytic techniques, hydrogenation and gasification are the main processes. They often make use of (parts of) existing petrochemical installations. Petrochemical plants have much greater capacity than plastics manufacturing plants. But they suffer a dramatic drop in economic efficiency with decrease in size. For this reason it would be completely uneconomical to build new plants dedicated to the plastics waste stream. The only solution is to use existing petrochemical complexes and adapt them so that they can use the waste stream to supplement their usual feedstocks.

Wastes containing mainly standard plastics, such as PE, PP, PS and PVC can be used for feedstock recycling. Feedstock recycling of specialty plastics, such as PET, PA, POM and PUR, requires a waste stream of appropriate composition. Special processes are employed.

The use of plastics waste as the raw material for petrochemical processes imposes certain restrictions on the quality of the feedstock, especially regarding traces of halogens (PVC), heavy metals and fillers (Table 24). If solid, the waste should have free-flow properties. If oil, it must be pumpable.

Although these restrictions vary from process to process, untreated waste does not usually fulfil them, and a pre-treatment step is needed to transform the plastics waste into a liquid form with a low chlorine content that can be treated further in existing installations.

Table 24: Standard specification for feedstock recycling[xxxi]

Contaminants	max. 4 %
Ash	max. 4,5 %
Chlorine	max. 2,5 %
Moisture content	max. 1 %
Bulk density	min. 300-350 kg/m^3

Degradative extrusion and low temperature thermolysis, that are normally considered as feedstock recycling processes, are basically pre-treatment steps, in which the plastic waste is converted into an easy to handle liquid form and partially dechlorinated.[xviii]

In the degradative extrusion process, the chloride content can be reduced to < 0,2 wt%, even if the waste stream contains up to 80 wt% PVC.[xxxii]
An important advantage of the process is that it can be decentralised because it can be carried out at a relatively small scale (100 to 2000 kg/h). The extrusion products could be blended in small percentages into the large feedstock streams for joint recycling in existing feedstock recycling processes.

Low temperature pyrolysis of plastics wastes yields a gas fraction (< C4), a condensate fraction and a residue or depolymerate fraction with a high molecular weight.
Experiments on a representative commingled plastics waste stream (containing 2 % PVC) have shown that a feedstock can be produced with a chlorine content below 20 ppm. When blended with naphtha or vacuum gas oil at the 20 % level, this is within the specification for most uses.[xxxiii]
Low temperature pyrolysis has been tested in several pilot or demonstration projects, integrated in refineries (BASF, BP), or as a pre-treatment step for a hydrogenation (Veba) or a gasification unit (Texaco).

For our purpose it does not seem necessary to include all kinds of feedstock recycling processes. Most real new initiatives remain in the pilot phase. Economical viability is linked to the scale. At present a constant and sufficiently large supply is not guaranteed.
Moreover, recent studies show that not all feedstock-recycling options perform equally well (see § A.2.4.6).

The BASF pyrolysis process will be retained as an example of a feedstock recycling process. For detailed process descriptions we refer to the studies of Tukker *et al*[xxx], Patel *et al*[xiii] and Heyde and Kremer[xxxi].

The BASF process consists of a depolymerisation unit, a thermolysis furnace and two distillation columns. Mixed PP/PE, PP/PE/PS and PP/PE/PS/PVC DSD fractions are transformed in a naphtha-like product, an aromatics fraction, pyrolysis gas and cokes. A 15.000 ton/year pilot plant was built in Ludwigshafen. The original planning was to build a 300.000 ton/year plant, but DSD could not guarantee a steady supply. The pilot plant was closed at the end of 1996.

In the KAB hydrogenation process MPW is hydrogenated together with the vacuum residue from crude oil distillation (25 % MPW). It yields a syncrude, which can be processed further in refineries. Process gas is also recovered. Finally, a hydrogenation residue is produced that can be used in coke production.).

In 1998 about 80.000 ton of MPW were processed. However, the activity was stopped at the end of 1999 because it was uneconomical.

Process data for BASF pyrolysis were taken from Heyde and Kremer[xxxi] (Table 25).

Table 25: Process data for the BASF pyrolysis process

Inputs	ton	GJ	Outputs	Ton	GJ
plastics waste	1	38,2	conversion gas	0,099	3.61
Hydrogen	0,003		aromatics fraction	0,262	
Electricity		0,38	naphtha	0,447	
Steam		3,15	cokes	0,179	3,80
			conversion by-products		-0,92

The cost data are taken from the MATTER database[xx] (Table 26

Table 26: Cost data for the BASF pyrolysis process

		2000	2010	2020
total cost of investment	1995 EUR/ (ton/year)	500	500	500
annual fixed operation and maintenance costs	1995 EUR/ (ton/year)	25	25	25
annual variable operation and maintenance costs	1995 EUR/ton	236	223	209
lifetime of new capacity	40 years			

Back-to-monomer recycling

PET may be de-polymerised using a range of chemical agents and processing conditions. In the early 1990's chemical recycling was seen as the best route for closed loop recycling of plastic. A limited amount of chemically recycled PET was supplied in the US market in the early 1990's. However, the decline in regulatory pressure and the relatively high cost of chemically recycled PET has made such PET currently not competitive.[xxix]

Use of plastics as reducing agent in blast furnaces

Plastics can substitute a maximum of 30 % of heavy oil used in blast furnaces in a 1/1 to 1/1,1 ratio. In Germany and Japan plastics are fed to blast furnaces in the form of pellets. Stahlwerken Bremen GmbH used 91.000 ton of waste plastics in 1997. According to the German Wirtschaftsvereinigung Stahl the blast furnace capacity in Germany would be sufficient to take in all the DS packaging waste (535.000 ton in 1996).[xiii] However, it seems the process is only economically viable because it is subsidised by DSD. An analysis by Cockerill Sambre would have shown that the practise would not be economically viable in Belgium.[xviii]

Advantages of the use of plastics in blast furnaces are the fact that the plastics waste can be treated in existing installations if the plastics can be fed in the form of pellets or in liquid form. Chlorine (PVC) can give problems (corrosion).

A.2.4.5 Energy recovery

Mono-incineration of plastics waste

Incineration of plastics in fluidised beds has been investigated in Japan and in Finland.
The main problem is that thermoplastics melt at higher temperatures. In the case of PVC containing wastes corrosion is an additional problem. Measures to minimise the danger of corrosion lead to a low electricity output (20 %).[xviii]
In Germany the logistical and economical conditions do not favour the incineration of mono-plastic streams.[xiii]

Co-incineration of plastics waste in domestic solid waste incinerators

Domestic solid waste incinerators are designed for a volume reduction of the waste and inertisation of harmful substances. Energy recovery is not their main purpose and their electricity output is low compared to electricity plants (20 - 24 %). Grate furnaces are only suited for the incineration of waste with a low calorific value. Although experiments in the incineration plant in Würzberg have shown that the share of plastics in the waste can be raised to 30 wt%, other arguments can be brought in against the co-incineration of large amounts of plastics in domestic solid waste incinerators. The calorific value of household waste is increasing. A higher calorific value leaves less room for adding high calorific value waste. Since the operator is normally paid according to the tons of waste treated, they are not inclined to incinerate additional quantities of high calorific value waste, unless the gate fee for these types of waste is increased.[xviii]

Co-incineration of plastics waste in cement kilns

Energy recovery in cement kilns enables CO_2 savings that are slightly higher than those that can be achieved in an advanced waste-to-energy facility, but cement kilns contribute far less to energy conservation. There is discussion if incineration in cement kilns can be compared to other waste treatment processes. Cement kilns are not subject to the same air emission standards as municipal waste incinerators and they generally use fuels with high carbon content. Hence, using plastics as fuel in a cement plant will reduce CO_2 emissions more in comparison with other processes where low carbon fuels and feedstocks are already used.[i]

According to the TN Sofres data co-incineration of post-user plastics waste in cement kilns is not widely developed in Western Europe (less than 0,5%). Plastic scrap is preferred to post-user plastic waste.[xii]

Co-incineration of plastics waste in coal-fired electricity plants

In the Scandinavian countries mixed domestic plastic waste has been added to coal fired electricity plants. In stationary fluidised beds up to 70 % of the thermal input can be plastics waste.[xviii]

According to the TN Sofres co-incineration of plastics waste in coal-fired electricity plants will grow in Western Europe to 250 kton in three years (about 1 % of total collectable post-user plastics waste).[xii]

A.2.4.6 Environmental perspectives

According to the study of Heyde and Kremer[xxxi] GHG emissions reduction is higher for mechanical recycling of films and bottles than for all of the feedstock recycling processes. The authors conclude that mechanical recycling has the potential to achieve considerably greater savings than feedstock recycling and energy recovery processes, if the recycled materials replace virgin plastics material and provided that the working up losses are low. If recycled materials substitute concrete or wood, the saving effects are in general considerably lower than in the case of feedstock recycling or energy recovery, disregarding special cases.

Patel *et al*[i,xiii] also compared several plastics recycling technologies. They calculated the savings in gross energy requirements and in gross CO_2 emissions compared to the incineration of plastics waste in an average German solid domestic waste incineration plant. They conclude that mechanical recycling can lead to the highest savings in CO_2 emissions. Mechanical recycling to polymer substitutes results in savings of 2250 kg CO_2/ton plastics waste for PE. Mechanical recycling to non-polymer substitutes result in a wide range of values since the environmental impact of primary production differs greatly depending on the substituted material. Moreover, it is not always clear what to assume for primary production.

Mechanical recycling only seems to provide real environmental benefits if virgin polymers are substituted or if the replaced products have a shorter life span than the plastic products (which is not the case for concrete or treated wood products).

They also conclude that there is a great difference between advanced waste-to-energy facilities and the average of all incineration plants (-1750 kg CO_2/ton plastics waste).

Use of plastics waste in blast furnaces and hydrogenation are preferable to an average waste incinerator (-1350 kg CO_2/ton plastics waste), but not as good as an advanced waste-to-energy facility.
Energy recovery in cement kilns enables CO_2 savings that are slightly higher than those that can be achieved in an advanced waste-to-energy facility, but cement kilns contribute far less to energy conservation.

Heyde and Kremer[xxxi] also compared several feedstock recycling processes and energy recovery processes. They used landfilling as the reference system. The use of waste plastics in blast furnaces and the BASF process yield the best results in terms of primary energy use (-29 MJ/kg), followed at some distance by mono-combustion and hydrogenation (-26 MJ/kg). Waste incineration (-15.9 MJ/kg) and gasification (-13.4 and -6.8 MJ/kg) yield considerably less favourable results. However, altering the conditions can lead to considerable differences. E.g. when comparing to the same waste incineration plant that was considered as advanced waste-to-energy facility in the study of Patel *et al*, plastics waste incineration leads to the same energy savings as the best feedstock recycling options. This is in line with the conclusions of Patel *et al*. In terms of GHG emissions, the same four processes that are most favourable in terms of primary energy consumption, have the potential to reduce the GHG emissions.

From both studies it can be concluded that energy recovery becomes comparable to feedstock recycling if the energy is used to a high extent. Incineration in domestic waste incinerators can compete with the better feedstock recycling processes, if they are integrated optimally in the heat net and if the bottom and fly ashes can be valorised. However, this is actually not the case in Belgium.[xviii]

Groenendaal and Gielen[xxv] find that in the period 1990-2050 plastic waste processing in Western Europe will shift from 90% disposal to 30% disposal, 42% incineration and blast furnaces and 28% recycling techniques (including re-extrusion, solvent separation, hydrogenation, hydrolysis). The way plastic waste is processed, does not change up to GHG penalties of 50 Euro/ton.

It can be concluded that mechanical recycling to the re-extrusion process results in the highest energy savings and greenhouse gas emission reductions. However, it is restricted to unmixed plastic waste streams.
Back-to-feedstock recycling processes seem only to have potential for mixed plastic waste streams that are difficult or expensive to collect separately. But even then the experience in Germany suggests that they are not economical in the actual conditions.
Energetic recovery from combustion only seems attractive for reducing GHG emissions in advanced waste-to-energy facilities.

A.3 Greenhouse gas emission reduction potential

A.3.1 General

The efficiency of most petrochemical processes is already high. The potential for energy related GHG emission reduction is limited. This is especially the case for the key steam cracking process.
Aims for increased energy efficiency are based on pinch technology, process integration (e.g. CHP), new process routes based on new catalysts, on new technologies for materials production or on new separation technology. Estimates indicate a potential of 10 - 20 %.[xxv]

According to Groenendaal and Gielen[xxv] "plastics are the most interesting petrochemical product group for GHG emission reduction. In several cases plastics can be replaced by renewable materials, biomass can replace oil and gas as a carbon source and plastic waste can be reused to produce new plastics." In their analysis they look at the potential for greenhouse gas emission in petrochemistry and plastics production using the integrated materials and energy model (MATTER MARKAL). This model theoretically covers all demand for petrochemicals and plastics, and takes into account possible interactions with other parts of the economy (see also *Greenhouse gas emission reduction and material flows. Final report* and *Greenhouse gas emissions and material flows. Part I*), especially under increasingly stringent greenhouse gas emission reduction targets.

Emissions of the petrochemical industry will decline from 320 Mt in the base case to 250 Mt in case of a 50 Euro/ton GHG tax (- 22 %). The main GHG emission reduction strategy is feedstock substitution (65 % of the GHG emission reduction, followed by N_2O emission mitigation (15 %), recycling and energy recovery (10 %) and increased materials efficiency (10 %). At GHG emission taxes of 100 Euro/ton and more, the energy and carbon feedstock input changes from fossil fuels to biomass.

An example of an interaction between changes in the petrochemical sector and in other sectors is the fact that, when applying a GHG emission tax of 100 Euro/ton, changes in the electricity production might affect the potential for GHG emission reduction through energy recovery from plastics waste. The market for transportation fuels will be affected by a change towards biofuels and electricity in the transportation sector. This will affect the availability of naphtha that is currently a by-product of oil refining. Hence, changes occur from the use of naphtha to the use of gas oil and LPG.

Basic petrochemical processes, such as steam cracking and aromatics plants have multiple inputs and outputs. The use of specific inputs and process conditions are determined by the supply of the inputs (e.g. as by-products of refineries) and the demand for all the outputs. For instance, steam cracker outputs depend on the feedstock. There might be some reduction of GHG emissions according to the feedstock. However, the choice of the feedstock will result in different outputs. This is difficult to evaluate based only on the ethylene use for PE and PET production. The same applies for the complicated interaction in aromatics plants, and the optimisation of the output. This is a question of matching overall supply and demand.

Considering the fact that the demand for ethylene or aromatics related to the specific end uses considered in this study is marginal, average outputs and average emission factors have to be considered.

A.3.2 Gross energy use and CO2 emission factors

A.3.2.1 Production of primary plastics

In its original series of eco-profiles of the European plastics industry[xxxiv] of APME CO_2 emission figures are given for the major thermoplastics (Table 27). Emissions increase from PE and PP to PS, PVC and finally PET.
In 1999 APME has updated these eco-profiles. Updated CO_2 emissions are significantly higher. According to the author this is due to the fact that the earlier reports reported the data as supplied, and only converted feedstock to fuel where this was specifically stated. This led to feedstock being overstated and, in some instances, air emissions being understated.[xxi]
For ethylene production in an average European plant the CO_2 emission factor has more than doubled (from 530 to 1200 kg CO_2/ton). The original estimates for PE, PP, PET and PS have been increased 1,5 to 1,8 times. On the contrary, emissions for PVC have changed relatively little. A weighted average of 2015 kg CO_2/ton[19] can be calculated.

