TNO-report
STB-99-55 Final

Chemical Recycling of Plastics Waste (PVC and other resins)

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Date
December 1999

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1. Introduction

For several years, debate has raged about the plastic PVC. Industry and environmentalists contend with each other virtually around the world. The environmentalists pursue a ban, industry aims to improve its environmental performance and believes that from an overall viewpoint there is no reason for such far-reaching measures against their material. In this context, the material pops up on the political agenda on a regular basis in a number of EU member states. Issues that are often the subject of debate include emissions from EDC/VCM/PVC production, the use of certain stabilisers and plasticisers (such as phthalates), and PVC waste management. Such debates have led in several EU member states to (in)formal measures against PVC. Such measures on the national level can lead to barriers to trade. As a result, an EU policy on such PVC-related issues is desirable. A policy at EU level prevents that differences in national policies hamper a proper functioning of the internal market, and can ensure an equal, appropriate level of environmental protection in member states.

In this context, the Commission aims to define a policy with regard to the subject of end-of-life PVC products. For this purpose, DG III and DG XI have commissioned various studies focussing on several aspects of PVC waste management. This concerns studies into:

1. Specific costs of incineration of PVC in municipal solid waste incinerators (MSWIs), which is being performed by Bertin, France;
2. Costs and benefits of diverting PVC from incineration, which is being performed by AEA, UK;
3. Landfill of PVC waste, which is being performed by a consortium led by Argus, Germany;
4. Mechanical recycling of PVC waste, which is being performed by a consortium lead by Prognos, Switzerland;
5. Chemical recycling of PVC[1].

The last study, on chemical recycling of PVC, is being carried out by TNO with DG III as the primary client. The overall aim of the project is to analyse the role that chemical recycling may have in a future European system for PVC waste management. Since both rather pure PVC waste and mixed plastic waste (MPW) containing PVC may in principle be treated by chemical recycling, this study cannot concentrate on PVC alone. Chemical recycling of PVC will therefore be treated within the broader context of chemical recycling of plastic waste. More specifically, the Terms of Reference (ToR) for the project asked us to address the following elements:

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[1] The term ‘feedstock recycling’ may be more often used than ‘chemical recycling’. Since the Terms of Reference for this study used the latter term, we will speak of chemical recycling in this report.

1. making an inventory of all current research programmes, pilot projects and commercial plants involved in the chemical recycling of plastics;
2. evaluating the technical issues related to the chemical recycling of plastics;
3. evaluating the possible future scenarios in the field of chemical recycling, including a forecast of probable industrial investments (member state by member state);
4. describing the effects on the environment and the risks, analysing costs and benefits, and making a comparative assessment of the environmental, economical and technical aspects of the various technologies for chemical recycling, mechanical recycling, and incineration with energy recovery for PVC and mixed plastics containing PVC.

The specific approach of how we dealt with these elements is discussed in the specific chapters related to these tasks. In general, the inventory of research programmes was based on a literature review and expert inquiry. For the most feasible chemical recycling options, an in-depth inquiry of the consortium backing such initiatives was performed. As for the scenarios, for PVC waste arising we could rely on the extensive modelling work performed by the European union of Plastics Converters (EuPC). On the basis of e.g. historical PVC consumption data and product-life times, theoretical PVC-waste arising was calculated and checked against practical data. This work has resulted in the most comprehensive and reliable estimates of PVC waste data available at EU level to date. In order to ensure a comparable basis of the projects, it is most likely that their data will be used as well in the studies of Prognos (mechanical recycling) and AEA (incineration). These parallel studies would result in dedicated information on mechanical recycling and incineration (with or without energy recovery). In order to avoid duplication of work, we intended to use these results wherever possible. Furthermore, several other major studies performed for e.g. APME were used. Cost data, particularly for collection, were based on a literature search. These data were sufficient to provide the basis for a comparative evaluation of risks, technical aspects, and costs.

Obviously, this project has clear links to the other four projects on PVC. The overall picture with regard to PVC waste management, and the possible place of chemical recycling in it, ideally needs to be made when the technical parts of all projects are ready. For instance, a comparison of environmental effects and costs between mechanical recycling and chemical recycling can best be done if detailed information on mechanical recycling is available. Yet, since this is the subject of a specific project, it was not effective for TNO to obtain detailed data themselves in order to be able to make a good comparison in this report. Hence, we restricted ourselves on areas covered by other projects. In this context, it was rather unfortunate that the results of the parallel studies became available to TNO only in a rather late stadium.

For this report, the following structure has been chosen:

- *Chapter 2* reviews the most viable initiatives with regard to chemical recycling, and also summarises the main competing technologies: incineration and landfill. A comprehensive gross list of initiatives on chemical recycling that have been taken in the last 5 years is attached as Appendix D to this report;
- *Chapter 3* reviews the sources of various types of PVC waste and the collection structures that have to be in place before chemical treatment is possible, as well as the associated costs;
- *Chapter 4* compares chemical recycling with alternative technologies for PVC waste or PVC-containing plastic waste;
- *Chapter 5* gives scenarios for chemical recycling. There is a discussion of the amounts of plastics available for chemical recycling, given the influence of competing technologies, the capacity created concerning chemical recycling plants, their location, leading to a description of the future of chemical recycling of PVC;
- *Chapter 6* ends with conclusions, and serves also as an executive summary.

The arguments and conclusions published in the report reflect the author’s position and the Commission does not necessarily endorse every opinion and conclusion as stated in this report.

2. Technologies for PVC and Plastics Waste Management

2.1 Introduction

This chapter discusses technologies for the waste management of PVC and related plastics. Obviously, the emphasis is on technologies for chemical recycling of PVC-containing plastics waste. However, since that would be mainly a technical description of different technologies, we decided to include summary descriptions of competing alternative waste management technologies also (Municipal Solid Waste Incinerator/MSWIs, cement kilns, mechanical recycling). However, we must stress that the main focus of this study is chemical recycling and that we refer to the parallel studies of Bertin, Prognos, and AEA for in-depth coverage of these other technologies. We also deliberately excluded emerging technologies that may become available as an alternative to MSWIs in the near future, based on pyrolysis or gasification of integral municipal solid waste. The reason for this is that the Terms of Reference for this project take plastic waste as a starting point, and do not aim at analysing treatment options for integral municipal solid waste.

In Appendix D, we have summarised some 70 initiatives, mainly from the last decade, in the field of chemical recycling of plastic waste. This inventory is based on 30 literature sources, a considerable proportion of reviews, in-house TNO expertise, and a cross-check with industry experts in the field of chemical recycling. The Appendix gives the name of each type of technology, the consortium backing the initiative, a description of the technology, its technical status, a possible start-up date, capacity, and acceptable chlorine content in the waste input. The technologies include degradative extrusion, pyrolysis, hydrogenation, gasification, incineration with HCl recovery, input as a reducing agent into blast furnaces, and glycolysis, hydrolyis, and methanolysis.

It appeared that most of the initiatives were still in the research phase, or were simply not suitable for PVC-containing waste. The latter is particularly true for technologies such as glycolysis and hydrolysis, which play a role only for well-defined mono-waste streams such as PET. Based on the literature survey, information from authorities, and consultation with industry, we selected about 10 initiatives that are currently generally regarded as the most serious ones for realisation on practical scale. About 6 of them are not designed for PVC waste specifically, but deal with mixed plastic waste (MPW) in general. These technologies mainly concentrate on recovering the organic part of the MPW. They often have restrictions with regard to the maximum permissible chlorine (or PVC) input; such limitations will be discussed extensively in the following sections. Four other technologies were designed to deal specifically with PVC waste (chlorine concentrations of well over 10%). They emphasise recovery of the chlorine fraction in a useful form. Hence, together with the competing technologies for chemical recycling, this chapter discusses 3 types of technologies:

1. Technologies for chemical recycling of mixed plastic waste;
2. Technologies for chemical recycling of PVC-rich waste;
3. Alternatives for chemical recycling (incineration, mechanical recycling).

As for the technical analysis of these treatment options, in the ideal case one would have liked to gain insight in the way how they deal with the most important constituting elements of PVC (i.e. carbon, chlorine, and other elements such as the metal present in the stabilisers). For this, an input/output balance for the technology has to be available. For the more classical treatment options like cement kilns and Municipal Solid Waste Incinerators (MSWIs) several studies have published such balances. For most chemical recycling technologies, however, mass balance calculations and measurements have not yet been made, or are not available as public information[2]. Auditing the firms and making mass balances is a major task, that falls well outside the scope of this project. Therefore, the assessment of the final fate of components like chlorine and metals had to be made on a rather global level.

The next sections discuss in more detail these three classes of treatment options for PVC waste.

2.2 Chemical recycling of mixed plastic waste

2.2.1 Introduction

Regarding the chemical recycling of MPW with a PVC content of up to several percent, the following initiatives seem to be most realistic for the coming 5 years. They are processes that are currently operating in practice, have operated but are temporarily shut down since the necessary waste supply was not ensured, or which have a fair chance of becoming operational in the short term. This concerns:

1. Texaco gasification process (NL, pilot in the US)
2. Polymer cracking process (consortium project, pilot)
3. BASF conversion process (D, pilot but on hold)
4. Use as reduction agent in blast furnaces (D, operational)[3]
5. Veba Combi Cracking process (D, operational but to be closed by 2000)
6. Pressurized fixed bed gasification of SVZ (D, operational)

These processes are discussed below. For each process, descriptions are given of the background (consortium, capacity, status), the process, the acceptance criteria, environmental effects, and gate fee.

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[2] For instance, in the study of Heyde and Kremer (1999) on waste management options of mixed plastics waste, the detailed mass balances for chemical recycling technologies were indicated as ‘confidential data’.

[3] In this proces MPW is used as a reducing agent, and hence generally seen as a form of chemical recycling. For instance, in Germany this is one of the most important technologies by which the ambitious German recycling target for plastic packaging waste is met (DSD, 1999).

2.2.2 Texaco gasification process

Background and current status

Texaco has had commercial experience with its gasification process for over 40 years. During this period, it has proven its high reliability and feedstock flexibility in 100 installations worldwide.

Until recently, Texaco's gasification process was not used specifically for plastics waste. Texaco sees the adaptation of the technology to the gasification of plastics waste as a relatively straightforward step and an attractive commercial opportunity. Experiments with mixed plastics waste were carried out at the pilot plant site (10 t/day) in Montebello, California, USA (Weissman, 1997).

A consortium comprising Texaco, Air Products, Roteb and VAM studied the possibility of commercialisation of the process in Pernis, Rotterdam. The plant, known as the Pax Rotterdam Plant, should utilise plastic waste from the VAM mechanical separation and should have a capacity of 40-50 kt/year of MPW for gasification. However, this initiative ceased when VAM and Texaco found that no mutually attractive gate fee could be agreed upon (1996-97). Currently, Texaco is trying to find new feedstocks in order to be able to continue the project. No decisions about erecting a large-scale plant in The Netherlands will be made unless more certainty about the supply of feedstocks at a commercially necessary gate fee has been obtained.

Description of the process

Figure 2.1 reviews the process. The Texaco process consists of two parts, a liquefaction step and an entrained bed gasifier. In the liquefaction step the plastic waste is mildly thermally cracked (depolymerisation) into a synthetic heavy oil and some condensable and non-condensable gas fractions. The non-condensable gases are reused in the liquefaction as fuel (together with natural gas). This liquefaction process is comparable to visbreaking of vacuum residue from oil refining.

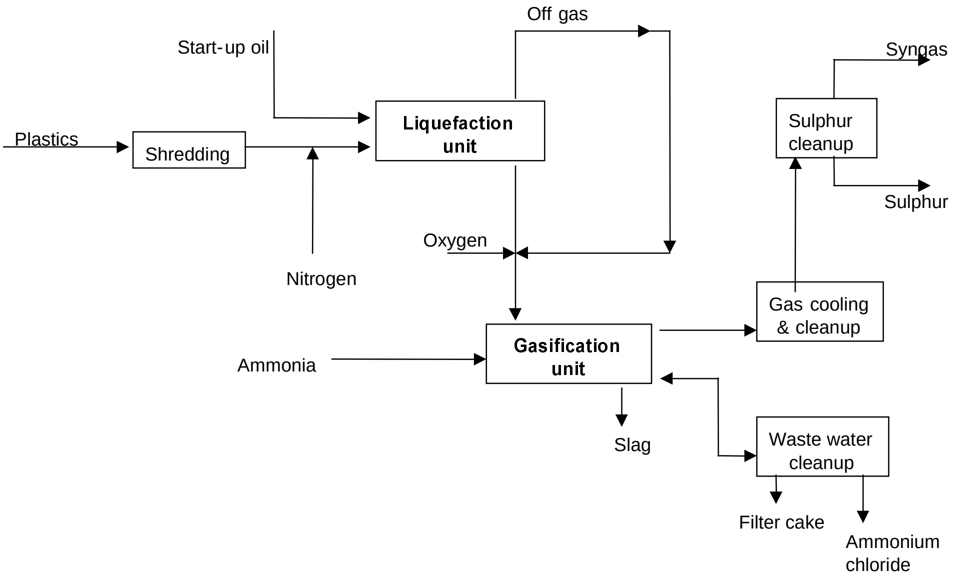
The heavy oil is filtered to remove large inorganic particles. The oil and condensed gas are then injected to the entrained gasifier. Also, chlorine-containing gases from the plastic waste are fed to the gasifier. The gasification is carried out with oxygen and steam at a temperature of 1200 – 1500 ºC. The gasification pressure is normally adjusted to the pressure of the process which will consume the resulting synthesis gas. After a number of cleaning processes (amongst others, HCl and HF removal), a clean and dry synthesis gas is produced, consisting predominantly of CO and H_2, with smaller amounts of CH_4, CO_2, H_2O and some inert gases.

Virtually all chlorine present in MPW is captured by washing the raw syngas under addition of NH_3 and converted into saleable NH_4Cl (Croezen and Sas, 1997). Sulphur from MPW is won back in a pure, saleable form. Ash from the process is converted into slag and fines. One may assume that any metals present in a PVC-formulation end up mainly in these solid residues. The slag meets the quality standards of the Dutch Building decree, and the fines are have a comparable quality to MSWI fly-ash (Croezen and Sas, 1997). Filtrated waste water from the scrubber and quench is distilled, yielding reusable water, crystallised NH_4Cl and a brine purge, that is recirculated to the gasifier.

In summary, the products of the process are:

- Synthesis gas. 150 tonnes of mixed plastics per day produces roughly 350,000 Nm^3 per day of clean synthesis gas. This gas (predominantly H_2/CO) can be used as feedstock in petrochemical processes.
- Pure sulphur.
- Saleable NH_4Cl.
- Vitrified slag. This has a quality that meets the requirements of Dutch legislation for secondary building materials.
- Fines. They have a quality that would match the quality of fly ash from Dutch municipal solid waste incineration plants.

Figure 2.1: A schematic representation of the Texaco process



Acceptance criteria for the input material

The plant in Pernis will be designed to tolerate up to 10% PVC in the MPW stream. There are plans to also treat larger PVC quantities and to recover the HCl. The tolerance of the gasification towards inorganics and paper are said to be up to 10% each. The following input specifications have been communicated to TNO:

Material texture	Dry to the touch, not sticky, free flowing
Physical description	Shredded or chipped

• Size	Less than 10 cm
• Physical fines content	Less than 1% under 250 µm
• Bulk density	> 100 g/liter
• Form at delivery	baled or agglomerated
• Plastics content	> 90 wt%
• Free metals	< 1 wt%
• PVC content	< 10 wt%
• Ash content	< 6 wt%
• Residual moisture	< 5 wt%
• Paper content	< 10 wt%

Resource needs and emissions
An LCA was performed by CE (Croezen and Sas, 1997) using a model waste stream mainly consisting of PE/PP/PS/others and 6-10% PVC. For environmental data we refer to that report.

Processing costs
The expected gate fee for the Texaco plant is 90 to 135 Euro (200 to 300 NLG) per tonne (50 ktonnes/yr capacity), which may decrease for a 200 ktonnes installation to 50 Euro (100 NLG) per tonne. Texaco considers a detailed breakdown of the operational costs and benefits of its process as confidential information.

2.2.3 The Polymer Cracking Process (consortium project)

Background and current status
BP Chemicals has led promotion of Polymer Cracking technology for feedstock recycling since its beginnings in the early 1990's. Since the challenge of recycling of plastics is industry wide, support has been provided by a Consortium of European companies to develop the technology – initially including Elf Atochem, DSM, Fina and Enichem. The consortium members at the time of the successful pilot plant trials in 1997 were BP Chemicals, Elf Atochem, EniChem, DSM, CREED and the APME[4].

The "Polymer Cracking Process", a fluid bed cracking process, was first tested on small labscale equipment in the early 1990's. The pure research phase has now ended with successful demonstration of the process at continuous pilot plant scale at BP's Grangemouth site using mixed waste packaging plastics. This pilot plant, which started up in 1994, has a nominal 400 tonne per year feed capacity, but runs continuously on a campaign basis at 50 kg/hr scale as it has limited product storage. The technology is now in the development phase with modifications in progress to the BP pilot plant to allow optimisation and scale-up.

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[4] APME supported the research and development phase of the project, but its policy is not to subvent a process once it becomes operational. If the project goes ahead, APME may consider giving support to testing of alternative feeds.

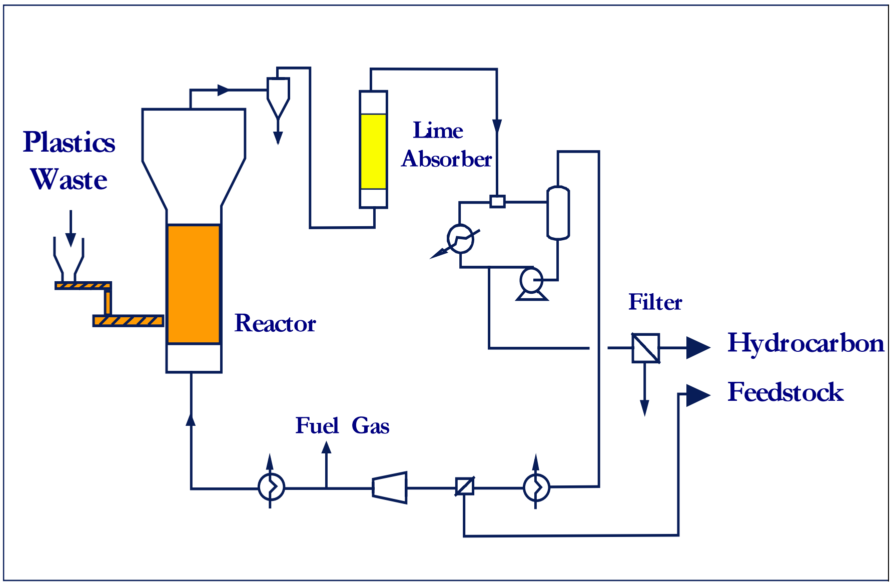
In 1998, BP Chemicals with UK partners, VALPAK and Shanks & McKewan, set up a project, POLSCO, to examine the scope for a projected 25 ktonne per year plant and logistics infrastructure in Scotland. This project is expected to end in 1999. The UK is seen as a potential first location for a plant due to the expected UK shortage in recycling capability to comply with EU & UK Packaging and Packaging Waste Directive. Project POLSCO has identified a suitable site location for a demonstration commercial scale plant. Liquid and gas products from the process have been accepted for use within BP's Grangemouth refinery. Project POLSCO is also considering feed supply and infrastructure in its scope. A plant could be built within 2 years of sanction and could be operational for 2003. The precise date will depend on many factors including economics. An engineering contractor has been found for design and scale-up activity. A plant to demonstrate technology scale-up could be built quicker and is one of many options being considered for development. BP Chemicals envisages great possibilities with this process. The challenge is to bring the partners and economic factors together for the first commercial plant.

Description of the process

Some elementary preparation of the waste plastics feed is required, including size reduction and removal of most non-plastics. This prepared feed is fed directly into the heated fluidised bed reactor which forms the heart of the Polymer Cracking process. The reactor operates at approximately 500°C in the absence of air. The plastics crack thermally under these conditions to hydrocarbons which vaporise and leave the bed with the fluidising gas. Solid impurities, including metals from e.g. PVC stabilisers and some coke, are either accumulated in the bed or carried out in the hot gas as fine particles for capture by cyclone. The decomposition of PVC leads to the formation of HCl, which is neutralised by bringing the hot gas into contact with a solid lime absorbent (ECVM, 1997). This results in a $CaCl_2$-fraction that has to be landfilled. The purified gas is cooled, to condense most of the hydrocarbon as valuable distillate feedstock. This is then stored and tested against agreed specifications before transfer to the downstream user plant. The remaining light hydrocarbon gas is compressed, reheated and returned to the reactor as fluidising gas. Part of the stream could be used as fuel gas for heating the cracking reactor, but as it is olefin-rich, recovery options are being considered. This flow scheme is illustrated below in figure 2.2.

The process flow diagram (see below) shows further details including recovery of the hydrocarbon in two stages since the heavy fraction becomes a wax at about 60°C. Once recovered, the light and heavy fractions could be combined together in a commercial plant ready for shipment to downstream refinery processing.

Figure 2.2: A schematic representation of the BP process



About 85% by weight of the plastic that enters the process is passed on as hydrocarbon liquid to the downstream plants. About 15% by weight is gas at ambient temperature and could be used to heat the process. In this way nearly all of the plastic is used with just the solids being separated as a waste product. The gas has a high content of monomers (ethylene and propylene) and other useful hydrocarbons with only some 15% being methane. As indicated above, the hydrocarbon is collected from the plant in two fractions since the heavy fraction is a wax below about 60° C. The heavy fraction is typically 60% by weight of the product with the light fraction being 40% by weight.

The process shows very good results concerning the removal of elements like chlorine. With an input of 10,000 ppm (or 1%) Cl, the products will contain around 10 ppm Cl. This is somewhat higher than the specifications of 5 ppm typical for refinery use. However, in view of the high dilution likely in any refinery or petrochemical application, BP assumes that this is acceptable (Brophy et al., 1997).Also, metals like Pb, Cd and Sb can be removed to very low levels in the products. Tests have shown that all the hydrocarbon products can be used for further treatment in refineries.

Acceptance criteria for the input material

A typical feed specification based on Grangemouth pilot plant tests is given in table 2.1. Plans exist to test other materials to examine further potential on other non-packaging feed supplies which may extend the limits of this specification. The maximum chlorine content (2% wt.) is that typically expected within plastics packaging waste streams.The process would tolerate short-term excursions of higher chlorine content e.g. 5% wt Cl. However, a structurally higher input than 2 % chlorine in feed waste would increase operating and investment costs to counter the aggressive operating environment and to ensure that the final hydrocarbon products remain acceptable for recycling.

Table 2.1: Input specifications for the Polymer Cracking Process

Material	**Unit**	**Normal**	**Limits**
Polyolefins	wt. %	80	min. 70
Polystyrene	wt. %	15	max. 30
PET	wt. %	3	max. 5
PVC	wt. %	2	max. 4
Total Plastic Content	wt. %	95	min. 90
Ash	wt. %	2	max. 5
Moisture	wt. %	0.5	max. 1
Metal pieces	wt. %		max. 1
Size	mm	1-20	
Fines sub-250 micron	wt. %		max. 1
Bulk Density	Kg/m^3	400	300

Resource needs and emissions

Total solids products are typically up to 0.2 kg/kg of total solids feed. Note, this total solids feed includes both feed plastic and the solids used as make-up in the process.

In terms of utilities, it is difficult to give precise data at this time as the process is still in the development stage. Conceptually, the process can run in self-sufficient heating mode. In this case, overall gas calorific requirement may need a small net export or import as the product gas quality varies with plastic feed specification and operating conditions.

The other main utilities needed are:

electric power approx.	60 kW/tonne feed plastic
cooling water	40 m^3/tonne feed plastic
steam	1.2 tonne/tonne feed

All emissions will be very low and will comply with local regulations. BP Chemicals are preparing to undertake a process-specific LCA (planned in 1999).

Processing costs

The cost of treatment to process one tonne is difficult to define since it depends on many factors such as scale, location, scope, preparation stages, and economic parameters used. Hence, comparison of the processes is difficult for this reason.

However, by way of example, BP Chemicals has produced the following costs, which may have an uncertainty of +/-30%. The investment costs of a plant of 25,000 tpa, located in Western Europe, in the 3rd quarter of 1998, are estimated as 20 to 15 Million £. The costs and revenues are given in table 2.2. Under these conditions, a gate fee of £172 per tonne (some 250 Euro) is necessary. For a 50,000-tpa plant this gate fee could be lower, and is estimated at £100 per tonne (some 150 Euro).These figures are net, i.e. include product values yet exclude collection and preparation.

Table 2.2: Cost specification of the Polymer Cracking process (in £ per tonne)

Costs		**Income**	
Capital charges	152	Products	100
Fixed costs	90	Gate fee	172
Variable costs	30		
Total	**272**	**Total**	**272**

2.2.4 The BASF Conversion Process

Background and current status

The BASF feedstock recycling process was designed to handle the recycling of mixed plastic waste supplied by the DSD collection system. A pilot plant was started in May 1994 in Ludwigshafen, with a capacity of 15,000 ton/yr. At the time the erection of a large scale plant was contemplated (1994), DSD estimated the total volume of mixed packaging plastics for feedstock recycling as around 750,000 tons per year. Based on that value, BASF offered to erect a recovery plant with a capacity of 300,000 tons per year. One year later DSD's estimation of the total volume of mixed plastic waste to be treated by feedstock recycling was changed to some 400,000 tonnes per year. For further development of the technology, the pilot plant was kept in production between May 1994 and autumn of 1996. BASF, after consultation with DSD and DKR, decided in 1996 not to pursue the project any further and to shut down the pilot plant (press release of 26.11.96). It seems that no agreement could be reached on a waste supply guaranteed in the long term for a gate fee that would be sufficient to cover the costs of a full-scale plant. Particularly due to the long mortgaging periods of such industrial installations, long-term commitments are essential to reduce the financial risks for the investor to reasonable levels.

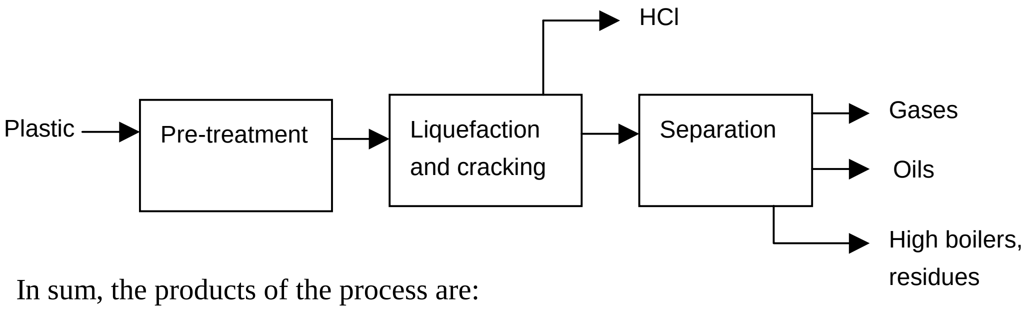
Description of the process

Before the waste plastics can be fed to the process, a pretreatment is necessary. In this pretreatment the plastics are ground, separated from other materials like metals and agglomerated. The conversion of the pretreated mixed plastic into petrochemical raw materials takes place in a multi-stage melting and reduction process. In the first stage the plastic is melted and dehalogenised to preserve the subsequent plant segments from corrosion. The hydrogen chloride separated out in this process is absorbed and processed in the hydrochloric acid production plant. Hence, the major part of the chlorine present in the input (e.g. from PVC) is converted into saleable HCl[5]. Minor amounts come available as NaCl or $CaCl_2$ effluent (Heyde and Kremer, 1999). Gaseous organic products are compressed and can be used as feedstock in a cracker.

In the subsequent stages the liquefied plastic waste is heated to over 400 ºC and cracked into components of different chain lengths. About 20-30% of gases and 60-70% of oils are produced and subsequently separated in a distillation column.

Naphtha produced by the feedstock process is treated in a steam cracker, and the monomers (e.g. ethylene, propylene) are recovered. These raw materials are used for the production of virgin plastic materials. High boiling oils can be processed into synthesis gas or conversion coke and then be transferred for further use. The residues consist of 5% minerals at most, e.g. pigments or aluminium lids. It seems likely that metals present in PVC-formulations mainly end up in this outlet. The process is carried out under atmospheric pressure in a closed system and, therefore, no other residues or emissions are formed The full process is summarised in figure 2.3.

Figure 2.3: Schematic representation of the BASF pyrolysis process



In sum, the products of the process are:

- HCl, which is neutralised or processed in a hydrochloric acid production plant;
- naphtha to be treated in a steam cracker;
- monomers, e.g. ethylene, propylene, which can be used for the production of virgin plastic materials;
- high boiling oils, which can be processed into synthesis gas or conversion coke and then transferred for further use;
- residues.

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[5] This HCl recovery seems slightly less efficient than the VEBA-process; Heyde and Kremer (1999) give for treatment of DSD agglommerate a HCl recovery of 11.6 g per kg for VEBA, and 10 g for BASF.

Acceptance criteria for the input material
The process was developed for the average PVC content in packaging waste (DSD waste), which is 4-5%, and thus the maximum chlorine content of the input material was considered to be 2.5%. It was not planned to separate PVC as part of a pretreatment.

Resource needs and emissions
A comparative study was carried out by the Arbeitsgemeinschaft Kunststoffverwertung into the environmental effects of the various methods of mechanical recycling and feedstock recycling and energy recovery (compared to landfilling) (1994-1995). A summary report was published by Heyde and Kremer (1997); we refer further to chapter 4 and that report.

Processing costs
Processing plastic waste by the BASF process would require a gate fee of 325 DM (160 Euro) per tonne for a plant with a capacity of 300,000 t/yr and a fee of 500 DM (250 Euro) per tonne for a plant capacity of 150,000 t/yr, respectively. No further details have been obtained about the cost structure of the plant.

2.2.5 Use of Mixed Plastic Waste in Blast Furnaces

Background and current status
For the production of pig iron for steel production, iron ore (Fe_2O_3) has to be reduced to Fe. This process takes place in a blast furnace. Coke, coal and heavy oil are normally used as reducing agents in this process. Iron and steel companies try to lower the consumption of coke, by partly replacing it with coal, gas or fuel oil (30% in weight seems to be the maximum), via coal injection technology. Recently, new developments have started to replace the conventional reducing agents by plastics waste. Though others like British Steel (UK) have done trials as well, the best-known pioneer in this field is Stahlwerke Bremen, Germany. Stahlwerke Bremen is a large German steel manufacturer which operates two blast furnaces to produce over 7000 t/day, or some 3 Million tpa pig iron. In 1993 Stahlwerke Bremen decided to examine the injection of solid plastic material in the blast furnace and carried out a one year test operation with a pilot plant. The first experiments started in February 1994 with a capacity of 50 t/day of plastic waste. Operation of a large size system started in July-August 1995 with a capacity of 75,000 t/yr, using agglomerated DSD waste. Several developments made it possible to increase the capacity of the plant. In 1998 some 162,500 ton of MPW was used in German blast furnaces, forming some 25 % of the amount of MPW recycled in Germany (DSD, 1999).

Currently, German blast furnaces are the only plants in Europe using plastics waste in this way. However, other blast furnace companies have also used waste as a reducing agent, like waste oil. The total pig iron production in the EU is some 90 million tonnes, or some 30 times the capacity of Bremen Stahlwerke. If all plants in the EU would opt for a similar intensive use of MPW, in theory a capacity of 5 Million tonnes MPW per annum would have to be available. Probably the main reason why this process only takes place in Germany is for cost reasons. As will be made clear in chapter 3, it is still less expensive to landfill and incineration MPW as a part of municipal solid waste, than to collect it separately and pre-treat it for use in blast furnaces. In Germany the special situation exists that very high recycling targets have to be reached, and that there is a party (DSD) that is in a position to contract large volumes of waste, at prices necessary for recycling technologies.

Description of the process

As described above, a reducing agent is needed in the pig-iron production process. Stahlwerke Bremen uses plastic waste as a substitute for fuel oil. In the blast furnace plastics are injected to the tuyeres in a similar way as coal or fuel oil. From a silo or big bags the plastics are filled on a screen where the fraction > 18 mm is separated. Also, no fibres or metal particles like wires or nails are allowed in the plastic waste. The smaller plastic waste particles (< 18 mm) go to the injection vessel where the injection pressure of about 5 bar is built up. The discharge and dosing work pneumatically without mechanical support. For continuous operation, it was found that a minimum value for the bulk density of 0.3 t/m^3 should be set.

One advantage of plastic waste is its low sulphur content compared with coal. However, plastic waste has a relatively high chlorine content due to the presence of PVC. The main part of the chlorine forms HCl going into solution in the washer (Janz and Weiss, 1996). Various groups have expressed concern about the possible formation of dioxines and furans. However, measurements during experiments have indicated that the emissions of dioxines and furanes were not significantly elevated, in relation to the strongly reducing atmosphere at 2100 ºC. Dioxin emissions with or without plastic input appeared to be about a factor 100 below the standard of 0.1 ng/Nm^3 TEQ TCCD (Janz and Weiss, 1996). This made a pretreatment for chlorine removal unnecessary. As for any additional metals present in PVC, it is likely that they end up in the product (steel), or in one of the residue flows from blast furnaces (slag, filter dust, etc.)[6].

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[6] It has to be noted, however, that the PVC throughput in the blast furnace kiln is just a fraction of the total material throughput. This is a similar situation as for e.g. MSWI’s, where PVC in general amounts to less than 1 % of the input. Under such circumstances, it appears to be rather difficult to measure if an increase of PVC input has an influence on the dioxin production. For MSWIs, this controversy is most outspoken. Most research reports claim that there is no significant relation (e.g. Rigo et al., 1995; Rijpkema and Zeevalking, 1997), but Greenpeace has published a number of reports that suggest otherwise (e.g. Costner, 1997). Furthermore, it has to be noted that the off-gas of blast furnaces is generally used as an energy carrier in other processes. Checks on dioxin formation are desirable there as well. The situation is further complicated by the fact that PVC is by no means the only chlorine source; raw materials and (particularly for blast furnaces close to sea) even the air used in incineration processes may have siginificant contributions to the chlorine throughput too.

Acceptance criteria for the input material

Stahlwerke Bremen possesses a government permit to use 500 tonne MPW per day with a chlorine content of up to 1.5 % (= ca. 3% PVC) as a 24 hr average. Though it is sometimes suggested that this PVC-content is mainly related to the quality criteria used in the DSD system rather than a technical necessary maximum, contact with Stahlwerke Bremen suggests otherwise. Chlorine has no added value in the process, and may only contribute to problems like corrosion in the blast furnace, etc. Hence, Stahlwerke Bremen would have liked to be able to use more stringent acceptance criteria, but this would simply put them out of the market since all MPW contains some PVC. The 1.5 % level seems to be a balance between commercial needs and a technical ideal.

Resource needs and emissions

A comparative study has been carried out by the Arbeitsgemeinschaft Kunststoffverwertung into the environmental effects of the various methods of recycling and energy recovery (compared to landfilling) (1994-1995). One of the processes studied was the blast furnace process of Stahlwerke Bremen. We refer further to chapter 4 and that study (Heyde and Kremer, 1999). For the discussion on the (probably limited) relevance of dioxin emission we refer to page 18.

Processing costs

No information was provided directly by the firm regarding the processing costs. Informally, various sources indicated that Duales System Deutschland provides a cost contribution of about 100 Euro per tonne. Such a contribution seems logical, since considerable initial investigations were needed to make this treatment route work properly. However, after a few years of processing plastic waste at these gate fees, one can expect that the initial research costs have been amply recovered. Furthermore, it is obvious that a main element in all specific chemical recycling routes, i.e. capital investment, is relatively low. The marginal costs that really need to be covered in any case are the balance of pretreatment and fuel cost saved. These amount to a few dozen Euro per tonne at most, and could even be negative (i.e. using plastic waste instead of coal forms a net financial gain). In sum, the actual costs for steelworks may range between a large margin from zero Euro to some 100 Euro per tonne. However, the practical gate fee will be established under the influence of market forces, and thus mainly depend on the availability and the price of competing technologies for the treatment of plastic waste.

2.2.6 Veba Combi Cracking Process

Introduction

Since 1981 Veba Oel AG has operated a hydrogenation plant at Kohleöl Anlage Bottrop (KAB) in Germany, using the improved Bergius Pier coal liquefaction technology. Coal has been converted by hydrogenation into naphtha and gas oil. In 1987 the plant was modified, applying the Veba Combi Cracking (VCC) technology to convert vacuum distillation residues of crude oil into synthetic crude containing naphtha, gas oil and heavy distillates. Since 1988 an increasing share of the petroleum residue feedstock was substituted by chlorine-containing waste (e.g. containing PCBs). In 1992/1993 the process was modified again by adding a depolymerisation unit in front of the plant to process exclusively mixed plastics waste from packaging (MPW) as collected by DSD. It can process ten tonnes of plastic waste per hour. As work is carried out in three shifts, the annual capacity of the depolymerisation and hydrogenation plant amounts to about 80,000 tonnes of mixed plastic waste. In 1998 some 87,000 tonnes were treated. Recently, information was published that DSD and Veba agreed to terminate a contract for the treatment of MPW on December 31, 1999, which originally would have ended in 2003. Since the plant has treated only DSD waste since 1993, Veba will close the KAB plant. No formal reasons are known for these decisions. However, it is widely believed that the hydrogenation process was unable to compete economically with treatment in Steelworks and with the SVZ process.

Description of the process

The plant configuration includes a depolymerisation section and the VCC section (see figure 2.4). Depolymerisation is required to allow further processing in the VCC section. In the depolymerisation section the agglomerated plastic waste is kept between 350-400ºC to effect depolymerisation and dechlorination.

The overhead product of the depolymerisation is partially condensed. The main part (80 %) of the chlorine introduced with PVC is present as HCl in the light gases. It is washed out in the following gas purification process, yielding technical HCl. The condensate, containing 18 % of the chlorine input, is fed into a hydrotreater. The HCl is eliminated with the formation water. The resulting Cl-free condensate and gas are mixed with the depolymerisate for treatment in the VCC section.

The depolymerisate is hydrogenated in the VCC section at 400-450ºC under high pressure (about 100 bar) in a liquid phase reactor with no internals. Separation yields a product which after treatment in a fixed-bed hydrotreater is a synthetic crude oil, a valuable product which may be processed in any refinery. From the separation a hydrogenated residue stream also results, which comprises heavy hydrocarbons contaminated with ashes, metals and inert salts. This hydrogenation bitumen is a byproduct which is blended with the coal for coke production (2 wt%). It is most likely that the major part of any metals present in a PVC formulation end up in this residue flow.

Light cracking products end up in off-gas (E-gas), which is sent to a treatment section for H_2S and ammonia removal. As indicated above, the main part of the chlorine present in the input (i.e. from PVC) is converted into usable HCl. Some 2% of the chlorine input is bound to $CaCl_2$ in the process by a 4 times leaner than stochiometric amount of CaO (Sas, 1994; Heyde and Kremer, 1999).

In summary, the outputs of this process are:

- HCl
- syncrude from the VCC section. This liquid product is free of chlorine and low in oxygen and nitrogen.
- hydrogenated solid residue, which can be blended with the coal for coke production
- off-gas

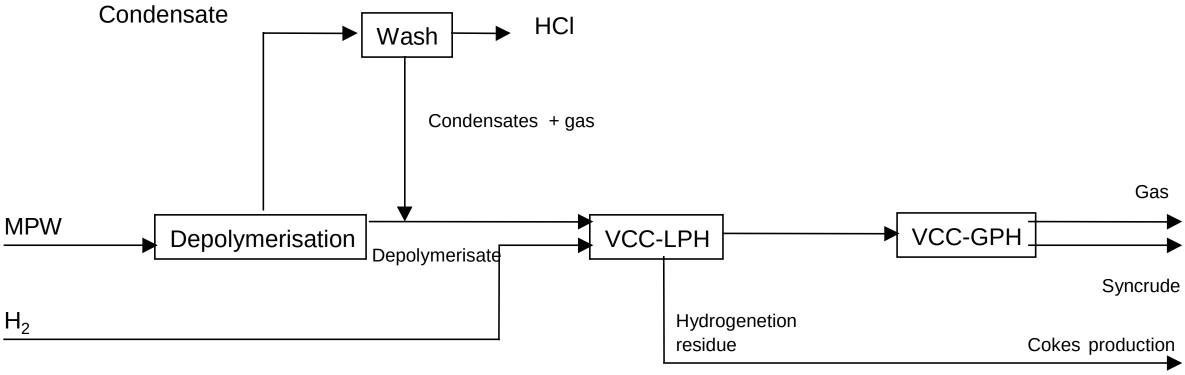

Figure 2.4: Schematic representation of the Veba Oel process

Acceptance criteria for the input material

The input specifications for the plastic waste input for treatment in the depolymerisation section are:

- particle size < 1.0 cm;
- bulk density ≥ 300 kg/m^3
- water content < 1.0 wt%;
- PVC < 4% (≤ 2 wt% chlorine)[7];
- inerts < 4.5 wt% at 650 ºC;
- metal content < 1.0 wt%;
- content of plastic ≥ 90.0 wt%.

The plant has been a proven option for MPW. In 1997, succesful tests were concluded of the treatment of electric and electronic (E&E) waste. For the test, 50 tons of E&E waste were mixed with some 250 tons of DSD waste (HCL, 1998).

Resource needs and emissions

The Dutch Centrum voor Energiebesparing en Schone Technologie (CE, Delft) performed a Life Cycle Analysis (LCA) in 1994 in which the VCC process was chosen as a realistic option for feedstock recycling (Sas, 1994). However, in this study the process was somewhat different from the current situation. In the CE

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[7] Some of our interviewees claimed that this process could deal with a PVC content of up to 10%. However, the firm repeatedly confirmed 2% chlorine or 4% PVC as the regular maximum.

report, for example, the calculation involved a mixture of plastic waste and vacuum residue (VR) as input for the VCC section. Currently, this is not the case: 100 % plastic packaging waste is processed.

Also a comparative study has been carried out by the Arbeitsgemeinschaft Kunststoffverwertung into the environmental effects of the various methods of mechanical recycling and feedstock recycling and energy recovery (compared to landfilling) (1994-1995). The contributors to the study were the “Fraunhofer-Institut München”, “Technische Universität Berlin” and “Universität Kaiserslautern”. Chapter 4 is partially based on this study (Heyde and Kremer, 1999).

Processing costs

According to information available at TNO, the gate fee for the VCC process is 250 Euro per tonne. A similar value has been mentioned by Pohle (1997: 120). It is the policy of Veba/KAB not to comment on or disclose gate fees or process costs. The price is negotiated between DSD and VCC; it reflects the price of competing outlets as well.

2.2.7 SVZ gasification process

Background and current status

The Sekundärrohstoff Verwertungs Zentrum (SVZ) “Schwarze Pumpe” operates a plant that converts several waste materials, included plastics, into synthesis gas, methanol and electricity. It originated from a coal gasification plant, but after several major investments it is currently mainly operating on waste material. It is currently fully operational. Waste and material that are accepted include contaminated wood, waste water purification sludge (including industrial sludges), waste derived fuel from MSW, paper fractions, plastic fractions, the light fraction of shredder waste, and liquid organic waste that arises from SVZ-related plants. The total capacity is about 410,000 tpa for solid material and 50,000 tpa for liquid material. The capacity for plastic waste is estimated at some 140,000 tpa in the near future. In 1998 some 100,000 tpa plastic waste was processed, mainly under contract from DSD. Furthermore, SVZ estimates that in other waste fractions several dozen kilotons of additional plastics were present.

Description of the process

The MPW is fed into a reactor, together with lignite (in the form of briquettes) and waste oil. This reactor is a solid bed gasification kiln. Oxygen and steam are used as gasification media, and are supplied in counter flow with the input materials. This processes synthesis gas (a mixture of hydrogen and CO), liquid hydrocarbons, and effluent. The liquid hydrocarbons are further processed by oil pressure gasification. The raw gases from this process, as well as from the solid bed reactor, are purified by the rectisol process. There components like H_2S and organic sulphur compounds are removed. The clean synthesis gas is used for various purposes. The main part, around 70 %, is used for the production of methanol. About 20 % is used for electricity production. The remainder is used in other processes. Waste gas products are incinerated; in the flue gas cleaning an amount of gypsum is produced which is proportional to the amount of sulphur in the input. As for the fate of chlorine present in PVC, neither from literature (e.g. Heyde and Kremer, 1999) nor the company itself information could be obtained. Since in no description a saleable chlorine product was indicated, it may be most likely that the chlorine comes available from such a washer as well, may be in part in the form of a salt fraction that has to be landfilled. In the process a slag is produced, that has rather good elution characteristics (landfill class 1 according to the German TA Siedlungsabfall). It is likely that the major part of any metals present in a PVC formulation end up in this slag. Process water is treated before discharging it.

Acceptance criteria for the input material

The gasification process has a high tolerance for various input parameters. The plant has proven to be capable of dealing with mixed plastics waste, waste derived fuel (a mixture of plastics, wood and paper), the shredder light fraction of car wrecks, and the plastic fraction from shredded white goods and electronics. As for chlorine tolerance, on a regular basis material containing up to 2% chlorine is accepted. Higher concentrations can also be tolerated, up to 6%; by ensuring a correct blend with the other waste input, an acceptable chlorine input is ensured. Yet, high chlorine concentrations are not preferred on a regular basis. It results in an acid environment in the unit, and hence a higher risk of corrrosion, and the need for neutralisation, leading to a salt that has to be landfilled at high cost. A number of main acceptance criteria are indicated below:

- Particle size: > 20 to 80 mm;
- Chlorine content: 2% as default, though higher concentrations are tolerable;
- Ash content: up to 10% or more;
- Caloric value: not critical.

Resource use and emissions

One of the Frauenhofer institutes, IVV, recently published an LCA on chemical recycling processes, including SVZ. Table 2.3 gives the inputs and the outputs of the central process on the basis of this source. We refer further to chapter 4 and Heyde and Kremer (1999).

Table 2.3: Inputs and outputs of the SVZ process

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

Processing costs
As stated in the introduction, SVZ in its present form was built around an existing plant. In order to become the present waste treatment and recycling facility, in total 450 Million DM (some 225 Million Euro) have been invested. SVZ felt a bit reluctant to comment on gate fees, since these depend highly on the volume and time period that a supplier wants to commit this volume to SVZ. However, indirectly one can deduce that SVZ's position is rather competitive compared to other chemical recycling initiatives. With the recent announcement of the closure of VEBA, SVZ remains the only major chemical recycling plant that is able to sustain the competition with cost-effective options like treatment in steelworks . Hence, we estimate the gate fee of SVZ as 150 Euro per tonne or less for MPW.

2.3 Chemical recycling of PVC-rich waste

2.3.1 Introduction

As for the chemical recycling of PVC-rich waste, with a high chlorine content, the following initiatives have been identified by TNO on the basis of a literature search and contacts with industry and authorities. All these processes aim to recover as much as possible of the chlorine present in PVC in a usable form (HCl or a saleable chloride salt). The processes in question include:

1. BSL incineration process (D);
2. AKZO Nobel steam gasification process (NL);
3. Linde gasification process (D);
4. NKT pyrolysis process (Dk).

These processes are discussed below. For each process, descriptions are given of the background (consortium, capacity, status), the process, the acceptance criteria, environmental effects and gate fee[8].

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[8] As indicated in Appendix D, various other chemical recycling options for PVC-rich waste are currently being investigated, including a thermal hydrolysis process of Stigmar, DK. Here we only considered those processes for which establishment of at least a pilot plant, and a probable scale-up, is likely.

2.3.2 BSL Incineration process

Background and current status

BSL Olefinverbund GmbH (80% DOW, 20% BvS) in Schkopau is building a plant for the processing of chlorine-containing fluid and solid waste streams. These waste streams originate from all kinds of sources, amongst others, production waste of BSL and DOW, but also Hg-contaminated sludge from waste water treatment installations. The goal is to process the waste by thermal treatment and to produce HCl using the energy from the process itself. The HCl produced will be used by BSL Schkopau in other processes, most notably membrane electrolysis for chlorine production. The plant will be based on a rotary kiln and will have a capacity of 45 ktonnes per year (i.e. not only PVC waste) with a heat production capacity of 25 MW at ca. 7500 production hours per year. Some 15,000 tonnes of this capacity is available for PVC, in relation to average caloric value and mix of different waste aggregations that the kiln can handle (see also page 26). Tests with mixtures of PVC waste and other waste have been carried out in the Stade, DOW kiln. The BSL incineration started up in mid-1999.

Description of the process

Figure 2.5 reviews the process. The plant consists of a pretreatment of the waste, the thermal treatment and energy recovery, the flue gas purification, the purification of the HCl and a waste water treatment installation. The rotary kiln is able to process solid, fluid, and gaseous waste streams into useful feedstocks and energy. If necessary, natural gas or liquid energy carriers can be added in order to reach the necessary high temperatures.

The waste is incinerated in the rotary kiln and a post-combustion chamber, directly after the rotary kiln, at temperatures of 900 to 1200ºC. During this treatment HCl is released and recovered. Based on the heat capacity of the waste, halogen content, and potential slag formation, an optimal mixture of wastes is determined. In this way a continuous production of high-quality HCl can be assured. Also, the formation of dioxines and furanes can be diminished in this way.

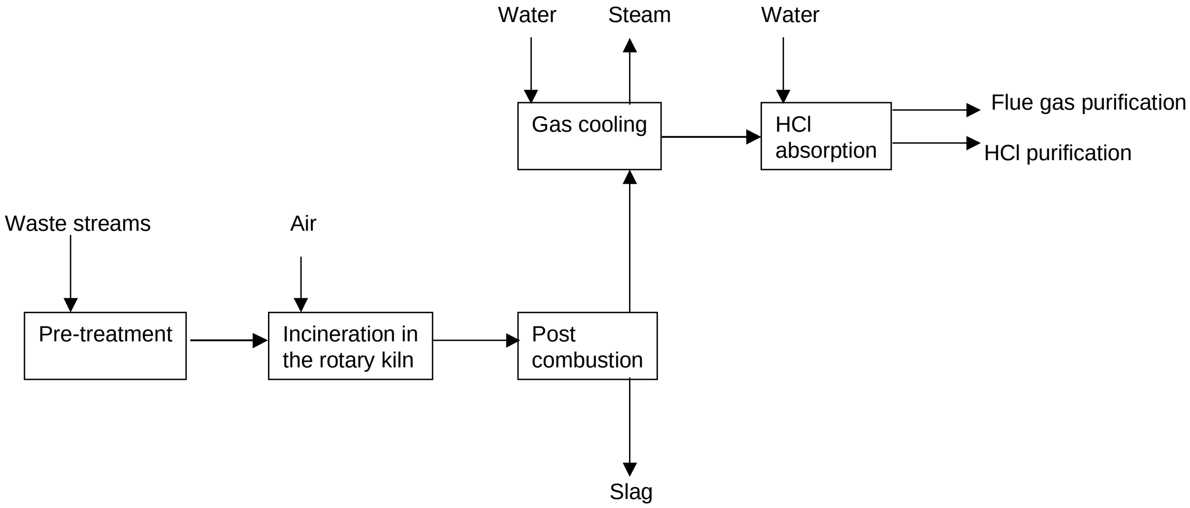
The flue gas from the post-combustion is cooled from 1200 ºC to 230 to 300 ºC. The steam produced from this process is added to the steam network of the BSL Schkopau site. In the next step of the process, the flue gas purification, the HCl is absorbed from the flue gas by water. Also, other impurities are removed from the gas. The raw HCl is then purified to a useful feedstock.

The inert products from the incineration are dependent on the chemical composition of the waste. It is likely that the main part of any metals present in a PVC-formulation will end up in this slag. The main products from the incineration of non-halogen-containing carbon hydrogens are water and CO_2. When halogen-containing carbon hydrogens are present, halogen-containing substances are also formed. However, the goal of the process is to oxidise the waste fully, so that no toxic chemicals (dioxines and furanes) are formed.

The useable products will be:

- HCl of high quality, which can be used in several production processes;
- Steam;
- Inert slag.

Figure 2.5: Schematic representation of (part of) the BSL incineration process



Acceptance criteria for the input material

The process has been designed for a mix of high-chlorinated wastes (solvents, chlorinated tars, plastics). Kilns like these usually have an optimal specification for the caloric value of their input. Hence, such kilns are usually fed with a mix of different wastes (e.g. PVC waste and other waste streams with a lower caloric value) in order to obtain a waste stream with an optimum composition. If the kiln were fed 100% PVC waste, this would on average produce an input with too high caloric values, leading to problems with temperature control. The chlorine content, on the other hand, is not critical. As long as the caloric value is within the acceptable range, the accepted chlorine content can be higher than 50%.

The accepted particle size for the incineration process is 10x10x10 cm. When larger parts are offered, a shredder is needed. No information about accepted moisture content, amount of dirt, etc. has been obtained.

Resource needs and emissions

Depending on the type of waste, natural gas or another energy carrier has to be added to the process. The emissions will fulfil legislation requirements. Calculations have shown that emissions will be about 1% of the permitted values. Purified waste water is reused in the process or further treated in the central waste water treatment process of the Schkopau site.

Solid waste streams are slag and filter residues. The slag is inert and can be used as a filler in mines. The filter residues can be partly fed to the rotary kiln and reprocessed into slag. Another part of the filter residue has to be landfilled (as chemical waste).

Processing costs
Pohle (1997:124) mentions a gate fee of 500 DM (250 Euro) per tonne for a plant of 250,000 tpa using a similar technology. Informally, information has been obtained that suggests even somewhat higher gate fees for PVC waste of some 700 to 1,000 DM (350 to 500 Euro) per tonne. The company felt that it could give no further details about processing costs.

2.3.3 Akzo Nobel Steam Gasification Process

Background and current status
Akzo Nobel, as a producer of chlorine and vinylchloride, started to study a process for feedstock recycling of mixed plastic waste containing PVC in 1992. Based on an investigation of all known processes, Akzo Nobel chose in 1994 to use fast pyrolysis technology in a circulating fluid bed reactor system. This technique has been developed by Battelle, Columbia, USA, for biomass gasification.
Akzo Nobel has conducted small-scale pilot plant tests (20-30 kg/hr) with PVC cable and pipe scrap. With support from ECVM, experiments on a larger scale (200-400 kg/hr) were carried out with mixed PVC waste (incl. artificial leather, roofing, flooring and packaging material). The results were promising.
While the project is on hold momentarily, plans exist to build a large-scale plant (50 ktonne per year) as soon as financing has been arranged. This new plant will start up 5 years after the decision that the plant will be built. It is not certain when that will be.

Description of the process
The process consists of two separate circulating fluid bed (CFB) reactors at atmospheric pressure (see figure 2.6):

- a gasification (or fast pyrolysis) reactor in which PVC-rich waste is converted at 700-900 ºC with steam into product gas (fuel gas and HCl) and residual tar.
- a combustion reactor that burns the residual tar to provide the heat for gasification.

Circulating sand between the gasifier and combustor transfers heat between the two reactors. Both reactors are of the riser type with a very short residence time. This type of reactor allows a high PVC waste throughput. The atmosphere in the gasifier is reducing, avoiding the formation of dioxins.

Depending on the formation of tars (as happened in the trial with mixed PVC waste), a partial oxidation (a gasifier) may be required to convert these tars into gaseous products. The product stream consisting of fuel gas and HCl is quenched to recover HCl. HCl is purified up to specification for oxychlorination. Additives in the waste stream, mainly consisting of chalk and metal stabilizers present in a

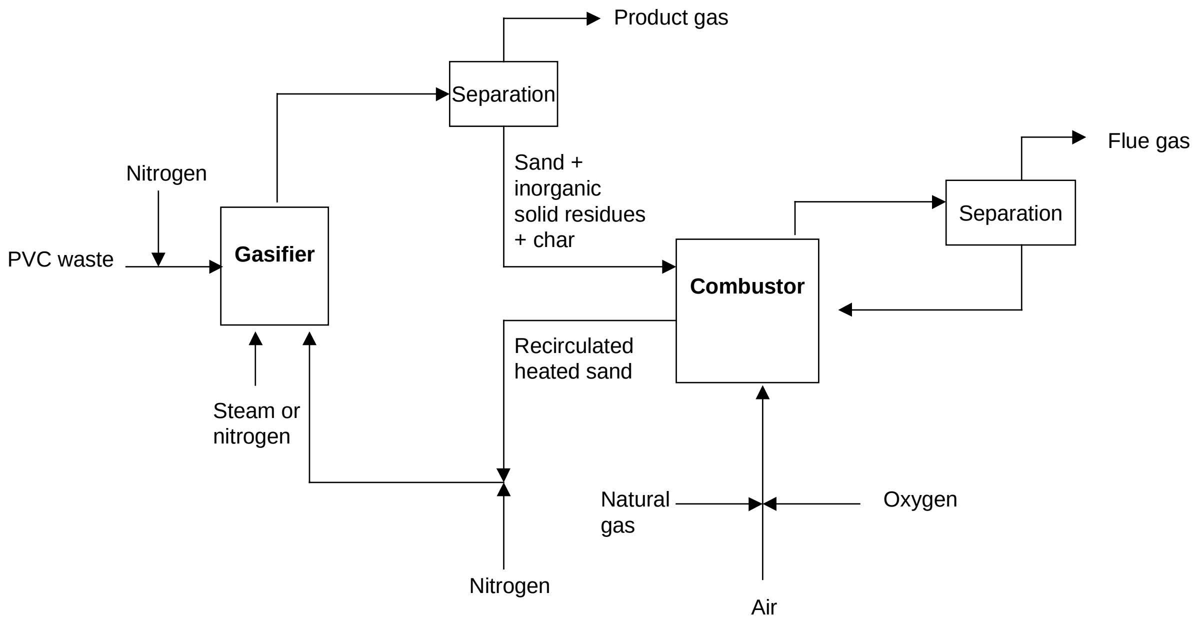
PVC-frormulation, are separated from the flue gas or as a bleed from the circulating sand.

The output of the reactor is a synthesis gas with variable composition, which is dependent on the input. If the input contains a lot of PP and PE, relatively a lot of ethylene and propylene will be formed. With proportionally more PVC, HCl and CH_4 will be more evident in the product gas. In any case CO and H_2 will be the main components. Also the feed/steam ratio will influence the composition of the gas. This needs further investigation. If HCl is present in the gas, it will be recovered. From the tests with 100% PVC waste, it appeared that the HCl recovery was higher than 90%, mostly 94-97%. The product from the combuster is fuel gas. Inorganics will be emitted as fly ash from the system.

Acceptance criteria for the input material

An input specification is not available yet. A broad spectrum of materials is expected to be acceptable. Examples are: wood, biomass, mixed plastic and pure PVC waste. Trials have been carried out with a waste stream consisting of pure PVC waste but also with a mixture of PVC, PE, other polymers, rests of Cu, Al, chalk, cement and fibres.

Figure 2.6: Schematic representation of the AKZO steam gasification process



Resource needs and emissions
Resource needs are also dependent on the input material. Further optimisation is necessary. As an example of waste containing 40% PVC and 25% inorganic fillers, the following numbers can be estimated:

Resource needs [amounts per tonne PVC]:

steam	0.3 t
process water	1.0 m^3
air	2.3 t
electricity	115,200 kWh
cooling water	86 m^3

Outputs [amounts per tonne PVC]:

HCl	0.21 t
synthesis gas	0.9 t

Waste [amounts per tonne PVC]:

Fly ash and bottom ash	0.22 t (to be disposed of)

Processing costs
Costs are mainly determined by investment cost and thus by the capacity of the plant. A 50-ktpa plant will cost about 55,000,000 NLG (ca. 25 MECU), but a large uncertainty exists in these costs. For example, if a very variable feed has to be processed with F, Br, S, etc., extra steps are necessary, comparable with HCl. It is very difficult to give more exact data at this stage of development.

2.3.4 Linde Gasification Process

Background and current status
Linde KCA in Germany is offering a process to gasify waste materials in a slag bath. The basic technology was developed in the 1950s for gasification of lignite and coal. The process was made suitable to treat PVC waste with the following objectives:

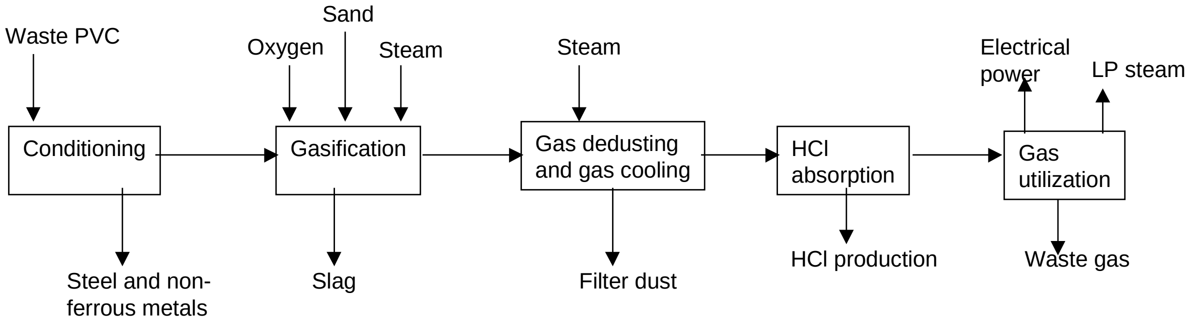
- maximum possible conversion of the chlorine contained in the PVC into an HCl gas suitable for use in oxichlorination;
- maximum possible conversion of the chemically bound energy of the waste PVC into other forms of energy;
- disposal of the unavoidable waste products of the process in a way complying with environmental regulations.

The European Council of Vinyl Manufacturers (ECVM) recently pronounced a preference for this process for the treament of PVC-rich waste. They regard the process as robust and economical. A pilot plant based on the Linde process is currently planned, supported by a financial commitment of 3 Million Euro from ECVM.The task of building the pilot plant has been assigned to Solvay's Tavaux plant, located in the eastern part of France. Work on building the unit will start this year to enable the unit to be operational towards the second half of 2000. Depending on the results obtained with this pilot plant, and other considerations, a decision on a large-scale plant with a capacity of about 25,000 tpa will be taken. It is unlikely that such a large-scale plant will be operational before 2005.

Description of the process

Figure 2.7 summarises the process. The plastic waste as delivered passes a conditioning process in which it is precrushed and separated from steel and non-ferrous metals before entering the reactor. A pressurised reactor filled with slag is heated up to 1400-1600 °C. The slag mainly consists of silicates. PVC, sand, oxygen and steam are fed into the reactor according to the process conditions. The process is exothermic. Resulting products in the reducing atmosphere are a synthesis gas (CO / H_2) containing HCl and a slag. It is likely that this slag contains most of any metal stabilisers present in the PVC-formulation. HCl is absorbed with water from the synthesis gas. The resulting hydrochloric acid has to be purified from heavy metals chlorides and other halogens. Pure HCl gas is produced by distillation of the hydrochloric acid. The HCl-free synthesis gas can be used as feed for chemical processes or as a fuel gas to produce power.

Figure 2.7: Schematic representation of the Linde KCA process (main part of basic flow diagram)



Acceptance criteria for the input material

With this process waste streams containing up to 100% PVC waste can be recycled. This can be all kinds of PVC, hard and softened types. No specific requirements are set on the input waste for treatment in the conditioning section. Conditioning of waste to meet the requirements for handling by the slag bath gasifier includes the following steps:

- Intake and storage of the waste;
- Crushing and screening of the waste to the required particle size;
- Separation of iron and heavy non-ferrous metals from the waste by magnet or gravity sifter, respectively.

Washing steps are not necessary. In addition, drying of the waste is not necessary, because moisture is not a problem for the process. In some cases steam will even be added.

Resource needs and emissions

Linde made available a material and energy balance of the Linde-KCA process. At an input of some 3 tphr PVC waste, an output of 3500-4000 m^3 combustible gas is achieved. HCl production depends on the waste feed and varies around 700 m^3/hr (STP). No dioxins or furans are expected to be generated using optimum process conditions.

Processing costs

The processing costs in a large-scale plant (25,000 t/yr PVC waste) have been estimated for a standard waste PVC stream defined by ECVM. Depending on the composition of the waste PVC, the costs and proceeds vary over a wide range (±20%). The supposed utility costs are based on the Wacker Chemie (Germany) site. The processing costs can be different at other locations. Considering all costs (capital costs, tax, overheads, etc., with the exception of transport and pretreatment) the total gate fee is about 400 DM (200 Euro) per tonne waste PVC for free on site delivery of appropriately pretreated material (this is a rough guess!). The plant will yield profit at a higher gate fee. The real costs can only be verified during evaluation of the pilot plant run. Pretreatment costs like milling and shredding will add another 250 DM (125 Euro) to the costs. The company feels that it is only possible to give reliable indications about the cost structure after experience with a pilot plant has been gained.

2.3.5 NKT Pyrolysis process

Background and current status

The investigation into the treatment of PVC cable waste started in 1993 on a laboratory scale and was continued in 1995 on a semi-technical scale. This project was financed by the Danish Environmental Protection Agency (EPA) and NKT Research Centre. During the period February 1998 - June 1999, a PVC building waste project was carried out. In this project, the process was optimised for the treatment of mixed PVC building waste on a semi-technical scale. This project is financially sponsored by the Danish EPA, the NKT holding, ECVM and the Norwegian company Norsk Hydro.

Furthermore, a pilot plant project was started in September 1998 and is due to finish in August 2000. This pilot plant project is financed by the Danish EPA and NKT Research Center. As part of the pilot plant project, a pretreatment plant for the treatment of about 1,000 ton/yr mixed plastic waste and a reactor for the treatment of 200 ton/yr of PVC waste are now under construction. Currently, the process exists on a semi-technical scale. The pretreatment section now exists as a pilot plant, while the pilot plant PVC reactor is still under construction.

The pilot plant may treat up to 250 kg/hr of mixed plastic waste. The PVC reactor may treat up to 1,800 kg/day of pretreated PVC waste. The feasibility of a full-scale demonstration plant is under consideration. NKT is evaluating the technical and economic feasibility of a 15,000 ton/yr plant for mixed PVC waste. The PVC reactors planned are being built in units each capable of treating about 1,700 ton/yr. There will be about 6-8 units, able to treat about 10,200 - 13,600 ton/yr of pretreated PVC waste. The number of reactor units will depend on the actual composition of the incoming plastic waste material.

No decision has been made yet for starting up this demonstration plant for both technical and commercial reasons. The process has to be tested on the pilot plant scale for its reliability, reproducibility, product purities, treatment economy, etc. In addition, uncertainty exists on collected PVC-waste availability, composition and also treatment prices.

Description of the process

The technology developed by NKT Research Center A/S transforms PVC waste into chemical products/raw materials (see figure 2.8). In the pretreatment section light plastics such as PE, PP, wood and the like are sorted out. Also, sand, iron, steel, brass, copper and other metallic pollutants are separated from the PVC.

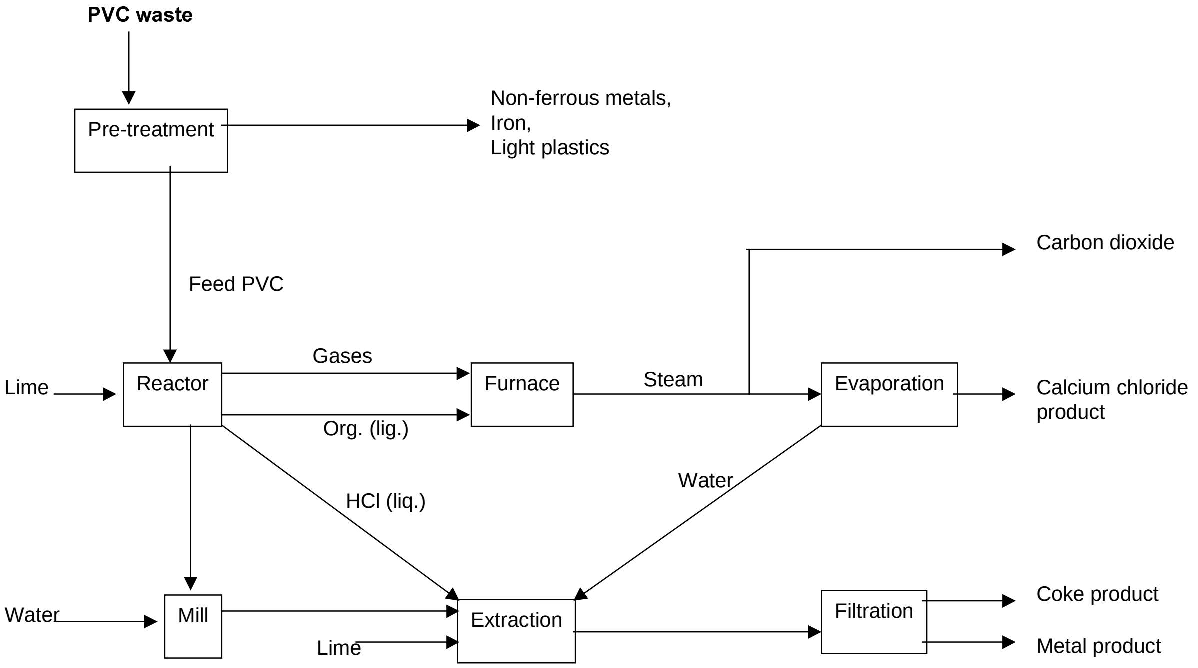
The chemical and thermal degradation of the PVC waste takes place in a reactor at low pressures (2-3 bar) and moderate temperatures (maximum 375ºC). In the process chlorine from the PVC reacts with fillers, forming calcium chloride. Simultaneously, the metal stabilisers that may be present in PVC-waste (lead, cadmium, zinc and/or barium) are converted to metal chloride. This consists of over 60 % lead and may be purified and re-used. After completion of the reactions, three main intermediate products are formed: a solid phase product, a liquid product and a gas phase product.