CH4 emissions (expressed as CO2 equivalents) add roughly 7 % to the CO_2 totals.

Patel *et al*[i,xiii] have calculated gross energy requirements and gross fossil CO_2 emissions for some petrochemical products (Table 27) "reflecting the German situation".[20]
Their figures are in the same line as the original APME figures, except for PET production. Patel compares his results to the 1993-1998 APME data. He sums up some reasons explaining the differences. He concludes that the own data might underestimate the real energy requirements, but differences in methods, and in the years and the regions analysed, do explain the data ranges to a large extent. The uncertainty due to the mentioned reasons is estimated at about 20%.
However, the new APME emission factors differ much more. Hence, there have to be other reasons explaining these differences. It seems differences in taking into account fuel used as feedstock and fuel used for process energy requirements are at the basis of the differences.

The differences between the old and the new APME figures and between the APME figures and the figures from Patel *et al* illustrate that calculating emission factors for production of organic chemicals is tedious because of the complex interactions of the petrochemical processes.

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[19] Average European market shares : suspension PVC : 80 %, emulsion PVC : 13 %, bulk PVC : 5 %[xxi]

[20] CO_2 emissions during the entire process chain, starting with the extraction of resources and ending with the saleable material ('cradle-to-factory gate'). In terms of technology, production is modelled in Western Europe in the mid 1990s. As far feedstock use for ethylene production and ammonia production and the ratio 'high severity' versus 'low severity' cracking are concerned the calculations refer to the production in Germany in 1995.

It is clear that the use of both sets of emission factors for calculations of emissions related to packaging will lead to different results.

Table 27: Gross GHG emissions for plastics production

kg CO_2 equivalents/ton		CO_2			CH_4
		Patel, 1999	APME 1993-1995	APME, 1999	APME, 1999
PE	LDPE	1240	1250	1900	143
	HDPE		940	1700	120
PP			1100	1900	128
PET		2070	2330	4300	210
PVC	PVC bulk	2080	1910	1800	130
	PVC suspension		1747	2000	155
	PVC emulsion		2741	2500	231
PS	GPPS	1870	1600	2600	189
	HIPS		1800	2700	193
	EPS		1800	2500	200
PC		3110		5000	378

A.3.3 Total GHG emissions related to plastics' consumption

Table 28 gives estimates for the total CO_2 emissions related to the consumption of plastics at different levels (plastic processors' consumption, final consumer consumption). To get the total GHG emissions the figures have to be increased by 7 %.

In mass terms PE and PP account for 70 % of plastics processors' consumption. Due to their relatively low CO_2 emissions however they only account for about 55 % of CO2 emissions. PET and PC on the contrary double their relative importance. PC accounts for 15 % of total CO2 emissions.

Depending on the figures for total plastics' consumption and the emission coefficients used total GHG emissions related to the consumption of primary plastics range between 2,4 and 5,5 Mton. CO_2 emissions related to final consumer consumption of plastic packaging mount to 0,6 - 1,4 Mton and to 0,5 - 1,0 Mton for domestic packaging.
These figures include life cycle emissions up to the point where the materials or products are ready for (intermediate or final) consumption. A large part of these emissions will take place abroad (intermediates or even the material or product itself imported). GHG emissions related to post-use treatment are not included.

To get an idea of the importance of this figure it can be compared to the total Belgian GHG emissions of approximately 144 Mton in 1997. The comparison is however not fully correct. The latter figure relates to emissions calculated according to the IPCC guidelines, and concerns the direct emissions caused by the production and consumption of goods and services in Belgium., whereas a part of the life cycle greenhouse gas emissions can be related to imported materials or products.

Table 28: Total CO_2 emissions related to plastics' consumption

Total plastics consumption by plastics processors			Patel			APME		
Product	[ton product]	[% of total]	[kg CO_2/ton]	[ton CO_2]	[% of total]	[kg CO_2/ton]	[ton CO_2]	[% of total]
PE	636.232	28,8	1.240	788.928	23,2	1.800	1.145.217	22,2
PP	918.267	41,6	1.250	1.147.834	33,7	1.900	1.744.707	33,8
PET	136.277	6,2	2.070	282.093	8,3	4.300	585.991	11,4
PVC	91.973	4,2	2.080	191.304	5,6	2.015	185.326	3,6
PS	257.720	11,7	1.870	481.936	14,1	2.600	670.072	13,0
PC	165.720	7,5	3.110	515.389	15,1	5.000	828.600	16,1
Total	2.206.189	100,0	1.545[a]	3.407.484	100,0	2.339[a]	5.159.913	100,0
total consumption APME[b]	1.303.000		1.545	2.013.000		2.339	3.048.000	
total consumption Fechiplast[b]	1.785.000		1.545	2.756.953		2.339	4.174.822	

Final consumer consumption of plastic packaging (1997)[b]								
Domestic	288.000		1.545	444.819		2.339	1.040.359	
distribution/industrial	107.000		1.545	165.263		2.339	386.522	
total	395.000		1.545	610.082		2.339	1.426.882	

[a] *calculated from total CO_2 emissions and total consumption*

[b] *refer to §A.1.3.4 and §A.1.3.6*

A.4 Conclusions

The analysis of the potential for the reduction of greenhouse gas emissions related to the use of plastics used for packaging and building can be split up in two large parts: reduction options in the production of plastics and reduction options in the treatment of waste plastics.

Plastics production and consumption

To make a full analysis of the actual flows of plastics used for packaging and building, and of intermediate organic chemicals, in Belgium both availability and reliability of statistics are problematic. Inconsistencies in the quantities reported, as well for the production statistics as for the foreign trade statistics, make any analysis of actual flows of plastics and intermediates for plastics production and consumption tedious.

The analysis of the flows shows that no clear link can be established between the Belgian petrochemical production and the final use of plastics in Belgium. At all levels of the production chain of plastic products important import and export streams exist. Hence, a detailed analysis of the specific features of the Belgian petrochemical sector would not give the required results for an analysis of life cycle greenhouse gas emissions related to the use of plastics for beverage packaging or for construction of houses.

For some plastics the use for packaging or construction covers an important part of the total production. However, the production of plastics, and of the necessary intermediate organic chemicals, is a part of the much larger, highly integrated petrochemical complex. Crucial petrochemical processes, such as the production of ethylene or aromatics, have multiple inputs and outputs. Decisions on which inputs to use and which outputs to produce are not based on the evolution in the demand for a limited group of specific final products, but on the complex interactions between supply and demand for inputs and outputs.

Hence, life cycle greenhouse emission factors related to the production of plastics for packaging or for building materials will depend on the evolution of the total petrochemical complex. The MATTER analysis shows that with moderate greenhouse gas emission taxes energy related greenhouse gas emissions can be reduced by about 20%. With drastic greenhouse gas emission taxes major changes in feedstock and products may occur.

Due to the complexity of the petrochemical processes calculating greenhouse gas emission factors for plastics is tedious. This is clearly shown by the striking differences in the older and the more recent versions of the APME ecoprofiles, which in their turn differ quite a lot from other detailed studies. In the context of this project it was not possible to analyse these contradicting results in depth.

Plastics waste

The quantity of plastics recycled in Belgium (exclusively mechanical recycling) is small compared to the total processors' consumption of plastics (about 2.5%). Recycling in

Belgium accounts for only 5 % of the total waste stream. It is for more than 90 % related to plastic packaging.

Technologies for recycling waste plastics are in full development. Mechanical recycling of unmixed plastics wastes seems to offer the largest potential environmental benefits. Especially in the case of plastic beverage packaging mono-plastic waste streams can be separated, and regranulated plastics can enter into competition with virgin polymers.

Feedstock recycling in Europe is actually an almost exclusively German affair. Feedstock recycling techniques have not yet proven to be economically and environmentally reliable. In the case of mono-plastic streams they don't seem to offer a higher potential for greenhouse gas reduction than mechanical recycling. Incineration with a highly efficient recovery of energy might be a valuable alternative. However, this requires integration in a well-developed heat net.

B PAPER AND CARDBOARD

B.1 Paper and cardboard flows

B.1.1 Paper and cardboard production: overview

A schematic overview of the paper and bardboard producing sector is given in Figure 5.

B.1.1.1 The raw material

Wood

This part of the study deals with the energy and material flows in the paper and cardboard industry. Wood flows and wood production will not be treated in detail here. Wood production however can play a major roll in the overall CO_2 balance of the produced paper and cardboard goods (see Nemry F., Lopez P. (2001) *Reduction of greenhouse gas emissions and material flows, Housing system analysis –Part I - Detailed description of the system and evaluation of the potential of emissions reduction*, Institut Wallon, Namur).

Recovered paper

Old paper is subdivided in 3 main groups (Table 29) based upon the purity and the wood containing or wood-free quality of the paper. The purity refers to the pre consumer (printer remains, cuts of paper rolls,…) or post consumer (read newspapers,…) status of the paper. The wood-containing or wood-free character of the paper refers to the pulp used during the production of the paper (see below). Recently a European list of standard qualities has been published with 50 categories. Many companies have their own classifications of old paper.

Table 29: Different grades of recovered paper[xxxv]

Grade	Composition	Use
low grades	mixed papers, old corrugated containers, board,…	packaging papers and board
de-inking grades	Newspapers and magazine, graphic papers,…	graphic papers, sanitary papers
high grades	Unprinted high quality paper, high quality cardboard,…	production of any paper product as pulp substitute

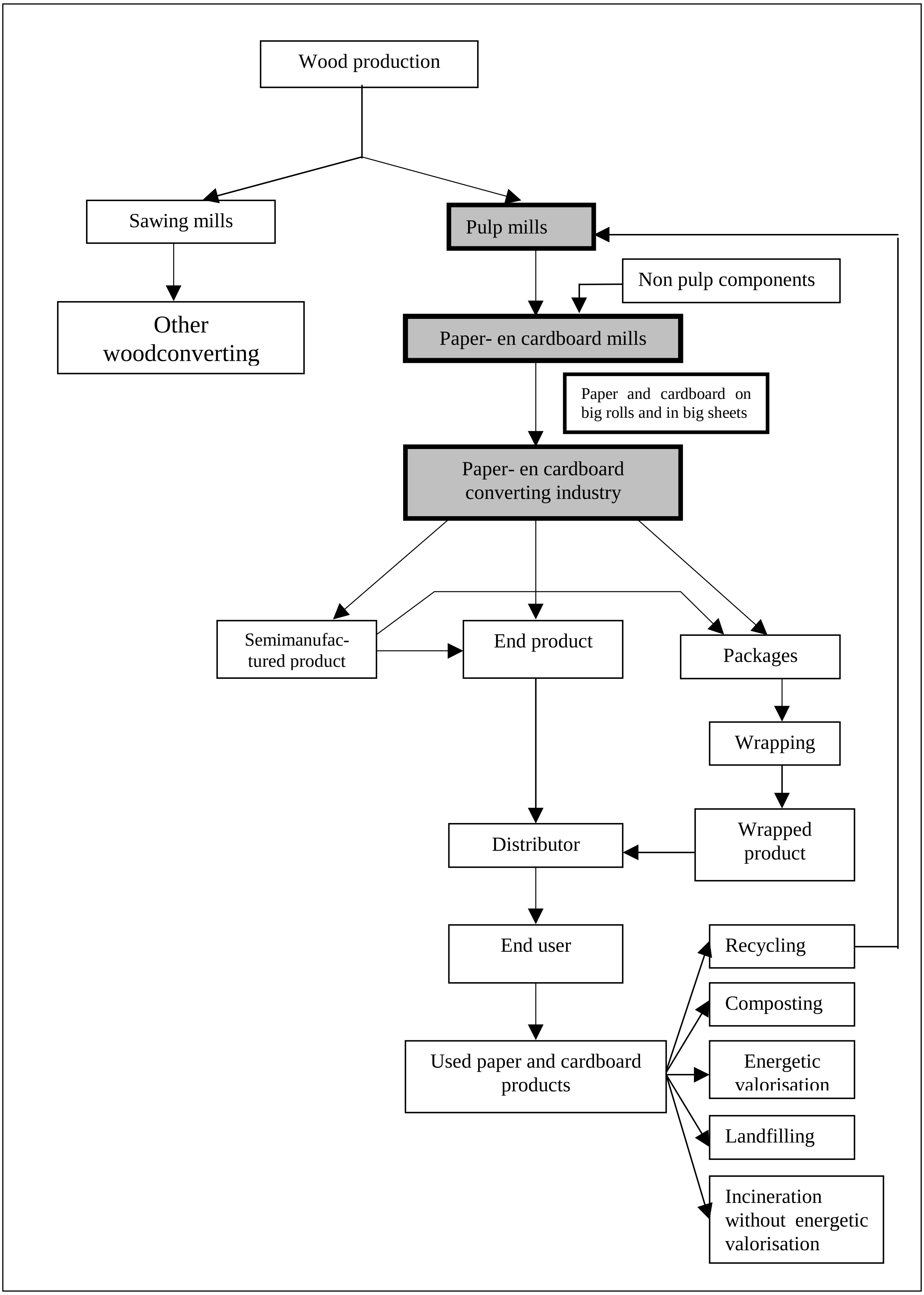

Figure 5: The paper and cardboard producing and converting industry

B.1.1.2 Pulp

A first step in the production of paper products is the production of pulp starting from the raw material. This is based on a separation of the fibres. The production of pulp can take place in non-integrated or integrated plants. Non integrated plants only produce pulp and sell this to paper producing plants. Integrated plants on the other hand have pulp and paper mills in the same plant.

Depending on the implemented production process a distinction is made between mechanical, chemical or recovered pulp as can be seen in Table 30.

Table 30: Different kinds of pulp[xxxvi]

Production process	**Input**	**Description**	**Yield[a] (%)**	**Use**
Mechanical pulp				
Grindstone	Softwood	Pulping process based on hitting the chopped wood against a grindstone.	95-97	Newspaper
Thermomechanical pulp (TMP)	Softwood	Pulping process based on heat treatment.	93-95	Newspaper, graphic paper, magazine paper
Chemi-thermomechanical pulp (CTMP)	Softwood and/or hardwood	Pulping process based on a pressurized heat treatment dealing with sodium carbonate or sodium sulfite before grinding.	90-94	Newspaper, graphic paper, magazine paper
Chemical pulp				
Sulphite pulp	Softwood and/or hardwood	The chemical processes are used to separate the cellulose fibres from other components of wood.	50-55	Packaging
Kraft pulp	Softwood and/or hardwood		50-55	Packaging
Other fibres pulp	Other fibres	Fibres of papyrus, the pappus of the cotton plant, rice,… are processed to pulp.		
Recovered paper				
Recovered paper pulp	Old paper	The old paper is grinded, solved in hot water, screened and cleaned.	85[xxxvii] (newsprint production) 89[xxxviii] (packaging paper and board)	Newspaper, packaging

[a] The yield is the amount of organic material that ends up in the pulp.