From the gas phase produced in the reactor (see figure 2.8), hydrogen choride is collected by absorption in water, and the light gases (mainly carbon dioxide, propane and ethane) are released after incineration. The liquid phase is separated into an organic condensate and an aqueous condensate. Hydrogen chloride solutions are reused in the downstream separation process. The solid phase is treated in a multistage extraction-filtration process. By controlling pH, temperature and the amount of water added, heavy metals are separated from the coke in the filtration and/or evaporation step in figure 2.8. Part of the chloride that is not internally re-used finally comes available as calcium chloride from the evaporation step in figure 2.8. To minimise the consumption of water, water is recycled between every extraction stage.

Currently, PVC-waste from Germany and Denmark is treated in the PVC-pretreatment plant in order to gain experience with the effects of pretreatment. In particular, the necessity for pretreatment from the product purity point of view is being evaluated. Furthermore, large variations in feed composition (10-100% PVC content) are being investigated. The pretreated PVC waste fraction will be further treated in the reactor and downstream separation process.

In sum, the products of the process are:
1) Calcium chloride product (< 1 ppm lead), which may be used as thaw salt or for other purposes;
2) Coke product (< 0.1 wt% lead and chlorine, respectively), which may be used as fuel in a cement kiln;
3) Metal concentrate (up to 60 wt% lead), which may be further purified and re-used;
4) Organic condensate, which may be used as fuel for the process.

Figure 2.8: Schematic representation of the NRC process



Acceptance criteria for the input material

Amongst PVC materials that have been processed are: cable, cable trays, flooring material, window frames, artificial leather, packaging, pipes, flexible hoses, ring binders and roofing material. There are no restrictions on the chlorine content of the incoming materials. Mixed PVC building waste containing metals, sand, soil, PE, PP, wood and rubber waste have been successfully treated. With the completion of the pretreatment pilot plant, the contents of other plastics and metals may now be reduced significantly.

Resource needs and emissions
To treat the PVC waste, lime and water are needed to run the process. From the process no dioxins, chlorine, metals or plasticisers are emitted. Also, there are no liquid waste streams in the process since all streams are recycled within the system. There is a small volume of carbon dioxide gas formed by the reaction between lime/limestone and hydrogen chloride.

The organic condensate produced provides the energy necessary for the reactor and for the evaporation of calcium chloride to a thaw-salt concentration. Excess energy is available in the coke product. Energy for pretreatment of the feed material (max. size is 0.5m x 0.5m) is around 25-35 kWh/ton. Electrical energy (30-40 kWh/ton) is also needed for the reactor treatment and downstream separation of the coke products.

Processing costs
The cost structure is currently under evaluation. Total treatment costs (gate fee costs) are likely to be of the order of 2000 DKK (or 250 Euro) per ton for a 15,000 ton/yr plant. The investment costs for such a plant are about 70 million DKK (or 10 million Euro).

2.4 Alternatives to chemical recycling

2.4.1 Introduction

Obviously, there are more traditional treatment options for PVC-containing waste than chemical recycling. Landfill, MSWIs and mechanical recycling are options as well. Some of these processes deal with mixed materials of which PVC is a part, and some need input of a rather clean PVC waste fraction. In this section, we have chosen to discuss the following technologies to some extent:

- Cement kilns;
- MSWIs (several flue gas cleaning options);
- Mechanical recycling;
- Landfill.

Furthermore, Solvay developed a process called ‘Vinyloop ®’, that is an intermediate between chemical and mechanical recyling and will also be discussed here. Since landfill, incineration and mechanical recycling are the subject of other extensive studies commissioned by the Commission, we do not discuss them in detail here. A good discussion particularly of mechanical recycling would need an analysis on a considerable level of detail, since the technologies and collection systems are waste specific. A proper analysis of mechanical recycling would imply simply a duplication of the work of Prognos. Hence, in a separate section we simply include a very generic description of landfill and mechanical recycling of PVC waste, and the related costs. We will describe incineration technologies, but will refrain from making strong statements on issues like specific treatment costs for PVC, the acceptance criteria with regard to chlorine, etc., since these issues are specific issues of research in the parallel studies performed by Bertin and AEA.

2.4.2 The Vinyloop PVC-recovery process

Background and current status

Solvay has developed Vinyloop® as a response to a challenge from one of its customers, Ferrari Textiles Techniques (France). This company is specialized in the production of architectural tarpaulin and canvas in PVC/polyester compound. They consider it important that their products be recyclable. The first industrial installation is being developed and will become operational by 2001 at Ferrari Textile Techniques. The process has in fact to be classified as mechanical recycling rather than chemical recycling. The method is based on physical principles. Where chemical recycling by definition breaks down a plastic into feedstock, in this process the chemical structure of PVC is unchanged. However, it was felt important to have this process described in at least one of the studies performed for the EU on PVC waste management. As a comment on the final draft, TNO was asked to include the process in their report. Due to the short time available, it was not possible to perform detailed inquiries about the process, and therefore the information included here is somewhat limited compared to the descriptions of the other processes.

Currently, a 25 kg/day (or about 1 tonne a year) experimental installation is available. A pilot plant with a capacity of some 1,000 tpa is planned for 2001. By 2002, Solvay claims to have probably 17,000 tons of capacity available.

Description of the process

The process is quite simple in principle. First, the products to be recycled are first cut and reduced in size. After that, PVC and its additives are selectively dissolved in a specific solvent such that they become separated from other elements. Finally, PVC is recovered by means of precipitation and dried and is ready for a new life.

As indicated, this has to be labelled as mechanical recycling, since the PVC polymer is not broken down into its feedstocks. Yet, unlike classical mechanical recycling processes, where the full PVC formulation is kept intact, here the components that make up the full formulation are separated. The Vinyloop® process is therefore capable of dealing with rather complicated formulations. Solvay claims that the regenerated PVC is comparable in quality to the primary product.

Acceptance criteria, resource needs and emissions, and costs

The process deals with selectively collected PVC products. The quality has to be about the same as for mechanical recycling. The tests on pilot industrial installations have shown that the Vinyloop® process is suitable for recycling all

PVC-compound materials tested so far: cables, pharmaceutical blister packs, floor coating, car dashboards, etc. The process is a closed loop system; i.e. there are no emissions to water. Details about the resource use (particularly the solvents, the crucial element in the process) are not publicly known. The gate fee will be in the order of magnitude of 350 Euro per tonne.

2.4.3 Cement kilns (energy recovery)

Background and current status

Cement production demands major amounts of fuel; coal, oil or gas. The energy costs of cement kilns can be up to 25% of the turnover, and the financial benefits of using waste as a fuel are obvious. Many cement kilns in the UK, Belgium, the Netherlands, Switzerland and other countries have therefore started to use pretreated waste streams as a fuel. Current practice shows that cement kilns are capable of dealing with the following types of waste:

1. liquid, high caloric fractions (as fuel);
2. liquid, low caloric fractions;
3. sludges (as raw material and fuel);
4. solid waste, including plastics (as raw material and fuel).

It has to be noted that for waste types 1), 3) and 4) the use in cement kilns can be regarded as a recovery operation. For waste type 2), however, there is no real benefit of using the material in the cement making process, and the kiln is merely being employed as a means for a (thermic) waste disposal operation. For this reason, various EU member states propose establishing minimum limits for the caloric value of waste to be used as an input in cement kilns.

Different cement kiln operators concentrate on different waste market segments. For instance, some Belgian and UK cement kilns are specialised in dealing with hazardous waste. However, also MPW is one of the waste types currently accepted as a fuel, though compared to hazardous waste it is less attractive due to the lower gate fee charged. In theory, the capacity of cement kilns to deal with MPW is enormous. The total cement production in Europe is around 250 Million tonnes or more, with an energy need of some 800-1,000 Bio MJ per annum (Caluori, 1998). Assuming that 1 tonne of plastics waste has a caloric value of 30,000 MJ, this equals 30 Million tonne of MPW. Even with 10% replacement of energy carrier by plastic waste, this would imply a capacity of 3 Million tonnes per annum.

Description of the process

Cement kilns produce a clinker by sintering alkalic raw materials such as lime ($CaCO_3$), clay (SiO_2 and Al_2O_3) and gypsum ($CaSO_4$) in a kiln at a very high temperature (1450°C in the solid fraction). The kiln can, in fact, be seen as a rotary kiln with a much longer length (200 metres). Furthermore, the solid materials flow in the opposite direction to the incineration gases. The length of the kiln results in a long residence time of incineration gases at high temperatures: 4 to 6 seconds at 1,800°C and 15 to 20 seconds at 1,200°C (CdO, 1995).

Compared to regular waste incineration the oxygen content, however, is much lower. Two processes are used to produce a clinker: a so-called wet process and a dry process. In the dry process the alkali raw materials are introduced in dry form into the kiln. In the wet process, these materials are introduced in the form of a slurry. The type of process used depends, amongst others things, on the source of the kiln’s raw materials. Some kilns use raw materials that are extracted from nearby lakes and in that situation the choice for a wet process is logical. A clear disadvantage of the wet process is that it needs much more energy than the dry process (5,000 MJ/tonne and 3,600 MJ/tonne clinker), as in the dry process no water has to be evaporated.

Because of the high temperatures, organic substances like MPW are effectively destroyed. Acidic substances such as HCl and SO_x are neutralised by the alkali raw materials, which act in fact as a caustic scrubber. Metals are bound in the clinker or in the fly ash. Fly ash is captured with an electrofilter and subsequently added to the clinker. In general, no other flue gas cleaning is applied.

Acceptance criteria for the input material

Cement kilns have proved to be relatively robust with regard to their input material. In most cases the input material should be chipped or shredded. The PVC content is generally limited by licence obligations, 1-2% chlorine often being the maximum for individual waste streams[9]. Since demands with regard to cement quality require a concentration of chlorine in cement of some 0.1 % at maximum, the average chlorine content of all fuels used combined may have to be somewhat lower[10]. This implies that waste with a high chlorine content has to be fed into the kiln simultaneously with wastes or fuel with a lower chlorine content[11].

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[9] See for instance the acceptance criteria of Ciments d’Obourg (CdO, 1995). Scoribel, the firm who pre-treats and combines different waste streams for use as a secondary fuel at Ciments d’Obourg, accepts 10 % chlorine in individual waste streams. Italy has produced a statutory order that limits the chlorine input in cement kilns to 0.9 %.

[10] Some suggest that apart from product quality also process-technical limitations play a role. We found no indications of such problems in literature or from our respondents (see also note 11).

[11] For cement kilns, the cement output is about 3 times or more higher than the fuel input (in tonnes; see CdO, 1995). A maximum of 0.1 % chlorine in cement thus implies a maximum average of 0.3 % chlorine in fuel. If only 10 % of the fuel comes from waste, and the other inputs have only a minor contribution to the chlorine throughput, in theory this waste can contain up to 3 % before product quality problems arise. In practice this percentage may be lower due to the contribution to the chlorine throughput of other raw materials. It has to be noted that representatives of Holderbank have indicated that they don’t see chlorine contents in waste in the ranges of 1-2 % as a major problem (Tukker et al., forthcoming). The Holderbank group is the major cement producer in the world with a European market share of several dozen percent. They are very actively promoting the use of secondary fuel in their plants.

Resource needs and emissions

Several LCAs have been performed by TNO (Tukker, 1996; TNO, 1996) making use of a waste-independent mass balance model. Given the specific composition of the particular waste, the model, based on a Belgian wet cement kiln, calculates the change in emissions to air and the components added to the clinker in case waste instead of fuel is incinerated. For PVC, the energy content basically replaces coal or oil, and the chlorine is essentially captured as chloride in the clinker.

Processing costs

Cement kilns are primarily constructed for other purposes than waste incineration. Hence, the main cost element for all other treatment options, i.e. capital investment, can be disregarded by cement kiln operators. The costs for the minor pretreatment activities (shredding, etc.) will probably largely be covered by the costs of the fuel saved. Hence, they tend to concentrate on those wastes for which they can ask the highest price while still being competitive with regular waste treatment options. The price for treatment in cement kilns will thus mainly depend on the availability and price of alternatives, and may range between a few Euro to 100 Euro per tonne. We assumed 50 Euro per tonne for further calculations.

2.4.4 Municipal solid waste incinerators (with energy recovery)

Background and current status

Municipal solid waste incinerators are a proven, robust technology for dealing with very different mixed waste types of different origin. The typical MSWI is built for dealing with waste of a caloric value between 9 and 13 MJ/kg. MSWI’s are currently a default technology for the treatment of integral household waste in countries such as Denmark, Sweden, the Netherlands and Germany. In Europe, on average some 7% of this integral household waste consists of plastics[12].

Description of the process

Municipal Solid Waste Incinerators (MSWIs) are in principle built for the treatment of municipal or similar industrial wastes. In such a kiln the waste, after it is tipped into a storage and has been made more homogeneous, is transferred to a grid-type kiln. This rolling grid is placed under a certain slope, so that the waste is slowly transported with such a speed, that full incineration takes place. At the end of the grid slags remain. The slags are treated in order to recover the ferrous and non-ferrous fraction. In some countries these slags are re-used, mainly in road construction. Just like in the case of a rotary kiln, the flue gases pass through cleaning equipment such as an electrofilter, an acid scrubber, a caustic scrubber, an active carbon scrubber and a DeNOx installation in order to comply with the demands of the EU incineration directive. In modern MSWIs, the energy is also

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[12] Treatment of plastics waste as long as it is part of integral household waste is no problem in MSWIs. However, if plastics waste would be collected separately and then be submitted to a MSWI, problems could arise since pure plastics waste has a high caloric value (30 MJ/kg or more).

recovered as much as possible (AOO, 1995). The flue gas cleaning process leads to fly ash and flue gas cleaning residue, which has to be landfilled. The main part of any metals present in a PVC formulation ends up in these residues. A large fraction of the chlorine input into the MSWI ends up in the flue gas cleaning residue. In dry flue gas cleaning , the amount of flue gas cleaning residue can be as high as 66 kg per tonne of waste incinerated (e.g. Sas, 1994). A process has been developed for the neutralisation of flue gases with sodium bicarbonate. As such, this has no significant influence on the amount of flue gas cleaning residue generated. However, this residue can be treated at a separate plant recovering soda and salt. In that case, much lower residual amounts of hazardous waste have to be disposed of. This process is called the NEUTREC system. A recovery unit is operational at a Solvay plant in Rosignano in Italy. To date, just a few MSWIs in Europe operate with this system.

Acceptance criteria for the input material

Normal municipal solid waste and similar material, including the regular plastics and PVC content, can easily be accepted by MSWIs. For dedicated waste streams, some elements have to be taken into account. First, if one wants to produce re-usable slags, the heavy metal input into the incinerator should be limited. Furthermore, an important point is the relatively low incineration temperature of MSWIs (850ºC). Some waste will not be efficiently destroyed. Furthermore, from a technical and financial viewpoint, one may wish to limit the input of certain components[13]. All this may result in certain acceptance restricions. We will not discuss these restrictions in detail here, since this aspect should be covered in the studies performed by Bertin and AEA for the Commission.

Resource needs and emissions

On the basis of various studies, a comprehensive evaluation of the emissions per ton of waste incinerated in a MSWI has been published by TNO (Tukker, 1996). The study basically resulted in mass balances for the components like heavy metals for an MSWI, and for the average process-related emissions per ton of waste incinerated. The data form an average for the state of the art Dutch MSWIs. It is likely that they are representative of most MSWIs that comply with state of the art emission standards. The most decisive is the influence of the type of flue gas cleaning equipment on the amount of flue gas cleaning residue. Wet scrubbers result in residues whose salt fractions can be discharged. Other scrubbers result in a flue gas cleaning residue that has to be landfilled 100%. The data in Tukker (1996) can be used to calculate the effects related to the incineration of 1 ton of waste:

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[13] For instance, considerable discussion has been going on about the specific costs for incineration of PVC in MSWIs, and the contribution of PVC to the formation of the amount of flue gas cleaning residue.

- as a function of the composition of the waste: the component-related emissions to air, water and waste residues on the basis of the mass balances;
- as a function of the caloric value of the waste: the process-related emissions to air and water;
- as a function of the ash content of the waste: the amount of slags and fly ash.

Processing costs

Many studies have tried to analyse the specific processing costs of certain components in municipal solid waste. Many assumptions influence such calculations (see e.g. Rijpkema and Zeevalkink, 1996). For this study, the actual gate fee is most relevant. Actual gate fees tend to depend highly on the market situation, since the marginal costs of MSWIs are low compared to investment costs. Price dumping is thus possible. Realistic gate fees are around 100 Euro per tonne (the Netherlands) to 150 Euro per tonne (Switzerland).

2.4.5 Other treatment

Finally, other relevant treatment options for PVC or plastics waste include landfill and mechanical recycling. Both options are part of other projects commissioned by the Commission. Mechanical recycling of plastics (be it PVC or other plastics), needs dedicated collection of the plastic waste in question. This seems only feasible for selected PVC flows. Landfill can accept PVC in any waste context (pure PVC, MPW, mixed materials).

Here, we will only address the costs of these alternative technologies. For landfill, costs vary highly across Europe in relation to landfill quality and landfill tax systems. Differences between some 2 Euro per tonne in some EU countries (for inert waste) and up to 280 Euro per tonne in e.g. some places in Germany may occur[14]. The latter value must be regarded as exceptionally high. Technically, even in countries with unfavourable circumstances like the Netherlands (high ground water level, soft soil), a price of some 50 Euro per tonne is enough to realise a controlled landfill (including aftercare systems). Hence, we will use this value as a basis for further analysis. The price level (gate fee) of mechanical recycling processes depends very much on the type of mechanical recycling.

2.5 Review of technical and economic aspects

Table 2.4 reviews the main aspects of the treatment technologies for PVC discussed in this chapter. The table summarises the type of material input, the maximum allowable chlorine content (often being one of the most crucial acceptance criteria), the gate fee, the technologies’ status, and the products

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[14] Data obtained a few days before the deadline for this project, most probably from the report of Argus on landfill for DG XI (see introduction).

produced from the PVC. Concerning the last point, the fate of the chlorine in PVC and the organic material in PVC are addressed. It has to be noted that the gate fee reflects only the costs of final treatment (so-called ‘hot box’ and mechanical recycling processes). The costs for collection and pretreatment (‘cold box’ processes) still have to be added. Such costs differ greatly for each type of waste and each type of final treatment, and will be discussed extensively in chapter 3.

Table 2.4: A review of technical aspects and gate fees (excluding collection/pretreatment, see chapter 3)

Process	**Input**	**Max. input Cl**	**Gate fee (Euro). Excl. collection /pretreatment**	**Status**	**Products/fate** **- Organic fraction** **- Chlorine** **- Metals**	**Capacity**	**Future potential**	**Remarks**
Texaco	MPW	5 %	100 (50)	Pilot	Syngas NH_4Cl-product In vitrified slag	-	Uncertain*	Betweek brackets: gate fee for a large scale plant
Polymer Cracking	MPW	2 %	200 (100-175)	Pilot	Liquid/gas $CaCl_2$ (landfill) In various residues	-	Uncertain*	5 % chlorine possible during short periods
BASF	MPW	2.5 %	250 (160)	Demo (closed)	Liquid/gas HCl (product) In residues	15 ktpa before 1996	-	On hold due to more economical competitors
Blast Furnace	MPW	1.5 %	Few-100?	Operational	Coal replacement Cl (to water) In iron or slag	162,5 ktpa in 1998	5 Mio tpa in the EU**	
Veba	MPW	2 %	250	Operational (to be closed)	Gas/syncrude HCl (product) Hydrogenated resid.	87 ktpa before 2000	-	Higher chlorine content possible during short periods
SVZ	MPW	2-5%	150 ?	Operational	Syngas/Meth-anol Cl to waste ? In landfill class 1 slag	110 ktpa in 1998		The higher chlorine levels are possible during shorter periods
BSL	PVC-rich, Various mixes	> 50 %	250	Operational	Energy HCl (product) Various solid residues	15 ktpa in 2000		
Akzo Nobel	PVC-rich, Various mixes	High	Not known yet	Lab/pilot	Syngas HCl (>90 %) Various solid residues	-		
Linde	PCV-rich, Various mixes	> 50 %	200	Pilot operat-ional in 2001	Syngas HCl (product) Various solid residues	2 ktpa in 2000	25 ktpa . 2005 ?	
NKT	PVC-rich, Various mixes	High	125-250	Pilot	Coke $CaCl_2$-product Metalchloride	< 1 ktpa in 1999	25 ktpa in future ?	Costs under evaluation
Vinyloop ®	PVC-rich waste	High	350	Pilot, operat-ional in 2001	PVC resin Other by-products	< 1 ktpa	17 ktpa in 2002	Specific form of mechanical recycling
MSWI	MSW ca	n.r.	100-150	Operational	Energy (20-40 %); Cl and metals to waste	N/A	N/A	See AEA (1999) study
Cement kilns	MPW	1-2 %	Few-100?	Operational	Energy (100 %), metals and Cl in cement	Some 100+ ktpa	3 Mio tpa in the EU**	
Mechancial recycling	PVC mono waste flow	High	Some 200+, much lower for cables	Operational	Recovered PVC	N/A	N/A	See Prognos (1999) study. Highly product specific
Landfill	MSW ca	n.r.	1-280	Operational	-	N/A	N/A	See Argus (1999) study

Note: MPW is Mixed Plastic Waste; MSW c.a. is municipal solid waste and comparable material

* Typical capacities considered are 50 ktpa to 200 tpa

** Theoretical potential if most blast furnaces and cement kilns in the EU will start to replace regular fossil resources by MPW

3. Possible collection structures in the PVC waste chain

3.1 Introduction

Given the technologies presented in chapter 2, various options are available to organise the PVC waste chain. They define the place and role of chemical recycling in this structure, and hence are important in determining the scenarios with regard to chemical recycling of PVC-containing waste.

For the purpose of this project, it is most useful to classify types of PVC waste by source. In general, they are already collected via different collection routes. Not totally coincidental, it is exactly the same waste flows employed in the APME reports on plastics waste generation in Europe (APME, 1997). This concerns:

- agricultural waste;
- building and demolition waste;
- household waste(packaging and non-packaging);
- distribution waste from offices, shops, etc. (mainly packaging);
- industrial waste;
- residues of end-of-life vehicles (ELVs or automotive waste);
- electrical and electronics waste (E&E-waste).

In the next sections, we will analyse which collection and pretreatment systems are needed to prepare a supply of waste that fits within the acceptance limits of the technologies discussed in chapter 2. For this purpose, it is useful to know the composition of the waste generated by each of these sources. Based on a report prepared for APME (1997), table 3.1 indicates which percentage of a waste flow consists of plastics. In chapter 5, we shall analyse in detail the amount of plastics waste and PVC waste, and will produce solid estimates of the amount of PVC in the plastics fraction. The European representative organisation of plastic converters (EuPC) made available a detailed estimate of the amount of PVC products in the waste stage. By dividing the EuPC total per category (e.g automotive) by the totals for plastics in general given by APME (1997), a theoretical PVC fraction could be calculated[15]. We have already given this percentage here, in order to be able to analyse what form of collection and pretreatment is necessary.

In the next section we shall discuss the possible structure of a PVC waste management system. After that, we shall consider the possible collection structures and the related costs per waste stream.

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[15] Obviously, this calculation contains uncertainties. One comment on the final draft of this report was that 23% PVC in plastics waste from the automotive sector is too high. However, in that case either the APME data or the EuPC data contain major errors.

Table 3.1: Percentage plastics in waste by source

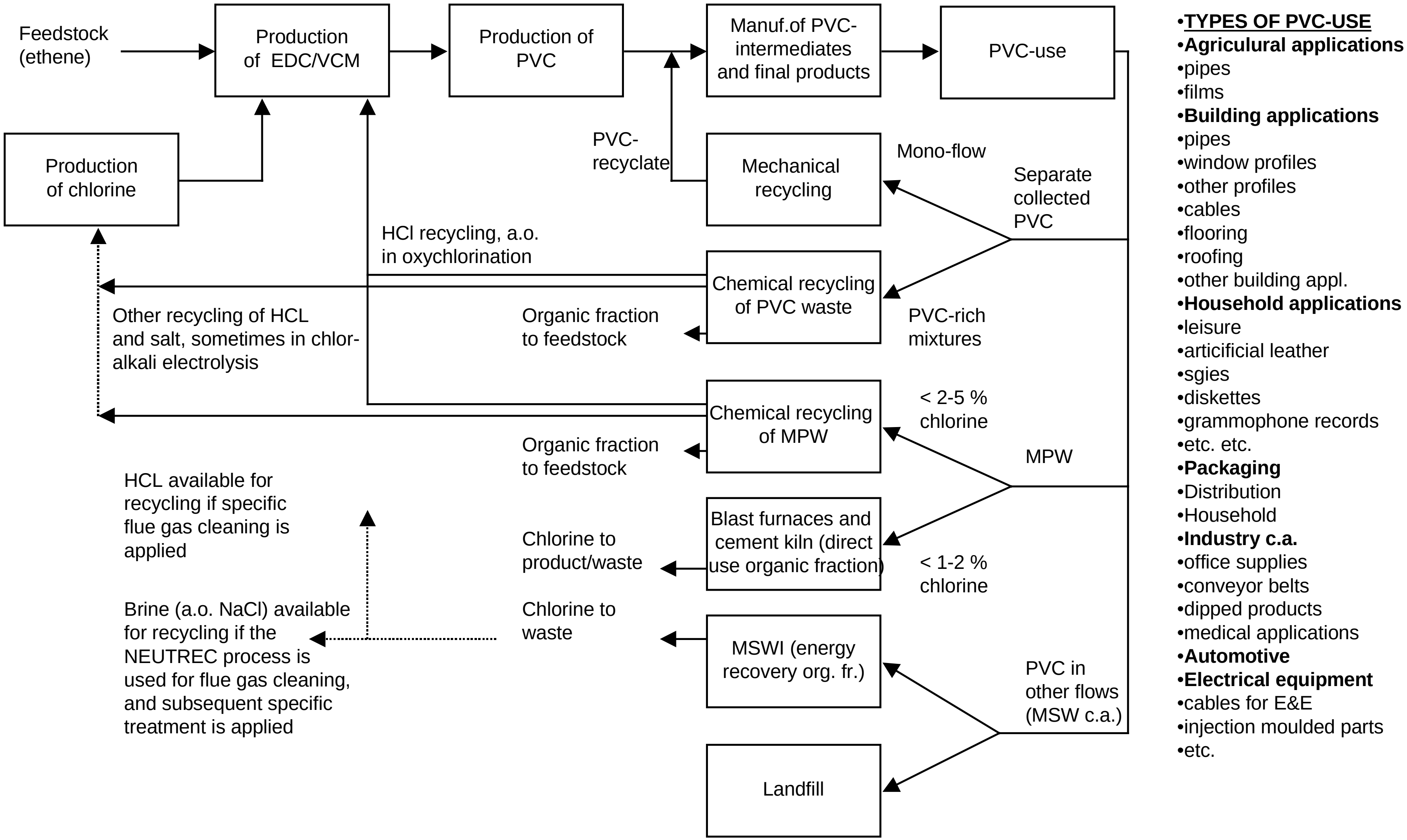
Waste type	**Fraction plastic waste in total waste**	**Fraction PVC in plastic waste (2000)**
Agriculture	0.03%	10%
Building	0.29%	40%
Houshehold waste	7.9%	
▪ non-packaging		16%
▪ packaging (excl. bottles)		4%
Distribution and Industry	1%	%
▪ distribution (packaging)		4%
▪ industry		14%
Automotive	7%	23%
E and E	15.4%	17%

3.2 An overview of the PVC waste management chain

PVC waste can become available for final treatment as a mono-stream, a PVC-rich mixture, as part of mixed plastics waste (MPW), and as part of mixed generic waste such as municipal solid waste (MSW). This mainly depends on the source of the waste and the extent of source separation.

Figure 3.1 indicates how the waste chain subsequently can be organised. It indicates via which routes the material chains can be closed, and at which level. For instance, via mechanical recycling options virgin PVC can be substituted, but the availability of a rather clean input of a PVC mono-flow, and a market for the recyclate must be ensured. For most of the chemical recycling options, the organic fraction of PVC is available as a feedstock, and the chlorine as HCl that can be used again in the production of PVC in oxychlorination or chlor-alkali electrolysis. Input into cement kilns and blast furnaces implies that the organic or energy contents is fully used, but the chlorine fraction is not. Input into MSWIs results in energy recovery. This is, however, for the average MSWI relatively inefficient. At MSWIs, the chlorine generally ends up in the waste fractions (slag, fly ash, flue gas cleaning residues). If special measures are taken, the chlorine is recovered as salt or HCl that can be used, for instance, in chlorine production. The figure also indicates the maximum chlorine content that can be tolerated. It has to be noted that neither re-use nor recycling can ever be 100 % efficient; the figure is in that sense a simplification since we did not include the residual waste flows from the recycling and recovery processes that are treated at a lower level of the waste hierarchy.

Figure 3.1: Simplified scheme for closing material chains related to PVC



The organisation of the collection chain is complex and can be varied in many ways. In order to deal with this complexity, we distinguished four main model routes for organising PVC waste management, and shall discuss them in comparison with their main classic competitors (like landfill and incineration):

1. Bring systems for mixed plastic waste (PVC recycled as a part of MPW);
2. Separation of MPW from integral solid waste, particularly municipal solid waste (PVC recycled as a part of MPW);
3. Bring systems for specific end-of-life PVC products;
4. Separation of plastics/PVC from complex waste streams (e.g. end-of-life products, or other integral waste streams).

Table 3.2 indicates which collection structure can be applied for each type of PVC waste, if (mechanical or chemical) recycling is being striven for. Agricultural PVC waste consists mainly of films, for which models 1), 2) or 3) may be applicable. For pipes from agriculture, model 3 may be applicable. For specific PVC waste flows from the building and construction sector, like pipes, window frames and flooring, model 3) is most relevant. For household waste, models 1) and 2) are most likely. This is also the situation for industrial and distribution waste, though for specific PVC products, model 3) may apply. As for E&E waste and ELVs, these are complex waste streams in which model 4) has to be applied if the PVC is to be recycled.

Table 3.2: Collection structures aimed at recycling of MPW and/or PVC

Collection system Waste type	**1: Bring system for MPW**	**2: Separation of MPW from integral waste**	**3: Bring system for PVC products**	**4: Separation from complex waste**
Agricultural	X	(X)	X	
Building/construction			X	
Household	X	X		
Industry/distribution	X	X	(X)	
Automotive				X
E & E				X

In the following sections we shall discuss particularly how the collection and pretreatment part of this flow chart can be organised. Also a rough idea of the total costs over the chain will be given. Many of the cost data were taken from the study ‘Treatment of plastics waste: an evaluation of environmental effects and costs’ (Sas, 1994), after cross-checking with other studies (e.g Hutterer and Pilz, 1998). The cost data must be regarded as tentative, since in relation to the complexity of the issue, our experience shows that cost data vary greatly between different literature sources. In this respect, it has to be clear that this study cannot be compared with some multi-year, in-depth studies into collection costs of (plastic) waste currently under way within other contexts. In order to allow for a comparison with the ‘classic’ routes of landfill and incineration, table 3.3 gives tentative costs for these routes as well. Based on chapter 2, costs for integral incineration in MSWIs have been set at 125 Euro per tonne, a normal price for countries with high-quality incinerators. For landfill, we used 50 Euro per tonne, but this proce varies considerably between EU countries (e.g. in relation to landfill taxes). Collection costs were taken from Sas (1994), but these are valid for integral solid waste and may be too high if the plastics or PVC waste is a by-product from other waste treatment processes. For instance, PVC cable sheeting is a by-product from copper recovery from cables, and the collection costs have already been paid to obtain the cables for recycling. For automotive waste, plastics are available in the shredding residue of cars, and the collection costs are irrelevant.

Table 3.3: Costs for landfill and incineration of PVC waste from different sources

Technology and acceptance criteria	**Landfill**	**MSWI**
Max. PVC input	n.r.	n.r.
Typical waste accepted	MSW	MSW
Collection and pre-treatment		
Integral collection*	160	160
Separation MPW		
Pre-treatment		
Agglomeration		
Logistics	40	40
Final treatment	50	125
Total costs	250	325

* Probably lower or irrelevant for (plastic) residues from the building and construction sector, E&E and automotive

3.3 Model 1: Bring system for mixed plastic waste

It is possible that plastics from agriculture, households, and industry and distribution are collected separately as a mixed fraction, a situation for which we made the calculation here. We have assumed that, at least for PVC, mechanical recycling is relatively unimportant when such a collection system is applied. It would imply that PVC has to be separated further from the MPW, but given the limited quantities of PVC in most MPW flows, and the high costs for separation, this seems unlikely to be a realistic option. The only option we see is that a kind of ‘downcycling’ in uncritical products takes place, which can be achieved by moulding a mixed plastic fraction including PVC. Treatment with a dedicated chemical recycling plant for PVC has no added value and was left out as well. This implies that this collection route is mainly relevant for recycling or recovery of PVC as a part of MPW.

The MPW can be prepared for cement kilns, blast furnaces, or dedicated chemical recycling plants. For the gate fees we refer to chapter 2; for chemical recycling we have assumed a value of some 150 Euro per tonne which is in the lower range of the gate fees supplied to us[16]. For cement kilns, a minor treatment (shredding/grinding) is often sufficient. For the other options, agglomeration has to take place, in order to enhance the density of the material. The collection costs were assumed to be slightly higher than for a ‘bring box’ and around equal to integrated collection of MSW. The minor pretreatment costs for cement kilns are based on in-house data from TNO. Costs for logistics and agglomeration have been taken from Sas (1994) after cross-checking with other sources.

On this basis, table 3.4 gives an impression of the total net treatment costs of MPW from this source. It shows that the cement kiln is probably the most cost-effective option, assuming that pretreatment indeed is minimal. The regular chemical recycling processes are more expensive than blast furnaces under the assumptions made. A comparison with table 3.2 indicates that all of the processes reviewed here are more expensive that integral collection and landfill, and that only cement kiln incineration may be able to compete with a MSWI.

Table 3.4: Tentative cost comparison of bring systems for MPW

Technology group and acceptance criteria	**Cement kiln**	**Blast furnaces**	**Texaco, VEBA, SVZ, Polymer Cracking**
Max. PVC input	1-2%	1-2%	10%
Typical waste accepted	MPW, RDF	MPW	MPW
Collection and pretreatment			
Collection point	160	160	160
Pretreatment	25		
Agglomeration c.a.		150	150
Logistics	40	40	40
Final treatment	50	50	150
Total costs	275	400	500

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[16] Only Texaco claims to be able to maintain a gate fee of 100 Euro or less. Furthermore, Texaco may have the advantage that no agglomeration has to be performed (Croezen and Sas, 1997). Under these conditions, the costs for the Texaco route would become only slightly higher than the blast furnace route.

3.4 Model 2: Separation of MPW from integral waste

As for the plastics in integral waste streams like household waste, these can also be made available for dedicated technologies via integrated collection and subsequent separation.