The difference in the yield of the respective pulping techniques is caused by a different degree of removal of several wood components. The TMP process retains most of the lignin in the pulp so the yield is substantial. Bundles of wood fibre, separated wood fibres and fibre fragments result from this operation. In the CTMP process however a preliminary treatment with chemicals softens the lignin. In this way the separation of the fibres occurs mostly between the fibres and less lignin is retained. The chemical process removes almost all of the lignin from the wood.

Apart from a different yield the different pulping treatments also result in a different quality of the pulp produced. The chemical processes result in a much greater strength of the fibres than the mechanical processes. The mechanical treatments however result in better optical and paper-surface properties. The choice of the pulping process depends on the paper product and quality that is to be obtained. For packaging, mainly chemical pulp and recovered paper pulp is used.

B.1.1.3 Non pulp components

During the paper making process non-pulp components are added. The non-pulp components can be divided into coating and fillers. Their function is to fill the holes in the fibre network. As a result the surface becomes smooth and can be printed more easily. They also improve the opacity and the whiteness of the paper.
Starch is added to glue the paper. In this way the absorption capacity is reduced and printing the paper becomes possible.

B.1.1.4 Paper and cardboard

A next step is the transformation of pulp in paper and cardboard. This process takes place in 3 steps: material preparation, passage through the paper machine and final processing. The paper machine removes the water from the stock and crosses the fibres into a paper form. Once again, the production can take place in an integrated or a non-integrated plant.

There are different ways to classify paper and cardboard. Table 31 gives a classification of paper and cardboard by use adopted by Cobelpa (the federation of Belgian producers of pulp, paper and cardboard) and by OECD (Organisation for Economic Co-operation and Development).

*Table 31**:** Classification of paper and cardboard by use*

COBELPA	**OECD**
Printing and writing paper ❖ Newsprint ❖ Uncoated paper ❖ Coated paper	Newsprint
	Printing and writing paper ❖ Uncoated ❖ Coated
Paper and cardboard for packaging	Paper and cardboard for packaging
Sanitary and household paper	Sanitary and household paper
Other paper and board	Other paper and board
	Thin paper
	Paper and board for construction

Table 32 on the other hand shows a classification of paper and board by weight.

*Table 32**:** Classification of paper and cardboard by weight*[xxxix]

Paper or board	Weight (g/m^2)
Tissue paper	10
Paper for newspapers and magazines	40 to 60
Printing and writing paper	70 to 80
Art paper	100
Cardboard	150 to 225
Hard cardboard	>225

A third classification is based on the production process used.

*Table 33**:** Classification of paper and cardboard by production process*[xxxix]

Pulp →	**Paper**
Mechanical pulp	Wood containing paper: contains lignin
Chemical pulp	Wood free paper: contains no lignin
Recovered pulp	Recovered paper
Bleaching process →	**Paper**
Cl_2	Chlorine containing paper
$ClO_2 + Cl_2$	Low chlorine paper
ClO_2	ECF: Elementary Chlorine Free
O_2, O_3, H_2O_2,…	TCF: Totally Chlorine Free

B.1.1.5 Paper and cardboard products

The paper and board converting industry produces either intermediates and packages for other companies or produces end products for the final consumers. The paper and cardboard products can be classified as shown below.

- *corrugated cardboard*
  consists of a corrugated medium that has been shaped into continuous rolling waves or flutes and that is glued at both sides with a linerboard facing. This adds to the rigidity of the cardboard.
- *folding cartons*
  packaging boxes, which may or may not be printed, and which are folded or glued.
- *different types of carton boxes*
  composed of compact cardboard, assembled boxes, e.g. shoe boxes,…
- *large content bags*
  composed of one to six layers of Kraft paper that can be combined with other materials like polyethylene, aluminium,…; they can meet high demands of protection for a great variety of products; usually industrial packages.
- *flexible packaging* and *small or medium sized bags*
  one or double layered, can also be combined with other materials like synthetic or aluminium, e.g. shopping bags, bags for bread,…

- *school and office products, envelopes, miscellaneous*, e.g. playing cards, waxed paper, wall paper, …

B.1.2 Production and consumption of paper and cardboard in Belgium

B.1.2.1 Pulp

Table 34 gives an overview of the production, exports, imports, apparent consumption and real consumption of pulp in Belgium in 1998, excluding recovered paper pulp that will be discussed in paragraph B.1.2.5.

Table 34: Production, exports, imports, apparent consumption, real consumption of pulp 1998 (excluding recovered paper pulp)[xl]

Production process	**Production (kT)**	**Exports (kT)**	**Imports (kT)**	**Apparent consumption[a] (kT)**	**Real consumption[b] (kT)**
Mechanical pulp	**171**	**0**	**22**	**193**	**192**
Grindstone	0	0	0	0	0
TMP Thermomechanical pulp	48	0	0	48	48
CTMP Chemi-thermomechanical pulp	123	0	22	145	144
Chemical pulp	**210**	**132**	**374**	**452**	**444**
Sulphite softwood	0	0	44	44	46
Kraft softwood	0	0	216	216	225
Sulphite hardwood	0	0	11	11	9
Kraft hardwood	210	132	103	181	164
Semi-Chemical pulp	**0**	**0**	**22**	**22**	**23**
Market deinked pulp	**0**	**0**	**2**	**2**	**2**
Other fibres	**0**	**0**	**0**	**0**	**0,003**
Total pulp[21]	**381**	**132**	**421**	**670**	**660**
[a] Apparent consumption: imports + production – exports [b] Real consumption: figures provided by the industry					

Since there are only three companies in Belgium that produce pulp starting from wood, the Belgian pulp production figures do not represent a large industrial sector. The imports exceed the local production. In this context it might be difficult to talk about ‘the Belgian pulp industry’. The companies are part of different international groups. Over the last few years however the Belgian pulp production figures have been relatively stable. Belgium represents about 0,8 % of the European pulp production with wood as a raw material.

Most of the Belgian paper and cardboard producing companies work as non-integrated units. They depend upon imported pulp for their paper and board production. North America and Scandinavia are the main suppliers.

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[21] Excluding recovered paper pulp that will be discussed in paragraph 2.5.

No exact data were found on the bleaching process used during the paper and cardboard production. The total amounts of bleached and unbleached pulp however are given by the FAO for Belgium and Luxembourg (Table 35). By far most of the pulp produced, imported and exported in Belgium (and Luxembourg) is bleached pulp.

Table 35: Figures of bleached and unbleached pulp for Belgium and Luxemburg in 1998[xli]*.*

Pulp used for paper production	Production (kT)	Import (kT)	Export (kT)
bleached sulphate pulp[a]	209	440	177
bleached sulphite pulp	16	60	2.8
total bleached	225	500	179.8
unbleached sulphate pulp		16	0.1
unbleached sulphite pulp		0.9	1.9
total unbleached	0	16.9	2
[a] sulphate pulp = kraft pulp			

B.1.2.2 Non pulp components

Table 36 gives an overview of the consumption of non-pulp components in Belgium in 1998.

Table 36: Consumption figures of non-pulp components in dry tons in Belgium 1998[xl]

Products	Domestic purchase (kT)	Imports (kT)	Total purchase (kT)	Real consumption (kT)
Kaolin	18	103	121	122
Calcium carbonatium	110	96	206	227
Talc	0	0,8	0,8	0,8
Titanium dioxyde	0,2	0,2	0,4	0,6
Other mineral products	0,6	3,4	4	4
Starch	15	18	33	33
Total non pulp	144	222	366	387

Non-pulp components account for 24 % of the material input for paper production in Belgium (192 kT mechanical pulp; 444 kT chemical pulp (Table 34) and 570 kT recovered paper pulp (Table 41)). This however does not imply that the same quantity of non-pulp components is required for the production of every kind of paper. The non-pulp components are mainly applied for the production of high quality papers, in which the Belgium market is highly specialised (see B.1.2.3), which explains the high non-pulp component consumption figures. The input of non-pulp components for the production of for example packaging paper is considerably lower (see §B.2.1.2).

B.1.2.3 Paper and cardboard

Table 37 shows the production and consumption figures of non-converted base paper in Belgium. This is not the final consumption of paper and board in Belgium.

Table 37: Production, export, imports, apparent consumption of paper and cardboard 1998[xl]

	Production (kT)	Exports (kT)	Imports (kT)	Apparent consumption[a] (kT)
Printing and writing paper	1103	840	1454	1716
▪ Newsprint	117	45	278	349
▪ Uncoated paper	228	108	535	656
▪ Coated paper	757	687	641	711
Paper and cardboard for packaging	239	125	1193	1307
Sanitary and household paper	83	11	69	141
Other paper and board	121	77	57	101
Total Paper and Board	1545	1053	2773	3265
[a] Apparent consumption = production + imports – exports				

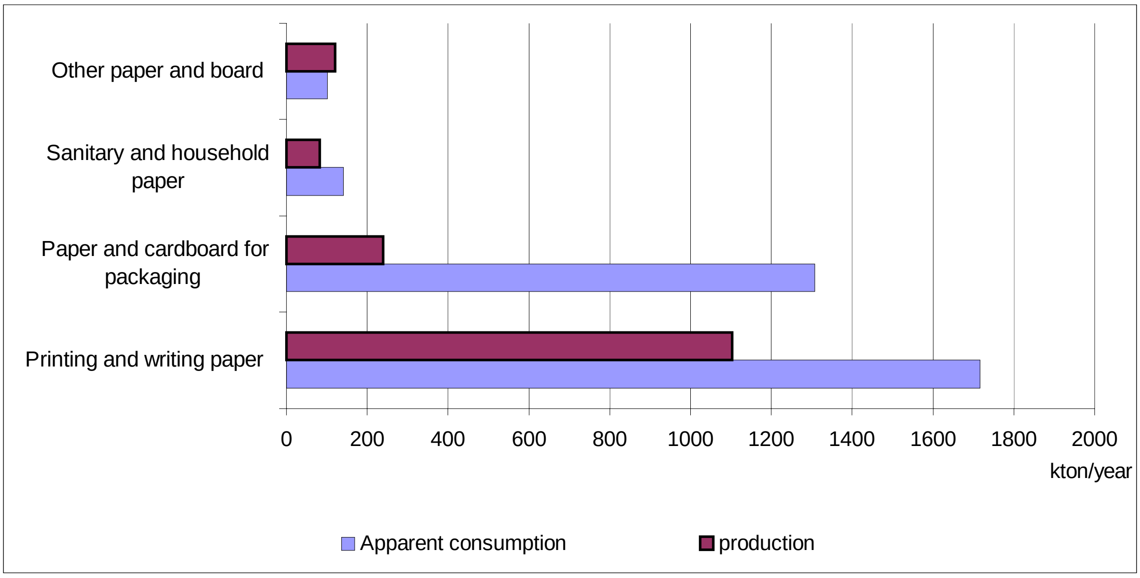

Figure 6: Production and apparent consumption of paper and cardboard in Belgium (1998)

Belgium covers more than 80 % of its needs for (non-converted) paper and cardboard with import, while more than 60 % of the production is exported, of which 80 % to neighbouring countries. This proves once more that the Belgian paper and board industry operates in a highly internationalised market.

Two third of the paper and board produced in Belgium is printing and writing paper. The production of paper and cardboard for packaging production makes out only 15 % of the total paper and board production in Belgium. There is a large import of paper and cardboard for packaging production in Belgium. This import exceeds the own production by a factor 5. Hence, a technology change in the Belgian production of paper and cardboard for packaging will have a very weak influence on the life cycle greenhouse gas (and other) emissions related to the final consumption of paper and cardboard packaging in Belgium. The other way round, changes in final consumption of paper and cardboard packaging will have a very weak influence on the Belgian production of paper and cardboard and on the related Belgian greenhouse gas (and other) emissions.

The figures given by Cobelpa match well with figures given by FAO.[xlii] These last figures comprise the paper and cardboard industry of Belgium and Luxembourg together.

The National Statistics Institute (NIS) uses a different kind of classification of paper and board products. This makes it quite difficult to compare the figures with those given by Cobelpa and FAO. The NIS statistics give a lower total production figure (1436 kT for 1998).

B.1.2.4 Paper and cardboard products

Whereas only 15 % of the total paper and cardboard producing industry in Belgium produces paper and cardboard for packaging, 75 % of the paper and cardboard converting industry converts paper and cardboard into packaging products. According to the NIS production statistics 1288 kT of paper and cardboard ware was produced in 1998, of which 977 kT was corrugated board, and paper and cardboard packaging material.

The difference in apparent consumption of paper and cardboard (3265 kT) and production of paper and cardboard products lies in the fact that much of the paper, like printing and writing paper, does not need to be processed further to end products.

According to the official trade statistics import and export of paper and cardboard packaging was 264 and 427 kT respectively.

Table 38: Production, import, export and apparent consumption of paper and cardboard packaging in 1998

	Production (kT)	Import (kT)	Export (kT)	Apparent consumption[a] (kT)
paper and cardboard packaging	977	265	427	815
[a] Apparent consumption = production + imports – exports				

The apparent consumption in Table 38 is the use of packaging by Belgian companies to pack their products. This products can be sold on the Belgian market or exported.

Fost Plus and Val-I-Pac provide figures of the packaging materials brought on the Belgian market (packaging used for packed products sold in Belgium) for household and industrial packaging respectively. Based on these figures the amount of household packaging products of paper and board (including beverage cartons) is estimated at 157 kT, while the industrial / distributional packaging products are estimated at 369 kT (see *Greenhouse gas emissions* *and material flows.Part II*). This gives a total of 508 kT of paper and cardboard packaging material brought on the Belgian market. Hence, there is a net export of about 300 kT of packaging in the form of packed products.

B.1.2.5 Paper and cardboard waste and waste treatment

Most of the paper and cardboard waste is recovered as paper pulp. There is however still a considerable fraction that is not recycled:

- recovered paper of a very inferior quality can be used as a source of energy (energetic valorisation (see Figure 1). Another option is the composting of paper and board together with the household organic waste.
- a fraction of the paper and cardboard will not be recovered and is landfilled, burnt without energetic valorisation or lost in the sewers (e.g. sanitary paper, wall paper, …).

Table 39 gives an overview of the flows of waste paper on the Belgian market.

Table 39: Waste paper purchase, import, export and consumption in 1998[xl]

	Domestic purchase (kT)	Converting waste (kT)	Imports (kT)	Exports (kT)	Apparent recovery[a] (kT)	Real Utilisation (kT)
Newsprint & Brochures	110	0	80	202	292	170
Corrugated & boards	127	21	143	412	490	221
White & superiors	3	15	25	45	38	18
Others & mixed	97	16	180	667	604	117
Total recovered paper	337	51	427	1326	1424	525
[a] Apparent recovery = utilisation + exports – imports						

The evolution of the total utilisation of waste paper by the national paper and board mills increased from 361 kton in 1996 to 525 kton in 1998 (and 570 kton in 1999[xliii]). This is low however compared to the apparent recovery (domestic utilisation + exports - imports) of waste paper (1019 kton in 1996, 1424 kton in 1998, 1588 kton in 1999). According to Table 40 the recovered paper utilisation as a % of production of paper and board is only 34 %. In the UK this is 65 % and in the Netherlands even 75 %. The low recovered paper utilisation in Belgium is caused by the production structure of the industry. Two third of the paper and board produced in Belgium is printing and writing paper. The quality of the recovered paper is not good enough to produce printing and writing paper. That is the reason why most of the waste paper that is collected in Belgium is exported (mostly to Asia).