In this calculation, the waste is assumed to be collected in a traditional way (i.e. containers for households and/or industry and distribution). Cost data have been taken over from Sas (1994), and are valid for semi-urban areas. For separation, a typical plant available at the Dutch VAM company in Wijster, Drenthe, was chosen[17]. For some time, this plant was the most likely supply of MPW for the Texaco initiative. The separated fraction has to be treated further, depending on the final fate of the MPW. Once again, for cement kilns just a minor pretreatment is needed. Since the waste has already passed through a separation step, the agglomeration and other pretreatment for chemical recycling can be less extensive.

On this basis, table 3.5 reviews a cost calculation. A comparison with table 3.3 makes clear that landfill and MSWIs are more competitive. Cement kilns can compete with MSWIs, depending on the gate fee that is charged. Once again, the dedicated chemical recycling plants cannot beat the blast furnaces, at least given the assumptions used here.

Table 3.5: Tentative cost comparison for treatment of MPW from integrated MSW

Technology group and acceptance criteria	**Cement kiln**	**Blast furnaces**	**Texaco, VEBA, SVZ, Polymer Cracking**
Max. PVC input	1-2%	1-2 %	10%
Typical waste accepted	MPW, RDF	MPW	MPW
Collection and pretreatment			
Integral collection	160	160	160
Separation MPW	60	60	60
Pre-treatment	25		
Agglomeration		90	90
Logistics	40	40	40
Final treatment	50	50	150
Total costs	335	400	500

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[17] VAM literally means 'Waste removal company'. They operate e.g. a separation plant, a composting plant, and a MSWI in the north-east of the Netherlands

3.5 Model 3: Bring system for specific PVC waste

For specific PVC products, dedicated collection of PVC waste is an option. The building and construction sector in particular is a major source of large end-of-life PVC flows, like flooring, cables and pipes. This concerns also the waste types for which mechanical recycling of PVC has been most successful. Hence, a comparison here with the chemical recycling technologies for MPW with a low PVC content is not useful. We prefer to compare the costs for mechanical recycling with the costs for chemical recycling of PVC-rich waste.

Regarding the latter technology, the Linde process has been chosen as the main example since ECVM selected it as the technology to receive their primary support. Costs for this technology are about 200 Euro per tonne, with 150 Euro for pretreatment (see chapter 2). We further added 40 Euro for logistics (compare table 3.5). For the mechanical recycling technologies, we used data provided to us (at the last minute) via the Prognos study (Prognos, 1999) on mechanical recycling of PVC. Table 3.6 reviews the results.

Particularly recycling of cable sheeting waste appears to be a cost-effective option, mainly since it is a by-product from copper recovery from cables. Hence, it is available concentrated in large quantities at cable recyclers. Furthermore, it can be used rather easily by other processors as a low-cost supplementary material in less critical applications via extrusion or moulding. For recycling of pipes, window frames, and flooring, collection and pretreatment are costs to be taken into account. Still, they appear to be more cost-effective than chemical recycling – which is logical, since the primary resin can be saved. Only for flooring do the cost estimates for mechanical recycling and chemical recycling seem to be similar.

Table 3.6: Tentative cost structure for recycling of PVC-rich waste

Technology group and acceptance criteria	**Mechanical recycling options (a)**				**BSL, Akzo Nobel, Linde, NKT**
	Cable residues (b)	**Window frames**	**Pipes**	**Flooring**	
Collection and pre-treatment					
Collection, logistics	p.m.	70	120	125	40
Pre-treatment	p.m.				150
Treatment costs	p.m.	375	440	350	
Proceeds	p.m.	-200	-300	-125	
Final treatment					200
Total costs	50	250	260	350	390

a) Cost data taken from Prognos (1999)

b) Prognos (1999) deduced via an indirect approach that the costs for mechanical recycling of cable residues would be 50 Euro per tonne, but could not give a breakdown between different cost categories

It is unlikely that the waste flows under consideration will be incinerated in view of their rather high PVC content. However, a comparison with table 3.2 makes clear that in most cases landfill is still a more cost-effective option than the technologies mentioned in table 3.6. This is particularly true if one considers that the collection costs included in table 3.2 are probably over-estimated for the waste flows discussed here.

3.6 Model 4: Separation of PVC or MPW from complex product waste

The final model is the separation of MPW or PVC from complex waste flows. The main examples of such flows are automotive and E&E waste.

For these waste flows, several strategies can be followed in order to ensure recycling of PVC:

1. Selective dismantling of PVC product parts followed by mechanical or chemical recycling of the PVC;
2. Separation of a mixed plastic flow from the product (e.g. after shredding), and chemical recycling of the mixed plastic waste fraction;
3. Separation of a mixed plastic flow from the product (e.g. after shredding), separation of the PVC fraction, followed by recycling.

Analyses of the optimal dismantling and/or recycling strategy for E&E products or ELVs form major studies in themselves. Such analyses should take into account the technical and economic possibility of several selective dismantling approaches, the extent to which technical and economic possibilities can be enhanced by a better product design, a detailed analysis of the technical and economic performance of a broad range of separation techniques, etc. Such detailed analyses fall well outside the scope of this project. However, some observations can be made.

First, there may be some parts in waste flows like automotive and E&E waste for which the first strategy is viable. For instance, Prognos (1999) suggests that from E&E waste components like cables, adhesive tapes and injection moulding parts may become partly available for low-quality mechanical recycling. One can imagine that for automotive waste similar options may be involved[18].

Second, we have doubts about the viability of the chemical treatment option of a mixed plastic waste separated from automotive and E&E waste. Table 3.1 indicates that the chlorine content of the plastic waste flows is rather high compared with the acceptance criteria for chemical recycling plants for MPW.

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[18] The Prognos (1999) report mentions no option for mechanical recycling. We feel that for the category automotive waste in Appendix B at least tarpaulins are a technically feasible candidate for separate collection and mechanical or chemical recycling. Furthermore, ECVM (1999b) claims that also dashboard shredding and cables are candidates for (post-)sorting and recycling

Furthermore, a publication of Brophy et al. (1997) at rather high PVC contents the chlorine contents in the cracking products may become problematic, at least in the case of the Polymer Cracking process. However, the PVC contents in these types of plastic waste is still too low to be treated cost-effectively by chemical recycling with the plants for PVC-rich waste. As indicated by table 3.5 and table 3.6 the gate fee and pre-treatment costs (excluding collection) for chemical recycling of MPW are considerably lower than for chemical reycling of PVC-rich waste. There are some uncertainties about whether our approach gives the correct PVC contents (see chapter 5). There have also been some positive tests with managing E&E waste at VEBA, but in that test the E&E waste was mixed with 5 times the amount of MPW from the DSD system, which has a rather low PVC content (HCL, 1998). This would suggest that it is rather uncertain whether chemical recycling with technologies designed for MPW would be feasible. The waste flow may only be treated there if PVC is removed first, or if it is blended with MPW with a low PVC content.

Finally, the economics of post-sorting of PVC seems an issue requiring attention. Technically, there may be several options available (e.g. APME, 1999). It is probably feasible to split up waste into a PVC-rich fraction (that can be treated with the recycling technologies for PVC-rich waste) and a PVC-lean fraction (that can be treated with the chemical recycling technologies for MPW). However, the costs may be high, particularly if one allocates the full costs of the additional separation step to PVC only. For instance, if a waste flow contains 15% PVC, and it is passed through a separation step that costs only 15 Euro per tonne throughput, the separation costs related to PVC are 100 Euro per tonne PVC throughput.

As for costs, table 3.3 compared with tables 3.4 to 3.6 gives clear indications that also for the plastic residues from E&E goods and automotive the economical pressure to end up with landfill is rather high. Only recycling targets or other incentives can steer the flow away from this outlet.

3.7 Conclusions

At this juncture, on the basis of the technical analysis in chapter 2 and the cost analysis here, the following interim conclusions can be drawn.

Landfill and MSWIs have the lowest gate fee and can deal with PVC as part of regular municipal solid waste, hence avoiding expensive separate collection, separation and/or pretreatment steps. Thus, without legal or other steering mechanisms, the other technologies will only be a competitive option in exceptional cases.

For PVC in mixed plastic waste (MPW), which currently is becoming available in most countries as a result of the implementation of the EU Packaging Directive, several technologies are available. Blast furnaces and cement kilns offer probably the most competitive gate fee due to an absence of the need of high capital investment. However, these technologies have constraints with regard to the maximum chlorine contents in the waste. Of the dedicated chemical recycling technologies, the Texaco process is least critical with an acceptable PVC content of 10%, where most others have lower maximum input values or can accept such high amounts during relatively short-term excursions only.

The VEBA, BASF and SVZ processes are the only ones that are or have been available in practice. The BASF initiative has been put on hold, as is planned for the VEBA process. The most likely reason is that they depend(ed) on contracts with DSD, which were not extended since DSD found more cost-effective treatment options .Furthermore, the initiatives for the Texaco process and Polymer Cracking process have also, after several years, not yet lead to investments in a full-scale plant. Rather, we found indications that potential waste suppliers initially interested in such a technology finally stepped back, since they found more cost-effective outlets for their MPW. This whole picture suggests that chemical recycling is financially still a rather uncertain business, a view that is indeed reinforced by our cost calculations. The basic point probably is that purpose-built recovery installations will always have trouble in competing with technologies built for another purpose, but which happen to be able to recycle or recover MPW – which is the case with blast furnaces and cement kilns. The latter have the advantage that capital investment does not need to be allocated to the MPW. Our analysis further suggests that chemical recycling of PVC-rich waste will only play a role for PVC that cannot be easily mechanically recycled for technical reasons.

4. Environmental comparison

4.1 Introduction

This section will give a mainly qualitative environmental comparison between the waste management technologies for MPW and PVC-rich waste. It has to be stressed that within the framework of this project, it was not possible to perform a full or even partial life-cycle assessment (LCA). Apart from this, the problem exists that many of the technologies for chemical recycling are still under development or, at least, not yet available as a full-scale plant. This inevitably results in data gaps, uncertainties, etc.

However, particularly for chemical recycling technologies for MPW, some LCAs have been performed. The most important include:

- an LCA performed by one of the Frauenhofer institutes, IVV, for APME and a number of German representative organisations (Heyde and Kremer, 1999). This LCA covered the BASF process, SVZ, VEBA, blast furnaces, MSWIs and mechanical recycling;
- two LCAs performed by the CE in Delft, the Netherlands, that compared e.g. MSWIs with the VEBA viz. the Texaco process (Sas et al., 1994; Croezen and Sas, 1997).

Apart from this, various other LCAs in the waste field have been performed that provide insight into the environmental strengths and weaknesses of incineration, energy recovery and material recovery processes for organic wastes. We refer among others to a series LCAs performed for Dutch waste management planning (e.g. AOO, 1995; Tukker, 1996, 1998 and 1999).

This material, and the data given in chapter 2 on individual technologies, allow for some generic conclusions about environmental performance. Below we give an analysis of chemical recycling technologies for MPW and PVC-rich waste.

4.2 Comparison of options for MPW

4.2.1 Introduction

We will concentrate the discussion of options for MPW on the technologies discussed in chapter 2. When comparing the options, it is good to keep in mind that:

- The Texaco, Polymer Cracking, VEBA and BASF processes all produce mainly liquid organics or gases that 'replace' primary oil- or gas-based resources[19];
- The SVZ process, blast furnaces and cement kiln all use the MPW as a replacement for coal[20];
- MSWIs use the caloric value of the MPW to produce heat and/or electricity;
- Mechanical recycling uses the MPW as a replacement of primary plastic resin.

As for MPW, it has to be noted that high-quality mechanical recycling plays no practical role in the comparison. For such a type mechanical recycling a rather pure waste is needed, and with MPW this is simply not the case.

We will discuss the strengths and weaknesses by LCA-theme below (cf. Heijungs et al., 1992; Udo de Haes et al., 1999). It has to be noted that the comparison in the LCAs we used as a basis was performed for MPW, whereas we in principle have to concentrate on PVC. We simply assumed that, as far as the organic material content is concerned, the results for MPW give some indication of the behaviour of PVC. We will discuss the fate of chlorine as a separate issue when we deal with resource use and waste.

4.2.2 Discussion by environmental theme

Energy and global warming

Energy use and global warming are usually interrelated, and therefore discussed under one heading. The FhG-IVV study concluded that chemical recycling processes such as VEBA, BASF, and blast furnaces score considerably better than MSWIs. This is a conclusion that follows from almost any LCA comparing the treatment of organic waste with a reasonable energy content. In blast furnaces, the energy content is used 100%, and the VEBA and BASF processes lead to conversion into feedstock materials with only minor energy losses. MSWIs, on the other hand, have a relatively low energy recovery efficiency. As a general rule, provided that the energy for additional collection efforts, cleaning and agglomeration is relatively low, such processes tend to score better than MSWIs. The importance of the collection chain was shown in the CE studies, which compared e.g. the VEBA and Texaco processes with MSWIs. The Texaco process scored somewhat better, since no agglomeration step was needed in the cold box feed route. As for cement kilns, it is unlikely that their performance will deviate much from that of blast furnaces. In both technologies the same raw material is replaced (coal), and feed preparation is not likely to be very different. This is indeed suggested by two recent LCAs carried out by TNO (Tukker, 1998 and

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[19] It has to be acknowledged that both BASF and VEBA have been closed down or will be closed down shortly, and that the other two processes have not yet been realised on a large scale.

[20] One could argue that in cement kilns other fuels are also replaced. However, coal appears to be the main energy source for cement kilns.

1999). One compared the use of waste oil in cement kilns with high-quality reprocessing to feedstock or fuel, and the other the use of this oil as a reducing agent in blast furnaces with this same high-quality reprocessing process. Apart from the fact that blast furnaces and cement kilns did not score much worse than the reprocessing step, by comparing the two studies one can see that the scores of the cement kiln and the blast furnace are very comparable for all aspects (e.g. Tukker et al., 1996).

As for the SVZ process, the FhG study gives the impression that it scores similarly to MSWIs. This is somewhat surprising, since the SVZ process also uses plastics waste as a replacement for coal. The main reason for this is the allocation procedure applied in the FhG study. The SVZ process was originally designed to produce, e.g. methanol via a coal gasification process. Usually, however, methanol is produced with syngas produced with natural gas, a much cleaner and more efficiently used resource. In the FhG study, SVZ supplied only part of its input with plastics, and for the other part still used coal, leading to an amount *x* of methanol. However, in order to calculate the net benefits from this process, methanol production based on gas was taken as the reference system (i.e. the environmental effects of the SVZ process were reduced by the effects of regular methanol production to calculate the net effects of the waste treatment). However, by this process of allocation, one in fact calculates the difference of environmental effects between the production of methanol via the gas route and the coal route (which of course are negative), and allocate this to the waste treatment. If one had allocated on an input basis (i.e. 1 MJ of plastic input replaces 1 MJ of coal), the score could have been similar to blast furnaces. Very recently, FhG seems to have published a new LCA on the SVZ process that indeed showed similar scores as for other chemical recycling options.

In sum, this analysis suggests that chemical recycling and direct use as an energy carrier (in e.g. cement kilns) lead to more or less comparable scores on energy use and global warming. Only MSWIs, even if they have energy recovery, must be suspected of scoring worse.

Human and ecotoxicity

The themes of human and ecotoxicity are very difficult to deal with in LCA. In this qualitative analysis, it is even harder to make sensible conclusions with regard to the emissions of toxic substances from the full waste management system. In this comparison, since it concerns MPW with a chlorine-containing material like PVC, dioxin formation is a point of attention. As a general rule, reducing environments and high temperatures promote the breakdown and prevent the formation of dioxins. This would suggest that blast furnaces and gasification processes like VEBA and Texaco have advantages in this respect. However, drawing conclusions is rather difficult. In principle, one should take into account aspects such as the chlorine content in the feedstocks produced, their future fate, etc. This is well beyond the scope of this study.

Ozone depletion
The most important ozone-depleting substances have been phased out. There is no reason to assume why one of the technologies at stake would score worse or better than others concerning this aspect.

Photochemical Ozone Creation (POCP), eutrophication (NP) and acidification (AP)
The themes of photochemical ozone creation, eutrophication and acidification often tend to be correlated with energy use. Additionally, however, the processes avoided related to the useful by-products are relevant, as well as the quality of the flue gas cleaning. Here, one often sees the following difference between coal and oil as replaced products. Usually, oil refining results in relatively important emissions of NOx, SOx and VOC. If the recycling process produces a product that avoids this process step, it will score relatively well on POCP, NP and AP. Here this effect may be relatively less important since many processes produce feedstocks that still have to be processed further in refineries. Indeed, the FhG study suggests that the different processes do not have very different scores for these aspects. Mechanical recycling, however, can score somewhat better under favourable conditions (minor effort for collection, etc.).

Waste and other resource use
For a good comparison of resource use other than energy, one needs rather good insight into the waste management systems, which falls outside the scope of this study. One aspect can be addressed here, a point that has a direct relation with waste production: the fate of chlorine in the process. In some processes (VEBA, BASF and Texaco) the chlorine becomes generally available as a product (HCl or NH_4Cl). The advantage is that this prevents the production of primary materials and that a waste salt is produced in the process that has to be landfilled. In its current form, the Polymer Cracking and probably also the SVZ process have the disadvantage that the chlorine comes available as a residue that has to be landfilled. In blast furnaces chlorine has no added value and will leave the furnace in the slag or as HCl emission. Classical MSWIs may let the chlorine end up in part in the flue gas cleaning residues, a topic that is discussed in detail in one of the studies on incineration commissioned by DG XI of the EC. In virtually all cases, any metals present in a PVC-formulation probably end up slag, fly-ash, or an other residual flow.

4.2.3 Conclusions

Overall, one could cautiously conclude that most chemical recycling processes may be somewhat more advantageous than incineration in an MSWI. Energy recovery is simply too low there. The LCAs we reviewed indicated that the processes that need the least pretreatment have advantages; in that context the Texaco process was found to be somewhat better than the VEBA process. Also, processes that recycle the chlorine content in PVC may have some advantages over those that do not. However, among the different chemical recycling technologies it is rather difficult to identify a clear ‘winner’. Most LCAs we reviewed could only reject clearly some energy-inefficient technologies, and the limitations of this analysis prevent further elaboration. As for cement kilns, there seems to be at first sight little reason why they should score worse than blast furnaces. Both technologies basically replace the same primary resource (coal) after a similar pretreatment of the plastics waste. Only if the quality of the coal that is replaced differs fundamentally are variations to be expected.

4.3 Technologies for PVC-rich waste

4.3.1 Introduction

As for the technologies for PVC-rich waste, an environmental comparison is even more difficult within the limitations of this study than for MPW. Apart from the BSL process, not any process is operational at full scale. Whereas for the treatment of MPW an extensive set of LCAs has been produced, for these technologies LCAs are entirely lacking. Therefore, the only thing that is possible is to give a very rough analysis on the basis of the data supplied by the developers of the technologies. This analysis concentrates on:

- The amount of energy recovery/efficiency of the feedstock use from PVC;
- The fate of the chlorine fraction;
- The fate of any metals present in a PVC formulation.

4.3.2 Discussion per theme

For the four technologies under consideration, all processes find a useful outlet for the chlorine fraction in PVC. The processes of BSL, Linde and Akzo Nobel produce HCl that can be used in e.g. oxychlorination or chlorine production, while the NKT process produces thaw salt. One could argue that HCl recovery leads to re-use in the original production cycle, whereas this is not the case with thaw salt. Concerning metals present in PVC, the NKT process has the advantage that they come available in a concentrated form as a metal chloride salt. For most other processes, we did not get the impression that such metals would come available in a form that allows a potential recovery.

Regarding energy/feedstock recovery efficiencies, the available data allow no clear conclusions. For BSL, much depends on the energy recovery system, since it concerns basically incineration. Much like the case with MPW incinerated in MSWIs, it may be the efficiency of processes that convert the feedstock to a useful material like syngas. However, data are lacking to make decisive conclusions.

As for the comparison with mechanical recycling, in general one sees in LCAs that this scores best (and better compared with energy recovery and feedstock processes) if it is possible to recycle without much effort being expended in cleaning, sorting, and upgrading the waste. Hence, it is likely that relatively straightforward mechanical recycling of rather ‘clean’ PVC waste (window frames, pipes, profiles) is better than chemical recycling. For waste that needs extensive sorting and pretreatment, this picture may be quite different.

4.3.3 Conclusion

For PVC-rich waste, due to data gaps it is not easily possible to indicate a clear environmental ‘winner’ among the chemical recycling technologies under consideration. One questionmark concerns the BSL process: is it possible to have an energy recovery that matches the efficiency of (feedstock) energy recovery in the other processes? The production of HCl may be valued higher than the production of thaw salt, which is the chlorine conversion product in NKT. Finally, for rather clean PVC waste it is likely that mechanical recycling will score better than chemical recycling.

4.4 Overall conclusion

Concerning the environmental performance of the different chemical recycling technologies, we made a comparative analysis based on existing LCAs for treatment of MPW and the data inventoried for chemical recycling plants for PVC and PVC-rich waste.

For PVC that is part of MPW, high-quality mechanical recycling cannot play a role since it has to become available in a rather pure form. If any mechanical recycling will take place it will be in the form of downcycling. The environmental benefits of downcycling usually are limited. MSWIs have a number of disadvantages, like a relatively low energy recovery compared with chemical recycling. Chemical recycling plants for MPW do not differ substantially in a mutual comparison. As for cement kiln incineration, it is unlikely that it will score substantially different to blast furnaces since in both cases coal (or oil) is replaced as a primary resource. It may be that chemical recycling plants which also recycle the chlorine (e.g. as HCl) have some advantages.

As for PVC-rich waste, it is likely that mechanical recycling scores better than chemical recycling provided it concerns high-quality recycling and the need for pretreatment is limited. On the basis of the available data, we could not identify clear ‘environmental winners’ or losers between the four technologies discussed.

5. Waste supply scenarios

5.1 Generic approach

5.1.1 Introduction

Waste supply scenarios have been developed for chemical recycling technologies. Two types of chemical recycling technologies have been examined, i.e. those dealing with mixed plastic waste (MPW) and PVC-rich waste; thus, the scenarios concentrate on the one hand on MPW in general and on the other on PVC in particular. When developing the scenarios, a breakdown was made into the waste types already defined in chapter 3:

- Agricultural waste;
- Building and construction waste;
- Household waste (divided into non-packaging and packaging);
- Distribution/large industry waste (divided into distribution waste, which is mainly packaging, and large industry waste);
- Automotive;
- Electrical and electronic waste (E&E).

For MPW, the most important groundwork for waste supply and management in the base year, 1995, was provided by the report series *Plastics waste management in Europe* (APME, 1997). For PVC, we relied mainly on data supplied by the EuPC (1999), the European representative organisation of plastics converters.

In the following two sections, we discuss how we developed a view of the current situation in generic terms and how we built up our scenarios for the future situation. Then sections describe the situation per waste category. Finally, we present conclusions that mainly aim to identify the market for chemical recycling technologies for MPW and for PVC-rich waste.

5.1.2 Situation in the base year

The APME report gives a breakdown of the MPW supply by category per EU member state. Furthermore, it gives the amount of mechanical recycling for agricultural, household, distribution and automotive waste, and the breakdown of energy recovery and incineration for household and distribution waste per EU member state. Making some minor assumptions, to be discussed below, we produced a full breakdown of plastics waste management per member state per category per treatment technology:

- Mechanical recycling;
- Energy recovery;
- Incineration;
- Landfill;
- Chemical recycling.

Regarding PVC waste, the EuPC data are based on the following approach. EuPC has established a database containing all new PVC uses by applications in the EU over the last decades. Using data about average life-times of these products, and their inherent variations, it is possible to calculate the theoretical amount of PVC waste per product group in a specific year. EuPC has produced a very detailed breakdown of the product waste groups. The waste groups are already divided into a number of main categories, which are almost the same as the 7 defined for plastics waste in general in the APME reports (see section 5.1.1). However, we did not need data in such detail as provided for all waste categories by EuPC. As will be explained in more detail in the following sections, the most important PVC wastes for which recycling schemes are set up, or which are likely to become available as separate fractions, are specific PVC wastes in the building sector. For the purpose of this study, we performed a minor regrouping of the EuPC data:

- Furniture was regrouped under household waste[21].
- Industrial hoses, office supply, other technical applications and chemical apparatus were re-grouped under a new heading ‘industry and commercial sources’. Health care waste was also added to this category.
- For E&E, automotive, household (non-packaging) and industry (non-packaging) and packaging, we just used aggregated data for these target groups.
- For building and construction waste we concentrated the 15 original categories into 7 groups: pipes, window profiles, other profiles (comprising cable ducts, other profiles, and building profiles and hoses), cables, flooring (comprising paste flooring and calendered flooring), roofing c.a. (roofing and inflatable structures), and others. From a recycling viewpoint, these are the main groups to be used[22].

There are several other points of interest concerning the EuPC data: 1) they are related to the formulated products, while APME uses data for pure resin, 2) no data for the base year 1995 were obtained and 3) no data for individual EU member states were obtained[23]. Using rough formulations given in a ECVM memorandum, we calculated back to pure resin[24]. This step was necessary in order to ensure that we could relate our PVC data on a common basis to the APME data. As for the lack of 1995 data, EuPC did provide estimates for 1998, which is

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[21] An alternative would have been building waste. However, we feel that household waste is probably more appropriate since furniture has, with exceptions, no direct relation with building.

[22] Only PVC bottles, which are also an important issue for mechanical recycling, are no longer visible as such in the group ‘households’. However, since the use of PVC bottles will decline rather fast in the near future, we assume this is probably acceptable.

[23] EuPC is still in the process of checking these detailed data with national member organisations.

[24] It is most likely this exercise produced some deviations. These formulations were provided in turn by EuPC. However, the formulations used by EuPC in the data provided to us were updated and improved. It is most likely that there are some minor deviations between the underlying pure PVC data in the data EuPC provided, and the data we calculated. However, for the purpose of this study (assessing the viability of recycling), such deviations do not pose a problem.

sufficient for our purposes [25]. As for the lack of EU member state data, we opted for a very pragmatic solution. By comparing the APME data for plastics in general and the EuPC data per waste category, a theoretical average PVC content in plastics waste per category could be calculated. We assumed this to be valid for all EU member states for the purpose of our calculations. As a general warning, we therefore stress that the *data on the level of individual member states and the detailed recalculated data on PVC-resin basis should not be used out of the context of this study*. We refer to Appendices A and B for detailed calculations.

5.1.3 Situation in 2000, 2005 and 2010

In order to assess the future situation, we chose as target years 2000, 2005 and 2010. Regarding plastics waste in general, in a conference paper of Mayne (1999), APME also indicated the forecasted growth of plastic waste supply for each of these sectors between 1995 and 2001 viz. 1995 and 2006[26]. Assuming that the annual growth rates given in this paper can be linearly extrapolated, we calculated the total and the future MPW supply per category in 2000, 2005, and 2010 (table 5.1).

Table 5.1: Calculation of MPW supply growth factors relative to 1995

	APME forecast in ktpa (Mayne, 1999)			**Calculated growth factor TNO**		
Waste type	1995	2001	2006	2000	2005	2010
Agriculture	293	316	331	1.065	1.118	1.177
Building	841	1162	1539	1.318	1.755	2.132
Household	10139	13311	15582	1.261	1.512	1.768
Industry	3083	4154	5162	1.289	1.613	1.920
Automotive	888	1176	1479	1.270	1.605	1.908
E and E	812	1110	1389	1.306	1.646	1.969

2000 growth factor: based on interpolation of APME 1995 and 2001 data

2005 and 2010 growth factor: based on inter/extrapolation of APME 1995 and 2006 data

We had to assume that this growth rate for each EU member state would be the same, since no country-specific growth rates are available. As for the waste management situation for MPW (i.e. the treatment technologies likely to be used), we analysed the following factors:

1. Targets for re-use and recycling for the waste stream under consideration given in EU and/or national legislation, likely to be in force in the year in

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[25] EuPC even provided data for 2015 and 2020, but in view of the maximum reliable extrapolation for other plastics to 2010 (see next section), we decided not to use these.

[26] This paper was based on a study of SOFRES and TNO, that predicted the future waste supply on the basis of parameters like the historical use of plastics in different applications and the life-time of each application (APME, 1998; Mayne, 1999). Since 1995 was the basis for these forecasts, we pragmatically chose 1995 as a basis in this study too. For Distribution plastic packaging waste, we assumed the same growth rate as for household packaging waste.

question. Particularly for packaging (household and distribution), automotive and E & E waste, recycling targets are or will be adopted in EU directives;
2. Realistically achievable percentages of mechanical recycling per waste stream. Here also the conference paper of Mayne (1999) gives some indications; we further based ourselves on other literature;
3. Targets for (energy recovery) for the waste stream in question;
4. Foreseeable bans on the landfill of organic waste in EU member states.

Chemical recycling has a rather protected market for that amount of waste, for which legal recycling targets exist. The only competition is from mechanical recycling. Landfill bans or recovery obligations are unlikely to enlarge the waste supply for chemical recycling. Such incentives still allow incineration with energy recovery and/or incineration in MSWIs, and as shown in chapter 3, chemical recycling cannot compete economically with these options[27]. However, one has to remember that the current recycling targets for plastics are low due to the lack of experience, and may well be tightened in the future. Hence, in order to calculate the waste for chemical recycling, we applied two scenarios:

a) A base scenario (a) for 2000, 2005 and 2010. On the basis of EU legislation (and national legislation) in force or in preparation, a legal recycling target was taken in these base years. The percentage that can be recycled by mechanical means was subtracted, yielding the waste supply for chemical recycling.
b) A high scenario (b) for 2010. For this high scenario, we assumed that recycling targets would be tightened up to the levels of competitive materials. We assumed that this was unlikely to happen before 2005, but in the longer term this may be realistic.

Regarding PVC specifically, EuPC made forecasts for 2000, 2005, and 2010 using the approach described earlier. This allowed us to calculate the percentage of PVC in plastics waste by waste category. For all categories except building waste, one can assume that, with only minor exceptions, the PVC will become available as a part of a MPW fraction. If PVC from these categories is chemically recycled, it will be together with other plastics and hence through a ‘PVC-lean’ chemical recycling technology. We could thus simply use the amount of MPW calculated as being treated by chemical recycling, multiplied by the PVC content, as the estimated amount of PVC treated by chemical recycling for low-PVC waste flows[28].

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[27] Only blast furnaces may be an exception here.

[28] Obviously, dedicated collection systems can give rise to higher amounts of PVC to be recycled. However, this has to be either mechanical, which falls outside the scope of this report, or chemical recycling of PVC-rich waste.

For a number of specific PVC waste flows, particularly from building and construction waste, the situation is different. First, several waste types which in principle will arise will not be available for treatment. The best examples are old sewage pipes, which often are just left in the ground at the end of their useful life. Second, for many important waste flows like pipes, profiles and window frames, mechanical recycling is probably a very important means to recycle waste. For specific waste flows with complicated formulations (e.g. flooring), chemical recycling may play a more important role. Hence, due to this complexity, PVC building waste will be discussed in more detail.

Most data are reviewed in detail in appendices A and B. Here, we give three aggregated tables with the expected total amount of plastic waste, PVC waste (pure resin and compound), and the percentage of PVC in the total amount of plastics waste (tables 5.2 to 5.4). It has to be noted that there are some striking points in these tables, which indicate that the databases for plastics waste which we used still leave room for improvement. For instance, one would expect that the PVC content in building waste would rise rather than diminish. Most PVC applications in the building sector are long-life applications, and thus the waste from past use will rise in future since only then is the end-of-life of the product reached. It is entirely possible that EuPC used lower growth rates for PVC than APME for MPW (Mayne, 1999). Furthermore, our calculated PVC fraction in E&E plastics is in line with the 22% mentioned in (HCL, 1998) for Germany, but deviates considerably from the 7% mentioned in a SOFRES report cited in (HCL, 1997b). The same source also suggests a lower PVC content in automotive plastics than calculated here.

5.1.4 General assumptions valid for each waste stream

Below, we will discuss the situation for each waste category. As for the future situation, wherever relevant, country-specific recycling and recovery targets will be included. Regarding landfill and incineration, the EU member states which currently have landfill bans for plastics waste or will have them in the near future are listed in table 5.5. It must be noted that in general these landfill bans are not for organic waste as such, but for non-inorganic waste that has not undergone pretreatment. In practice, one must expect that certain residues from pretreatment, which contain plastics, still may be landfilled. Another situation exists in Wallonia (Belgium): here a separated fraction or End-of-Life Vehicles (ELVs) as such cannot be landfilled, but integral waste or the shredder light fraction from ELV shredding, including the plastics, can be landfilled. As for the diversion of plastics waste from MSWIs, only Denmark pursues an active policy: a voluntary agreement has been adopted to divert PVC from incinerators.

Table 5.2: Overview of plastic waste supply by category (in kton pure resin)

Year **Waste type**	**1995** (a)	**2000**	**2005**	**2010**
Agriculture	286	305	320	337
Building	817	1077	1433	1742
Househ. Other	3390	4274	5127	5995
Packaging (Househ+ Distr.).	8777	11065	13273	15521
Industry	658	848	1061	1263
Automotive	856	1087	1374	1633
E and E	793	1036	1305	1561
Total EU	15577	19692	23893	28051

(a) There are minor deviations between these 1995 data and those in table 5.1. The APME forecasts in table 5.1 were only disclosed for Europe as a whole, while we concentrated in this study on the EU member states only. Furthermore, the APME forecast is based on a study of SOFRES/TNO, that used slightly different data from those in the APME (1997) overviews of plastics waste management in Europe (also produced by SOFRES) which we used here. Table 5.1 reviews the only available growth data made public by APME. We assumed that applying these growth rates to the other APME data would not result in major mistakes (APME, 1997)

Table 5.3: Overview of PVC waste supply by category (in kton pure resin)

Year **Waste type**	**1998**	**2000**	**2005**	**2010**
Agriculture	28	29	28	25
Building				
# pipes	32	39	60	87
# window profiles	25	31	52	84
# other profiles	165	191	260	333
# cables	9	11	15	20
# flooring	174	186	211	243
# roofing	8	8	9	10
# other	81	82	86	94
Housh. Other	532	582	673	789
Packaging (househ., distr.)				
# bottles	302	236	128	70
# other PVC-packaging	390	408	457	519
Industry	89	98	115	141
Automotive	180	195	208	216
E and E	136	150	178	209
Total EU (pure resin)	**2151**	**2245**	**2481**	**2841**
Total EU (formulated compound)	3508	3707	4118	4608

Table 5.4: Percentage PVC in plastics waste, pure resin

Year **Waste type**	**2000**	**2005**	**2010**
Agriculture	10%	9%	8%
Building	40%	33%	30%
Housh. Other	16%	14%	13%
Packaging (househ., distr.)*	4%	4%	3%
Industry	14%	12%	11%
Automotive	23%	19%	16%
E and E	17%	14%	14%
Total EU	11%	10%	10%

* Packaging excluding bottles; including bottles it would be 8% in 2000 and 4 % in 2010

Table 5.5: Landfill bans in force or planned for plastics waste.

Country	**Waste subject to ban**	**In force by**
Austria	Organic material	1 January 2004
Belgium	Separated collected waste ELVs	
Germany	Waste with over 5% organic material	2005
France	Untreated waste	2002
Netherlands	Listed wastes, includes organics	Now
Sweden	Organic material	2005

- Italy: under discussion
- Finland: ban on landfill of biodegradable waste only

5.2 Agricultural waste

5.2.1 Current situation

APME (1997) gives a breakdown of the amount of agricultural MPW and of mechanical recycling rates per country[29]. Furthermore, APME (1997) indicates that energy recovery of agricultural waste also takes place but gives no country specification. On the basis of the APME report, we knew the amount of energy recovery per country for household and distribution waste. APME also gave the total energy recovery per country. This left a minor, unspecified amount of energy recovery per country for agriculture (total EU plus Norway and Switzerland 8 ktpa), automotive (123 ktpa) and E&E (105 ktpa). We assumed that for each country the residual available MPW treated by energy recovery could be allocated proportionally to agricultural, automotive and E&E waste. By subtracting

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[29] According to APME, some countries export plastics for mechanical recycling, and others import them. We included the exports *from* a country in the recycling percentage of plastics waste for a specific country. After all, recycling took place on waste originating in that country.

mechanical recycling and energy recovery from the total amount per country, the amount landfilled was calculated.

5.2.2 Future situation

For the future situation, we assumed a slight increase of the current average mechanical recycling rate (27%) to some 35% in 2005 and 2010. Though higher rates are achieved in EU member states, there is no legal incentive in any of them to do so. Some countries have covenants and voluntary schemes specifically to deal with films (mainly PE). Examples are Ireland and the Netherlands. However, we feel it is unlikely that these wastes will be treated by chemical recycling, at least not with the more expensive dedicated chemical recycling plants. If applied, mechanical recycling will most likely be the more cost-effective option.

5.2.3 Availability of waste for non-mechanical recycling

We have assumed that the availability of agricultural plastic waste for non-mechanical recycling, or chemical recycling in particular, will be close to zero. There is simply no incentive to steer the waste flows in that direction.

5.3 Building waste

5.3.1 Current situation

For building waste, APME (1997) gives no breakdown of mechanical recycling. However, APME (1997: 55) gives the total mechanical recycling rates per country, and also recycling rates in all other categories with the exception of E&E. We inferred the recycling rates for E&E per country, which led by subtraction to the mechanical recycling rates for plastic building waste. According to APME, energy recovery and incineration of plastic building waste was zero in 1995. The amount of landfill can be calculated by subtracting the recycled building waste from the total amount of plastic building waste.

5.3.2 Future situation

General

In the future, there may be an EU recommendation in the field of building waste management. However, it is unlikely to provide enforceable recycling targets such as in the case of the (future) directives on Packaging waste, E&E waste, and automotive waste. Thus, formally at the EU level no recycling targets are expected.

Regarding national recycling targets, they are listed in table 5.6, both for MSW and PVC in particular. It has to be recognised that many EU countries have recycling targets with regard to building and construction waste. However, plastics are only a tiny fraction of this waste stream, and targets specific for plastics have in general rarely been set. Furthermore, it has to be acknowledged that PVC dominates other plastic waste. Hence, where collection and recycling schemes are set up for plastics from the building sector, many PVC fractions become available in a rather pure form. It will then be decided whether mechanical or chemical recycling (as PVC-rich waste) should be done. This latter option will be discussed below.

Table 5.6: Country-specific recycling targets

Country	**PVC**	**Remark**	**Reference**
Denmark	41% recycling, 1995	Voluntary agreement	HCL, Dec. 1997
Germany	Several voluntary schemes		Inquiry
Netherlands	Many recycling schemes available	Covenants	

PVC

For the future situation, Mayne (1999) indicated that a mechanical recycling rate of 6% for plastics waste would probably be the achievable maximum. It is likely that this will be mainly PVC. As indicated in table 5.4, the amount of PVC in building plastics waste excluding pipes, windows, cables, and flooring (which are likely to be collected separately) is some 20%. This plastic fraction may arise, together with wood residues, etc., after/during crushing or treatment of the stony fraction. Due to a lack of legal or economic incentives in virtually all EU member states, it is unlikely that this fraction will be made available for chemical recycling. At best, landfill bans in several EU member states will steer this waste to energy recovery as the next most cost-effective option.

As for the major PVC flows, several recycling schemes, mainly based on mechanical recycling, have been and will be set up, particularly in the northern EU countries (notably Scandinavia, Germany, Austria and the Netherlands). These schemes mainly rely on covenants between the authorities and the PVC-industry, or voluntary incentives of the PVC industry[30]. Since it concerns high PVC content applications, these waste flows are unlikely to become available for generic chemical recycling plants, built for generic plastics waste. Hence, we give here a specific analysis for the most important PVC building waste streams. The analysis is reviewed in tables 5.7 and 5.8.

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[30] Examples include the Dutch recycling schemes for pipes (WAVIN), flooring (Forbo), and window frames (backed by a Ministerial Decree), and German schemes for windows, roofing and floorings (Stuurgroep PVC, 1999; AgPU, 1999).

Table 5.7: The potential for chemical recycling of building waste (after Prognos, 1999)

Waste type	Availability	Mech. Rec. rate	Total mechanical recycling	Available for chemical recycling
# pipes	29%	65%	19%	10%
# window profiles	100%	55%	55%	45%
# other profiles	100%	40%	40%	60%
# cables	30%	80%	24%	6%
# flooring (a)	100%	8%	8%	92%
# roofing (b)	100%	55%	55%	45%

a) Prognos (1999) assumed that only calendered flooring could be recycled mechanically. This is about 30-35% of the flooring market. With an estimated 25% mechanical recycling for calendered flooring, this implies some 8% mechanical recycling of all flooring.

b) Prognos (1999) gave no value for roofing, where roofing recycling schemes are in existence or being set up, e.g. in the Netherlands. We used here an average value for PVC from building waste, still much lower than that estimated by ECVM (1999)

Table 5.8: The potential for chemical recycling of building waste in kton in 2000-2010

Waste type	Total PVC-waste (pure resin)			Theoretically available for chemical recycling (% table 5.7)		
	2000	2005	2010	2000	2005	2010
# pipes	39	60	87	4	6	9
# window profiles	31	52	84	14	23	38
# other profiles	191	260	333	115	156	200
# cables	11	15	20	1	1	1
# flooring	186	211	243	171	193	223
# roofing	8	9	10	4	4	5
Total	466	607	777	307	384	475

The first factor that decides the availability for chemical recycling is the *waste availability*. For instance, many of the PVC pipes and cables are likely not to be excavated after their useful life. The availability estimates have been taken over from EuPC (see Appendix B). For all other PVC-flows, it has been assumed that the availability is in principle 100 %, being the maximum amount that can be collected. The second factor is the potential for *mechanical recycling*. This is determined by two elements: the amount of relatively ‘clean’ PVC waste that can be obtained, and the market for this PVC. We used the recycling efficiencies calculated by Prognos (1999).

In theory, the remainder is then available for chemical recycling. According to table 5.8, this comes down to values of some 300 to 475 ktpa pure resin (roughly 500 to 750 kpta compound).

5.3.3 Availability of waste for non-mechanical recycling

The building sector is the most important source of PVC waste. If recycling takes place, it will be mainly mechanical recycling. Chemical recycling – in this case with techniques for PVC-rich waste – may play a role for waste flows that cannot be mechanically recycled. In theory, the available amount rises from some 300 ktpa in 2000 to 475 ktpa in 2010 (pure resin). It has to be noted, however, that this calculation is largely theoretical. The current recycling targets are virtually all based on voluntary agreements. Such agreements exist for sometimes only a selection of the waste streams mentioned, in only a limited number of EU member states (most notably Germany, Austria, the Netherlands, and the Scandinavian countries). Furthermore, landfill is in most EU member states still available as a cost-effective competitor[31]. Though good estimates are hard to make, we feel that the under the current agreements and incentive structures an EU-wide separate collection rate of some 25-30 % of PVC for (chemical) recycling may be achieved at best. This implies a chemical recycling of some 100 ktpa (pure resin) by 2010, corresponding roughly with 160 ktpa compound. This forecast can only change fundamentally if either industry or governments set hard, EU-wide targets for PVC recycling.

5.4 Household waste (non packaging)

5.4.1 Current situation

As for household waste (non-packaging), APME (1997) gives the amount of mechanical recycling, energy recovery and incineration. The amount for landfill is once again calculated from the totals. According to APME, mechanical recycling is not considered for non-packaging household waste.

5.4.2 Future situation

Regarding non-packaging plastics in household waste, there is no legal incentive for recycling at the EU level. As for the current situation, we have assumed that mechanical recycling will be minimal. At best, landfill bans in some EU member states will steer these waste flows to MSWIs as the most cost-effective option left.

5.4.3 Availability of waste for non-mechanical recycling

Though the amounts of non-packaging household MPW are substantial, the lack of a legal recycling incentive will inevitably lead to the situation that the waste is treated in the most cost-effective way allowed. Separated collection, cleaning and subsequent treatment by chemical recycling is simply too expensive, and will only

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[31] Even the obligation in the future EU Landfill Directive, that waste should be treated before being landfilled, will probably not change this situation. If there is a lack of incentive, plastics will probably be collected as a part of generic building waste. This most probably will be treated via crushers, leading to a re-usable stony fraction and a residual fraction that includes the plastics. This fraction can be considered as treated, and thus may be landfilled.

play a role in exceptional situations. In sum, we assume that for this waste stream chemical recycling plays no role.

5.5 Packaging waste (household and distribution)

5.5.1 Current situation

Since in most countries the packaging legislation deals with both household waste packaging and distribution packaging, we treat these two categories under one header.

Regarding packaging household waste, APME (1997) gives the amount of mechanical recycling, energy recovery and incineration. The amount for landfill is once again calculated from the totals. According to the APME report, mechanical recycling only plays a role for packaging. In general, mechanical recycling is low for household waste (3-5% at most) with the exception of Germany. This has to do with the DSD system and stringent targets in the German VerpackungsVerordnung in place there, resulting in a very high recycling rate. The amount of landfill is once again calculated by subtraction.

Distribution packaging waste has already achieved rather high mechanical recycling rates, some 28% in 1995 (APME, 1997). Incineration and energy recovery rates have also been taken over from APME (1997). The amount of landfill can be calculated by subtraction.

Totals are calculated in Appendix A. Appendix A makes it clear that the average mechanical recycling rate is some 13% for this combined category. This category is also the only one for which chemical recycling plays a role: some 99 ktpa in 1995, in Germany only. Since then, chemical recycling has expanded rapidly in Germany. In 1998 the amount of chemical recycling grew to 361,000 ton, of which 162,500 ton ended in blast furnaces, 110,000 ton at SVZ, and 87,000 ton at VEBA (DSD, 1999) [32]. With an average of some 3% PVC in these wastes, this implies chemical recycling of about 10,800 ton PVC in 1998 as a part of plastics packaging waste.

5.5.2 Future situation

For packaging household waste, we developed two scenarios for the future situation.

Scenario a)

In scenario a) we applied for 2005 and 2010 the recycling target of 15% that is included for individual plastics in the EU Packaging Directive (EU, 1994; 1997).

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[32] Minor amounts were treated by PARAK, which concentrates on a dedicated process for foil recovery and for which it is still unclear whether it should be listed as material rather than chemical recycling (DSD, 1999).

However, we applied national targets if they were more ambitious. For 2000, the EU Packaging Directive does not yet need to be implemented, and here we only used the targets in national legislation. Table 5.9 reviews these national targets.

A part of this recycling target will probably be met by mechanical recycling. As for household waste plastic packaging, mechanical recycling appears to be rather difficult to realise. For distribution packaging, the situation is clearly better. As a minimum, we assumed that a mechanical recycling rate of some 12% would be achieved, being the current rate in the pioneering countries with packaging recycling legislation. If countries have already reached higher mechanical recycling rates, we assumed that they would achieve these in future as well. As for Germany, there is a legal target for mechanical recycling that we used as a basis. It concerns 60% overall recycling, of which 60% is mechanical recycling, leading to an assumption of 36% mechanical recycling for Germany.

By subtracting the achievable mechanical recycling rate from the legal recycling targets, the percentage available for chemical recycling was calculated. Figures below zero (i.e. the legal target can be covered fully by mechanical recycling) were set at zero (implying no market for chemical recycling).

Table 5.9: Country-specific recycling targets if they deviate from the EU directive

Country	**Packaging waste in general**	**Plastics**	**Remark**	**Reference**
Austria	80% in 1999		Collection target	Inquiry
Belgium	50% recycling 80% recovery	15%	Targets by 1999	Inquiry
Germany		60% recycling by 1999	Of which 60% mechanical recycling	VerpackV. (1998)
Greece		15% by 2005		
Ireland		15% by 2005		
Netherlands		27% recycling	8% additional effort on gray waste	(HCL, Nov. 1996)
Portugal		15% by 2005		
Spain		15% recycling in 2000 20% recycling in 2001		
Sweden	30% in 2001			

Scenario b)

Scenario b) assumes that the recycling rates for individual packaging materials will be harmonised by 2010. The EU Packaging Directive demands 25-45% recycling for packaging waste in general. We assumed that by 2010 a target of 45% has to be reached for plastics, about half of which (22.5 %) will be mechanical recycling. This reflects the German situation, where over half the plastics packaging for recycling is mechanically recycled. Only for Germany did we apply the currently already higher legal recycling target of 60% and mechanical recycling rate of 36%.

5.5.3 Availability of waste for non-mechanical recycling

Full calculations can be found in Appendix A. The forecast for the amount of MPW for chemical recycling is about 1 Million ton in scenario a) and 3.5 Million ton in scenario b). It has to be stressed that the incentives necessary to make scenario b) reality are not yet in place, and also not yet foreseen in forthcoming legislation. Even scenario a) may be too optimistic. The calculations for Germany are probably biased since the German targets concentrate on consumer packaging waste rather than consumer and distribution waste combined, and only consumer packaging is sent for chemical recycling. Since distribution packaging makes up about 33% of the total amount of packaging there (see Appendix A1.3), the potential calculated for Germany in Appendix A3.2, A4.2, A5.2 and A6.2 may need to be corrected downwards by one-third. Furthermore, if mechanical recycling is more successful than the 12 % assumed in scenario a), the waste supply may for chemical recycling may drop an other few hundred kiloton.

Hence, once again, we must conclude that the position of chemical recycling is almost fully determined by how stringent the targets are that countries have set. Furthermore, if one could accept the arguments often heard that high-yield energy recovery is just as environmentally acceptable, the situation would change dramatically. With some 3 % PVC in plastics packaging waste, chemical recycling of 1 to 3.5 Million tons of MPW implies some 30 ktpa to 100 ktpa PVC treated by this route. It has to be noted that the low scenario is already somewhat optimistic, but on the other hand, part of this capacity may be realised with plants that can tolerate somewhat higher PVC percentages than 3 %. Against this background, we feel that under the current incentive structure chemical recycling of 50 ktpa pure PVC (or some 80 ktpa compound) as a part of plastic packaging waste by 2010 is probably a realistic expectation[33].

5.6 Industry

5.6.1 Current situation

The recycling rates for industry MPW were assumed to be zero by APME (1997) in 1995. Incineration and energy recovery rates have also been taken from APME (1997). The amount of landfill can be calculated by subtraction.

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[33] Obviously, if the rather cost-effective blast furnaces will dominate the structure for chemical recycling in the future, only some 30 ktpa pure resin can be treated in view of their low PVC tolerance. If, on the other hand, the structure for chemical recycling will be dominated by the technology of Texaco, that has a PVC tolerance of 10 %, much higher values are possible: up tp 100 ktpa pure PVC in scenario a) and 350 ktpa in scenario b)

5.6.2 Future situation

Regarding plastics in industrial waste, there is no legal incentive for recycling at the EU level. Nor have we found substantial recycling targets on the national level that will have a considerable impact on the EU level. Just like the current situation, we have assumed that mechanical recycling will be minimal. This is probably inaccurate, but this assumption has no direct impact on the amount available for chemical reycling: it is simply unlikely that a rather expensive technique like chemical recycling will be used voluntarily. At best, landfill bans in some EU member states will steer these waste flows to MSWIs as the most cost-effective option left.

5.6.3 Availability of waste for non-mechanical recycling

The lack of a legal recycling incentive will inevitably lead to the situation that industrial plastic waste is treated in the most cost-effective way allowed. Separated collection, cleaning and subsequent treatment by chemical recycling is simply too expensive, and will only play a role in exceptional situations. In sum, we assume that for this waste stream chemical recycling plays no role.

5.7 Automotive

5.7.1 Current situation

APME (1997: 67) gives mechanical recycling rates for automotive waste per EU member state. However, some 4 ktpa is not allocated to a specific country, and exports for recycling (some 9 ktpa) are not allocated either. We assumed that 1 ktpa would have to be allocated to the non-EU countries Norway and Switzerland[34], leaving 12 ktpa to be divided over the EU member states. We calculated which EU member states still had room for mechanical recycling ‘left’[35], and arbitrarily allocated 2 ktons to Germany, Italy and France, and 1 ktpa to the others. Regarding how we dealt with incineration, we refer to the approach described under agricultural waste.

5.7.2 Future situation

For the future situation, we developed two scenarios.

Scenario a)

From 2005 there will be most likely an EU Directive on Automotive Waste in place, calling for 80% recycling and 85% recycling and recovery of the materials from end-of-life vehicles (ELV; HCL, 1997b). Since, however, already some 75%

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[34] Under this assumption the amount of mechanical recycling of automotive waste allocated to EU member states would fit the known total amount of mechanical recycling in EU member states for all waste streams.

[35] APME (1997) gives the total mechanical recycling rates per EU member state for household waste, distribution and agricultural waste also.

of ELVs consists of steel that is rather easily recyclable, only 5 out of the remaining 25% (20% relative) has to be recycled[36]. Only 7% of an ELV is plastic waste. It may thus well be that the overall recycling target will be met by recycling of other materials and not plastic. However, we assumed that plastics have to contribute proportionally to bridge this gap, implying a 'legal' recycling target of some 20%[37]. As indicated in table 5.10, Austria, Germany, the Netherlands and Sweden have recycling targets of some 85%. This implies that from the 25% remaining non-metal material some 10% (40% relative) has to be recycled. For these countries, we assumed a 'legal' recycling target of 40% for the plastic fraction.

Part of these recycling targets may be realised by mechanical recycling. Mayne (1999) estimated on the basis of a specific, confidential study that about 10% mechanical recycling would be the maximum achievable. By subtracting this 10% from the legal recycling target, the theoretical fraction of plastics available for chemical recycling was calculated.

Table 5.10: Country-specific recycling targets

Country	**ELV in general**	**Remark**	**Reference**
Austria	85% recycling by 2002 95% recovery		(HCL, March 1997); Inquiry
France	90% recovery by 2002	For new models	(HCL, March 1997)
Germany	85% by 2002 95% by 2015	Target for recycling	(HCL, Nov. 1996) (Martens, 1998)
Netherlands	86% by 2000	Target for recycling	(HCL, Nov. 1996)
Spain	90% recovery by 2002	For new models	(HCL, March 1997)
Sweden	85% recycling by 2002 95% recycling by 2015		Inquiry
UK	40% ASR reduction by 2002 80% ASR reduction by 2015	Corresponds with about 90 and 95% recovery	(HCL, March 1997)

Scenario b)

In scenario b), we have assumed that all legal recycling rates will be the same for all automotive materials by 2010. This implies that the general recycling target of 80% for automotive waste in the draft EU Directive is now applied specifically to plastics. We assumed that EU member states would not set higher targets for plastics. All other assumptions are similar to scenario a).

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[36] Furthermore, some 10 of the remaining 25% has to be recovered (40% relative).

[37] For 2015, higher recycling rates are foreseen, but this falls beyond the time horizon of this study.

5.7.3 Availability of waste for non-mechanical recycling

Appendix A calculates the amount of plastics waste that could potentially be available for chemical recycling.

For 2010, the theoretical amount of plastics waste for non-mechanical recycling may be about 250 kton in scenario a) or some 1 Million tonnes in scenario b). It has to be noted, however, that this value is only true *if* for plastics the average recycling rate for automotive waste in general will be applicable. If the recycling target for automotive waste can be achieved by recycling non-plastics materials, the supply of plastics for chemical recycling may also be zero. Furthermore, it can be expected that through planned recycling in the future, much higher amounts of mechanical recycling may be feasible.

As indicated in section 3.4, chemical recycling plants for PVC-rich waste are probably no cost-effective option for waste that has no high PVC-content. The MPW fraction of automotive waste can be characterised as such. These technologies are only an option for presorted PVC waste.

Regarding the feasibility of chemical recycling with technologies for MPW, the following observation can be made. The calculated PVC content in automotive plastics waste has been between 16 and 23% in all target years (see table 5.3). Though a large part of this is car underbody protection, which may not end up in the MPW fraction of ELVs, it is clear that such values may be problematic. The values are above the acceptance limits of all technologies for MPW we analysed[38]. For the most cost-effective option, use in blast furnaces, it seems out of the question that the maximum of 2-3% PVC input can be met without PVC separation. We feel that only after dedicated research into the feasibility of chlorine removal by pre sorting of the MPW fraction or process-internal measures, and/or the influence of such high chlorine quantities on the feedstock quality produced, can conclusions about the feasibility of chemical recycling of MPW from ELVs be drawn[39].

In sum, the analysis of the best way to deal with PVC from automotive waste, and the role of chemical recycling in it, requires a detailed analysis of the possibilities for selective dismantling and presorting of PVC parts. As stated in section 3.6, such an analysis falls well beyond the scope of this project.

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[38] Only SVZ claimed that they did successful tests with the shredder light fraction of shredded ELVs. This seems only to be feasible if more than ELV plastics alone are introduced, leading to a lower average PVC content, and utilising their maximum tolerance to chlorine (6%).

[39] The situation may not be that critical if our calculated PVC amounts are wrong. For instance, a table included in HCL (1997b) suggests a PVC content of some 8%. However, such values can only be true if either the EuPC- or otherwise the APME data we used need major revisions.

5.8 Electrical and electronic waste

5.8.1 Current situation

APME (1997) gives only a total mechanical recycling rate for the EU, and not per member state. We allocated the total amount of 18 kton arbitrarily to those countries who still had ‘room in their recycling budget’. We assumed that France and Finland would not recycle MPW from building waste and thus that their remaining recycling budget had to be covered by E&E waste. We further arbitrarily chose Italy, the UK and Germany as the countries where this recycling would take place, and averaged over this some 3% of the total waste, which is somewhat above the EU average (which was available in APME). As for incineration with energy recovery, we refer again to agricultural waste for the calculation method. Landfill was once more calculated by subtraction.

5.8.2 Future situation

Regarding the future situation, we followed an assumption of Mayne (1999) based on confidential studies that for E&E waste mechanical recycling would be limited to a maximum of 3% in 2005 onwards. Concerning the legal recycling rates, the EU is preparing a directive on E&E waste (EU, 1998). This directive is still a draft, and the targets still have to be set. It defines 11 classes of E&E products. For three of them the *collection* rate should be 80/90% and for the other classes, 40/60%. For the collected fraction, the *recycling rate* for five classes should be 70/90% and for the others, 40/60%. Using average values, the combined collection/recycling rates are at best thus 85% (collection) 80% (recycling), or 68% overall recycling. In the worst case, the combined collection/recycling rate is just 50%, 50% or 25%, respectively. Taking this into account, the directive thus seems to be heading towards a situation in which some 45% of the total E&E waste flow will be recycled. Plastics make up only 15% of the total amount of E&E waste (APME, 1997). It is entirely possible that the average recycling target of 45% will be reached by recycling the non-plastic materials. In the best case (seen from the point of view of chemical recycling) a 45% recycling target will be met for plastics also, and we calculated with this value. This, however, seems rather optimistic given the fact that for packaging plastic since it already appears difficult to meet the target of 15% in the EU directive, and the plastic fraction in E&E waste is probably equally difficult to recycle[40].

Many countries have national take-back schemes. Some of them are listed in table 5.11. It has to be noted that some national schemes ask for take-back, but are less

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[40] Note that we assumed that PVC would have to meet the same recycling target as all other materials. Hence, unlike for packaging and automotive waste, no second scenario was developed for 2010.

specific about recycling or recovery targets for plastics in particular. Hence, there is no need to include country-specific recycling rates for E&E plastics.

Table 5.11: Country-specific recycling targets

Country	E&E waste	Remark	Reference
Finland	85% recovery	Target not binding	Inquiry
Germany	Under negotiation	Certain part of E&E waste	
Italy	-	Take-back scheme available	Inquiry
Netherlands		Take-back scheme	Inquiry

5.8.3 Availability of waste for non-mechanical recycling

Appendix A contains calculations for the amount of plastics waste that could potentially be available for chemical recycling. It is the ‘legal’ recycling target of 45% based on the EU directive for E&E waste, minus a few percent achievable by mechanical recycling.

For 2005 and 2010, this amount in theory may be up to some 500 kton in 2005 and 600 kton in 2010. It has to be noted, however, that this value is only valid *if* for plastics the average recycling rate for E&E in general will be applicable. If 45% recycling of E&E waste can be reached by recycling the non-plastics materials alone, the supply of plastics for chemical recycling may also be zero.

As for the feasibility of treatment with technologies for PVC-rich waste, the same situation probably exists as for automotive waste. The PVC content is probably not high enough to allow for cost-effective treatment with chemical recycling plants for PVC-rich waste.

Regarding the feasibility of chemical recycling with technologies for MPW, the following observation can be made. The calculated PVC content in E&E plastics waste is between 14 and 17% on A pure resin basis in all target years (see table 5.4). There may be some uncertainty about this value, but it fits rather well with an estimate for German E&E waste of 22% if one assumes this value includes additives (HCL, 1998). For the two operational chemical recycling plants, this amount cannot be tolerated by Bremen Stahlwerke and only temporarily by SVZ (if mixed with other, PVC-lean waste). At the same time, there have been positive tests at VEBA and SVZ with E&E plastics waste (before the former shut down). At least for the VEBA test, it is known that a mixture of 1 part E&E-plastics waste and 5 parts DSD-plastics waste with a low PVC content was used, implying that any PVC in the E&E fraction was diluted considerably (HCL, 1996). Some of the technologies currently on hold, e.g. the Texaco process with its acceptance limit of 10%, can probably deal with this waste under the condition that it is diluted with PVC-lean waste. Another option is to separate the PVC in advance.

In sum, there is a potential amount of E&E plastic waste for chemical recycling available. However, the legal provisions are currently not designed to ensure a supply. Furthermore, the PVC content is above the current limits of chemical recycling plants[41]. Therefore, investment in dedicated chemical recycling plants for this waste stream is rather uncertain. If the average recycling target can be met by recycling non-plastic materials, it may well be that E&E plastic waste will be treated with cost-effective thermal energy recovery[42].

5.9 Conclusions

This scenario analysis has shown the (economic) potential for chemical recycling of both plastics waste in general and PVC waste in particular. As a basis we used the assumption that a relatively expensive technology like chemical recycling can only compete with e.g. landfill or MSWIs if there is a legal incentive to treat the waste with such a technology. Furthermore, we assumed that a certain amount of plastics waste would be mechanically recycled.

There are, in principle, three categories for which such an incentive structure is or will be put in place: automotive, E&E, and packaging waste.

Concerning particularly automotive and to a lesser extent E&E plastic waste, the PVC content is 16-23% or 14-17%. This is much lower than the levels for which the recycling plants for PVC-rich waste were constructed. However, such PVC levels are too high in relation to the PVC tolerance for most chemical treatment plants for MPW. For blast furnaces PVC contents of over 2-3% are out of the question. Several other techniques can tolerate up to 10% PVC or somewhat more, like Texaco. However, for most other technologies in the current situation such levels can only be tolerated for relatively short periods or when the waste is very diluted with MPW with a low PVC content. At this juncture we are reluctant to conclude that chemical recycling of such mixed plastics waste is a proven option. Research into the possibilities of in-plant chlorine removal and/or the effects of high chlorine contents on the feedstocks produced should be performed first. At best, it will be possible to mix this waste with MPW with lower PVC contents to make full use of the PVC tolerance of the least critical processes. Another option is to remove PVC by presorting first, so that it becomes available for chemical recycling of PVC-rich waste. However, the analysis of such sorting and collection schemes forms a project in itself.

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[41] Just like for automotive waste, a detailed analysis of the possibilities for selective dismantling and presorting of PVC parts may contribute to an assessment of the best way to deal with PVC from E &E waste, and the role of chemical recycling in it. As stated in section 3.6, such an analysis falls well beyond the scope of this project.

[42] Some of these technologies, like cement kilns, have restrictions with regard to the maximum chlorine contents of their waste input.

For packaging waste, it appears that the supply of waste depends entirely on the outcome of the debate about recycling or recovery targets. In most countries, the targets of 15% per material in the EU Packaging Directive probably can largely be met by mechanical recycling, leaving only a minor need for chemical recycling. Only in Germany is the situation fundamentally different, in view of the very stringent recycling targets set under the DSD system. Here chemical recycling appears to be a necessity in the current situation, albeit the method of choice has become limited to SVZ and Bremen Steelworks (not a purpose-built plant). There are ongoing debates about the ecological advantages of chemical recycling over, for instance, use as a fuel in e.g. cement kilns. As we indicated in the previous chapter, there is indeed little reason to assume that this type of treatment is less environmental friendly than blast furnaces. It is obvious that as long as this debate goes on, no one will invest the large sums of money needed for a dedicated chemical recycling plant. As has already been aired earlier in interviews with representatives from the plastics industry: the problem with chemical recycling is not the technology, but the certainty about markets and funding (Cemicalweek, 1996). And we would like to add: the certainty about ecological benefits.

The EU packaging directive may lead to a need for chemical recycling of MPW of some 1 Million tpa in 2010. If the recycling targets are tightened to the high levels achieved by other materials (assumption: 45%), this supply may be 3.5 Million tpa in 2010 (assuming mechanical recycling is limited to 22.5%). It may be entirely possible that steelworks will be a relatively cost-effective method of choice in the future. Typical allowed PVC contents for these technologies are about 2-3%, which is just in the range of the current PVC contents in packaging waste. With a supply of 1 to 3.5 Million tpa of MPW for chemical recycling, this would imply treatment of some 30 to 100 ktpa ton PVC. However, under the current incentive structure even the 1 Million tpa scenario is already somewhat optimistic. On the other hand it can be assumed that part of the infrastructure will be realised with technologies with a somewhat higher PVC-tolerance. Therefore, we feel that treatment of 50 kton pure PVC as a part of plastic packaging in 2010 seems a reasonable expectation. This corresponds to 80 ktpa PVC compound.

Dedicated chemical recycling of PVC is most likely to be valid for concentrated PVC waste flows from the building sector that cannot be recycled. We calculated a theoretical market in the EU of 300 tot 475 ktpa (pure resin). The main problem here is that the whole enterprise currently rests on a voluntary action of industry, in various countries supported by a PVC waste policy aimed at PVC recycling via ‘voluntary’ agreements. However, this incentive structure is only in place in a part of the EU. Under the existing and forthcoming landfill legislation, in most EU countries it will still be legally possible to landfill PVC building residues. Here, the main problem will be once again a guaranteed waste supply and funding before chemical recycling can really take off on a large scale. Until either industry or the government sets stringent recycling targets EU-wide, a market of 100 ktpa pure resin, or 160 ktpa PVC compound, seems to be at best the upper limit achievable in 2010.

6. Summary and Conclusions

6.1 Introduction

In this study, we analysed the potential of chemical recycling technologies to deal with plastics waste, and PVC waste in particular, in the EU during the next decade. The following elements have been addressed:

1. An assessment of the current initiatives with regard to chemical recycling in the EU;
2. An evaluation of the collection structures necessary to make plastics waste available for chemical recycling, and the related overall costs of waste management over the whole chain;
3. A comparative assessment of the environmental aspects of these waste management structures;
4. A scenario analysis with regard to the potential waste supply for chemical recycling.

These elements will be addressed below[43].

6.2 Current initiatives

For this study, a broad survey was carried out, leading to a list of several dozen potential chemical recycling technologies and initiatives. However, in practice during the last 5 years, there have been only a limited number of initiatives that either have lead to the realisation of a concrete plant, or may lead to the realisation of such a plant in the near future. The plastics waste we analysed can become available in principle in two ways: as a mixed plastic waste (MPW) fraction, with a rather low PVC content, or as a PVC-rich plastics fraction. Therefore, we classified these initiatives into technologies for MPW and technologies for PVC-rich waste. Table 6.1 summarises the status of each of these initiatives. The table makes clear that:

1. Chemical recycling of MPW has only been realised in practice in Germany, where some 360 ktpa MPW were treated in 1998. Only there were waste supply and funding guaranteed due to the existence of the DSD system. Assuming that this waste has a PVC-content of some 3%, this implies the treatment also of some 10,800 tpa PVC;
2. Of the three purpose-built chemical recycling plants, two have in the meantime been shut down. Use of plastics as a reducing agent in blast furnaces is in terms of volume the most important technology. In potential, if all blast furnaces in the EU would be used this way, a potential theoretical capacity of

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[43] Summary and conclusions form a condensed review of the former chapters of a report. We refer to the former chapters for a detailed review of our line of analysis and the literature sources used.

5 million tonnes MPW is available. However, there are to our knowledge no steelworks with similar plans at the moment; this is probably very related to the fact that only in Germany an incentive structure is in place that makes large-scale (chemical) recycling of plastics economically viable.

3. Two initiatives outside Germany have, to date, not been able to arrange waste supply at a sufficient gate fee that allowed for investment in a full-scale plant. At this moment, there is no idea of whether and when such investments will be made;
4. For PVC-rich waste there is currently one incineration-based technology operational, which can treat some 15,000 tpa PVC. Furthermore, two pilots will become operational shortly. For both, an evaluation of the possibilities for scaling them up to capacities of some 15,000 tpa will be made. It is unlikely that these larger-scale plants will become operational before 2005;
5. Regarding non-chemical re-use possibilities, in particular co-combustion of MPW in cement kilns may become important in the future. In 1995 the amounts of plastics waste treated here were rather low, but the potential is very large. If cement kilns in the EU were to fill 10% of their energy needs with MPW, this would imply a capacity of some 3 Million tonnes MPW.

Table 6.1: A review of options for chemical recycling of MPW and PVC-rich waste, including cement kilns

Technology	**Status**	**Capacity**	**Future potential**
MPW			
Texaco (NL)	Pilot/on hold	-	Uncertain*
Polymer cracking (UK)	Pilot/on hold	-	Uncertain*
BASF (D)	Closed in 1996	15 ktpa before 1996	-
VEBA (D)	Closed by 1-1-2000	87 ktpa before 2000	-
Blast furnaces	Operational (D)	162,5 ktpa in 1998	5 Mio tpa in the EU**
SVZ (D)	Operational	110 ktpa in 1998	
Cement kilns	Operational		3 Mio tpa in the EU**
PVC-rich waste			
BSL (D)	Operational	15 ktpa in 1999	
Linde (D/F)	Pilot under constr.	2 ktpa in 2001	15 ktpa > 2005 ? ***
NKT (Dk)	Pilot under constr.	< 1 ktpa in 1999	15 ktpa in future ? ***

* Typical capacities considered are 50 ktpa up to 200 ktpa

** Theoretical potential

*** No decision on realisation yet

6.3 Collection structures and costs

The chemical recycling initiatives have to compete with current waste management practices in the EU, still mainly based on landfill and incineration. The main difference with regard to the collection structure is that for chemical recycling of MPW, the MPW has to be available in a rather pure form, or at least separated from other waste. This implies either separate collection or sorting of MPW from municipal solid waste that is collected in integral form. Furthermore, for most chemical recycling technologies the mixed plastic fractions have to undergo pretreatment like agglomeration to increase the density and to make the MPW waste available in a form that can be accepted. For blast furnaces and cement kilns the PVC content in waste is a limitation as a tolerance of some 2-3% or less is possible[44]. For most of the other chemical recycling plants, somewhat higher values are acceptable (4-5% for some, and 10% for others as the maximum); however, except for the Texaco plant, these limits apply mostly during relatively short periods (at least not continuously).