Over the period of the last ten years the exports of waste paper almost tripled. In 1989 the waste paper exports were less than 600 kT against 1715 kT in 1999. The imports rose from less than 100 kT to 697 kT

Table 40: Recovery of waste paper[xliii]

	1996	1997	1998	1999
Total recovered paper utilisation as a % of production of paper and board	27	32	34	34
Recovery of waste paper as a % of paper and board consumption	38	41	44	48

In the last ten years the recovery of waste paper (as a % of paper and board consumption) has substantially increased. The collected quantity of paper and board waste has substantially increased since the foundation of Fost Plus and Val-I-Pac (see *Greenhouse gas emissions and material flows. Part II)*. Today almost three quarters of the potentially recoverable amount of paper and cardboard is collected.[xxxv]

The amount of recycled pulp and the pulp quality that can be used depends highly upon the converted product one wishes to obtain. Newspaper can be produced using 90 % of recycled pulp, while paper for magazines in Belgium consists only of 30 % recycled pulp. Cardboard for packaging can be produced using over 90 % of recycled pulp. From these recovery percentages it follows that the newsprint and packaging producers are the greatest recovered pulp buyers in Belgium. The pulp grades used by the different industries are shown in Table 41.

Table 41: Usage of recovered paper pulps in Belgium[xliv]

	Mixed Grades (kT)	Corrugated Kraft (kT)	Newspapers and Magazines (kT)	High grades (kT)	Total Usage of Recovered Paper (kT)
Pulp quality[a]	Low grades		De-inking grades	High grades	
Newsprint + other graphic papers			171	10	181
Packaging papers	76	198	7		281
Household & sanitary	1			9	10
Others	47	51			98
Total	124	249	178	19	570
[a] the grades are explained in Table 29.					

B.1.3 Summary and conclusions

Table 42 summarises the production and consumption data. The import / consumption ratios and the export / production ratios for the pulp, paper and board industry in Belgium show once more (Table 42) that the Belgian industry is highly internationalised. 64% of the pulp and 85 % of the paper and board consumed in Belgium have been produced in other countries. The figures are even more pronounced for packaging paper and board.

Table 42: Production and consumption figures for Belgium in 1998

	Production (kT)	Import (kT)	Export (kT)	Consumption (kT)	Import/Con-sumption (%)	Export / Production (%)
Pulp[a]	381	421	132	660	64	35
Paper and cardboard	1545	2773	1053	3265	85	68
Paper and cardboard for packaging	239	1193	125	1307	91	52
Paper and cardboard packaging (finished products)	977	265	427	815	33	44
[a] excluding recovered paper pulp						

Two third of the paper and board produced in Belgium is printing and writing paper. The production of paper and cardboard for packaging production makes out only 15 % of the total paper and board production in Belgium. Import of paper and cardboard for packaging production exceeds the own production by a factor 5.

Whereas only 15 % of the total paper and cardboard producing industry in Belgium produces paper and cardboard for packaging, 75 % of the paper and cardboard converting industry converts (mainly imported) paper and cardboard into packaging products.

The recovered paper utilisation as a % of production of paper and board is only 34 % because the quality of the recovered paper is not good enough to produce printing and writing paper. Most of the waste paper that is collected in Belgium is exported.

As for the production and consumption of plastics there is a very weak link between the consumption of final paper and cardboard products on one hand and the production of the base materials on the other hand (pulp, base paper and cardboard). There is also a very weak link between the total recovery of waste paper in Belgium on one hand and the use of recovered paper pulp by Belgian paper and cardboard producers on the other hand.

B.2 Paper and cardboard production processes

B.2.1 General aspects

B.2.1.1 Major data sources

The description of paper and cardboard production processes and of the main greenhouse gas emission mitigation options is mainly based upon two recent studies that consider the energetic and the environmental problems linked to the production of paper and cardboard while giving attention to the economic costs. The two documents are:

- European Integrated Pollution Prevention and Control Bureau (EIPPCB); Sørup P. et al. (2000) *Draft Reference Document on Best Available Techniques in the Pulp and Paper Industry*, Institute for Prospective Technological Studies, Seville[xlv].

- Hekkert M.P., Worell E. (1997) *Technology Characterisation for Natural Organic Materials. Input data for Western European MARKAL*, Department of Science, Technology & Society, Utrecht[xlvi].

The first document searches for the Best Available Techniques in the paper and board sector by considering the applied processes and techniques, the present consumption and emission levels and the techniques that respond to the BAT principles. In the remainder of the text, it will be referred to as BREF (Best available techniques REFerence document).

The second document mainly tries to give realistic values of the material inputs, the energy inputs and the related costs for the different production processes now and in a period of time (20 years, 50 years). These data are the basis for the Markal Matter 4.2 model input on paper and cardboard production.[xlvii] It will be referred to further as MATTER

Although these two documents differ completely in the data sources they have consulted, the figures they present match considerably well. The BREF study refers mainly to SEPA Report 4712[22] (1997) and a Finnish BAT Report[23] (1997). The MATTER study mainly refers to *PPI's International Fact and Price book 1997, Pulp and Paper International* from 1996 and 1997. Besides these main sources they have both consulted a lot of literature upon specific production processes. These sources also differ. They will be referred to in the text.

B.2.1.2 Integrated and non-integrated plants

About 30 % of the European paper mills are integrated with pulp production. Mechanical paper grades, like newsprint, SC and LWC, are usually integrated with mechanical pulp and often buy small amounts of chemical pulp. Especially for recovered paper manufacturing the level of integration is high; nearly all recovered paper mills include recovered paper processing, some of them adding purchased pulp.

Bleached kraft is the dominating grade for market pulp (more than three quarters of the whole production).

Integrated plants have two major advantages to non-integrated plants. There is a substantial saving in energy, because the pulp does not have to be dried first to be rewet in the pulpers. Furthermore there is a surplus of heat that is generated in the pulping process and that can be used during the paper production to dry the base paper.

B.2.1.3 Paper and cardboard for packaging

We will focus further on the production of paper and cardboard for packaging.

Packaging paper is a diverse product category. It contains different packaging paper grades and cardboard products. The critical quality of packaging papers is their strength. Depending on the packaging paper type different shares of waste paper are used in the production process. The major raw materials used for different packaging papers are given in Table 43.

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[22] Jaakko Pöyry Consulting AB (1997) *SEPA-Report 4712-4; Energy conservation in the pulp and paper industry*.

[23] Ministry of Environment in Finland (1997) *The Finnish Background Report for the EC Documentation of Best Available Techniques for Pulp and Paper Industry,* Edita LTD, Helsinki.

Table 43: Major raw materials used for manufacturing packaging paper

Paper grade	Major raw materials used
Kraft wrapping (high strength product)	mainly unbleached Kraft pulp no added fillers, coloured
Kraftliner or Testliner (heavy weight product)	unbleached Kraft pulp and recovered paper pulp or recovered paper pulp only no added fillers
Board (heavy weight product)	all fibre types including recovered paper pulp often different compositions in different ply mostly multi ply sheet

As indicated previously, paper and cardboard for packaging is to a large extent produced from chemical pulp and recovered paper pulp. Hence, these technologies will be looked at in more detail.

For beverage packaging it is mainly cardboard we are dealing with (trays, boxes, liquid packaging board). The quantity of non-pulp components added during the production of packaging cardboard is limited. According to a Swiss inventory about 85 - 115 kg of fillers (china clay and calcium carbonate) (of which 50 to 80 % are retained in the paper web), 11 kg of aluminium sulphate and 4 - 7 kg of synthetic binder are used for the production of 1 ton of cardboard when using mainly recovered paper pulp. [xlviii]

B.2.1.4 GHG emissions

GHG emissions related to energy use

Energy supply plays a major role in the pulp and paper/board producing industry. The costs of energy supplies can be as high as 20 % of the cost price of the product. The total primary energy consumption of the Belgian pulp and paper/board producing industry amounts to 27.645.000 GJ (in 1998). This corresponds to a specific primary energy consumption of 14,7 GJ/ton.[xlix]

The paper and board converting industry on the other hand consumes considerably less energy.

When recovered paper is used as raw material the energy consumption for the production of pulp will be substantially lower.

The energy related greenhouse gas emissions do not only depend on the applied production process. The layout of the plant (integrated or non-integrated) and the consumed fuels are also important factors in the amount of CO_2 emitted to the air.

Direct GHG emissions

The production processes within the paper and board industry do not result in direct greenhouse gas emissions. However, paper and cardboard waste dumped in landfill sites leads to methane emissions. This is also true for wastewater that is anaerobically purified.

The emissions resulting from the burning of bark and wood residues are not counted for as direct GHG emissions since they are part of the energy production.

B.2.1.5 GHG emission mitigation

Fuel switch

The CO_2 emissions resulting from the different fuels as described in 1.1.2.1, theoretically offer a possibility to reduce greenhouse gas emissions by switching between fuels. This however has to be considered for each separate company, taking into account every specific situation.

Increased energy efficiency – cleaner technology

The installation of energy efficient technologies usually is linked with investments to replace, rebuild or upgrade process equipment. These investments are mostly not applied only for energy saving. Production efficiency, improvement of product quality and reduction of overall costs are the most important basis for investments.

- Co-generation of heat and power (CHP)

The energy requirement and the heat-power ratio in the paper and board industry are very appropriate for the use of co-generation. The characteristics of the processes such as high and balanced electricity and heat needs, and regularity of operation over the year are also favourable.

- Secondary boilers or recovery boilers

Recovery boilers, which burn bark and wood residues, can be installed at the plant to support the energy supply. Because trees have initially converted CO_2 into wood, they are often considered a CO_2-neutral resource.

- Big versus small plants

In many cases there exist important differences in environmental performance between bigger and smaller paper plants. The economies of scale facilitate investments in clean technology for bigger mills. In addition these mills have more financial and human resources for research and development.

Recycling and reuse

Reuse of products mostly applies to goods where the product’s technical life exceeds its economical life. This does not apply to paper products and certainly not to packaging goods, which often have a very short technical life. These goods however lend themselves very well to recycling. (see § B.1.2.5 and § B.2.3).

In Western Europe about 45 % of the total fibres used for papermaking are recycled fibres. [xlv] For certain applications however there is a maximum to the proportion of the recovered paper pulp caused by the quality that is required for the end product.

Table 44: Share of recovered paper pulp in different end products[xlv]

End product	Recovered paper pulp (%)
Liner and fluting	85.9
Carton boards	52.2
Newsprint	49.0
Tissue and other hygiene papers	66.9

Paper fibres can only be used a limited number of times (5 to 6 times). As a result a proportion of new fibres always has to be added to ensure paper strength.

Increased materials efficiency

An increase in the production output (smaller fall-out) can be realised by a better adjustment of the stock preparation and the paper machine. An increase in the rate of production will result in higher energy consumption, but the efficiency of the energy use will be considerably higher.

B.2.2 Kraft (sulphate) pulp production[24]

B.2.2.1 Process description

An overview of the different wood pulping processes is given in Figure 7. As mentioned above mainly unbleached kraft pulp is used for packaging paper and board. An alternative chemical pulping process is the sulphite process. This process is however less applied in Europe (2.2 million tons to 17.4 million tons for the Kraft process). The imports in Belgium of the sulphite pulp are also rather limited in comparison to the Kraft pulp (55 tons to 319 tons). The sulphite pulping process is not applied in Belgium. It will not be considered further.

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[24] The pulping processes discussed below are all based on wood or recovered paper as raw material. There is however also the option to produce wood from non-wood fibres, like cereal, rapeseed and linseed straw, miscanthus, flax, hemp and kenaf. The production of pulp from non-wood fibres is however very limited at this moment in Europe (only 0.4 % of the total pulp production). Therefore the production of pulp from non-wood fibres will not be considered in this text. Furthermore the discussion of the problems associated with the production of non-wood fibres would lead beyond the scope of this study.

The Kraft process is the dominating pulping process. This is caused by its superior pulp strength properties, its application to all wood species and the efficient chemical recovery system, where 95 % of the reagents are being recycled and the lignin is used to create one of the reagents. But the chemistry of the Kraft process carries with it an inherent problem of producing a darker pulp caused by the chromophoric groups of the residual lignin. This implies that in many applications bleaching of the pulp is required.

The different steps the wood chips follow, are: wood handling, cooking, brown-stock washing, oxygen delignification, post-oxygen washing, bleaching and pulp drying.

All wood species can be used as raw material. Logging and sawmill residues can also be pulped with the kraft pulp process. The wood required for manufacturing 1 tonne of chemical pulp is usually between 4 and 6.6 m^3. The density of wood is between about 0.4 and 0.6 g/cm^3. Hence, about 2,65 ton of wood is needed for 1 ton of chemical pulp.

The wood handling stage consists of the debarking and the chipping of the wood into uniform sized chips. The fibres from these chips are liberated from the wood matrix in the cooking plant as the lignin is removed by dissolving in the chemical solution at a high temperature. Part of the hemicellulose is dissolved as well. The active cooking chemicals (white liquor) are sodium hydroxide (NaOH) and sodium sulphide (Na_2S). The cooking process can be performed either in batch digesters or in a continuous digester.
The pulp coming from the digester contains both fibres and spent cooking liquor (black liquor). The black liquor is removed from the pulp and led to the chemical recovery system, where cooking chemicals and energy are recovered.

After cooking, delignification of the fibres can be continued by oxygen in one-stage or in two stages, with or without intermediate washing. Oxygen delignification can be combined with conventional and extended cooking. The degree of further delignification is 40-50 % in a one-stage system and can be up to 70 % in a two-stage system. The overall pulp yield might decrease by 1.5 – 2.5 % and there is still lignin left that has to be removed by other means when high brightness pulp is demanded.

The brightness of Kraft pulp is rather low, below 30 % ISO[25], whereas fully bleached pulp has a brightness of 88 % ISO or higher. Bleaching plants tend to discharge effluent to external treatment, making them important wastewater producing systems. Much research however has been done over the last decades to reduce the discharge of chlorides and other unwanted inorganic elements.

Since packaging in many cases does not require bleached paper pulp, no further attention will be given here to these problems.

The yield of the chemical pulping process is about 50 to 55% (Table 30).

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[25] % ISO: Brightness unit according to ISO, the International Organisation for Standardisation.