For a number of typical collection situations for MPW (bring-systems, sorting from integral waste), we calculated tentative waste management costs over the whole chain of collection, pretreatment and final treatment. For PVC-rich waste, which is mainly generated in the building sector, the comparison was primarily relevant for chemical recycling of PVC-rich waste and mechanical recycling. The comparison is reviewed in table 6.2. This strongly suggests that purpose-built chemical recycling plants for MPW under the current conditions probably face considerable difficulty to compete financially with blast furnaces, and in any case

Table 6.2: Tentative cost comparison of treatment of MPW or PVC-rich waste, including collection and pre-treatment

Technology	**Typical waste input**	**Max. PVC content**	**Tentative costs over the full chain (Euro per tonne)**
Mixed plastic waste			
Landfill	MSW	n.r.	250
MSWIs	MSW	n.r	325
Cement kilns	MPW	2-3%	275-335
Blast furnaces	MPW	2-3%	400
Chemical recycling of MPW	MPW	10% or less	500
PVC-rich waste			
Chemical recycling of PVC	PVC-rich mixture	n.r.	390
Mech. recycling cables	Cable sheeting	n.r.	50
Mech. recycling flooring	Flooring waste	n.r.	350
Mech. recycling other	Profiles etc.	n.r.	250

Note: the PVC-rich wastes are assumed to be kept separated on-site, implying low collection costs compared with MSW. Costs estimates may have a margin of error of several dozen percent, due to the complexities of the collection structures and the rather different estimates and assumptions found in literature.

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[44] Or some 1-1.5% chlorine. Values may vary per installation, and legal demands may vary per country.

with cement kilns, MSWIs and landfill[45]. Furthermore, it seems that chemical recycling of PVC-rich waste is in financial terms no real alternative in those situations where mechanical recycling has proven already to be technically feasible, with the possible exception of flooring. This would imply that chemical recycling plants for PVC-rich waste would have to concentrate on those flows for which mechanical recycling is not feasible. The very low costs of recycling of cable sheeting is related to the fact is that the sheeting is a by-product of recovery of copper from cables, and hence already available in concentrated form in large amounts without the need for collection or pretreatment.

6.4 Environmental comparison

The environmental comparison was mainly based on a large number of LCAs that already had been performed.

Concerning MPW, landfill and MSWIs, even if the latter have energy recovery, score relatively low in environmental terms. The energy recovery at MSWIs is in general rather limited (some 20% heat and 20% electricity at best). This makes the options in which MPW is directly used as a replacement for fossil fuels as energy carrier or reducing agent (cement kilns and blast furnaces) or transformed into feedstock (dedicated chemical recycling) the better ones. In general, the LCAs we analysed did not allow a clear preference to be made for one of the chemical recycling technologies analysed (incuding use in blast furnaces). For cement kilns, like blast furnaces they use MPW as a direct replacement for oil or coal. Hence, it is very unlikely that they would score differently in LCAs than blast furnaces. For PVC that is collected as a part of MPW, high-quality mechanical recycling is difficult to realise and has been excluded from the comparison.

Regarding PVC-rich waste, it is most likely that direct mechanical recycling, if possible, is preferable in environmental terms, particularly if it concerns recycling to high-quality products.

6.5 Waste supply scenarios

6.5.1 Introduction

From the former sections, we concluded that chemical recycling in general only has a chance if there are legal or other steering instruments available that steer the waste away from the more cost-effective competitors (cement kilns, MSWIs, landfill). Hence, we analysed how much MPW was available in the base year 1995 on the basis of the APME series with plastics waste management data in Europe.

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[45] We used an average situation for chemical recycling plants, and did not always obtain detailed gate fees for confidentiality reasons. The situation for SVZ and for the Texaco initiative is probably better than reviewed here.

We further forecast the waste supply growth until 2010. For the same waste categories, we obtained data from the EuPC about PVC waste supply in 1998 and our future target years. Then, for the waste categories we defined, we analysed if EU legislation or national legislation would demand specific recycling targets for the waste stream under consideration. For 2010, we developed an extra scenario for packaging waste and automotive waste, assuming that plastics would have to meet the same recycling targets as all other materials in the waste stream. Making rough assumptions on the achievable amount of mechanical recycling, we then could calculate the potential percentage for which chemical recycling would be needed. Regarding recovery targets or landfill bans, they in principle have no influence on the need for chemical recycling since more cost-effective outlets like MSWIs and cement kilns are still allowed here. Furthermore, also under the forthcoming Landfill Directive it will probably still be possible to landfill PVC-containing residues originating from other waste treatment processes

6.5.2 Plastic waste with a low PVC content

Table 6.3 shows the result of this analysis for three target years. It appears that for categories like agricultural waste, industrial waste and non-packaging household waste, chemical recycling probably will have no role due to the lack of legal or other steering instruments. As for automotive and E&E waste, the PVC contents we calculated in the MPW seem to be almost prohibitive given the acceptance criteria for most chemical recycling options for MPW, but too low for economically viable treatment in plants for PVC-rich waste. By selective dismantling or pre-sorting, however, in principle a PVC-rich fraction could be made available for mechanical or chemical recycling; in that case MPW residue could become suitable for chemical recycling technologies of MPW. We feel, however, that the costs of such solutions may be high, and research into the optimal structure for dealing with E&E and automotive plastics waste falls well outside the scope of this report.

The table shows that if chemical recycling of MPW has a chance under the current steering system, this will be mainly in the field of packaging. The EU packaging directive may lead to a need for chemical recycling of about 1 Million tpa MPW in 2010. If the recycling targets are tightened to the high levels achieved by other materials (assumption: 45%), this supply may be 3.5 Million tpa in 2010 (assuming mechanical recycling is limited to 22.5%). However, even under the current legislation the uncertainties about a supply of 1 Million tpa is are considerable. If this amount is reached and the technologies in place can handle 5 % PVC on average, this implies an outlet for some 50 ktpa pure PVC (80 ktpa compound). In any case, purpose-built chemical recycling plants would still face in financial terms an important potential competition from blast furnace operations. Furthermore, the possibility that it may be accepted that direct use in e.g. cement kilns is an equally environmentally advantageous option presents another important market uncertainty for those involved in realising dedicated chemical recycling initiatives.

Table 6.3: The theoretical potential supply of MPW for chemical recycling based on recycling targets and feasible mechanical recycling (in kton)

Waste type	**PVC content (2000)**	**2000**	**2005**	**2010**		**Remarks**
				Scen. a)	**Scen. b)**	
Agriculture	10%					No incentives
Building	40%					No incentives
Housh. Other	16%					No incentives
Packaging (Hh +D)	4%	836	1023	1196	3456	*,**
Industry	14%					No incentives
Automotive	23%	15	224	266	1143	***
E and E	17%		548	656	656	***

* The model did not take into account that German targets are for household waste only. This probably led to an over-estimation of some 200 ktpa.

** If other countries achieve higher mechanical recycling rates than the assumed 12% (22.5% in scenario b), the supply drops by another few 100 ktpa.

*** Current targets for automotive and E&E do not concentrate specifically on plastics. If targets are met by recycling other, easier to recycle materials, this amount could drop. Furthermore, in view of the high PVC content, treatment by chemical recycling plants for MPW is questionable

6.5.3 PVC-rich waste

Concerning PVC-rich waste, we have already seen that chemical recycling is probably mainly relevant for flows from building waste and only for those fractions for which mechanical recycling is no technical option. The PVC industry has set up recycling systems for the most important building waste flows, often backed by voluntary commitments to national or regional authorities. However, this is true mainly in Scandinavia, Austria, Germany and the Netherlands. As shown in table 6.4, the potential supply for chemical recycling could be some 300 to 475 ktpa pure PVC (500 to 750 ktpa compund). However, unless an incentive system is imposed to steer PVC from building applications to recycling EU-wide, we feel that a market of 100 ktpa pure PVC or 160 ktpa compound is the best upper limit achievable in 2010. This volume could grow if pre-sorting of PVC from other waste streams would take off on a large scale, but as indicated under automotive and E&E waste, we have doubts about the financial viability

Table 6.4: The theoretical potential supply for chemical recycling of PVC-rich waste (in kton)

Waste type	**2000**	**2005**	**2010**	**Remarks**
Agriculture	-	-	-	No incentives
Building	307	384	475	See note a)
Housh. other	-	-	-	No incentives
Packaging (Hh +D)	-	-	-	PVC content too low
Industry	-	-	-	No incentives
Automotive	?	?	?	Only if PVC is pre-sorted
E and E	?	?	?	Only if PVC is pre-sorted

a) Theoretical amount if an EU-wide goal of 100% mechanical or chemical recycling is achieved for pipes, (window) profiles, cables, flooring and roofing

6.6 Overall conclusions

From our analysis it follows that the market for dedicated chemical recycling plants for MPW is beset by a lot of uncertainties. They require a market protected by legal recycling targets, and these are not always available or set on the level of specifically plastics.

For chemical recycling of MPW, the main potential market is currently packaging waste. However, it is quite possible that in most countries the current targets for plastics are met by mechanical methods, leaving no need for chemical recycling. Furthermore, there are options available with a large potential that can in principle be very competitive in price, like blast furnaces with potential capacities of 5 Million tpa MPW in Europe. Competition from cement kilns cannot be excluded in view of their apparently similar environmental advantages. They represent a potential capacity of 3 Million tonnes MPW per annum in Europe. We feel that these market problems and uncertainties have led to the closure of two dedicated chemical recycling plants in Germany, and the problems to get the Texaco and Polymer Cracking processes going. From the point of view of PVC, it is not advantageous that blast furnaces seem to be the most competitive form of chemical recycling at the moment, in view of their low PVC tolerance. The most likely future scenario is that chemical recycling will mainly play a role for packaging, and that blast furnaces will play a main part in this. Even under a not too pessimistic assumption that in future 1 Million tpa MPW will be treated, with chemical recycling technologies with on average a PVC tolerance of some 5%, this implies an outlet for 50 ktpa PVC (pure resin, some 80 ktpa compound).

For MPW from automotive or E&E waste, chemical recycling with dedicated technologies for MPW may cause problems. Though they can tolerate higher PVC contents, the even higher PVC contents in the MPW fractions from these waste flows make firm statements about the feasibility difficult. At best, it will be possible to mix this waste with MPW with lower PVC contents to make use of the full PVC tolerance of the least critical processes. Another option is to remove PVC by pre-sorting first, so that it becomes available for chemical recycling of PVC-rich waste. The analysis of such sorting and collection schemes forms a project in itself.

Concerning PVC-rich waste, in the short term there is a capacity of some 15,000 tpa available at BSL (albeit at relatively high costs and in a process that treats chlorinated waste in general) and less than 2 ktpa at two pilot plants. The pilot plants may be expanded to larger plants by 2005, and then at best offer increased capacity to about 40-50 ktpa (provided this scale-up is done). The incentive structures for recycling currently rest primarily on voluntary agreements by the PVC industry in a number of EU member states. Under the existing and forthcoming landfill legislation, in most EU countries it will still be legally possible to landfill PVC residues from other waste treatment processes. Until either industry or government sets stringent recycling targets EU-wide, a market of 100 ktpa PVC (160 ktpa compound) seems to be the best upper limit achievable in 2010.

In sum, under the incentive system that as can currently be foreseen, we expect that chemical recycling will be at best an outlet for 50 ktpa PVC (80 ktpa compound) as a part of MPW, and for 100 ktpa PVC (160 ktpa compound) as PVC-rich waste. This is a limited part of the likely PVC waste supply in the EU in 2010, about 2.8 Million ton PVC (4.7 Million ton compound). At the same time, it has to be stressed that this is the result of mainly a *legal-economic* forecast. As for the technical potential, assuming generous funding will be made available and that the right incentive structure to steer PVC and MPW to (chemical) recycling will be organised, the situation is probably fundamentally different. Purpose-built chemical recycling plants for MPW have been a technical success in Germany with at least 3 different technologies. They closed for economic and not technical reasons. BSL has an operational plant for PVC-rich waste. We see no reason why the plants currently in the pilot- or scale-up stage (i.e. the Polymer Cracking and Texaco processes for MPW, and the Linde, NKT and Akzo Nobel processes for PVC-rich waste) would face insurmountable technical problems. It is merely a question of whether future legal and economic structural arrangements will make them viable in economic terms – where it has to be noted that in some specific applications this may imply relatively high costs for management of the PVC waste.

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Appendix A: Waste supply scenarios for plastics waste

The approach of working out the scenarios is discussed in chapter 5 of the report. The following steps were taken:

1. Appendix A1 gives the waste management situation for plastics waste by EU member state in the base year 1995, based on APME (1997).
2. Appendix A2 (particularly table A2.2) recalculates for each waste stream, and for each EU member state, the percentage mechanical recycling, energy recovery, incineration (without energy recovery), landfill and chemical recycling in 1995, on the basis of Appendix A1 (Table A1.2).
3. Appendix A3.1 gives the total plastics waste supply for 2000 by EU member state, using the 1995 data given in Appendix A1 and the waste growth factors per plastic waste category calculated in chapter 5, Table 5.5. Appendix A3.3 gives our estimates for feasible mechanical recycling per waste category per member state, and the legal recycling target per waste stream per member state. Further explanation about the assumptions per waste stream is given in chapter 5. The difference is a percentage of that waste potentially available for chemical recycling. The percentages in Appendix A3.3 are multiplied by the waste volumes in Appendix 3.1, giving a theoretical amount of mixed plastics waste for chemical recyling in Appendix 3.2.
4. Appendices A4 and A5 repeat this exercise for 2005 and 2010.
5. Appendix A6 provides an extra scenario in 2010 for packaging waste and automotive waste, assuming that plastics will have to meet the same (high) recycling targets as other materials (see chapter 5). For packaging waste, it was assumed that half of the recycling target would be met by mechanical recycling.

The main text (chapter 5, tables 5.2-5.5 and chapter 6, table 6.3) condenses the results of the former Appendices. They give the total MPW supply per category in the target years, the PVC waste supply (see Appendix B) and the theoretical percentage PVC per waste category, as well as the theoretical amount of MPW available in the EU for chemical recycling per waste category.

All data are in kton pure resin, unless stated otherwise.

Table A1.1: Post-user plastic waste generation by country and end-use sector in 1995, in kton (APME, 1997)

	Total EU	Austria	Belgium	Denmark	Finland	France	Germany	Greece	Ireland	Italy	Netherland	Portugal	Spain	Sweden	UK
Agriculture	286	7	10	6	6	46	53	7	3	65	11	5	28	7	32
Building	817	17	59	14	12	153	224	6	8	95	46	6	39	16	122
Housh. Other	3390	11	26	16	60	809	803	73	41	338	162	15	634	155	247
Packaging (Hh, D)	8777	193	322	143	126	1530	1523	171	92	1583	503	167	862	189	1373
Industry	658	13	35	13	12	109	151	7	5	91	33	11	56	17	105
Automotive	856	18	32	12	11	172	194	8	7	130	39	10	54	18	151
E and E	793	16	41	15	15	131	183	7	6	109	40	14	67	21	128
Total EU	15577	275	525	219	242	2950	3131	279	162	2411	834	228	1740	423	2158

Table A1.2: Post-user plastic waste management by country and end-use sector in 1995 (TNO-laboration of APME, 1997)

	Total EU	Austria	Belgium	Denmark	Finland	France	Germany	Greece	Ireland	Italy	Netherland	Portugal	Spain	Sweden	UK
Total	**15577**	**275**	**525**	**219**	**242**	**2950**	**3131**	**279**	**162**	**2411**	**834**	**228**	**1740**	**423**	**2158**
#Mech. Recyc.	1335	46	48	17	11	168	609	3	2	159	75	3	65	18	111
#Legal Recyc.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
#Energy rec.	2516	35	171	132	0	591	788	9	0	243	197	14	79	166	91
# Incineration (D1)	468	0	34	0	0	243	0	0	1	65	0	0	13	0	111
#Landfill	11159	194	272	70	231	1948	1635	267	159	1944	562	211	1583	239	1845
# Market ch.rec.	99	0	0	0	0	0	99	0	0	0	0	0	0	0	0
Agriculture	**286**	**7**	**10**	**6**	**6**	**46**	**53**	**7**	**3**	**65**	**11**	**5**	**28**	**7**	**32**
#Mech. Recyc.	76	2	2	2	1	7	3	1	0	29	10	1	13	0	5
#Legal Recyc.	0														
#Energy rec.	8	0	0	0	0	1	2	0	0	2	0	0	1	0	0
# Incineration (D1)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
#Landfill	202	5	8	4	5	38	48	6	3	34	1	4	14	7	27
# Market ch.rec.	0														
Building	**817**	**17**	**59**	**14**	**12**	**153**	**224**	**6**	**8**	**95**	**46**	**6**	**39**	**16**	**122**
#Mech. Recyc.	30	0	1	0	0	0	21	0	0	4	1	0	0	0	3
#Legal Recyc.	0														
#Energy rec.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
# Incineration (D1)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
#Landfill	787	17	58	14	12	153	203	6	8	91	45	6	39	16	119
# Market ch.rec.	0														
Household other	**3390**	**11**	**26**	**16**	**60**	**809**	**803**	**73**	**41**	**338**	**162**	**15**	**634**	**155**	**247**
#Mech. Recyc.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
#Legal Recyc.	0														
#Energy rec.	718	1	14	13	0	227	265	0	0	37	57	0	19	73	12
# Incineration (D1)	132	0	3	0	0	89	0	0	0	14	0	0	6	0	20
#Landfill	2540	10	9	3	60	493	538	73	41	287	105	15	609	82	215
# Market ch.rec.	0														
Packaging	**8777**	**193**	**322**	**143**	**126**	**1530**	**1523**	**171**	**92**	**1583**	**503**	**167**	**862**	**189**	**1373**
#Mech. Recyc.	1149	43	43	15	8	144	562	2	2	112	61	2	49	17	89
#Legal Recyc.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
#Energy rec.	1492	22	145	108	0	339	430	0	0	147	133	0	21	84	62
# Incineration (D1)	326	0	30	0	0	149	0	0	1	51	0	0	7	0	89
#Landfill	5711	128	105	20	118	898	432	169	89	1273	309	165	785	88	1133
# Market ch.rec.	99	0	0	0	0	0	99	0	0	0	0	0	0	0	0
Large industry	**658**	**13**	**35**	**13**	**12**	**109**	**151**	**7**	**5**	**91**	**33**	**11**	**56**	**17**	**105**
#Mech. Recyc.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
#Legal Recyc.	0														
#Energy rec.	64	1	7	9	0	1	30	0	0	2	3	0	0	7	3
# Incineration (D1)	9	0	2	0	0	5	0	0	0	0	0	0	0	0	2
#Landfill	585	12	26	4	12	102	121	7	5	89	30	11	56	10	100
# Market ch.rec.	0														
Automotive	**856**	**18**	**32**	**12**	**11**	**172**	**194**	**8**	**7**	**130**	**39**	**10**	**54**	**18**	**151**
#Mech. Recyc.	62	1	2	0	1	14	16	0	0	11	3	0	3	1	10
#Legal Recyc.	0														
#Energy rec.	126	5	3	1	0	13	33	5	0	30	2	7	20	1	7
# Incineration (D1)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
#Landfill	668	12	27	11	10	145	145	3	7	89	34	3	31	16	134
# Market ch.rec.	0														
E and E	**793**	**16**	**41**	**15**	**15**	**131**	**183**	**7**	**6**	**109**	**40**	**14**	**67**	**21**	**128**
#Mech. Recyc.	18	0	0	0	1	3	7	0	0	3	0	0	0	0	4
#Legal Recyc.	0														
#Energy rec.	108	5	2	1	0	11	28	4	0	26	2	6	17	1	6
# Incineration (D1)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
#Landfill	667	11	39	14	14	117	148	3	6	80	38	8	50	20	118
# Market ch.rec.	0														

Table A1.3: Worksheet disribution packaging and household packaging in 1995(based on APME , 1997)

	Total EU	Austria	Belgium	Denmark	Finland	France	Germany	Greece	Ireland	Italy	Netherland	Portugal	Spain	Sweden	UK
Housh. Pack.	**6451**	**146**	**229**	**81**	**87**	**1200**	**968**	**126**	**55**	**1277**	**332**	**91**	**700**	**127**	**1032**
#Mech. Recyc.	506	13	10	2	1	18	405	0	1	23	10	0	10	5	8
#Legal Recyc.	0														
#Energy rec.	1253	18	126	65	0	336	319	0	0	140	116	0	21	60	52
# Incineration (D1)	298	0	25	0	0	132	0	0	1	51	0	0	7	0	83
#Landfill	4295	115	68	14	86	714	145	126	53	1062	206	91	662	62	890
# Market ch.rec.	99	0	0	0	0	0	99	0	0	0	0	0	0	0	0
Distribution	**2326**	**47**	**93**	**62**	**39**	**330**	**555**	**45**	**37**	**306**	**171**	**76**	**162**	**62**	**341**
#Mech. Recyc.	643	30	33	13	7	126	157	2	1	89	51	2	39	12	81
#Legal Recyc.	0														
#Energy rec.	239	5	19	43	0	3	111	0	0	6	17	0	0	25	10
# Incineration (D1)	28	0	5	0	0	17	0	0	0	0	0	0	0	0	7
#Landfill	1416	12	37	6	32	184	287	43	36	211	103	74	123	25	243
# Market ch.rec.	0														

Table A2.1: Post-user plastic waste generation by country and end-use sector in 1995, in kton (APME, 1997)

	Total EU	Austria	Belgium	Denmark	Finland	France	Germany	Greece	Ireland	Italy	Netherland	Portugal	Spain	Sweden	UK
Agriculture	286	7	10	6	6	46	53	7	3	65	11	5	28	7	32
Building	817	17	59	14	12	153	224	6	8	95	46	6	39	16	122
Housh. Other	3390	11	26	16	60	809	803	73	41	338	162	15	634	155	247
Packaging (Hh, D)	8777	193	322	143	126	1530	1523	171	92	1583	503	167	862	189	1373
Industrry	658	13	35	13	12	109	151	7	5	91	33	11	56	17	105
Automotive	856	18	32	12	11	172	194	8	7	130	39	10	54	18	151
E and E	793	16	41	15	15	131	183	7	6	109	40	14	67	21	128
Total EU	15577	275	525	219	242	2950	3131	279	162	2411	834	228	1740	423	2158

Table A2.2: Post-user plastic waste management by country/sector, 1995, in % (TNO-calculation largely based on APME, 1997)

	Total EU	Austria	Belgium	Denmark	Finland	France	Germany	Greece	Ireland	Italy	Netherland	Portugal	Spain	Sweden	UK
Total (kton)	**15577**	**275**	**525**	**219**	**242**	**2950**	**3131**	**279**	**162**	**2411**	**834**	**228**	**1740**	**423**	**2158**
#Mech. Recyc.	9%	17%	9%	8%	5%	6%	19%	1%	1%	7%	9%	1%	4%	4%	5%
#Legal Recyc.	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
#Energy rec.	16%	13%	33%	60%	0%	20%	25%	3%	0%	10%	24%	6%	5%	39%	4%
# Incineration (D1)	3%	0%	7%	0%	0%	8%	0%	0%	1%	3%	0%	0%	1%	0%	5%
#Landfill	72%	71%	52%	32%	95%	66%	52%	96%	98%	81%	67%	93%	91%	57%	85%
# Market ch.rec.	1%	0%	0%	0%	0%	0%	3%	0%	0%	0%	0%	0%	0%	0%	0%
Agriculture	**286**	**7**	**10**	**6**	**6**	**46**	**53**	**7**	**3**	**65**	**11**	**5**	**28**	**7**	**32**
#Mech. Recyc.	27%	29%	20%	33%	17%	15%	6%	14%	0%	45%	91%	20%	46%	0%	16%
#Legal Recyc.	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
#Energy rec.	3%	5%	2%	1%	0%	2%	4%	4%	0%	3%	1%	9%	5%	1%	1%
# Incineration (D1)	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
#Landfill	71%	67%	78%	66%	83%	83%	90%	81%	100%	52%	8%	71%	49%	99%	83%
# Market ch.rec.	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Building	**817**	**17**	**59**	**14**	**12**	**153**	**224**	**6**	**8**	**95**	**46**	**6**	**39**	**16**	**122**
#Mech. Recyc.	4%	0%	2%	0%	0%	0%	9%	0%	0%	4%	2%	0%	0%	0%	2%
#Legal Recyc.	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
#Energy rec.	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
# Incineration (D1)	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
#Landfill	96%	100%	98%	100%	100%	100%	91%	100%	100%	96%	98%	100%	100%	100%	98%
# Market ch.rec.	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Household other	**3390**	**11**	**26**	**16**	**60**	**809**	**803**	**73**	**41**	**338**	**162**	**15**	**634**	**155**	**247**
#Mech. Recyc.	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
#Legal Recyc.	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
#Energy rec.	21%	12%	55%	80%	0%	28%	33%	0%	0%	11%	35%	0%	3%	47%	5%
# Incineration (D1)	4%	0%	11%	0%	0%	11%	0%	0%	1%	4%	0%	0%	1%	0%	8%
#Landfill	75%	88%	34%	20%	100%	61%	67%	100%	99%	85%	65%	100%	96%	53%	87%
# Market ch.rec.	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Packaging (Hh, D)	**8777**	**193**	**322**	**143**	**126**	**1530**	**1523**	**171**	**92**	**1583**	**503**	**167**	**862**	**189**	**1373**
#Mech. Recyc.	13%	22%	13%	10%	6%	9%	37%	1%	2%	7%	12%	1%	6%	9%	6%
#Legal Recyc.	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
#Energy rec.	17%	12%	45%	76%	0%	22%	28%	0%	0%	9%	27%	0%	2%	45%	5%
# Incineration (D1)	4%	0%	9%	0%	0%	10%	0%	0%	1%	3%	0%	0%	1%	0%	7%
#Landfill	65%	66%	32%	14%	94%	59%	28%	99%	97%	80%	61%	99%	91%	46%	83%
# Market ch.rec.	1%	0%	0%	0%	0%	0%	7%	0%	0%	0%	0%	0%	0%	0%	0%
Large industry	**658**	**13**	**35**	**13**	**12**	**109**	**151**	**7**	**5**	**91**	**33**	**11**	**56**	**17**	**105**
#Mech. Recyc.	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
#Legal Recyc.	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
#Energy rec.	10%	10%	20%	70%	0%	1%	20%	0%	0%	2%	10%	0%	0%	40%	3%
# Incineration (D1)	1%	0%	5%	0%	0%	5%	0%	0%	0%	0%	0%	0%	0%	0%	2%
#Landfill	89%	90%	75%	30%	100%	94%	80%	100%	100%	98%	90%	100%	100%	60%	95%
# Market ch.rec.	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Automotive	**856**	**18**	**32**	**12**	**11**	**172**	**194**	**8**	**7**	**130**	**39**	**10**	**54**	**18**	**151**
#Mech. Recyc.	7%	6%	6%	0%	9%	8%	8%	0%	0%	8%	8%	0%	6%	6%	7%
#Legal Recyc.	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
#Energy rec.	15%	29%	8%	8%	0%	7%	17%	59%	0%	23%	5%	73%	38%	5%	5%
# Incineration (D1)	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
#Landfill	78%	65%	85%	92%	91%	85%	75%	41%	100%	69%	87%	27%	57%	89%	89%
# Market ch.rec.	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
E and E	**793**	**16**	**41**	**15**	**15**	**131**	**183**	**7**	**6**	**109**	**40**	**14**	**67**	**21**	**128**
#Mech. Recyc.	2%	0%	0%	0%	7%	2%	4%	0%	0%	3%	0%	0%	0%	0%	3%
#Legal Recyc.	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
#Energy rec.	14%	28%	6%	6%	0%	8%	15%	57%	0%	23%	4%	44%	26%	4%	5%
# Incineration (D1)	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
#Landfill	84%	72%	94%	94%	93%	90%	81%	43%	100%	74%	96%	56%	74%	96%	92%
# Market ch.rec.	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Table A3.1: Post-user plastic waste generation by country and end-use sector in 2000, in kton (extrapolation)

	Total EU	Austria	Belgium	Denmark	Finland	France	Germany	Greece	Ireland	Italy	Netherland	Portugal	Spain	Sweden	UK	Growth factor '95
Agriculture	305	7	11	6	6	49	56	7	3	69	12	5	30	7	34	1,065
Building	1077	22	78	18	16	202	295	8	11	125	61	8	51	21	161	1,318
Housh. Other	4274	14	33	20	76	1020	1012	92	52	426	204	19	799	195	311	1,261
Packaging (Hh +D)	11065	243	406	180	159	1929	1920	216	116	1996	634	211	1087	238	1731	1,261
Industry	848	17	45	17	15	141	195	9	6	117	43	14	72	22	135	1,289
Automotive	1087	23	41	15	14	218	246	10	9	165	50	13	69	23	192	1,270
E and E	1036	21	54	20	20	171	239	9	8	142	52	18	87	27	167	1,306
Total EU	19692	348	666	277	306	3730	3964	351	205	3041	1055	288	2196	534	2732	

Table A3.2: Theoretical availability for chemical recycling of MPW per end-use sector in 2000, summary (in kton)

	Total EU	Austria	Belgium	Denmark	Finland	France	Germany	Greece	Ireland	Italy	Netherland	Portugal	Spain	Sweden	UK
Agriculture		0	0	0	0	0	0	0	0	0	0	0	0	0	0
Building		0	0	0	0	0	0	0	0	0	0	0	0	0	0
Housh. Other		0	0	0	0	0	0	0	0	0	0	0	0	0	0
Packaging (Hh +D)	836	0	7	5	5	58	461	0	0	60	94	0	87	7	52
Industry		0	0	0	0	0	0	0	0	0	0	0	0	0	0
Automotive	15	0	0	0	0	0	0	0	0	0	15	0	0	0	0
E and E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total EU															

High uncertainties for packaging; high values almost fully related to exceptionally high national recycling targets
Technical feasibility for automotive and E&E questionable

Table A3.3: Calculation of the market percentage for chemical recycling. In bold: total supply by sector (in kton)

Agriculture	305	7	11	6	6	49	56	7	3	69	12	5	30	7	34
#Mech. Recyc.		35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%
#Legal Recyc.		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
#Energy rec.															
# Incineration (D1)															
#Landfill		0%	0%			0%	0%				0%			0%	
# Market ch.rec.		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Building	1077	22	78	18	16	202	295	8	11	125	61	8	51	21	161
#Mech. Recyc.		6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%
#Legal Recyc.		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
#Energy rec.															
# Incineration (D1)															
#Landfill		0%	0%			0%	0%				0%			0%	
# Market ch.rec.		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Household other	4274	14	33	20	76	1020	1012	92	52	426	204	19	799	195	311
#Mech. Recyc.		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
#Legal Recyc.		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
#Energy rec.															
# Incineration (D1)															
#Landfill		0%	0%			0%	0%				0%			0%	
# Market ch.rec.		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Packaging (Hh+D)	11065	243	406	180	159	1929	1920	216	116	1996	634	211	1087	238	1731
#Mech. Recyc.		22%	13%	12%	12%	12%	36%	12%	12%	12%	12%	12%	12%	12%	12%
#Legal Recyc.		15%	15%	15%	15%	15%	60%	0%	0%	15%	27%	0%	20%	15%	15%
#Energy rec.															
# Incineration (D1)															
#Landfill		0%	0%			0%	0%				0%			0%	
# Market ch.rec.		0%	2%	3%	3%	3%	24%	0%	0%	3%	15%	0%	8%	3%	3%
Industry	848	17	45	17	15	141	195	9	6	117	43	14	72	22	135
#Mech. Recyc.		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
#Legal Recyc.		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
#Energy rec.															
# Incineration (D1)															
#Landfill		0%	0%			0%	0%				0%			0%	
# Market ch.rec.		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Automotive	1087	23	41	15	14	218	246	10	9	165	50	13	69	23	192
#Mech. Recyc.		10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
#Legal Recyc.		0%	0%	0%	0%	0%	0%	0%	0%	0%	40%	0%	0%	0%	0%
#Energy rec.		85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%
# Incineration (D1)															
#Landfill		0%	0%			0%	0%				0%			0%	
# Market ch.rec.		0%	0%	0%	0%	0%	0%	0%	0%	0%	30%	0%	0%	0%	0%
E and E	1036	21	54	20	20	171	239	9	8	142	52	18	87	27	167
#Mech. Recyc.		3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%
#Legal Recyc.		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
#Energy rec.															
# Incineration (D1)															
#Landfill		0%	0%			0%	0%				0%			0%	
# Market ch.rec.		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Table A4.1: Post-user plastic waste generation by country and end-use sector in 2005, in kton (extrapolation)

	Total EU	Austria	Belgium	Denmark	Finland	France	Germany	Greece	Ireland	Italy	Netherland	Portugal	Spain	Sweden	UK	Growth factor '95
Agriculture	320	8	11	7	7	51	59	8	3	73	12	6	31	8	36	1,118
Building	1433	30	104	25	21	268	393	11	14	167	81	11	68	28	214	1,755
Housh. Other	5127	17	39	24	91	1223	1214	110	62	511	245	23	959	234	374	1,512
Packaging (Hh +D)	13273	292	487	216	191	2314	2303	259	139	2394	761	253	1304	286	2076	1,512
Industry	1061	21	56	21	19	176	244	11	8	147	53	18	90	27	169	1,613
Automotive	1374	29	51	19	18	276	311	13	11	209	63	16	87	29	242	1,605
E and E	1305	26	67	25	25	216	301	12	10	179	66	23	110	35	211	1,646
Total EU	23893	422	816	337	371	4525	4826	423	248	3679	1280	348	2649	647	3322	

Table A4.2: Theoretical availability for chemical recycling of MPW per end-use sector in 2005, summary (in ton)

	Total EU	Austria	Belgium	Denmark	Finland	France	Germany	Greece	Ireland	Italy	Netherland	Portugal	Spain	Sweden	UK
Agriculture		0	0	0	0	0	0	0	0	0	0	0	0	0	0
Building		0	0	0	0	0	0	0	0	0	0	0	0	0	0
Housh. Other		0	0	0	0	0	0	0	0	0	0	0	0	0	0
Packaging (Hh +D)	1023	0	8	6	6	69	553	8	4	72	114	8	104	9	62
Industry		0	0	0	0	0	0	0	0	0	0	0	0	0	0
Automotive	224	9	5	2	2	28	93	1	1	21	19	2	9	9	24
E and E	548	11	28	10	10	91	127	5	4	75	28	10	46	15	88
Total EU															