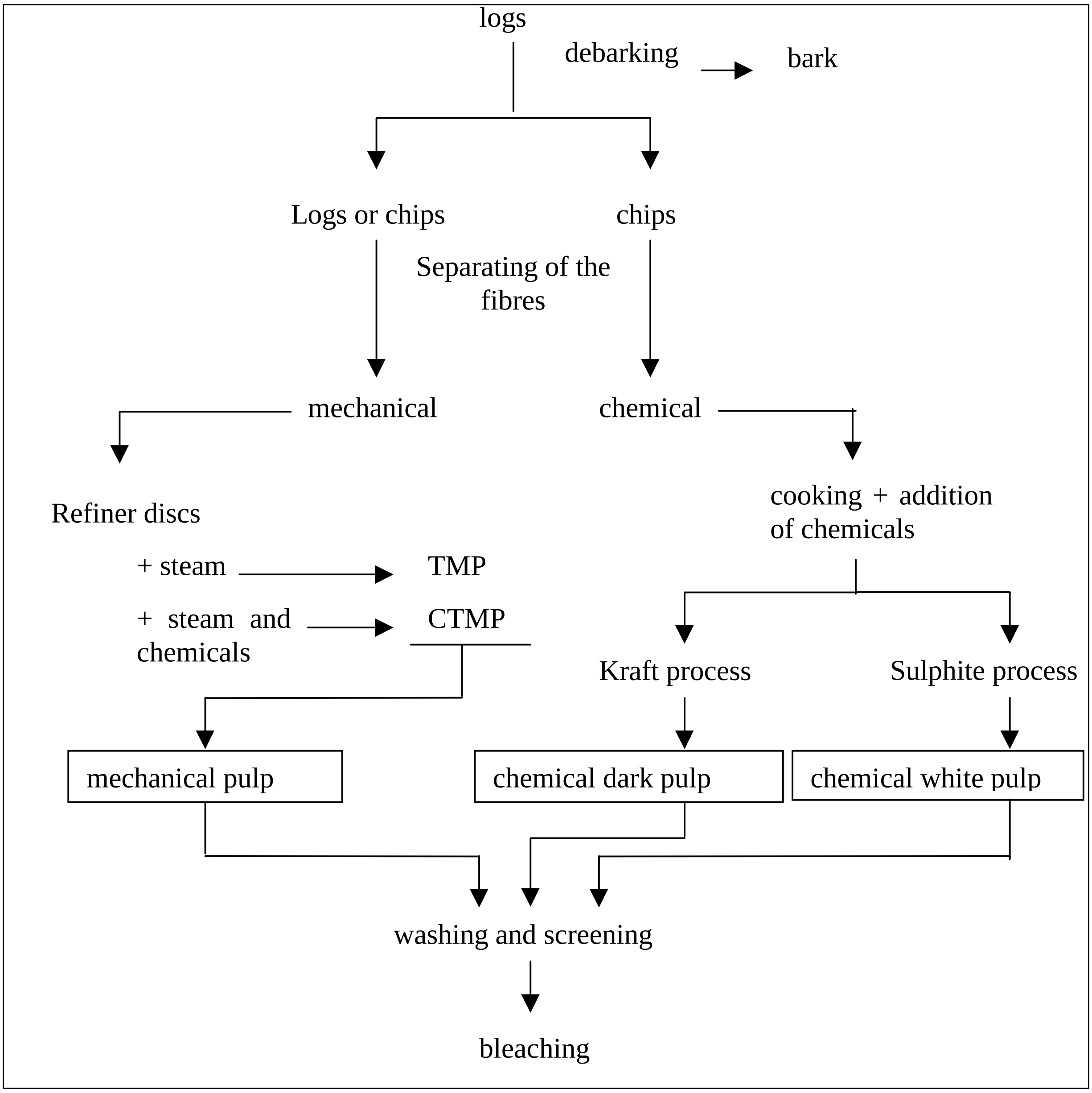

Figure 7: The pulp production with wood as raw material[xxxix]

B.2.2.2 Energy use

The BREF states that information on energy balances of whole paper and pulp mills in many European countries is poorly available.

Chemical pulping plants are energy-intensive installations that consume high amounts of energy but at the same time produce steam and electrical power on site by use of regenerative fuels. Thus, modern non-integrated Kraft pulp mills are energy self-sufficient mainly because of efficient energy recovery by burning 50 % of the incoming wood in the recovery boiler (strong black liquor) and the use of bark as auxiliary fuel. Furthermore secondary energy from different process steps can be recovered as warm and hot water (40-50 °C). Fossil fuels are mainly used as support fuel.

The BREF study gives the approximate needs of process heat and power at energy efficient kraft pulp mills. For making bleached kraft pulp 10 - 14 GJ/ADt[26] of heat and 600 - 880 kWh/ADt of electricity is consumed. These figures include the energy for drying the pulp, which equals about 25 % of the total heat energy and 15 - 20 % of the electrical energy. This energy consumption is not necessary in the integrated production process. The MATTER data for the year 2000 are comparable, if we take into account that energy for drying is not included.

Major steam users in a Kraft pulp mill are the digesters, evaporators and the pulp driers. These processes account for about 75 % of the steam use of the pulp mill. The electricity use is more evenly distributed over the mill. Pumps and fans are the major consumers, 40-45 % and 15-20 % respectively.

The conventional power plant configuration in a non-integrated kraft pulp mill is a recovery boiler and a bark boiler feeding a backpressure turbine with intermediate steam tapping and, possibly, condensing. The strong black liquor is burnt in the recovery boiler. The generated heat is used for the generation of high-pressure, superheated steam. Part of its energy content is utilised for generating power in a backpressure turbine. Medium-pressure steam from the turbine and low-pressure exit steam are utilised for covering the heat energy demand in the kraft pulp process.

In an integrated pulp and paper mill the excess heat produced by the pulp mill is not quite enough to cover the energy consumption of the paper production. The additional demand for heat has to be produced in wood/bark boilers and auxiliary boilers.

The MATTER study gives data for energetic recovery of black liquor and bark in a Tomlinson recover boiler. Black liquor and bark from the production of 1 ADt of pulp yield 14,4 MJ steam and 2,16 MJ electricity. In the BREF study a heat surplus of 0,5 to 1,0 GJ/ADt is estimated, after satisfying the electricity demands of the pulp plant. This corresponds to a comparable energetic recovery.

B.2.2.3 Technological perspectives

The BREF mentions several techniques to consider when determining BAT. Some of them have an influence on the energy consumption of the pulp mill. The MATTER document also mentions techniques having an effect on the energy use in the pulp mill.

Dry debarking

In recent years dry debarking has been installed in many mills. It creates bark with lower water content, which will result in a better energy balance for the mill. On the other hand energy consumption in debarking may increase.

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[26] ADt: Air dry metric tonne of pulp meaning dry solids content of 90 %. Note that an air dry tonne of paper is defined as paper with 6 % moisture content.

Modified cooking or extended delignification

The reduction of the emissions to water is the main reason to implement this technique. A beneficial effect is also a reduction of the consumption of expensive bleaching chemicals. The lignin content in the pulp entering the bleach plant is decreased (which also means a loss of yield and increased wood consumption). The amount of organic substances going to the recovery boiler is increased.

Heat and electricity demand increase by 0.5 GJ/ADt and 0.27 GJ/ADt respectively which is compensated by a higher recovery of organics. Using the high-grade heat in the spent pulping liquor to preheat white liquor and chips can further save energy.

Medium consistency processing.

Large amounts of electricity are being used by pumps. Due to low consistency of the pulp (1-3 % in washers, 1 % in screening and 3-12 % in bleaching) large amounts of water have to be pumped. Increasing the overall consistency of the pulp (8-15 %) can lead to 10 % reduction of the energy consumption for pumping.

Pulp drying.

Most of the energy used in the dryer is used to evaporate the water. By using state of the art double wire technology, the consistency of the pulp before drying can reach 50 % (instead of 45 % normally).

Black liquor evaporation.

Black liquor concentration is usually the biggest steam using operation in a Kraft pulp mill. Black liquor is evaporated by heating it with steam (140 °C). Evaporated water is used in the next drying section (multiple effect evaporator). By using more effects, less steam is required for this operation. Modern mills use a 5 or 6 effect evaporator while older mills use 4-5 effects. To minimise steam use 6 or 7 effects are used. Large steam savings can be achieved by using less water in the brown stock washing (where the fibres are separated from the spent pulp liquor).

Increasing the dry solids content of the black liquor can lead to an increase in the capacity of the recovery boiler.

Black liquor gasification.

The black liquor can be gasified and the flue gasses can be used to fuel a gas turbine/steam turbine combined cycle. According to the BREF study theoretical balance calculations show that black liquor based Integrated Gasification with Combined Cycle Technology (IGCC) may reach a power efficiency of about 30 % calculated on the heat value of the black liquor. This may be compared with 12-13 % for the conventional recovery boiler. However, at the same time the overall efficiency (power + steam) would decrease by about 5 % to about 75

%. Thus, the production of process steam decreases. In a situation with a surplus of steam, pulp mills will become net exporters of electricity.

Black liquor gasification can only gradually be introduced in the paper industry, mainly because of the lifetime of present recovery boilers. Before 2010, the IGCC technology is only expected to play a marginal role in the overall Kraft industry.

Few precise quantitative data are given on the effect of these techniques on the overall energy consumption and/or recovery. In the MATTER database no changes in energy consumption are considered over the period 2000 - 2020.

B.2.2.4 Other environmental impacts

In (integrated) Kraft pulping the major concerns are in order of importance: water use, wastewater discharge, energy consumption (steam and electricity), solid waste such as rejects, sludge and ash, air emissions from energy generation (SO_2, NO_x, CO_2, dust) and locally noise, waste heat to water and odour.

Emissions to the atmosphere from a Kraft pulp mill consist mainly of sulphur-containing compounds such as sulphur dioxide and malodorous reduced sulphur compounds like methyl mercaptan, dimethyl sulphide and hydrogen sulphide. The latter compounds are commonly referred to as total reduced sulphur (TRS).

From furnaces nitrogen oxides are also emitted and furthermore small amounts of dust (solid particulates) as fly ash.

From bleach plants and from bleaching chemical preparation chlorine compounds may leak to the atmosphere. Volatile Organic Compounds, mainly turpenes, are emitted to the atmosphere from wood chips stored in heaps outdoors.

B.2.2.5 Prices / cost

The Kraft pulping is a very capital-intensive process. The cost data for Kraft pulping are much higher than those for mechanical pulping.

Table 45: Cost data Kraft pulping

Kraft pulp mill	Costs (EUR/ton)
Investments	1355
O&M	75
of which labour	60
Tomlinson recovery boiler	
Investments	145
O&M	7

B.2.3 Recovered paper pulp

B.2.3.1 Production process

The recovered paper processing system varies according to the paper grade to be produced. For newspaper production and for the production of graphical paper, high waste paper pulp qualities are necessary. A de-inking mill is required to produce these types of pulp. For the production of packaging paper and board however a non-de-inking mill is sufficient.

These two systems differ considerably on certain processing steps. Still, a waste paper plant consists normally of the following general steps:

- Pulping: the waste paper is defibrillated and contaminants are removed.
- Coarse screening and cleaning: removal of coarse non-fibrous contaminants with minimal losses of useful fibre.
- Fine screening and cleaning: removal of fine non-fibrous contaminants with minimal losses of useful fibre.
- Other processes: optional de-inking, bleaching,…
- Thickening and storage: de-watering and thickening by disc filters and screw presses to achieve the pulp consistency needed.

The yield differs considerably for the different production processes. The low quality pulp for packaging paper and board attains a yield of 89 %. The efficiency for high quality graphical papers is 69 %. Newsprint production has a yield of 85 %.

Cardboard for packaging can be produced using over 90 % of recycled pulp. Use of up to 100 % of recycled fibres for packaging paper and board is reported.[xxxv]

B.2.3.2 Energy use

Recovered paper pulping requires substantially less total energy for processing than is needed for chemical and especially for mechanical pulping. The shift in raw material mixes however is dependent upon the prices on the international market.

Table 46 gives data for the energy consumption in the non-integrated recovered paper pulping process. The MATTER data refer to the production of low quality paper pulp. The data given in the BREF-study refer to the production of pulp for packaging paper. The data given by BREF are considerably smaller than the MATTER data. They are from operational experiences provided by a supplier.

The MATTER data suggest that considerable improvements in electricity use can be expected.

Table 46: Energy consumption for non-integrated recovered paper pulping

	MATTER 2000	MATTER 2020	BREF
Steam (GJ/ton)	1.1	1.0	0
Electricity (Gje/ton)	1.7	0.9	0.54 - 0.90

B.2.3.3 Technological perspectives

According to the MATTER Report the pulping process has developed over the years from low consistency pulping to high consistency pulping. This evolution has taken place because high consistency pulping uses less energy because less water needs to be moved and contaminants are not degraded as much as in low consistency pulping. This way the contaminants can be removed more easily later on. The typical energy requirement of a low consistency pulper is in the range of 0.11-0.16 GJ/ton, while a high consistency pulper uses 0.05-0.09 GJ/ton.

Next to anaerobic techniques as first stage of biological wastewater treatment and co-generation of heat and power (CHP), that are more widely applicable in the pulp and paper industry the BREF Report presents some other techniques to reduce the energy consumption and subsequently the related air emissions.

- Upgrading of stock preparation plants (integrated plants) with decreased electricity consumption and emissions.

Depending on the stock preparation concept, electrical power demand can vary between 0.16 GJ/ton and 0.34 GJ/ton. A minimised stock preparation concept however can result in more shut downs and web breaks.

- The Continuous Batch Fibre Recovery System (CBFR) to processing recovered paper in a complete system.

The Continuous Batch Fibre Recovery System has the potential to improve the competitiveness of smaller mills and paper machines because it can economically process recovered paper materials in quantities as low as 3 ton/day. The primary aim is to provide mini recycling mills close to the source of recovered paper.

The system can also process more difficult materials (such as milk cartons, drink boxes, wax-coated corrugated etc.) that contain high quality fibre but are typically not sorted because they are generated in small volumes and are not regarded as economically to recycle.

B.2.3.4 Other environmental impacts

The environmental impact of recovered paper processing (integrated plants) includes emissions to water, solid waste generation and atmospheric emissions related to energy generation by combustion of fossil fuels in power plants.

B.2.3.5 Prices/costs

The investment costs for a recovered paper pulping plant are obviously lower than the investment costs for a Kraft pulping plant (Table 47).

Table 47: Cost data for recovered paper pulping

	Costs (ECU/ton)
Investments	550
Other manufacturing costs	31
labour	24

B.2.4 The paper and board production

B.2.4.1 Production process

A paper mill consists of three parts: stock preparation, paper machine and finishing.

In the stock preparation stage the pulp is dispersed in 20 times the amount of water (stock). The quality of the stock can be adjusted by adding additives. The stock is then treated in refiners in order to get a good fibre to fibre bonding that is needed for the desired paper quality. Finally the pulp is cleaned.

The next stage in the paper mill is the paper machine. Here the water is removed from the stock and the fibres are left in a sheet. The paper machine can be divided in a wet end and a dry end. The wet end is the forming of the sheet. The stock with a consistency of 1.5 – 1 % is dispersed on a fine wire screen. Then the water is removed leaving a sheet with a consistency of 15 – 20 % (95 % of the water is removed). The water removal is achieved by gravitational dehydration and next by passing through a vacuum section.