High uncertainties for packaging; high values almost fully related to exceptionally high national recycling targets
Technical feasibility for automotive and E&E questionable

Table A4.3: Calculation of the market percentage for chemical recycling. In bold: total supply by sector (in kton)

Agriculture	320	8	11	7	7	51	59	8	3	73	12	6	31	8	36
#Mech. Recyc.		35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%
#Legal Recyc.		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
#Energy rec.															
# Incineration (D1)															
#Landfill		0%	0%			0%	0%				0%			0%	
# Market ch.rec.		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Building	1433	30	104	25	21	268	393	11	14	167	81	11	68	28	214
#Mech. Recyc.		6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%
#Legal Recyc.		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
#Energy rec.															
# Incineration (D1)															
#Landfill		0%	0%			0%	0%				0%			0%	
# Market ch.rec.		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Household other	5127	17	39	24	91	1223	1214	110	62	511	245	23	959	234	374
#Mech. Recyc.		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
#Legal Recyc.		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
#Energy rec.															
# Incineration (D1)															
#Landfill		0%	0%			0%	0%				0%			0%	
# Market ch.rec.		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Packaging (Hh+D)	13273	292	487	216	191	2314	2303	259	139	2394	761	253	1304	286	2076
#Mech. Recyc.		22%	13%	12%	12%	12%	36%	12%	12%	12%	12%	12%	12%	12%	12%
#Legal Recyc.		15%	15%	15%	15%	15%	60%	15%	15%	15%	27%	15%	20%	15%	15%
#Energy rec.															
# Incineration (D1)															
#Landfill		0%	0%			0%	0%				0%			0%	
# Market ch.rec.		0%	2%	3%	3%	3%	24%	3%	3%	3%	15%	3%	8%	3%	3%
Large industry	1061	21	56	21	19	176	244	11	8	147	53	18	90	27	169
#Mech. Recyc.		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
#Legal Recyc.		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
#Energy rec.															
# Incineration (D1)															
#Landfill		0%	0%			0%	0%				0%			0%	
# Market ch.rec.		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Automotive	1374	29	51	19	18	276	311	13	11	209	63	16	87	29	242
#Mech. Recyc.		10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
#Legal Recyc.		40%	20%	20%	20%	20%	40%	20%	20%	20%	40%	20%	20%	40%	20%
#Energy rec.		85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%
# Incineration (D1)															
#Landfill		0%	0%			0%	0%				0%			0%	
# Market ch.rec.		30%	10%	10%	10%	10%	30%	10%	10%	10%	30%	10%	10%	30%	10%
E and E	1305	26	67	25	25	216	301	12	10	179	66	23	110	35	211
#Mech. Recyc.		3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%
#Legal Recyc.		45%	45%	45%	45%	45%	45%	45%	45%	45%	45%	45%	45%	45%	45%
#Energy rec.															
# Incineration (D1)															
#Landfill		0%	0%			0%	0%				0%			0%	
# Market ch.rec.		42%	42%	42%	42%	42%	42%	42%	42%	42%	42%	42%	42%	42%	42%

Table A5.1: Post-user plastic waste generation by country and end-use sector in 2010, in kton (extrapolation)

	Total EU	Austria	Belgium	Denmark	Finland	France	Germany	Greece	Ireland	Italy	Netherland	Portugal	Spain	Sweden	UK	Growth factor '95
Agriculture	337	8	12	7	7	54	62	8	4	76	13	6	33	8	38	1,177
Building	1742	36	126	30	26	326	478	13	17	203	98	13	83	34	260	2,132
Housh. Other	5995	19	46	28	106	1431	1420	129	73	598	286	27	1121	274	437	1,768
Packaging (Hh +D)	15521	341	569	253	223	2706	2693	302	163	2799	889	295	1524	334	2428	1,768
Industry	1263	25	67	25	23	209	290	13	10	175	63	21	107	33	202	1,920
Automotive	1633	34	61	23	21	328	370	15	13	248	74	19	103	34	288	1,908
E and E	1561	32	81	30	30	258	360	14	12	215	79	28	132	41	252	1,969
Total EU	28051	496	962	395	435	5312	5673	495	291	4313	1503	408	3104	759	3904	

Table A5.2: Theoretical availability for chemical recycling of MPW per end-use sector in 2010, Scenario a, summary (in ton)

	Total EU	Austria	Belgium	Denmark	Finland	France	Germany	Greece	Ireland	Italy	Netherland	Portugal	Spain	Sweden	UK
Agriculture		0	0	0	0	0	0	0	0	0	0	0	0	0	0
Building		0	0	0	0	0	0	0	0	0	0	0	0	0	0
Housh. Other		0	0	0	0	0	0	0	0	0	0	0	0	0	0
Packaging (Hh +D)	1196	0	9	8	7	81	646	9	5	84	133	9	122	10	73
Industry		0	0	0	0	0	0	0	0	0	0	0	0	0	0
Automotive	266	10	6	2	2	33	111	2	1	25	22	2	10	10	29
E and E	656	13	34	12	12	108	151	6	5	90	33	12	55	17	106
Total EU															

High uncertainties for packaging; high values almost fully related to exceptionally high national recycling targets
Technical feasibility for automotive and E&E questionable

Table A5.3: Calculation of the market percentage for chemical recycling, scenario a. In bold: total supply by sector (in kton)

Agriculture	337	8	12	7	7	54	62	8	4	76	13	6	33	8	38
#Mech. Recyc.		35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%
#Legal Recyc.		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
#Energy rec.															
# Incineration (D1)															
#Landfill		0%	0%			0%	0%				0%			0%	
# Market ch.rec.		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Building	1742	36	126	30	26	326	478	13	17	203	98	13	83	34	260
#Mech. Recyc.		6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%
#Legal Recyc.		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
#Energy rec.															
# Incineration (D1)															
#Landfill		0%	0%			0%	0%				0%			0%	
# Market ch.rec.		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Household other	5995	19	46	28	106	1431	1420	129	73	598	286	27	1121	274	437
#Mech. Recyc.		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
#Legal Recyc.		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
#Energy rec.															
# Incineration (D1)															
#Landfill		0%	0%			0%	0%				0%			0%	
# Market ch.rec.		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Packaging (Hh+D)	15521	341	569	253	223	2706	2693	302	163	2799	889	295	1524	334	2428
#Mech. Recyc.		22%	13%	12%	12%	12%	36%	12%	12%	12%	12%	12%	12%	12%	12%
#Legal Recyc.		15%	15%	15%	15%	15%	60%	15%	15%	15%	27%	15%	20%	15%	15%
#Energy rec.															
# Incineration (D1)															
#Landfill		0%	0%			0%	0%				0%			0%	
# Market ch.rec.		0%	2%	3%	3%	3%	24%	3%	3%	3%	15%	3%	8%	3%	3%
Large industry	1263	25	67	25	23	209	290	13	10	175	63	21	107	33	202
#Mech. Recyc.		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
#Legal Recyc.		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
#Energy rec.															
# Incineration (D1)															
#Landfill		0%	0%			0%	0%				0%			0%	
# Market ch.rec.		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Automotive	1633	34	61	23	21	328	370	15	13	248	74	19	103	34	288
#Mech. Recyc.		10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
#Legal Recyc.		40%	20%	20%	20%	20%	40%	20%	20%	20%	40%	20%	20%	40%	20%
#Energy rec.		85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%
# Incineration (D1)															
#Landfill		0%	0%			0%	0%				0%			0%	
# Market ch.rec.		30%	10%	10%	10%	10%	30%	10%	10%	10%	30%	10%	10%	30%	10%
E and E	1561	32	81	30	30	258	360	14	12	215	79	28	132	41	252
#Mech. Recyc.		3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%
#Legal Recyc.		45%	45%	45%	45%	45%	45%	45%	45%	45%	45%	45%	45%	45%	45%
#Energy rec.															
# Incineration (D1)															
#Landfill		0%	0%			0%	0%				0%			0%	
# Market ch.rec.		42%	42%	42%	42%	42%	42%	42%	42%	42%	42%	42%	42%	42%	42%

Table A6.1: Post-user plastic waste generation by country and end-use sector in 2010, in kton (extrapolation)

	Total EU	Austria	Belgium	Denmark	Finland	France	Germany	Greece	Ireland	Italy	Netherland	Portugal	Spain	Sweden	UK	Growth factor '95
Agriculture	337	8	12	7	7	54	62	8	4	76	13	6	33	8	38	1,177
Building	1742	36	126	30	26	326	478	13	17	203	98	13	83	34	260	2,132
Housh. Other	5995	19	46	28	106	1431	1420	129	73	598	286	27	1121	274	437	1,768
Packaging (Hh +D)	15521	341	569	253	223	2706	2693	302	163	2799	889	295	1524	334	2428	1,768
Industry	1263	25	67	25	23	209	290	13	10	175	63	21	107	33	202	1,920
Automotive	1633	34	61	23	21	328	370	15	13	248	74	19	103	34	288	1,908
E and E	1561	32	81	30	30	258	360	14	12	215	79	28	132	41	252	1,969
Total EU	28051	496	962	395	435	5312	5673	495	291	4313	1503	408	3104	759	3904	

Table A6.2: Theoretical availability for chemical recycling of MPW per end-use sector in 2010, Scenario b, summary (in ton)

	Total EU	Austria	Belgium	Denmark	Finland	France	Germany	Greece	Ireland	Italy	Netherland	Portugal	Spain	Sweden	UK
Agriculture		0	0	0	0	0	0	0	0	0	0	0	0	0	0
Building		0	0	0	0	0	0	0	0	0	0	0	0	0	0
Housh. Other		0	0	0	0	0	0	0	0	0	0	0	0	0	0
Packaging (Hh +D)	3456	0	128	57	50	609	646	68	37	630	200	66	343	75	546
Industry		0	0	0	0	0	0	0	0	0	0	0	0	0	0
Automotive	1143	24	43	16	15	230	259	11	9	174	52	13	72	24	202
E and E	656	13	34	12	12	108	151	6	5	90	33	12	55	17	106
Total EU															

High uncertainties for packaging; high values almost fully related to exceptionally high national recycling targets

Technical feasibility for automotive and E&E questionable

Table A6.3: Calculation of the market percentage for chemical recycling, scenario b. In bold: total supply by sector (in kton)

Agriculture	337	8	12	7	7	54	62	8	4	76	13	6	33	8	38
#Mech. Recyc.		35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%
#Legal Recyc.		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
#Energy rec.															
# Incineration (D1)															
#Landfill		0%	0%			0%	0%				0%			0%	
# Market ch.rec.		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Building	1742	36	126	30	26	326	478	13	17	203	98	13	83	34	260
#Mech. Recyc.		6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%
#Legal Recyc.		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
#Energy rec.															
# Incineration (D1)															
#Landfill		0%	0%			0%	0%				0%			0%	
# Market ch.rec.		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Household other	5995	19	46	28	106	1431	1420	129	73	598	286	27	1121	274	437
#Mech. Recyc.		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
#Legal Recyc.		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
#Energy rec.															
# Incineration (D1)															
#Landfill		0%	0%			0%	0%				0%			0%	
# Market ch.rec.		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Packaging (Hh+D)	15521	341	569	253	223	2706	2693	302	163	2799	889	295	1524	334	2428
#Mech. Recyc.			23%	23%	23%	23%	36%	23%	23%	23%	23%	23%	23%	23%	23%
#Legal Recyc.			45%	45%	45%	45%	60%	45%	45%	45%	45%	45%	45%	45%	45%
#Energy rec.															
# Incineration (D1)															
#Landfill		0%	0%			0%	0%				0%			0%	
# Market ch.rec.		0%	23%	23%	23%	23%	24%	23%	23%	23%	23%	23%	23%	23%	23%
Large industry	1263	25	67	25	23	209	290	13	10	175	63	21	107	33	202
#Mech. Recyc.		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
#Legal Recyc.		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
#Energy rec.															
# Incineration (D1)															
#Landfill		0%	0%			0%	0%				0%			0%	
# Market ch.rec.		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Automotive	1633	34	61	23	21	328	370	15	13	248	74	19	103	34	288
#Mech. Recyc.		10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
#Legal Recyc.		80%	80%	80%	80%	80%	80%	80%	80%	80%	80%	80%	80%	80%	80%
#Energy rec.		85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%
# Incineration (D1)															
#Landfill		0%	0%			0%	0%				0%			0%	
# Market ch.rec.		70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%
E and E	1561	32	81	30	30	258	360	14	12	215	79	28	132	41	252
#Mech. Recyc.		3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%
#Legal Recyc.		45%	45%	45%	45%	45%	45%	45%	45%	45%	45%	45%	45%	45%	45%
#Energy rec.															
# Incineration (D1)															
#Landfill		0%	0%			0%	0%				0%			0%	
# Market ch.rec.		42%	42%	42%	42%	42%	42%	42%	42%	42%	42%	42%	42%	42%	42%

Appendix B: Waste supply scenarios for PVC waste

This Appendix gives the underlying data for the scenarios for PVC waste supply. Estimates for 1998, 2000, 2005 and 2010 were obtained from EuPC, detailed into many individual waste categories. We reprocessed their data as follows:

1. Appendix B1 gives the original EuPC data, expressed as ‘available PVC waste’. EuPC already subtracted here PVC that would not be collected, would be left buried in the ground, etc. The related percentages estimated by EuPC are given in the column ‘availability’. By dividing the EuPC data by this availability, the total potential PVC waste supply was calculated in the next four columns[46]. These data are formulated PVC. We had obtained for each waste category also the percentage of additives and plasticisers (column % additives). We used this to calculate in the rightmost 4 columns the PVC amount per category as pure resin.
2. Appendix B2 regrouped the EuPC data into categories necessary for our report. Some waste streams which in B1 were under households are now under a new category Industry, which includes medical applications. Furniture is added under households.
3. Appendix B3 aggregates these data into the main categories relevant for this study. We split up packaging into bottles and other packaging, and gave a breakdown into 7 categories for PVC building waste.

Further explanations can be found in chapter 5. Appendices B2 and B3 are all in ton per annum pure resin, unless indicated otherwise.

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[46] Only for pipes and cables it is obvious that much is left in the ground after their useful life, so we estimated that only 30% or 29%, respectively, would be part of the potential waste supply.

Table B1.1: Original data supplied by EuPC and amount of pure PVC-resin calculated by TNO (in ton)

					Available waste in year (formulated re				Total waste in year (formulated resin,				Pure PVC in year (TNO calculation)			
	Europe Intermediates	Europe Finished product	Availabibity of post consumer waste %	Total additives in PVC compounds (%)	1998	2000	2005	2010	1998	2000	2005	2010	1998	2000	2005	2010
P	**PVC**	**Total PVC**	**63**		**2.593.301**	**2.738.798**	**3.037.774**	**3.443.614**	**3.508.414**	**3.707.090**	**4.118.361**	**4.680.798**	**2.151.091**	**2.245.450**	**2.480.533**	**2.840.599**
F	Cables	Cables dom	30	53	19.747	22.640	31.613	42.983	19.747	22.640	31.613	42.983	9.281	10.641	14.858	20.202
F	Films plastis	Films for bu	50	39	5.188	6.077	8.807	12.191	10.376	12.154	17.614	24.382	6.329	7.414	10.745	14.873
F	Floor	Flooring pas	80	54	206.899	219.370	242.105	280.534	258.624	274.213	302.631	350.668	118.967	126.138	139.210	161.307
F	Floor	Floor, calen	80	70	147.579	159.824	190.688	217.304	184.474	199.780	238.360	271.630	55.342	59.934	71.508	81.489
F	Hoses and p	Building pro	80	46	90.445	95.960	98.211	95.419	113.056	119.950	122.764	119.274	61.050	64.773	66.292	64.408
F	Coatings	PVC wallpa	80	56	116.089	114.712	107.985	103.315	145.111	143.390	134.981	129.144	63.849	63.092	59.392	56.823
F	Coatings	Air-inflated	80	56	9.819	10.336	10.887	10.968	12.274	12.920	13.609	13.710	5.400	5.685	5.988	6.032
F	Coatings	Roof coveri	50	56	2.674	3.056	3.986	4.668	5.348	6.112	7.972	9.336	2.353	2.689	3.508	4.108
F	Organo-,Pla	Varnishes -	80	65	15.104	15.941	17.931	21.050	18.880	19.926	22.414	26.313	6.608	6.974	7.845	9.209
R	Rigid films	Pipe insulati	80	6	790	1.009	1.738	2.729	988	1.261	2.173	3.411	928	1.186	2.042	3.207
R	Sheets	sheets for b	80	6	2.634	3.239	5.249	8.045	3.293	4.049	6.562	10.057	3.096	3.806	6.168	9.453
R	Pipes and fi	Pipes	29	13	36.639	44.271	68.497	99.707	36.639	44.271	68.497	99.707	31.876	38.516	59.592	86.745
R	Windowprof	Profiles for	90	20	27.625	34.450	58.342	94.761	30.694	38.278	64.824	105.290	24.556	30.622	51.860	84.232
R	Other profile	Profiles for	80	24	104.953	127.897	195.094	268.534	131.191	159.871	243.868	335.668	99.705	121.502	185.339	255.107
R	Other profile	Profiles for	80	24	4.348	5.395	8.947	14.100	5.435	6.744	11.184	17.625	4.131	5.125	8.500	13.395
P	**For buildin**	**Building pr**	**57**		**790.534**	**864.177**	**1.050.080**	**1.276.309**	**976.130**	**1.065.559**	**1.289.064**	**1.559.196**	**493.472**	**548.096**	**692.846**	**870.591**
F	Cables	Cables for e	80	53	157.787	175.684	210.267	248.253	197.234	219.605	262.834	310.316	92.700	103.214	123.532	145.849
F	Films plastis	Insulation &	80	39	28.401	29.834	33.094	37.260	35.501	37.293	41.368	46.575	21.656	22.748	25.234	28.411
F	Hoses and p	profiles and	80	46	6.555	7.793	10.995	13.350	8.194	9.741	13.744	16.688	4.425	5.260	7.422	9.011
F	Other plast.	Inject.mould	80	58	29.552	31.490	35.715	41.821	36.940	39.363	44.644	52.276	15.515	16.532	18.750	21.956
R	Other profile	Electrical ap	80	24	1.763	2.153	3.203	4.130	2.204	2.691	4.004	5.163	1.675	2.045	3.043	3.924
P	**For electric**	**Electrics, e**	**80**		**224.058**	**246.954**	**293.274**	**344.814**	**280.073**	**308.693**	**366.593**	**431.018**	**135.970**	**149.801**	**177.981**	**209.150**
F	Cables	Cars cables	95	53	57.572	64.657	75.126	80.295	60.602	68.060	79.080	84.521	28.483	31.988	37.168	39.725
F	Films plastis	Instrument	95	39	35.877	37.572	37.940	37.953	37.765	39.549	39.937	39.951	23.037	24.125	24.361	24.370
F	Films plastis	Cabletapes	95	39	14.585	16.005	18.615	21.789	15.353	16.847	19.595	22.936	9.365	10.277	11.953	13.991
F	Hoses and p	Cars hoses	95	46	41.567	44.243	43.500	39.518	43.755	46.572	45.789	41.598	23.628	25.149	24.726	22.463
F	Coatings	Foamed film	95	56	52.027	52.994	48.613	44.576	54.765	55.783	51.172	46.922	24.097	24.545	22.515	20.646
F	Coatings	Tarpaulins	95	56	25.671	28.239	32.310	34.606	27.022	29.725	34.011	36.427	11.890	13.079	14.965	16.028
F	Organo-,Pla	Underfloor	95	65	121.268	134.585	142.774	147.374	127.651	141.668	150.288	155.131	44.678	49.584	52.601	54.296
F	Other plast.	Others, inje	95	58	12.971	14.182	16.020	19.128	13.654	14.928	16.863	20.135	5.735	6.270	7.083	8.457
R	Other profile	profiles for	95	24	4.015	4.479	5.566	7.398	4.226	4.715	5.859	7.787	3.212	3.583	4.453	5.918
R	Others	Battery sepa	95	6	6.013	6.255	8.302	9.956	6.329	6.584	8.739	10.480	5.950	6.189	8.215	9.851
P	**For automo**	**Automotive**	**95**		**371.566**	**403.211**	**428.766**	**442.593**	**391.122**	**424.433**	**451.333**	**465.887**	**180.073**	**194.789**	**208.039**	**215.744**
F	**Films plasti**	**Agriculture**	**80**		**22.391**	**23.264**	**22.538**	**20.309**	**27.989**	**29.080**	**28.173**	**25.386**	**27.989**	**29.080**	**28.173**	**25.386**
F	Films plastis	Blood and i	50	39	11.450	12.216	13.319	14.490	22.900	24.432	26.638	28.980	13.969	14.904	16.249	17.678
F	Hoses and p	Medical hos	50	46	4.468	4.208	3.748	3.336	8.936	8.416	7.496	6.672	4.825	4.545	4.048	3.603
F	Organo-,Pla	Dipped prod	50	65	5.242	5.734	6.321	7.390	10.484	11.468	12.642	14.780	3.669	4.014	4.425	5.173
F	**For Medici**	**Medicine**	**50**		**21.160**	**22.158**	**23.388**	**25.216**	**42.320**	**44.316**	**46.776**	**50.432**	**22.464**	**23.462**	**24.722**	**26.454**
F	Films plastis	Furniture	80	39	18.304	20.242	24.849	29.983	22.880	25.303	31.061	37.479	13.957	15.435	18.947	22.862
F	Hoses and p	Furniture pr	80	46	1.210	1.410	1.921	2.288	1.513	1.763	2.401	2.860	817	952	1.297	1.544
R	Rigid films	Furniture, ki	80	6	5.896	6.971	10.310	14.297	7.370	8.714	12.888	17.871	6.928	8.191	12.114	16.799
R	Rigid films	Frames for	80	6	2.497	3.276	5.666	8.307	3.121	4.095	7.083	10.384	2.934	3.849	6.658	9.761
R	Other profile	Furniture ot	80	24	8.874	10.719	16.332	22.875	11.093	13.399	20.415	28.594	8.430	10.183	15.515	21.731
P	**For Furnitu**	**Furniture**	**80**		**36.781**	**42.618**	**59.078**	**77.750**	**45.976**	**53.273**	**73.848**	**97.188**	**33.066**	**38.610**	**54.531**	**72.697**
F	Films plastis	Bags, lugga	80	39	39.351	40.900	41.412	42.827	49.189	51.125	51.765	53.534	30.005	31.186	31.577	32.656
F	Films plastis	Officesupply	70	39	74.365	72.984	72.230	70.797	106.236	104.263	103.186	101.139	64.804	63.600	62.943	61.695
F	Films plastis	Camping, le	70	39	32.301	33.468	33.646	33.913	46.144	47.811	48.066	48.447	28.148	29.165	29.320	29.553
F	Films plastis	miscellaneo	50	39	12.256	11.835	7.796	8.069	24.512	23.670	15.592	16.138	14.952	14.439	9.511	9.844
F	Hoses and p	Garden hos	80	46	14.882	16.107	18.240	20.327	18.603	20.134	22.800	25.409	10.045	10.872	12.312	13.721
F	Hoses and p	Drinking hos	80	46	28.514	29.466	26.737	21.992	35.643	36.833	33.421	27.490	19.247	19.890	18.047	14.845
F	Hoses and p	Other indus	70	46	10.173	11.026	12.493	13.900	14.533	15.751	17.847	19.857	7.848	8.506	9.637	10.723
F	Hoses and p	Other profile	50	46	14.145	17.075	25.595	32.313	28.290	34.150	51.190	64.626	15.277	18.441	27.643	34.898
F	Coatings	Artificial lea	70	56	67.846	78.401	85.829	88.028	96.923	112.001	122.613	125.754	42.646	49.281	53.950	55.332
F	Coatings	Conveyor b	80	56	28.129	29.943	32.023	36.943	35.161	37.429	40.029	46.179	15.471	16.469	17.613	20.319
F	Coatings	miscellaneo	50	56	2.966	3.210	3.389	3.043	5.932	6.420	6.778	6.086	2.610	2.825	2.982	2.678
F	Organo-,Pla	Rotational	70	65	8.197	8.822	9.501	10.647	11.710	12.603	13.573	15.210	4.099	4.411	4.751	5.324
F	Organo-,Pla	Slush mould	70	65	10.456	11.505	13.488	15.106	14.937	16.436	19.269	21.580	5.228	5.753	6.744	7.553
F	Organo-,Pla	miscellaneo	50	65	25.970	30.130	40.958	54.678	51.940	60.260	81.916	109.356	18.179	21.091	28.671	38.275
F	Other plast.	shoes, soles	50	58	57.143	59.497	65.958	73.180	114.286	118.994	131.916	146.360	48.000	49.977	55.405	61.471
F	Other plast.	miscellaneo	50	58	34.673	41.710	47.231	56.582	69.346	83.420	94.462	113.164	29.125	35.036	39.674	47.529
R	Rigid films	Office suppl	80	6	13.845	15.732	20.287	24.801	17.306	19.665	25.359	31.001	16.268	18.485	23.837	29.141
R	Rigid films	Printed films	80	6	17.896	20.177	25.768	32.887	22.370	25.221	32.210	41.109	21.028	23.708	30.277	38.642
R	Rigid films	Credit cards	80	6	13.451	15.677	20.166	25.738	16.814	19.596	25.208	32.173	15.805	18.420	23.695	30.242
R	Rigid films	Diskettes	80	6	4.020	3.719	1.614	1.087	5.025	4.649	2.018	1.359	4.724	4.370	1.896	1.277
R	Rigid films	Other techn	50	6	11.535	12.775	15.464	20.038	23.070	25.550	30.928	40.076	21.686	24.017	29.072	37.671
R	Sheets	Chemical ap	80	12	5.131	6.120	9.640	15.422	6.414	7.650	12.050	19.278	5.644	6.732	10.604	16.964
R	Sheets	Miscellaneo	50	12	18.304	21.313	26.162	29.980	36.608	42.626	52.324	59.960	32.215	37.511	46.045	52.765
R	Other profile	Miscellaneo	50	24	12.403	15.505	25.951	39.392	24.806	31.010	51.902	78.784	18.853	23.568	39.446	59.876
R	Gramophon	Gramophon	50	3	7.729	8.581	10.474	11.520	15.458	17.162	20.948	23.040	14.994	16.647	20.320	22.349
R	Other rigid	Other rigid	50	6	31.283	33.591	39.115	50.847	62.566	67.182	78.230	101.694	58.812	63.151	73.536	95.592
P	**For househ**	**Household**	**61**		**596.964**	**649.269**	**731.167**	**834.057**	**953.821**	**1.041.611**	**1.185.598**	**1.368.801**	**565.712**	**617.550**	**709.508**	**830.933**
F	Films plastis	Packaging-	60	39	45.960	45.630	44.814	44.013	76.600	76.050	74.690	73.355	46.726	46.391	45.561	44.747
F	Organols-,P	Cans	60	65	26.339	27.011	27.435	28.542	43.898	45.018	45.725	47.570	15.364	15.756	16.004	16.650
R	Rigid films	Rigid films	60	6	209.209	220.935	252.535	292.340	348.682	368.225	420.892	487.233	327.761	346.132	395.638	457.999
R	For bottles	Bottles	77	6	248.339	193.571	104.699	57.671	321.803	250.834	135.671	74.731	302.495	235.784	127.531	70.247
P	**For packag**	**Packaging**	**67**		**529.847**	**487.147**	**429.483**	**422.566**	**790.983**	**740.127**	**676.978**	**682.890**	**692.346**	**644.062**	**584.734**	**589.643**

Table B2.1: Data of table B1.1 regrouped in TNO categories (in ton)

					Pure PVC in year (TNO calculation)			
	Europe ˝ Intermediates	Europe Finished product	Availabibity of post consumer waste %	Total additives in PVC compounds (%)	1998	2000	2005	2010
P	**PVC**	**Total PVC**	**63**	**0**	**2.151.091**	**2.245.450**	**2.480.533**	**2.840.599**
F	Cables	Cables domestic installations	30	53	9.281	10.641	14.858	20.202
F	Films plastisiced	Films for building applications	50	39	6.329	7.414	10.745	14.873
F	Floor	Flooring paste based	80	54	118.967	126.138	139.210	161.307
F	Floor	Floor, calendered	80	70	55.342	59.934	71.508	81.489
F	Hoses and profiles	Building profiles and hoses	80	46	61.050	64.773	66.292	64.408
F	Coatings	PVC wallpaper	80	56	63.849	63.092	59.392	56.823
F	Coatings	Air-inflated structures,containers,Ma	80	56	5.400	5.685	5.988	6.032
F	Coatings	Roof coverings, paste	50	56	2.353	2.689	3.508	4.108
F	Organo-,Plastisols	Varnishes - coil coating	80	65	6.608	6.974	7.845	9.209
R	Rigid films	Pipe insulation film	80	6	928	1.186	2.042	3.207
R	Sheets	sheets for buildg. applications	80	6	3.096	3.806	6.168	9.453
R	Pipes and fittings	Pipes	29	13	31.876	38.516	59.592	86.745
R	Windowprofiles	Profiles for windows	90	20	24.556	30.622	51.860	84.232
R	Other profiles	Profiles for other building applic.	80	24	99.705	121.502	185.339	255.107
R	Other profiles	Profiles for cable ducts	80	24	4.131	5.125	8.500	13.395
P	**For building**	**Building products**	**57**	**0**	**493.472**	**548.096**	**692.846**	**870.591**
F	Cables	Cables for e&e	80	53	92.700	103.214	123.532	145.849
F	Films plastisiced	Insulation & adhesive tapes	80	39	21.656	22.748	25.234	28.411
F	Hoses and profiles	profiles and hoses for electrical	80	46	4.425	5.260	7.422	9.011
F	Other plast.conv.	Inject.moulding a.o.elec.applications	80	58	15.515	16.532	18.750	21.956
R	Other profiles	Electrical appliances	80	24	1.675	2.045	3.043	3.924
P	**For electrics**	**Electrics, electronics**	**80**	**0**	**135.970**	**149.801**	**177.981**	**209.150**
F	Cables	Cars cables	95	53	28.483	31.988	37.168	39.725
F	Films plastisiced	Instrument panels a.o.films	95	39	23.037	24.125	24.361	24.370
F	Films plastisiced	Cabletapes and cablebinders	95	39	9.365	10.277	11.953	13.991
F	Hoses and profiles	Cars hoses & profiles	95	46	23.628	25.149	24.726	22.463
F	Coatings	Foamed films / artificial leather	95	56	24.097	24.545	22.515	20.646
F	Coatings	Tarpaulins for lorries	95	56	11.890	13.079	14.965	16.028
F	Organo-,Plastisols	Underfloor protection	95	65	44.678	49.584	52.601	54.296
F	Other plast.conv.	Others, injection moulding for cars	95	58	5.735	6.270	7.083	8.457
R	Other profiles	profiles for cars	95	24	3.212	3.583	4.453	5.918
R	Others	Battery separators	95	6	5.950	6.189	8.215	9.851
P	**For automotive**	**Automotive**	**95**	**0**	**180.073**	**194.789**	**208.039**	**215.744**
F	**Films plastisiced**	**Agriculture**	**80**	**0**	**27.989**	**29.080**	**28.173**	**25.386**
F	Films plastisiced	Blood and infusion bags	50	39	13.969	14.904	16.249	17.678
F	Hoses and profiles	Medical hoses	50	46	4.825	4.545	4.048	3.603
F	Organo-,Plastisols	Dipped products	50	65	3.669	4.014	4.425	5.173
F	Hoses and profiles	Other industrial hoses	70	46	7.848	8.506	9.637	10.723
F	Coatings	Conveyor belts	80	56	15.471	16.469	17.613	20.319
R	Rigid films	Office supply	80	6	16.268	18.485	23.837	29.141
R	Rigid films	Other technical applications	50	6	21.686	24.017	29.072	37.671
R	Sheets	Chemical apparatus	80	12	5.644	6.732	10.604	16.964
F	**Medicine, ind.**	**Medicine, industry**	**50**	**0**	**89.380**	**97.670**	**115.485**	**141.272**
F	Films plastisiced	Furniture	80	39	13.957	15.435	18.947	22.862
F	Hoses and profiles	Furniture profiles	80	46	817	952	1.297	1.544
R	Rigid films	Furniture, kitchens	80	6	6.928	8.191	12.114	16.799
R	Rigid films	Frames for drawers	80	6	2.934	3.849	6.658	9.761
R	Other profiles	Furniture other applications	80	24	8.430	10.183	15.515	21.731
P	**For Furniture**	**Furniture**	**80**	**0**				
F	Films plastisiced	Bags, luggage a. cushions	80	39	30.005	31.186	31.577	32.656
F	Films plastisiced	Officesupply, books, photogr.articles	70	39	64.804	63.600	62.943	61.695
F	Films plastisiced	Camping, leisure, toys, sport	70	39	28.148	29.165	29.320	29.553
F	Films plastisiced	miscellaneous plastisiced films	50	39	14.952	14.439	9.511	9.844
F	Hoses and profiles	Garden hoses	80	46	10.045	10.872	12.312	13.721
F	Hoses and profiles	Drinking hoses	80	46	19.247	19.890	18.047	14.845
F	Hoses and profiles	Other profiles	50	46	15.277	18.441	27.643	34.898
F	Coatings	Artificial leather (not car)	70	56	42.646	49.281	53.950	55.332
F	Coatings	miscellaneous coatings	50	56	2.610	2.825	2.982	2.678
F	Organo-,Plastisols	Rotational mouldings	70	65	4.099	4.411	4.751	5.324
F	Organo-,Plastisols	Slush mouldings	70	65	5.228	5.753	6.744	7.553
F	Organo-,Plastisols	miscellaneous organosols a. plastis.	50	65	18.179	21.091	28.671	38.275
F	Other plast.conv.	shoes, soles	50	58	48.000	49.977	55.405	61.471
F	Other plast.conv.	miscellaneous (fibres etc.)	50	58	29.125	35.036	39.674	47.529
R	Rigid films	Printed films	80	6	21.028	23.708	30.277	38.642
R	Rigid films	Credit cards	80	6	15.805	18.420	23.695	30.242
R	Rigid films	Diskettes	80	6	4.724	4.370	1.896	1.277
R	Sheets	Miscellaneous sheet products	50	12	32.215	37.511	46.045	52.765
R	Other profiles	Miscellaneous	50	24	18.853	23.568	39.446	59.876
R	Gramophone	Gramophone records	50	3	14.994	16.647	20.320	22.349
R	Other rigid	Other rigid products	50	6	58.812	63.151	73.536	95.592
P	**For household**	**Household**	**61**	**0**	**531.861**	**581.951**	**673.276**	**788.812**
F	Films plastisiced	Packaging-wrapping a.other films	60	39	46.726	46.391	45.561	44.747
F	Organols-,Plastisols	Cans	60	65	15.364	15.756	16.004	16.650
R	Rigid films	Rigid films	60	6	327.761	346.132	395.638	457.999
R	For bottles	Bottles	77	6	302.495	235.784	127.531	70.247
P	**For packaging**	**Packaging**	**67**	**0**	**692.346**	**644.062**	**584.734**	**589.643**

Table B3.1: PVC waste arisings per end-use category, aggregated, in ton

Year Waste type	1998	2000	2005	2010
Agriculture	27989	29080	28173	25386
Building				
# pipes	31876	38516	59592	86745
# window profiles	24556	30622	51860	84232
# other profiles	164886	191400	260131	332910
# cables	9281	10641	14858	20202
# flooring	174309	186072	210718	242796
# roofing	7754	8374	9496	10140
# other	80810	82471	86191	93566
Housh. Other	531861	581951	673276	788812
Packaging (househ., distr.)				
# bottles	302495	235784	127531	70247
# other PVC-packaging	389851	408278	457203	519395
Industry	89380	97670	115485	141272
Automotive	180073	194789	208039	215744
E and E	135970	149801	177981	209150
Total EU	2151091	2245450	2480533	2840599

Table B3.2: PVC waste arisings per end-use category, aggregated, in kton

Year Waste type	1998	2000	2005	2010
Agriculture	28	29	28	25
Building				
# pipes	32	39	60	87
# window profiles	25	31	52	84
# other profiles	165	191	260	333
# cables	9	11	15	20
# flooring	174	186	211	243
# roofing	8	8	9	10
# other	81	82	86	94
Housh. Other	532	582	673	789
Packaging (househ., distr.)				
# bottles	302	236	128	70
# other PVC-packaging	390	408	457	519
Industry	89	98	115	141
Automotive	180	195	208	216
E and E	136	150	178	209
Total EU	2151	2245	2481	2841

Appendix C: List of organisations contacted

Within the context of the project, the following organisations were contacted for obtaining information. We thank each of them kindly for their help and cooperation. Obviously, listing the organisations contacted here does not imply that they necessarily agree with the contents of this report.