The dry end consists of a press section and a drying section. In the press section water is squeezed out of the sheet by passing it through multiple pairs of cylinders. The consistency of the sheet increases to 40 – 50 % (1 – 2 % of the initial water is removed).
The drying section consists of 40 – 60 steam heated cylinders. Water in the sheet is removed by evaporation. The consistency of the sheet after drying is about 94 % (1 % of the initial water is removed in this step).

The finishing stage consists of smoothing the surface of the paper products, winding it on reels, cutting, packing and dispatching.

B.2.4.2 Energy use

Paper industry is very energy intensive. The electricity consumption depends to a certain extent on the paper grade produced. The lowest values correspond to packaging paper or corrugated base paper. The higher power demand for other papers mainly arises from the more intensive refining.

The BREF study gives the approximate needs of process heat and power associated with the use of BAT for production of fine paper and tissue, but not for packaging paper. For uncoated fine paper process heat requirements are estimated at 7.0 - 7.5 GJ/ton. For board production in modern paper mills electricity consumption of 550 and 680 kWh/ton are reported for linerboard and multiply board respectively.

The MATTER data for packaging paper for the year 2000 are slightly lower: 6.0 GJ/ton heat and 1.8 GJe/ton electrical energy.

B.2.4.3 Technological perspectives

The BREF Report gives an overview of the role of energy in every process step together with the potential for energy saving (The main parameters having an influence on the specific energy consumption of the paper machine are the dry matter content and the degree of heat recuperation in the drying section. The dry matter content depends on the efficiency of the mechanical dehydration section (Table 48).

The stock preparation has a very important influence on the overall energy efficiency of the production process. An unsatisfactory stock preparation may result in a large production fall-out because the required paper quality is not met. The rejected paper has to be repulped and cleaned.

The refiners offer high potential for energy saving. Many refiners are for example incorrectly sized or not well maintained. This results in a high no load power, which reduces refiner efficiency. Furthermore, incorrect refiner fillings will cause an increased use of energy to achieve a given property. New refiners with enhanced efficiency can save energy because of the very low no load power associated with these refiners.

Another important factor is the design of the paper machine as such that the de-watering of the paper is as high as possible before the paper enters the drying section. A large enough gravitational section and a good design of the vacuum section are the major points of attention here.

Finally the pressing and drying sections offer great potential for energy saving. The drying step in the paper machine is the least energy efficient operation. Only 1 % of the initial water is removed while it uses 90 % of the total heat demand of the paper machine.

The main parameters having an influence on the specific energy consumption of the paper machine are the dry matter content and the degree of heat recuperation in the drying section. The dry matter content depends on the efficiency of the mechanical dehydration section.

Several techniques can reduce the steam consumption of the drying process:

- forming the sheet with a minimum of water (dry sheet forming, high consistency forming);
- improving the pressing section and drying section so less steam is needed for drying (impulse drying, condebelt drying, press drying, air impingement drying);
- making use of the latent heat of the evaporated moisture (steam impingement drying, airless drying).

Table 48: The role of energy and the potential for energy savings in the different production processes of papermaking.

Main processes	**Main process units**	**Type and role of energy in each process**	**Potential for energy saving**
Stock preparation	Slushing	Up to 0.22 GJ/ton to break up dry pulp	Moderate
	Cleaning/screening	The amount of pumping energy and stock heating depend on the number of stages required and the type of fibre (recycled fibre needs more than virgin).	Low for virgin fibre
	Refining	Very energy intensive. Electrical energy is mostly used to drive the rotor in the refiner. Depends strongly on the paper properties to be achieved; 0.36-10.8 GJ/ton	High
Wet end	Forming and draining	It uses large amounts of electricity for machine drive and vacuum processes. Energy efficient design of the headbox and twin wire machine leads to power savings; About 0.25 GJ/ton is used for vacuum systems (varies with grade and porosity).	Moderate
Dry end	Pressing	It is not energy intensive in itself but efficient dewatering can give very large energy savings in the dryers.	Moderate
	Drying	Apart from refining it is the most energy intensive process in papermaking. Mostly heat energy.	Very high
	Size press and 2nd dryer section	Heat energy for after size press drying.	Low
	Calandering	Electrical energy for machine drives and pressing.	Low
Coating	Coating and dryer	Electrical and heat energy for re-drying.	Low

The MATTER report cites estimates that on the long term the steam consumption can be reduced by 75-95% without an increase in electricity consumption. A possible way to reach these reductions is a combination of impulse drying, steam impingement drying and a number of small improvements (see Table 49). The costs of this paper machine configuration will be less than current configurations.

As mentioned before the use of combined heat and power generation (see section 1.1.3.2) can offer substantial additional energy savings.

Table 49 gives potential energy savings and penetration rates of some new technologies in papermaking as given in the MATTER study.
The BREF study gives less optimistic prospects. For impulse drying the steam savings are estimated at 10 - 25 %. It is stressed that many obstacles have been encountered in the development work. The technology has been developed since the beginning of the 70s without any final breakthrough. For Condebelt® drying the main advantage are savings in raw material (the same paper quality can be achieved with less fibre), rather than savings in energy.

Table 49: Energy consumption of new technologies in papermaking (MATTER data)

	Condebelt® drying	Impulse drying	Air impingement drying	Steam impingement drying
Steam (GJ/ton)	-20 %	-60 %	-25 %	-13 %
Electricity (Gje/ton)	-	+8 %	+3 %	-8 %
Penetration rate 2020	50%	33%	50%	50%

B.2.4.4 Other environmental perspectives

Air emissions from paper and board mills are mainly related to energy generation and not to the papermaking process itself. This makes that saving energy will lead to a reduction in air emissions.

The emission levels depend on the type of fuels used (coals, oils, gas) and the implementation of emission control technologies for reduction of SO_2 and NO_x, particulates and non-incinerated organic gaseous substances.

B.2.4.5 Prices /costs

Table 50: Cost data for paper and board production

	Non-integrated mill	Integrated mill[a]
	EUR/ton	EUR/ton
Investments	1058	2413
O&M	59	134
o.w. labour	47	107

[a] Combination of a paper machine and a Kraft pulp mill that produces unbleached Kraft pulp.

The costs for paper production are relatively high. They are almost in the range of the costs for Kraft pulping.

B.2.5 Integrated pulp and paper making

As already mentioned integrated pulp and paper making plants save on energy use for drying the pulp. Table 51 gives an overview of energy data for the integrated production of paper and board grades composed of different pulping grades.

Table 51: Energy use of integrated pulp and paper producing processes.

Pulp production process	Paper type produced	Source	Electricity[a] (Gje/ton)	Steam (GJ/ton)
Kraft	Kraftliner	BREF	3.6 – 4.7	14.0 – 17.5
Kraft	Sack paper	BREF	3.6 – 5.4	14 – 23
Kraft	Packaging paper	MATTER	3.7	11.7
Recovered paper mill	Testliner and Wellenstof	BREF	2.5 – 2.9	6.0 –6.5
Recovered paper mill	Carton board and folding boxboard	BREF	3.2 – 3.6	8 – 9

It can be seen in Table 51 that the integrated paper/board production with recovered paper as a raw material is much more energy efficient than the processes using wood as a raw material.

B.2.6 The conversion of paper and board to packaging material

Table 52 gives an overview of the processes involved in producing packaging material starting from paper or board.

Table 52: Production processes in the paper and board converting industry

	Corrugated cardboard	Folding carton	Assembled boxes	Great content bags	Small and medium sized bags	Flexible packaging
glue lamination	X	X	X			X
extrusion		X		X	X	X
corrugated board machine	X					
offset printing		X	X			
helio printing						X
flexo printing	X		X	X	X	X
cutting	X	X	X	X	X	X
blanking	X	X	X		X	
folding	X	X	X	X	X	X
gluing	X	X	X	X	X	X
window material		X	X		X	
Sewing				X		
Drying	X	X	X	X	X	X

Energy use for the production of packaging products is generally very small, compared to the energy required for the production of paper and board.

B.2.7 Summary of energy data for production of packaging board

To be able to take into account trends in pulp and paper production when estimating the impact of changes in end use of beverage packaging on greenhouse gas emissions (see *Greenhouse gas emissions and material flows. Part II*), the following data will be used as representative for the production of packaging board. They try to summarise the data given in both above-mentioned studies.

For recovered paper pulping we will base ourselves on the BREF data, using the upper limit as the actual average over all pulping plants, and the lower value as the potential improvement that can be reached by 2015.

Table 53: Summary of energy data for pulp production

		pulp production, integrated		pulp production, non-integrated		recovered paper pulp production	
inputs		2000	2015	2000	2015	2000	2015
wood	ton/ton	2.35	2.35	2.35	2.35		
recovered paper	ton/ton					1.12	1.12
steam	GJ/ton	12	12	8.75	8.7	0	0
electricity	GJe/ton	2.5	2.5	2.35	2.35	0.9	0.75
recovery		2000	2015	2000	2015	2000	2015
steam	GJ/ton	14.5	14.5	14.5	14.5		
electricity	GJe/ton	2.1	2.1	2.1	2.1		

Table 54: Summary of energy data for packaging board production

		packaging board production	
inputs		2000	2015
pulp	ton/ton	1.02	1.02
steam	GJ/ton	7	6.3
electricity	GJe/ton	1.8	1.8

B.2.8 The collection of paper and cardboard waste

The old paper recuperators collect the paper at paper converting companies, printing offices, publishing companies, administrations and the distribution sector or they receive the paper waste from the old paper collectors. The old paper collectors are societies, intercommunals, towns, … The households can also deliver their paper at container parks.

The old paper recuperators mainly have a logistic function. They are the link between collectors, local producers of paper and board waste and the global market. The preliminary treatment by the old paper recuperators is rather limited.

To increase the grade of the waste paper sometimes a limited mechanical or manual sorting takes place. The mechanical treatment consists of a paper and cardboard separator. This machine has a number of axes on which elliptical discs are assembled. Paper and cardboard waste is fed at one side of the machine. Paper and the smaller cardboard fraction fall down between the discs, while the larger cardboard fraction is collected at the other side of the machine. The manual sorting is mainly applied for the separation of newspapers and magazines out of a mixed fraction.

In a next step the paper is shredded if necessary. Finally the paper waste is pressed into bales. After sorting, a rest fraction of about 1 to 10% of the collected quantity remains, that cannot be processed to paper or board. This fraction is burnt or composted.

The sector of the old paper recovery is labour intensive and demands investments in infrastructure (storage), installations (conveyor belts, shredders, presses,…) and means of transport (lorries, trailers, containers,…). The prices of the old paper show major fluctuations caused by world market prices.

The energy consumption for the preliminary treatment is restricted to the driving of the motors for the conveyor belts, the shredders,…

A specific recovery method is applied to beverage cartons. After collection and mechanical or manual sorting, the beverage cartons are pressed into bales and transported to the recycling plants. The beverage carton can be repulped or it can be processed to Tectan material. In Belgium all beverage cartons are repulped.

Repulping is performed in a pulper with a grid to separate the fibres from the polyethylene/aluminium fraction. The pulp of beverage cartons consists of long high quality fibres. These can be used in a number of applications like paper bags and strong cardboard. It is not always clear what happens to the aluminium and polyethylene. According to FOST Plus, actually three possibilities exist: landfilling (but this practice disappears), energetic valorisation at the pulping site or in cement ovens or, finally, material recycling (mainly in the larger pulping plants).

The paper recuperation companies do not have relevant emissions to air or water. The only waste that is created is the rest fraction after sorting.

B.3 Conclusions

As for the production and consumption of plastics there is a very weak link between the consumption of final paper and cardboard products on one hand and the production of the base materials on the other hand (pulp, base paper and cardboard). There is also a very weak link between the total recovery of waste paper in Belgium on one hand and the use of recovered paper pulp by Belgian paper and cardboard producers on the other hand.

Energy use is the basic issue to address when considering reductions in greenhouse gas emissions in pulp and papermaking. Both process energy use and energetic recovery can be addressed. For energetic recovery it seems that a major breakthrough might be the IGCC technology for gasification of black liquor. However, major application of this technology is not expected before 2010.

There is quite some potential for CHP. However, it is hard to quantify the potential based on the existing data. The same applies for energy use as such and the other energy saving measures: data are poorly provided and it is difficult to come to quantified conclusions.

The use of recycled paper pulp provides an important potential for reducing energy use. However, the choice of system boundaries is essential for the evaluation of greenhouse gas emissions. Energy use in pulp and paper production from wood is to a large extent biomass based (burning of bark and black liquor). Net CO_2 emissions from sustainably grown biomass are often considered to be zero. On the other hand, papermaking from recovered pulp might have to rely on external fossil energy sources. In that case the production of paper from wood pulp leads to less net emissions than the production of pulp from waste paper.

However, the real benefit from energy recovery for the overall system depends on the potential alternative uses for biomass. In case this biomass could also be used for energetic purposes with a comparable efficiency, reducing the energy consumption for papermaking through recycling would make this CO_2 neutral energy source available for other applications, where it could replace fossil energy sources.

Hence, the final greenhouse gas emission balance depends on the possible alternative uses for this biomass. In the model used for calculating greenhouse gas emissions related to beverage packaging (PackMark) it has been assumed that recovered energy can be used for other purposes as well.

C ALUMINIUM

The analysis of aluminium flows is based on the results of a strategic research project of Vito: Van Holderbeke M., De Schutter F. (1999) *Stofstroomanalyse van aluminium: top down benadering; tussentijds rapport,* strategisch onderzoeksproject M8053, VITO Mol.[l]

The analysis of the production processes is for a large part based on *Reference document on Best Available Techniques in the Non Ferrous Metals Industries* of the the European IPPC Bureau.[lv]

C.1 Aluminium flows

C.1.1 Aluminium production: overview

A schematic overview of the paper and bardboard producing sector is given in Figure 8.

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C.1.1.1 The raw material

Bauxite

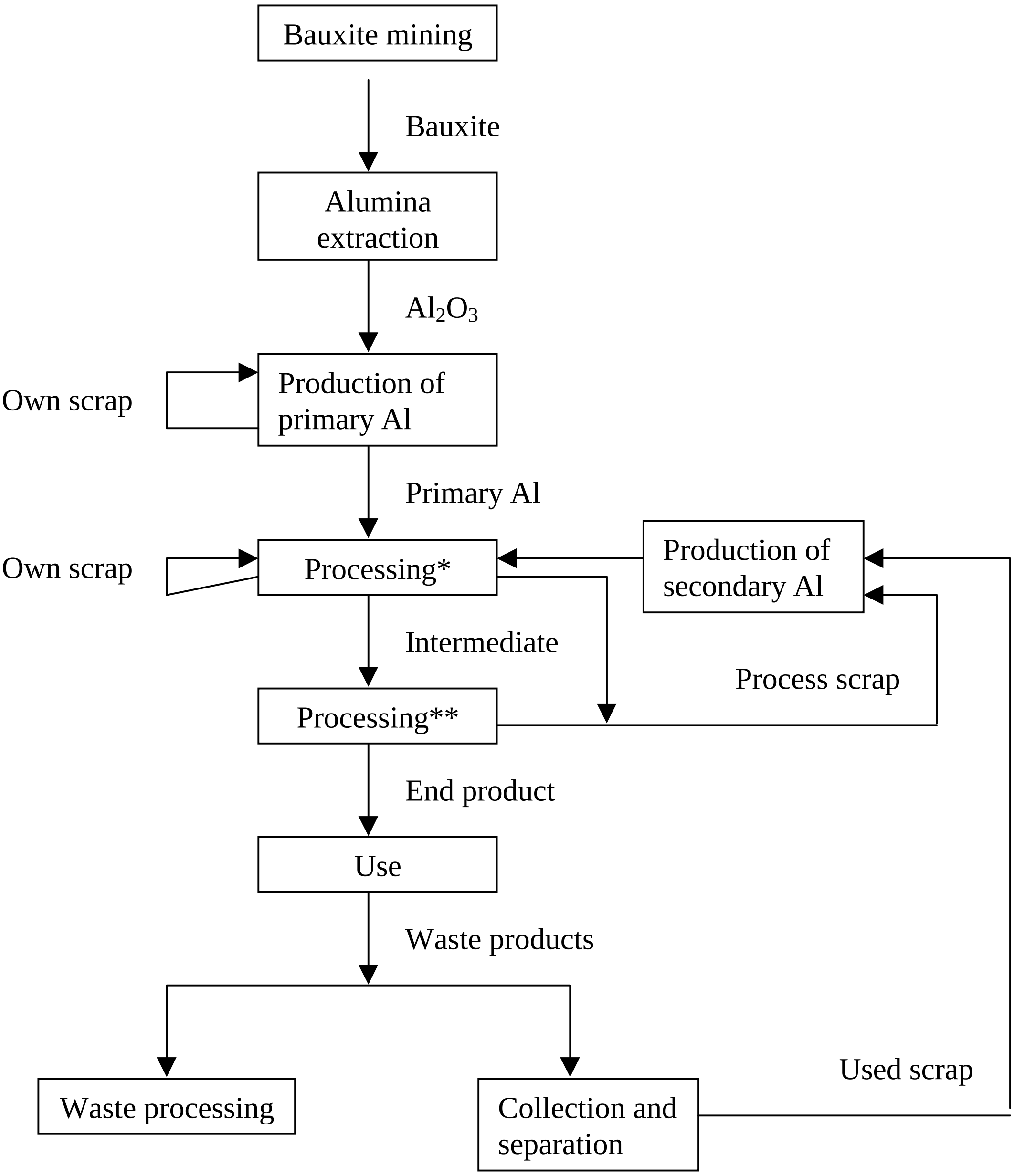
Bauxite is a tropical soil type with high aluminium content (approximately 50 % Al_2O_3). The alumina extraction process is in most cases located in the country where the bauxite is found (due to lacking environmental restrictions and high transportation costs). The production of aluminium from bauxite results in primary aluminium production. It consists of three major process steps:

- the extraction of alumina (Al_2O_3) from bauxite ore by the Bayer process
- the anode production
- the primary electrolysis and smelting of alumina to aluminium by the Hall-Héroult electrolytic melting process.

Primary aluminium can be processed to all possible semi-manufactured products.

Process scrap

Process scrap (or new scrap) is produced during the manufacture of intermediates up to the point when they are sold to the final consumer. Most scrap comes directly from the manufacturers. The composition of the alloy is therefore known. In addition the scrap is most often clean. As a result most of the new scrap can be processed into high quality applications such as wrought products. 90 to 100 % of the process scrap is recycled.



*	wrought products: rolling, extrusion;
	cast alloys: casting
**	The processing is not always necessary for the cast alloys. 80 to 90% of the castings are end products.

Figure 8: The aluminium producing and converting industry

Used scrap

Used scrap or post consumer scrap arises when an aluminium product is thrown away at the end of its life span. This life span can vary significantly according to the application for which it has served. The life span of aluminium in constructions can be over thirty years, while the life span of aluminium in packaging is normally one year or less. The used scrap is collected through a network of metal merchants, who bring it upon the international market. The scrap first has to be collected and sorted in order to give a relatively uniform product. The combination of different alloys and different metals however does not allow the used scrap to be processed into high quality products like wrought products. The used scrap is mainly used to produce cast alloys, since they have a high tolerance for deviations in the alloy composition.

C.1.1.2 Production of semi manufactured products

Aluminium is easily pliable. The addition of different alloying elements (such as magnesium, manganese, silicon) gives the material its strength.

Wrought products

Wrought products (rolled, extruded) have a low tolerance to deviations in alloy composition. Therefore they consist mainly of primary aluminium.

Rolled products are produced by passing a suitable ingot at 500°C through a succession of rolling mills to obtain the required width and thickness of sheet metal. Cold rolling and annealing steps mostly follow these hot rolling steps.
Rolled products are mostly used in the packaging sector (52%) and the construction sector (26 %).

Extruded products are made by forcing cylindrical billets at 450–570°C through a die of the required shape. Before rolling and extrusion, the aluminium ingots sometimes have to be remelted.
Extruded products are mainly applied in the construction sector (54 %). They are not used in the packaging sector.

Cast alloys

Cast products have a larger tolerance to deviations in alloy composition. They consist mainly of secondary aluminium.
Cast products are manufactured by pouring molten metal into a mould. These moulds can be disposable and made of sand or permanent metal moulds. The metal can be forced in the mould under pressure or poured under gravity.
Cast products are mainly used in the transportation sector (75 %). 21% of the cast products are found in the building and construction sector. In the packaging sector they are not used.

C.1.1.3 Production of end products

Many processing technologies can be applied to the aluminium semi-manufactured products like reforming, linking, separating, gluing,… The end products are very diverse.

C.1.1.4 Use of aluminium products

The major fields of application of aluminium are found in the building sector, the transport sector and the packaging sector.

The aluminium offers some material qualities that are very favourable in different sorts of applications. We will mainly focus on the material qualities of aluminium, which might present an advantage when used in packaging applications and construction.

Aluminium in packaging

In the packaging sector a division is made into three main packaging groups: flexible aluminium packaging, semi-rigid containers and rigid aluminium containers. The end products are very diverse. The use of aluminium for packing beverages is limited. Only 10 to 15 % of the beverage cans on the Belgian market are aluminium cans.

Table 55: Aluminium end-consumer packaging

Packaging group	**Typical applications**
Flexible aluminium packaging	Flexible laminated foil
	Foil/board cartons
	Foil lidding and diaphragms
	Unsupported foil
Semi-rigid containers	Foil containers
Rigid aluminium containers	Beverage cans
	Collapsible tubes
	Bottles
	Food cans
	Aerosol containers

Aluminium in construction

Extruded, rolled and cast aluminium products are commonly used for window frames and other glazed structures ranging from shop fronts to large roof superstructures for shopping centres and stadiums; for roofing, siding, and curtain walling, as well as for cast door handles, catches for windows, staircases, heating and air-conditioning systems.

C.1.1.5 Aluminium recycling

The energy required to remelt aluminium is only 5 % of the energy input that is needed for the primary forming process. The energy is stored in the metal and this determines to a large extent its value.
Aluminium can be indefinitely recycled without loss of quality. It can be reused in the same applications with relatively simple treatments. Scrap from aluminium alloys however cannot be transformed in pure aluminium. That is why aluminium used to be recycled in function of the request for alloys by the founding industry.

The collection of aluminium scrap has to be seen on an international market, given the low specific gravity of aluminium, which makes the transport costs less substantial.

One has to be very careful in the way one expresses the recycling of aluminium. Expressing the recycling rate of aluminium as:

$$\frac{\text{amount of recycled scrap}}{\text{total amount of scrap produced}}$$

gives a false picture, since a larger amount of process scrap in this case would result in a higher recycled content. A larger amount of process scrap however would be the result of a less efficient production process and this is to be avoided. It is better to define the recycled content of a product as:

$$\frac{\text{amount of recycled used scrap}}{\text{total amount of used scrap produced}}$$

This ratio however is hard to determine. An increase in the used scrap is to be expected in the next few years. This is mainly caused by the continuous increase in aluminium consumption over the last years and the release of many aluminium applications with a long life span that were manufactured after World War II. These two factors contribute to a potential aluminium stock. When this stock gets on the market the recycling rate of used scrap can increase, because of possibilities to develop more efficient recycling routes.

Due to the increased environmental awareness of the people more material becomes available for recycling. Organised collection systems further increase the rate of recycling.

The recycling rate differs greatly for different sectors (Table 56).

Table 56: The recycling rate (based on used scrap) of different product groups in Europe[li]

Product group	Recycling rate
Transport	90 %
Construction	85 %
Packaging (European average)	30 %
Packaging (Germany until 1992)	3-6%
Packaging (Germany 1998)	40%

A recycling rate of 85% for the construction sector means that 85% of the metal that is used in the construction sector today will be recycled to become part of a new product. The figures for Germany give a good example of what can be reached through an increased environmental awareness and a well-organised collection system. Another example is the recycling of used aluminium beverage cans in Europe. According to the European Aluminium Association (EAA) the average European recycling rate has increased from 30% in 1994 to 37% in 1996 and even 40% in 1999. In Belgium the recycling rate in 1999 was only 25%. Other countries like Switzerland, Norway and Sweden had by then already reached a recycling rate of 80% or even 90%.

Another important concept when it comes to recycling is the notion of 'recycled content'. 'Recycled content' refers to the portion of scrap that is used for the production of a specific product. Again a distinction should be made between process scrap and used scrap. In practice this distinction however is not made. The figures in literature reflect the portion of both process scrap and used scrap. The same remark as before can be made: a higher portion of used scrap indicates a less efficient production process rather than a higher recycled content. As a consequence caution is needed when interpreting figures on recycled content.

C.1.2 Production and consumption of aluminium in Belgium

C.1.2.1 Production, import and export

Table 57 gives the production, import and export figures of aluminium, intermediates, end products and aluminium waste for the BLEU in 1997. The production figures are obtained from the production statistics from the National Statistics Institute. The foreign trade figures are provided by the National Bank of Belgium.

Many production figures do not appear in Table 57 because they fall under confidentiality rules. The trade figures are also rather incomplete. There are for example no figures on the *storage means of Al for all kinds of goods with a content ≤ 300 l like cans, reservoirs, tins,…*, which includes packaging.

Belgium is a net importer of rough aluminium and a net exporter of intermediates and end products. This means that Belgium is an aluminium processing country. Belgium has no production of primary Al. (The small amount of export of primary Al in Table 57 probably has to be interpreted as a form of speculation.) Secondary Al on the other hand is produced in Belgium. There are however no exact production data available.

The total production of intermediates in Belgium is 380 kT. The proportion of castings was not provided by the NIS statistics. The European Aluminium Association (EAA) however gives a production figure of 19.2 kT of castings for the year 1995.[lii] This is a rather small figure compared to the non-castings (about 360 kT). Castings are very suitable for the application of secondary aluminium as a base material.

Table 57: Production, import and export figures of Al in 1997

Product category	**Aluminium product**	**Production (kT)**	**Import (kT)**	**Export (kT)**
Raw material:		/	400	87
Primary Al	Al non alloyed, rough	/	352	10
Secondary Al	In ingots or fluid	/	48	77
Semimanufactured products:		380	151	332
Castings	Fittings	/	0.5	1
Non-castings	Bars and profiles of Al	47	151	331
	Wires of Al	61	/	/
End products[a]:		/	90	118
Packaging	Storage means of Al for all kinds of good with a content of ≤ 300 l; for example cans, reservoirs, tins,…	/	/	/
	Storage means of Al for all kinds of goods with a content of > 300 l; for example reservoirs, tubs,…	/	16	4
Building and construction	Prefabricated constructions of materials other than wood, steel and iron	/	8.4	45.9
	(Part of) constructions of Al; for example plates, bars, profiles, tubes of Al prepared for use in construction works, bridges, masts,…	19.1	/	/
	Doors, windows, window/door frames and doorsteps of Al	/	11.7	12
Waste:	Residues of waste of Al	/	134	157
	Axes and residues of Al	/	25	13

/ means no data were provided

[a] products totally manufactured out of Al

No data were found on the production of end products in Belgium. The packaging sector produces about 40% flexible packages, 30% semi-rigid containers and 30% rigid containers. The exports of intermediates are considerably larger than the exports of end products. The trade in Al waste also exceeds the trade in end products.

C.1.2.2 Consumption

The average consumption of semi-manufactured aluminium products is roughly 200 kT. This consumption can be considered as the input for the Belgian end production sector.

Belgium consumes some 20% of the semi-manufactured products itself, while 80% of the semi-manufactured products is exported and processed to end products outside Belgium. The EAA gives an overview of the semi-manufactured aluminium products according to end use (Table 58).

Table 58: Classification of the semi-manufactured aluminium products according to end use in Belgium (EAA)

Sector	End use (kT)
Building, construction and public works	26.5
Packaging	15.7
Total inland	75.6

20% of the aluminium processed in Belgium is consumed by the packaging industry, while 35% is consumed by the building and construction sector. These figures however only apply to the wrought semi-manufactured products. The cast alloys are not included in these figures given the complication that they can be semi-manufactured products as well as end products. Of all cast alloys in Belgium it can be estimated that 80-90% are end products and 10-20% are semi-manufactured products.

The per capita consumption of aluminium in Belgium was 13.9 kg in 1996 according to the EAA. This is somewhat lower than the European average in that year, which was 16.9 kg.[lii] More recent consumption figures were not found.

Different data were found on the consumption of aluminium beverage cans in Belgium (the Benelux). The EAA claims an aluminium can share of 23% of the can market. Other sources give a share of aluminium cans of only 9%.[liii] Based on FOST Plus figures a share of 10 – 15 % could be expected.
The share of aluminium cans varies considerably with the different countries. In the USA 95% of the cans are made out of aluminium.

C.2 Aluminium production processes

C.2.1 Introduction

The use of aluminium for beverage packaging and for construction of single-family houses is limited compared to other materials used. Therefore the following overview of aluminium production processes and related greenhouse gas emissions has been kept rather superficial.

C.2.2 Primary aluminium production

The aluminium producing and processing industry knows one major energy consuming process step, namely the production of primary aluminium. Once the primary aluminium is produced the energy required to process the aluminium further or to recycle the aluminium is only a small fraction of this first process step. Not only is the production of primary aluminium very energy intensive, there are also direct GHG emissions related to this process.

C.2.2.1 The production process

Alumina (Al_2O_3) is at present exclusively produced from bauxite. The extraction is performed with the Bayer process. The alumina is dissolved in hot caustic soda (NaOH), separated from impurities, re-crystallised as the hydrate and finally calcinated (converted to oxide) at 1200°C. On average, between 4 and 5 tons of bauxite are needed for 2 tons of alumina, from which 1 ton of aluminium can be produced.

Primary aluminium is obtained from alumina by the Hall-Héroult electrolytic melting process. The pure alumina is continuously dissolved in a cell containing molten cryolite (Na_3AlF_6), through which an electric current is passed. The cells are operated with pre-baked anodes, which are usually produced from petroleum coke and pitch. The carbon anodes are consumed in the process at a rate of about 0.41 ton carbon/ton of aluminium. Oxygen and the anode carbon react to produce CO_2. Various additives, such as aluminium fluoride (AlF_3) and magnesium and lithium fluoride (MgF_2 and LiF_2), reduce the melting point of the electrolyte.

C.2.2.2 GHG emissions

The overall chemical reaction for primary aluminium production is:

$$2Al_2O_3 + 3C \rightarrow 4Al + 3CO_2$$

The chemical reaction enthalpy is 29.2 GJ/ton aluminium. The current practice however requires substantially more energy. The losses are to a large extent a consequence of the (electricity consuming) primary smelting process.

Electricity represents a significant share of the consumed energy. The primary energy consumption linked with electricity generation however varies significantly all over the world. Since the alumina extraction process is in most cases located in the country where the bauxite is found, it is impossible to determine the exact primary energy consumption linked with all the primary aluminium produced.
Therefore the European Aluminium Association (EAA) has worked out a specific model taking into account a domestic European based production of 60 % and imports from other parts of the world of 40%. This model represents (according to the EAA) the 1994 European average situation.

According to EAA a total energy supply of 143 GJ is required for the production of 1 ton of primary aluminium (Table 59).

Gielen and Van Dril[liv] give energy figures for the separate process steps (Table 60). The electrolysis process consumes by far the most energy.

Table 59: Energy consumption for the production of one ton of primary Al according to a model used by the European Aluminium Association

Energy resource	Electrical (GJ/ton)	Thermal (GJ/ton)	Total (GJ/ton)	Energy resource share for electricity production (%)
Hydro power	28	0	28	50.8 %
Nuclear power	9	0	9	15.0 %
Crude coal	29	2	31	25.6 %
Crude gas	12	7	18	6.4 %
Crude oil	5	51	56	2.2 %
Total	83	60	143	100 %

In the IPPC Best Available Technique Reference Document on the Non Ferrous Metals Production Process (BREF)[lv] not many energy figures are given, but they seem to be in the same range as the figures provided by the other two sources.

Table 60: Energy consumption for the different process steps

Process step	Fuel (GJ/ton)	Electricity (Gje/ton)	Total primary energy (GJ/ton)
Alumina extraction[a]	20.4	1.7	24.7[c]
Electrolysis (incl. anodes[b])	23.0	48.0[d]	143
Casting	1.8	0.0	1.8
Total	45.2	57.8	169.5

[a] Alumina extraction includes the energy use for bauxite mining, raw materials preparation and the Bayer process.

[b] The energy content of the coke and pitch, which is about 14.4 GJ/ton aluminium is not included in these figures.

[c] The BREF gives figures from 8.0 to 13.5 GJ/ton for the production of alumina (only the Bayer process)

[d] The BREF gives figures of 53 to 61 GJe/ton for electrolysis electricity production.

The GHG emissions were calculated using the EAA model (Table 61).

Table 61: GHG emissions related to primary aluminium production

Energy resource	Total energy (GJ/ton Al)	GHG emission factor (kg $CO_{2eq.}$ /GJ)	GHG emissions (kg $CO_{2eq.}$/ton Al)
Hydro power	28	0	0
Nuclear power	9	0	0
Crude coal	31	94	2936
Crude gas	18	56	1028
Crude oil	56	73	4108
Total	143		8072

A total energy related CO_2 emission of 8.1 kg is released with every kg of primary Al produced. The Bundesamt für Umwelt, Wald und Landschaft (BUWAL) uses an electricity producing energy model for which 66% of the produced energy is obtained from hydropower. This model gives a GHG emission of 1.3 kg CO_2 per kg alumina produced and 7.6 kg CO_2 per kg Al produced.[lvi]

Next to these energy related CO_2 emissions the production of primary aluminium also produces direct CO_2 emissions during the electrolysis process. The CO_2 emissions related to anode consumption are 1.4 to 1.7 kg CO_2/kg Al produced.[lv]

Other greenhouse gases are produced during the production of primary aluminium. When the alumina concentration in the bath during the electrolytic process is too low, tetrafluoromethane (CF_4) and hexafluoroethane (C_2F_6) gases are produced during the so called ‘anode effect’. The low concentration of alumina results namely in a high dissipation of energy and a chemical reaction between the carbon anode and fluoride. The control of cell voltage and aluminium additions is a major factor in controlling anode effects. Emission levels range from 0.1 kg PFC per ton Al produced for the most recent plants to 0.5 kg PFC per ton Al produced as present average European emission level.[27]

Table 62 gives an overview of the greenhouse gas emissions related to primary aluminium production. They are based on the average emission level for PFC and a CF_4/C_2F_6 ratio of 9/1.

Calculations for European primary aluminium smelters show that the total quantity of PFC gases emitted, calculated as CO_2 equivalent emissions was about 15 million tonnes in 1990. Improvements in controlling the electrolysis process have however significantly reduced the PFC emissions over the past ten years. In 2000 a CO_2 equivalent emission of below 6 million tonnes should be reached.

Table 62: Greenhouse gas emissions related to primary aluminium production

Emission source	GHG emissions[a] (kg $CO_{2eq.}$/kg Al)	GHG emissions share (%)
Energy related emissions	8.1	61
Process related CO_2 emissions	1.6	12
Process related CF_4 emissions	2.6	20
Process related C_2F_6 emissions	0.9	7
Total emissions	13.2	100

[a] Average values were taken for easy reference
CF_4 and C_2F_6 have a 100 years Global Warming Potential of 6500 and 9200 respectively

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[27] The MATTER input data give emissions of 1.2 kg CF_4 and 0.05 kg C_2F_6 per ton aluminium produced. These values are rather high.

C.2.2.3 Technical improvement options

Most of the improvement options are situated within the alumina extraction processes. These processes involve 15% of the energy consumption required to produce primary aluminium (see Table 60). Significant improvements of energy efficiency are still possible for the bauxite mining, the raw materials preparation and the Bayer process.

The Hall-Héroult electrolytic melting process on the other hand, which is the most energy consuming process (it consumes 84% of the energy required to produce primary aluminium), is a mature technology. Small improvements of 0.2 to 0.5 % per year can be expected from autonomous efficiency improvement, caused by improved cell design, improved bath design,…

However some technological improvement options offer significant emission reduction potential:

Aluminium Hall-Héroult process with point feeders

A computer control of the electrolysis process based on active cell databases and monitoring of cell operating parameters minimises the energy consumption and reduces the number and the duration of anode effects. More than 99 % fume collection from cells is achieved on a long-term basis by among other things minimising the time to open covers and change the anodes and employing a programmed system for cell operations and maintenance. Moreover an efficient cleaning method in the rodding plant is installed to recover fluorides and carbon based on effective extraction and filtration systems. According to the BREF document PCF emission can be reduced to 0.02 – 0.1 kg/ton aluminium.

Inert anodes

The current Hall-Héroult cell uses carbon anodes that are oxidised in the aluminium production process. In principle, the anode oxidation can be avoided if a suitable inert material can be found. In such a case the production and consumption of carbon anodes could be avoided. Unclear however is the impact of inert anodes on the electricity consumption. Introduction of inert anodes seems currently far away given the problems with anode stability. The BREF Report mentions inert anodes in a pilot stage and reports this technology as an emerging technique. The MATTER input data give 2020 as start year for the technique.

New cathodes

Currently liquid aluminium is used as cell cathode material in the Hall-Héroult process. The unstable surface of the cathode, caused by the fluctuation in height of the molten aluminium due to waves formed by electromagnetic and hydrodynamic effects, however can cause short-circuiting of the cell. To avoid this effect, conventional cells separate the anode and

the cathode by a large gap, resulting in high voltage differences and low average energy efficiencies for the cells of less than 50 %.
In contrast, titanium diboride cathodes can be wetted with a thin film of aluminium, which then drains to a sump. This provides a stable cathodic surface, allowing the cell to operate with a much narrower anode-cathode gap. The narrower gap results in a significant decrease in the voltage difference between the anode and the cathode, thus improving energy efficiency. This can result in up to 20% electricity saving[liv] compared to a conventional cell.

C.2.3 Secondary aluminium production

C.2.3.1 Separation of aluminium scrap

Separation of the aluminium fraction from the other waste fraction can occur with the Eddy Current technology. A separation between conducting and non-conducting materials is realised by passing metallic particles, which can conduct electricity, through a magnetic field so eddy currents are produced in the particles. The conducting particles are then deflected in the magnetic field and shot out of the material stream. Depending on the resistance against the magnetic field a separation between materials with variable electric conductivity is possible.

C.2.3.2 The remelting process

Aluminium is easily remelted because the melting temperature is relatively low. A major constraint for aluminium recycling however is the variation in alloy content and the content of impurities in the recycled scrap. Alloys for casting purposes can contain higher amounts of a number of alloying elements and are thus more easily produced from scrap than wrought aluminium products. The increasing diversity of aluminium alloys however poses problems for the production of secondary aluminium that can be wrought.

Several aluminium smelting oven types can be discerned. Their application depends generally on the scrap characteristics. Important oven types are the reverbatory smelter with side-charge well and more recently, the tower smelter and the vertical flotation smelter (only suited for small particles). For more information we refer to the BREF document where an overview is given of the furnaces that are being considered BAT for secondary aluminium production.

Special attention deserves the treatment of slag. Salts are added to the smelt in order to separate other elements from the aluminium. This slag is chemical waste and contains significant amounts of aluminium that can be recovered. The slag is nowadays treated to produce secondary materials that can serve as input for e.g. cement production.

C.2.3.3 GHG emissions

The production of secondary aluminium consumes substantially less energy. The energy requirement for refining aluminium scrap is only 5-10 % of the energy that is required for the primary production process. Table 63 gives the energy consumption to remelt one ton of aluminium following the European model provided by the European Aluminium Association. Energy figures for the separate process steps for the preparation of secondary aluminium from mixed scrap are given in Table 64.

Table 63 Energy consumption to remelt one ton of Al according to the European model (from EAA)

Energy resource	Total energy consumption (GJ/ton)
Hydro power	0.2
Nuclear power	0.4
Crude lignite	0.2
Crude coal	0.4
Crude oil	1.5
Crude gas	3.4
Total	6.1

The total energy figure to remelt one ton of Al according to the model from the EAA (6.1 GJ) is somewhat smaller than the figure provided by Gielen and Van Dril (7.3 GJ).

Table 64: Secondary aluminium production energy balance

Process step	Fuel (GJ/ton)	Electricity (GJe/ton)	Total primary energy (GJ/ton)
Scrap preparation	0.0	0.4	1.0
Scrap smelting	4.5	1.1	7.3
Slag treatment	2.2	0.3	3.0
Casting	1.8	0.0	1.8
Total	8.5	1.8	13.1

The GHG emissions related to the model presented by the European Aluminium Association are calculated in Table 65.

A total energy related CO_2 emission of 356.3 kg per ton remelted Al is produced. This is only 4 % of the energy related CO_2 emissions within the primary aluminium production. Consequently the difference in emissions compared to the primary production process is substantial.

BUWAL gives CO_2 emissions of 403 kg per ton secondary aluminium produced, using an energy model with 66% hydropower (see C.2.2.2).[lvi]

Table 65: GHG emissions related to aluminium remelting

Energy resource	Total energy (GJ/ton Al)	GHG emission factor[i] (kg CO_2 eq./GJ)	GHG emissions (kg CO_2 eq./ton Al)
Hydro power	0.2	0	0
Nuclear power	0.4	0	0
Crude lignite	0.2	94	18.8
Crude coal	0.4	94	37.6
Crude oil	1.5	73	109.5
Crude gas	3.4	56	190.4
Total	6.1		356.3

C.3 Summary and conclusions

Belgium is a net importer of rough aluminium and a net exporter of intermediates and end products. The exports of intermediates are considerably larger than the exports of end products. The trade in Al waste also exceeds the trade in end products.

The use of aluminium for beverage packaging and for construction of single-family houses is limited compared to other materials used. Therefore the overview of aluminium production processes and related greenhouse gas emissions has been kept rather superficial.

The aluminium producing and processing industry knows one major energy consuming process step, namely the production of primary aluminium. Once the primary aluminium is produced the energy required to process the aluminium further or to recycle the aluminium is only a small fraction of this first process step.

40 % of all greenhouse gas emissions in the production of primary aluminium (5 kg $CO_{2eq.}$/kg Al) are specific process emissions. More than half of these process emissions are emissions of PCF. Although PCF emissions have already been reduced by 60 % between 1990 and 2000, they can be reduced to 20% of the actual level through further improvements in the electrolysis process.

Process emissions related to the oxidation of the C anode can be avoided through the use of inert anodes. This technology is actually in the pilot phase.

Greenhouse gas emissions related to the production of secondary aluminium are only 3% of those related to the production of primary aluminium. Thus, recycling offers obvious reductions in greenhouse gas emissions.

D CONCLUSIONS

Material flows: general

The flows (production, intermediate and final consumption, imports, exports) and the production and waste treatment processes of plastics, paper and cardboard and aluminium used for the production of beverage packaging or, in some cases, construction of single family houses were analysed. The focus was on the features and developments, related to the production and the waste treatment of these materials, that might have an important influence on the life cycle greenhouse gas emissions caused by the final consumption of beverage packaging and single-family houses in Belgium.

For each of the materials quantitative data on the production, import, export and consumption at the different levels in the production and consumption chain have been collected and compared. Then standard technologies for the production of the materials have been described briefly and opportunities for technological improvements resulting in reductions of greenhouse gas emissions have been identified.

The material flow analyses show that care has to be taken when interpreting production and consumption data. Production data for the production of the primary materials and the corresponding consumption data (refering to the consumption of materials by primary processors) can be derived quite easily from official production and foreign trade statistics. However, most often different processing steps still have to be carried out before these (transformed) materials reach the final consumer. At each of these intermediate production steps often quite important imports and exports occur. Hence, the consumption of the base material by the Belgian transformer is quite different from the consumption of the transformed material by the Belgian final consumer.

The analysis of the actual flows of plastics and of intermediate organic chemicals in Belgium also shows that both availability and reliability of statistics are problematic. Inconsistencies in the quantities reported make any analysis of actual flows of plastics and intermediates for plastics production tedious.

For some materials data are not complete enough to analyse all types of flows up to the level of the final consumer. Some data are not reported in the statistics for reasons of confidentiality. Flows are often expressed in monetary values, which is not relevant for a material flow analysis.

A specific difficulty in tracing the material flows up to the level of the final consumer is the quantification of materials used for packaging or for components. Packaging and components are imported and exported as parts of products, and do not appear as such in the foreign trade statistics.

Detailed analyses of the flows show that no clear link can be established between the Belgian petrochemical production and the final use of plastics in Belgium. At all levels of the production chain of plastic products important import and export streams exist. Similar conclusions could be drawn for paper and cardboard and aluminium.

Important cross-boundary flows also exist for selectively collected waste materials, that have been sorted according to grades and qualities and that are internationally traded as secondary raw materials.

The products studied only use a limited part of the total materials production. Moreover, many materials production processes, especially in the petrochemical sector have multiple inputs and outputs.

Specific materials, production processes

For specific conclusions for each of the materials, the production processes and the potential for greenhouse gas emission reduction we refer to the conclusions at the end of each of the respective chapters.

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