Representative organisations
- ECVM, Brussels, Belgium
- APME, Brussels, Belgium
- DKR, Germany
- EuPC, Germany
- Danish Plastics Federation
- Centro Di Info Sul PVC, Italy
- PVC Steering Committee, the Netherlands
- Finnish Plastics Industry Federation
- BPF, UK
- SPMP, France,
- Solvay, Belgium
- Plast- och Kemibrancherna, Sweden
- Iberian PVC Forum, Spain/Portugal
- AgPU, Germany
- API, Austria
- VKE, Germany

Industry
- Texaco, Rotterdam, the Netherlands
- BP, UK
- BASF, Germany
- Bremen Stahlwerke, Germany
- VEBA, Germany
- SVZ ‘Schwarze Pumpe’, Germany
- BSL, Germany
- Akzo Nobel, the Netherlands
- Linde, Germany
- NKT, Denmark
- Solvay, Belgium
- EVC, Belgium
- Vestolit, Germany

Others

- German Ministry of Environment
- Austrian Ministry of Environment
- Prognos A.G., Switzerland
- SOFRES, France
- DG XI, DG III, EU, Brussels

Obviously, apart from direct contact with such organisations, other information was obtained via a literature search and an internet survey. If such information was sufficient, no direct further contact was established.

Appendix D: Gross list of initiatives for feedstock recycling

This Appendix presents the gross list of initiatives in the field of feedstock recycling. It is the result of a literature search, including some information from companies involved in these projects. The processes in this table are listed per type of technology:

- degradative extrusion
- pyrolysis
- hydrogenation
- gasification
- incineration
- blast furnace
- cement kilns (although this is not a real feedstock recycling process)
- depolymerisation processes for condensation polymers (not suitable for PVC)

Of these processes the following elements are listed (if available) in the table:

a. name of the technology;
b. actors involved in the development;
c. a description of the technology including:
    - accepted materials and the input specification (some processes need pre-treatment of the plastic waste);
    - outputs: types and quality of secondary materials;

d. current technical status (research, feasibility proven, pilot plant or commercial);
e. summary of some important data concerning this project:
    - date of start-up;
    - capacity in tonnes per annum;
    - acceptation criteria with regard to the chlorine content;

f. the information source.

a	b	C	d	e	f
Technology name	**Actor(s) involved**	**Description**	**Technical status**	**Start-up date** **Capacity** **Chlorine content**	**Literature**
Degradative extrusion					
IKV extrusion process	Institüt für Kunststoff-verarbeitung (IKV), Aachen	IKV has developed several process options which pretreat the waste plastics by degradative extrusion at 300 - 400 ºC. Laboratory experiments have been carried out with a Werner & Pfleiderer twin screw extruder of the type ZSK 30. All types of plastics mixtures processed during testing were degraded to low viscosity oily melts. Tests starting with mixture containing up to 80 wt% PVC always show a chlorine content of less than 0.2 wt%. Besides that viscosity is considerably reduced. Chalk filled PVC products showed high amounts of inorganic chloride. Research is continuing.	Research	Date: 1991 Cap: ? Chl: tests up to 80% PVC	[13] [5, p414,415,416]
Leuna degradative extrusion	Leuna Werke AG, EWvK, Werner&Pfleiderer	Leuna has been developing degradative extrusion technology since the mid seventies and is cooperating with EWvK and Werner&Pfleiderer. Results of tests are claimed to demonstrate the feasibility of further processing the extruded melts by technology options such as visbreaking and hydrogenation. A large scale experiment in Leuna has been carried out in 1993. Costs for this pretreatment: 178 DM/t.	Feasibility proven	Date: 1993 Cap: ? Chl: ?	[13] [5, p.415, 416 419]
Stahlwerke Bremen degradative extrusion	Stahlwerke Bremen (former Klöckner)	Technology developed to handle plastic waste with PVC. Degradative extrusion is used to remove HCl and to lower the viscosity. Extrusion equipment has been obtained from Erwepa in Erkrath. At 200 kg/hr the chlorine content was lowered to < 0,5% processing a DSD fraction. Model mixtures resulted in < 0,05%. The technology was developed for pretreatment of PVC containing waste for use in a blast furnace. However, experiments showed that pretreatment is not necessary.	Research	Date: 1992 Cap: 400 kg/hr; Chl: < 5%, planning: higher content	[5, p.415, 470, 476, 485] [24] [25]

Pyrolysis					
Akzo process	Akzo Nobel, The Netherlands	Technology: Fast pyrolysis (or steam gasification) in a circulating fluidised bed system (two reactors) with subsequent combustion. Research at Akzo started in 1992, technology chosen was based on Battelle process. Experiments with 100% PVC waste have been carried out with promising results. Project momentarily on hold because of financing problems. Process conditions: hot circulating sand bed, steam at 700-900 ºC; Input: mixed waste including high percentage of PVC waste; Input quality: shredded waste; Output: HCl, CO, H_2, CH_4 and, depending on the feedstock composition, other hydrocarbons, fly ash.	Pilot	Date: 1994 Cap: 20-30 kg/hr Chl: high PVC content planned: 50 kt/yr	[10] [14] [15] [21]
BASF cracking process	BASF AG	Technology: liquid phase thermal cracking (pyrolysis/ depolymerisation). The technology was developed to process DSD waste. Due to lack off waste no large scale plant was build and the pilot plant was shut down. Process conditions: ca. 400 ºC; Input: plastics waste; Input quality: max. 8% PVC [11]; Output: HCl, petrochemical gaseous and liquid feedstocks;	Pilot (shut down)	Date: 1994-1996 Cap: 15,000 t/yr Chl: max. 8% PVC	[5, p.435, 453] [9] [11, p.21] [13] [27] [28]
NRC process	NKT Research Centre A/S, Denmark	Technology: Pyrolysis with subsequent metal extraction. The aim is to produce purified calcium chloride instead of HCl. Pilot plant project started in September 1998 and will finish in August 2000. Process conditions: p= 2-3 bar, T= max. 375 ºC; Input: PVC waste (cables, flooring, profiles, ..); Input quality: pretreatment of mixed plastic waste: separation of PE, PP, wood etc., resulting in almost pure PVC waste; Output: Calcium chloride, coke, organic condensate (for use as fuels) and heavy metals for metal recycling.	Research Pilot is being build	Date: pilot plant August 2000 Cap: pretreatment 1000t/yr; pyrolysis 200 t/yr PVC. Chl: up to 100% PVC	[15] [23]

Polymer Cracking process	BP Chemicals, Elf Atochem, DSM, Enichem, CREED and APME (also Fina in an earlier stage of the project)	Technology: Cracking of plastic waste in a fluidized bed reactor of sand. The product (paraffinic wax) is cleaned from fine particles and HCl (amongst others) and fractionated. 80-90% of the plastic waste is recovered as liquid product. Ca. 20 ppm chlorine remains with an input containing 2% PVC. Process conditions: T = ca. 500ºC; Input: clean plastic waste, incl. 2wt% PVC (max. 4%), minimum amount of plastics 90 wt%; Output: main product is paraffinic wax to be used as a feed for refineries or steam crackers.	Pilot	Date: 1994 (pilot) Cap: 50 kg/hr; 25,000 ton/yr planned; Chl: < 2 wt% PVC (max. 4%)	[1] [5,p.428-433] [7, p.8] [11, p.20] [12] [17] [31]
KEU process	Kraftanlagen Heidelberg Energie und Umwelttechnik (KEU)	Technology: Pyrolysis in a vertical reactor at 350-550ºC with pyrolysis gas and coke as products. HCl is stripped from the gas with water (ca. 40% yield). Remaining gas is burned. Pyrolysis coke and oil are burned in a rotary drum incinerator at 1250 ºC to produce energy. Resulting slag/ash is vitrified in a special oven at 1500 ºC. Trials show low HCl yield and high chlorine content in coke. Further research is necessary. Process conditions: 350 – 550 ºC; Input: PVC waste; Input quality: pelletised or granulated; Output: energy, slag, dust.	Research	Date: 1998 Cap: ? Chl: high PVC content	[10] [15]
Battelle process	Battelle Memorial Institute (Columbia, Ohio)	Technology: High temperature gasification in a sand filled fluid bed in which both steam and nitrogen can be used as transport gas. Technology is patented in 1992 (US5,136,117). The Akzo process is based on this technology. Process conditions: 800 – 1000 ºC, t=2 sec.; Input: PE, PS, PVC, mixed plastics; Input quality: shredded, particle size < 2,5 cm; Output: 40% ethylene, 27% methane, 17% H_2, small amounts of other substances.	Pilot	Date: 1992 Cap: 9 kg/hr (planned: 500 t/day) Chl: tests with 100% PVC are carried out.	[1] [13] [20]

PARAK process	Paraffinwerk Webau GmbH	The technology is based on destructive distillation of polyolefines. A combination of thermal cracking processes and fractionation of the product using distillation has been developed. From polyolefine waste ca. 50 wt% paraffins (C18 to C50) and waxes are produced and ca. 40 wt% oil with high quality. A plant based on this technology was build by Paraffinwerk Webau (1981) en was further developed by Baufeld Oel GmbH München. A pilot plant was then build at Webau with a capacity of 20,000 tonnes per year. Input material are DSD films and bottle waste.	Pilot	Date: 1997 Cap.: 20.000 t/yr Chl: as low as possible	[32] [33]
Fuji process	Fuji Recycle Ind., Mobil Oil, Nippon Steel Corp., Shinagawa Fuel Co.,	Technology: Low temperature catalytic cracking (low temp. pyrolysis) process at ca. 400 ºC. The input material has to be thermally pretreated at 250ºC. Development problem is the sensitivity of the zeolite catalyst towards impurities coming from the waste. Separation of PVC from polyolefines takes place by wet techniques (e.g. sink-float). After tests with a pilot (500 t/yr, start up 1988) a commercial plant was erected in 1992 in Hyogo (5000 t/j). Processing costs are said to be $225 per ton. A second plant can also accept PVC in the PO waste streams. Processing conditions: T= 400 ºC, catalyst: ZSM-5; Input : polyolefines waste; Output : 80% oil, 15% gas, 5% solid rest fraction; Input quality: separation of impurities and PVC with sink-float technique.	Operational	Date: 1992 Cap: 5000 t/yr Chl: as low as possible after wet separation.	[1, tab.1+5] [5, p.428] [11, p.20]
Wayne process	Wayne Technology Corp.	Technology: High temperature pyrolysis at 900 ºC; Input: PE, PP, PS, wood pellets; Output: 75-89% medium oil, 15-20% light oil; A demonstration plant was build with a capacity of 50 t/day.	Feasibility proven	Date: ? Cap.: 50 t/day Chl: ? (low)	[1]

Toshiba process	Toshiba Corp.	Technology: Pyrolysis Process conditions: p>10 atm, NaOH Input: Plastics containing chlorine (20%) with other plastics (no epoxide resins); Output: 90% oil; Input quality: powder.	Research	Date: ? Cap: ? Chl: 20% chlorine containing plastics	[1]
Veba pyrolysis process	Veba Oel AG in Gelsenkirchen (Veba Pyrolyse anlagen)	Technology: High temperature pyrolysis. Further treatment of products in hydrogenation or gasification plant. Process conditions: p=1 kPa, T= 600-800ºC, t=30 min.; Input: DSD mixed plastics, DSD-light and heavy fraction, DSD-PUR, waste; Input quality: Depolymerised (oil at 250-300 ºC); Output: 35-58% light oil, 23-40% gas, heavy oil fraction is carried back in the process.	Operational, tests with plastic waste	Date: 1986 Cap: 500 kg/hr (planned: 10 t/hr) Chl: ?	[1] [5, p.435] [13]
Berliner process	BC Berlin Consult GmbH	Technology: High temperature pyrolysis; Process conditions: 650 – 750 ºC; Input: DSD-plastics; Output: 5% cokes, 2% metals, 3% inert solids, 38% BTX and light fraction, 3% medium fraction, gas.	Pilot	Date: ? Cap: planned: 20.000 t/yr Chl: ?	[1]
Noell, Dr. Otto-Verfahren	Noell (Salzgitter, Germany)	Technology: High temperature pyrolysis in a rotary kiln. About 25% of the feedstock can be converted into oil. The uncondensed gas is burned at 1200 ºC and the produced heat then used as pyrolysis heat necessary for the reactor. Process conditions: T = 650 – 750 ºC, medium pressure, N_2; Input: Plastic waste, tests with: 65% linear, 20% cyclic monomer structure, 15% PVC; Input quality: bulk density 250 kg/m^3; Output: cokes, pyrolysis oil, gas.	Technology proven	Date: 1983 Cap: 6 t/hr Chl: < 15% (?)	[1] [5, p.435] [11, p.20]

Hamburg/ABB process	University of Hamburg, ABB, C.R. Eckelmann	Technology: High temperature pyrolysis using a fluidized bed; Technique was developed at the university of Hamburg with a lab pilot plant of 20-60 kg/hr. At the university it was determined that with PVC, nylon and polycarbonates problems arose in the reactor. A demonstration plant was build in Ebenhausen at Ingolstadt (Ger.) operated by ABB. The pilot worked well with polyolefines, but problems existed with PVC. Operation stopped in 1990 due to different technical problems and the lack of any economical prospect. Process conditions: fluid bed 600 – 900 ºC; Input: plastic waste; Output: pyrolysis gas (methane, ethane, propane) light gasoline oil, tar, toluene/benzene rich fractions (in total up to 50% liquid product, depending on input material); the oil can be converted into organic chemicals. Input quality: shredded, PVC separated.	Pilot	Date: 1986 Cap: 2 * 1 t/hr Chl: as low as possible Closed in 1990	[1] [5, p.435-443] [11, p.19]
Veba visbreaking process	Veba Oil, EWvK	Visbreaking as pretreatment for hydrogenation. see: VCC process (Hydrogenation).	Operational	Date: oct. 1993 Cap: 80,000 t/yr Chl: < 10 wt% PVC	[13] [5]
Leuna visbreaking process	Leuna-Werke GmbH	Technology: Visbreaking (thermal degradation in a stirred reactor). Experiments have been carried out on labscale. Large scale experiments are planned in 1994. The project has stopped in 1996 due to lack of interest although good results were obtained. Process conditions: T=460-470ºC, p=10 bar, t=6-9 min.; Input: PE, PP, DSD light fraction mixed with petrochemical residues; Input quality: ca. 5% plastic waste mixed with vac. residue; Output: no difference with 100% residue input.	No further research; project stopped.	Date: 1994 Cap: ?; planned 100.000 t/yr Chl: < 2%	[1] [13]

KWU process	Siemens KWU (Kraftwerk Union Umwelttechnik)	Technology: Low temperature pyrolysis in a rotary kiln with combustion of gas products; Process conditions: 450-500 ºC; Input: unsorted plastic waste; Output: 65% gas, 35% solids (stones, glass, metals). Costs are said to be ca. 200 DM per ton.	Pilot (400 kg/hr) Operational in Ulm (Germany)	Date: ? Cap: 3 t/hr Ulm (planned: 100.000 t/yr) Chl: x%	[1] [5, p.435] [11, p.24]
DBA process	DBA (Deutsche Babcock Nalagen)	Technology: Low temperature pyrolysis in a rotary kiln with combustion of gas products; Plant build in Burgau, Günzburg. Process conditions: 450 – 500 ºC indirect heating; Input: plastics waste; Output: energy; Costs: ca. 160 DM/ton waste.	Operational	Date: 1980 Cap: 6 t/hr Chl: ?	[5, p.435] [11, p.25]
Kobe Steel process	Kobe Steel	Technology: pyrolysis in a rotary kiln. A plant has been build in Kobe, Japan. Process conditions: 500-700 ºC indirect heating; Input: plastics waste; Output: oil, gas (as energy source).	Operational	Date: ? Cap: 1 t/hr Chl: ?	[5, p.435] [18]
Leuna steam cracking process	Leuna-Werke GmbH	Technology: Degradative extrusion + steam cracking. Light plastic waste fraction is treated with degradative extrusion. The product of this extrusion is mixed with paraffin from hydrocracking. This mixture is the input for the steam cracker. Tests have been carried out in production plant. The project has stopped in 1996 due to lack of interest although good results were obtained. Process conditions of extrusion: T = 400-500ºC; Process conditions of steam cracker: T<800ºC, t=1 sec., H_2; Input: mixture of hydrocrack paraffin and 13 wt% plastic waste; Output: C2, C3 and C4 monomers.	No further research, project stopped.	Date: 1993 Cap: planned: 40.000 t/yr Chl: input for steamcracker: < 0,0005%	[1] [5, p.403, 416]

Ebara process	Tsukishima, Japan	Technology: pyrolysis. The process consists of two fluidised beds one for pyrolysis and the other one for combustion. The fluidised bed is generated by a flow of air. The product is mostly oil, which is directly burned to recover energy. A plant has been build in Yokohama, Japan; Input: plastics waste; Output: energy.	Operational	Date: ? Cap: 4 t/hr Chl: ?	[5, p.435] [18]
Chevron process	Chevron/Mobil	Technology: Processing in cokes oven. Input: plastics waste as heated material in used motoroil Output: ?	?	Date: ? Cap: ? Chl: ?	[1]
Lyondell process	Lyondell Petroleum Co.	Technology: Processing in cokes oven. Input: PE, PP, PS, refinery and pyrolysis products; Input quality: processed by pyrolysis of Conrad Ind.; Output: monomer or others.	Research	Date: ? Cap: ? Chl: ?	[1]
Exxon process	Exxon	Technology: Processing in cokes oven. Exxon has carried out tests to add plastics waste to the Esso-coker in the refinery in Karlsruhe. Input: 5% mixed plastic waste.	No further research; project stopped	Date: ? Cap: planned: 50.000 t/yr Chl: ?	[1]
Amoco	Amoco Chem. Corp.	Technology: Catalytic cracking. Processing conditions: 490-580 ºC; Input: PE, PP, PS. plastic waste mixed with vacuum gas oil; Input quality: in solution in heat refinery fraction.; Output: Naphtha, light mineral oil gases.	Pilot	Date: 1991 Cap: ? Chl: ?	[1] [13]
Kentucky	University of Kentucky	Technology: Catalytic cracking; Process conditions: T=400-450ºC, p=56 atm, zeolith cat., H_2; Input: plastic waste; Output: 90% oil.	Research	Date: ? Cap: ? Chl: ?	[1]

Mazda	Mazda Motor Corp.	Technology: Catalytic cracking; Process conditions: metal salt; Input: shredder material from cars; Output: 60% oil (petrol, kerosene).	Pilot	Date: ? Cap: ? Chl: ?	[1]
Nikon	Nikon Rikagaku	Technology: Catalytic cracking; Process conditions: T=200-250ºC, p=1 atm, metal cat.; Input: plastic waste; Output: 80% oil; Input quality: particle size 10 mm.	Pilot	Date: ? Cap: 8 t/day Chl: ?	[1]

Hydrogenation					
Veba VCC process	Veba Oel AG in Bottrop	Veba combi cracking process. The plant configuration includes a depolymerisation (visbreaking) section and the VCC section. A plant has been realised in the KAB (Kohleölanlage Bottrop) site. Process conditions: Depolymerisation: T=350-400ºC Hydrogenation: 400-450 ºC, p= ca. 100 bar, CaO, H_2; Input: mixed plastics (MPW from DSD, metals have to be removed, max 4% PVC); Output: syncrude (liquid product), gas, HCl, hydrogenation residue.	Operational	Date: 1993 Cap: 10 tonnes per hr; up to 80.000 t/yr, Chl: < 2 wt%	[5, p.428, 444-453] [1, p.215, 220] [10] [11, p.21] [9] [13] [22] [28]
RWE hydrogenation process	RWE-Entsorgungs AG	Technology: Hydrogenation after depolymerisation of plastic waste. Plastic waste is mixed with oil (vacuum residue) followed by depolymerisation (10 kg/hr). After that hydrogenation of the depolymerizate (without mixing with residue which is different from VCC) takes place. HCl is removed after depolymerisation. Process conditions: T=400-500ºC, p=300-400 bar, H_2; Input: dirty plastic waste; Output: 80% oil, 10% heat gas, solids.	Nor further research, project stopped	Date: 1990 Cap: 10 kg/hr Chl: ?% Planned: 70.000 t plastic waste in 1996	[1] [5, p 448] [11, p.22] [9]
Hiedrierwerke process	Hiedrierwerke Zeitz GmbH	Technology: Cracking by hydrogenation Process conditions: T=400ºC, p=250 bar, H_2; Input: 100% plastic waste; Input quality: visbreaking melt; Output: paraffin oil, gas.	Project stopped	Date: ? Cap: 120.000 t/yr planned Chl: ?	[1] [2, p.461]
Freiberg process	Bergakademie Freiberg	Technology: Cracking by hydrogenation; Process conditions: T=400-435ºC, p=28 MPa, t=45 min, H_2 ; Input: PVC, PE, PS, PUR; Input quality: small particles; Output: oil and gas, solids.	Project stopped	Date: ? Cap: ? Chl: ?	[1]

Böhlen process	Sächsische Olefinewerke AG, Böhlen	Technology: Cracking by hydrogenation; Process conditions: T=450-470ºC, p=27 MPa, H_2 , 3,5 m^3/h CaO; Input: PE, regranulate from film, household waste; Input quality: 8-11% plastics, dissolved in vacuum residue; Output: 80% oil .	Project stopped	Date: ? Cap: 2-3,5 kg/h Chl: ?	[1] [2, p.455]
ITC process	Inst. für technische Chemie und Umweltschutz GmbH	Technology: Cracking by hydrogenation Process conditions: T=708 K, p=1-10 MPa, t=30 min, zeolite cat., methanol, H_2 ; Input: PE, PS, PP; Output: 80% liquid and gaseous hydrocarbons.	Research	Date: ? Cap: ? Chl: not designed to treat PVC	[1] [13]

Gasification processes					
Texaco process	Texaco	Technology: gasification of pretreated mixed plastic waste. The technology is based on heavy oil gasification and consists of two parts, a liquefaction step (pretreatment) and an entrained bed gasifier. A pilot is available in the USA. A project to erect a large scale plant (40-50 kt/year of MPW) in Rotterdam (Pax project) ceased around 1997. This was due to lack of feedstock with the right specification. Process conditions: T steam = 1200-1500 ºC, p= 20 - 60 bar, O_2, steam; Input: mixed plastic waste, incl. max. 10% PVC, plastics content > 90 wt%; Input quality: roughly cleaned and shredded plastic waste; Output: Synthesis gas (mainly CO and H_2), slag, fines.	Pilot	Date: Cap: 10 t/d Chl: < 10 wt% PVC Project for large scale plant in NL was ceased ca. 1997.	[1] [5, p. 458, 471] [6, p.15-16] [11, p.22] [10] [17] [28]
Shell process	Shell-Chemicals	The Shell process for heavy oil gasification can be used for the gasification of plastic waste. The preprocessing of the plastic waste has to ensure that the preprocessed waste can be added to the normally used input materials: low temperature reactor (to remove HCl) and degradation (e.g.by visbreaking, vacuumvisbreaking). Research is still going on to determine the best way of preprocessing and optimum blend composition. Target (status 1993) was to produce a feedstock containing less than 10 ppm, chlorine from a waste stream containing 10 wt% PVC. The work on the Shell feedstock recycling project ceased in 1995 (reason?). Process conditions: T_E<280 ºC, T_A =1350 ºC, p=40-100 bar, O_2, steam, etc.; Input: mixed plastic waste incl. PVC; Input quality: removal of chlorine (200-400ºC), visbreaking (400-500ºC); Output: Synthesis gas.	Pilot	Date: ? Cap: ? Chl: x% Ceased in 1995	[1] [5, p. 458, 471, 485] [13] [16]

Molten metal technology	Molten Metall Technology	Technology: Catalytic extraction processing; gasification in a metal bath. For the treatment PVC rich waste streams a nickel seems most suitable. PVC is decomposed into the elements Cl, C and H. By adding pure oxygen HCl and synthesis gas are formed. However only 30% of HCl is recovered in lab-scale experiments. Further research work with PVC was abandoned in 1998. Process conditions: T = 1400 ºC, p= 7-8 bar; Input: unsorted organic waste; Output: Synthesis gas, HCl, metals, slag.	Research with PVC has stopped	Date: ? Cap: 36.000 sq-ft plant Chl: high content	[1] [10]
Laubag process	SVZ (Sekundär verwertunszentrum) Schwarze Pumpe	Already since decades Laubag operates pressurised fixed-bed gasification as well as pressurised oil gasification and slurry gasification. Laubag uses Schwarze Pumpe processes. A 50 ktons plant is in operation using DSD waste. Pressurised fixed-bed gasification: The plant was developed for gasification of brown coal briquettes and modified for partly use of plastics waste (also shredder waste from ELV). Since ’92 around 40,000 tonnes of plastic waste from DSD were processed. Process conditions: drying (250-400 ºC), degassing (400-800 ºC), gasification (800-1000ºC), combustion (1000-1400ºC), ash zone (250-600 ºC), p=25 bar; Input: up to 30% plastic waste, steam, O_2; Output: heat, ash, tar oil (ash and tar oil is gasified in an entrained-flow gasification process to produce synthesis gas.	Operational	Date: 1992 Cap: 100 kt/yr plastic waste Chl: < 10%	[1][5, p.466] [10][11, p.23] [13]

Linde process	Linde KCA	Technology: Gasification in a molten slag bath. Research has been successful, plans for erecting a pilot plant exist, but no decision has been made yet. Process conditions: T = 1400-1600 ºC, pressurised, O_2/steam; Input: PVC, sand, oxygen and water; Output: synthesis gas (CO/H_2), HCl, slag.	Research	Date: not known yet Cap: 100 kg/hr (planned) Chl: up to 100% PVC waste	[10] [15] [26]
BFE process	BF Entsorgungstech. und Bergakademie Freiberg/Sachsen	Technology: Gasification; Input: mixed plastic waste, household waste.	Research	Date: ? Cap: ? Chl: ?	[1]
Leuna gasification	Leuna-Werke GmbH	Technology: Gasification; Test in production plants have been carried out. Project stopped due o lack of interest although positive results were obtained. Input: 5% DSD light fraction and 95% restfraction of vacuum visbreaking; Input quality: degradative extrusion; Output: Synthesis gas.	No further research, project stopped	Date: 1994 Cap: 60,000 t/yr Chl: 2% PVC	[1]
Thermoselect	Thermoselect SA in Locarno	Technology: Gasification of household waste; no preparation is necessary. The process consists of shredding, pretreatment (600ºC) and gasification. A demonstration plant was tested in 1992 in Verbania (Italy). The technology has to be compared with the incineration of domestic waste. Thermoselect modules have a maximum of 10 t/hr. Plans exist to build a plant in Karlsruhe (D). Process conditions: T_1=2000 ºC, T_2=1600 ºC, O_2; Input: unsorted domestic waste; Output: synthesis gas, mineral, metals.	Pilot	Date: 1992 Cap: 4.2 t/hr Chl: ?	[1] [5, p.464] [11, p.26]

Inland pulse process	Inland Container Corp. Ontario, California	Technology: Pulse combustion technology The pulse combustion technology is developed some 10 years ago by Forbes Energy Engineering Inc. to incinerate oil and gas. This technique was used for paper and plastics waste by Inland Container Corp. A demonstration plant was build in 1992. The pulsation way of heating is five times more effective than conventional heating. The waste reacts with the steam resulting in a H_2 rich synthesis gas. Half of the heat is used for the process, the rest can be sold. Process conditions: steam; Input: paper and waste plastics; Output: synthesis gas 30-50% H_2 and CO.	Feasibility proven / demonstration plant	Date: 1992 Cap: 1 t/hr Chl: ?%	[1] [5, p.462]
Union Carbide process	Union Carbide	First step is pyrolysis of solid organic waste to combustable gas and cokes. The cokes are gasified with oxygen. The anorganic components form the slag of the process. The useful product is fuel gas (10,600-11,200 kJ/Nm^3). After pretreatment, the waste is pyrolysed in a shaft kiln with three zones: for drying, reaction and firing. A pilot plant of 5 t/day and a commercial plant of 200 t/day are in operation in the USA. Input : plastic waste, O_2; Input quality: ground and free of metal; Output: combustable gas and fuel gas.	Operational	Date: ? Cap: 200 t/day Chl: ?	[5, p.459] [19]
SFW process	SFW-Funk	Starting form the experiences with the Saarberg-Fernwärme GmbH, Saarbrücken, (pilot 100 kg/hr, since 1975) a plant was build in 1977 to gasify domestic waste (1 t/hr). The pilot has proven to be suitable for this goal in 15.000 hours functioning. Technology: Gasification in a shaft kiln; Process conditions: T = 800- 900 ºC, air/O_2 ; Input: plastic waste; Output: gas suitable for external use.	Feasibility proven	Date: 1977 Cap: 1 t/hr Chl: ?	[5, 459]

ZSG process	?	Technology: Two stage gasification process: first partly degassing pyrolysis at temperatures up to 450 ºC. Secondly the coke from the first step is gasified in a shaft kiln up to 1000 ºC. The pyrolysis gas is cracked into a useful gas. Input: plastic waste, air; Output: gas from both steps.	?	Date: ? Cap: ? Chl: ?	[5, p.460]
Kiener process	?	Start of the development of this process was already in 1974. After some research and building of pilot plants a plant was build in 1984in Aalen, Baden Württemberg. Technology: Shredded waste is degassed in a rotary kiln at 450-500 ºC. The carbonization gas is combusted at 1100-1200 ºC into a combustable gas. Input: ground solid plastic waste; Output: Combustable gas (CO, CO_2, H_2, CH_4, N_2, H_2O).	Operational	Date: 1984 Cap: 35.000 t/yr Chl: ?	[5, p.460]
Babcock-Rohrbach process	?	Technology: Thermally decomposition of shredded car tyres with simultaneous partial oxidation in a fluid bed reactor. The process can be adapted for plastic waste. Operational for household waste in 1987 in Günzburg (Germany). Input: mostly shredded car tyres; Output: fuel gas to be used in rotary cement kilns or lime kilns.	Operational	Date: 1987 Cap: ? Chl: ?	[5, p.460]
Eisenmann process	Eisenmann Maschinenbau KG in Holzgerlingen	The machines are developed in several capacities and special adaptations are possible for different input materials. For preprocessing just a grinding step is necessary (10-30 mm). Capacities varying from 30 to 1600 kg/hr A plant using this machine had been build in 1987 in Nordrhein-Westfalen which is used for gasifying 750 kg/hr PE film and other films. Technology: Fluid bed reactor; little preprocessing necessary; Process conditions: T= 600-800 ºC, O_2 from air, natural gas; Input: plastic waste; Input quality: shredded plastic waste; Output: Combustable gas.	Operational	Date: 1987 Cap: 750 kg/hr Chl: ?	[5, p.460]

Lurgi-Eco process	Lurgi AG	The Lurgi-Eco process was developed by Lurgi AG. A commercial plant based on this technique is build in the MVA Coburg. Domestic waste is ground after metal separation and used for gasification (1,4 bar with air). Technology: Circulating fluidized bed reactor; Process conditions: T= 930-950 ºC, p=1,4 bar, coal; Input: domestic waste; Output: Combustable gas for use in industrial furnaces.	Pilot	Date: 1983 Cap: ? Chl: ?	[5, p.462]
HTG process	Voest-Alpine AG DOW Europe SA	Technology: high temperature gasification process (HTG). A demonstration plant is build in Linz (Austria) in 1992. The gas which is the product of this process can be used as low-heat value combustable gas in a power plant that produces steam. Metals are recovered from the process by separating them from the slag. Using oxygen as gasifying agent yields a synthesis gas that can be used as feedstock in chemical processes. Processing conditions: T=1600 ºC, air, cokes (as filter); Input: combination of liquid and solid waste; solid waste is e.g. car shredder waste, domestic waste; Output: combustable gas/ synthesis gas, slag.	Pilot	Date: 1992 Cap: ? Chl: ?	[5, p.463-4]
ÖMV process	OMV, Entsorgungsbetriebe Simmering (EBS)	Technology: High temperature gasification using the HTG process. Pilot in 1992-4. Plans exist to build a large commercial plant is Schwechat in 1995/96.	Pilot	Date: 1992 Cap: 25.000 t/yr 700.000 t/yr planned Chl: x%	[1] [5,p.464]

Veba gasification process	Veba Oel Technolgy GmbH, Werner & Pfleiderer	Already around ’70 Veba Oel and Fa. Werner & Pfleiderer developed a process for the gasification of coal and cokes. In 1993 some tests were planned with plastics in a modified pilot plant. Also PVC was part of the tested plastic waste fractions. Dehydrochlorination is carried out by degradative extrusion before gasification. Technology: entrained flow gasification; Processing conditions: steam (in last part of extrusion), O_2, T= 1500ºC, p=60 bar; Input: solid plastic waste, fluid waste materials; Input quality: dry and ground (< 20 mm); Output: synthesis gas or combustable gas (depending on input material) and slag.	Pilot	Date: 1993 Cap: 2,5 t/hr Chl: tests carried out with 10 and 29% PVC	[5, p.469]
Menges und Fisher process	Menges and Fischer	Technology: Combination of degradative extrusion and gasification. (Extrusion can be carried out at 300-350 ºC in order to remove HCl, followed by extrusion at 600ºC and gasification at 1600 ºC.) Input: plastic waste; Input quality: removal of stones and metal before extrusion; Output: Synthesis gas or combustable gas.	Patent idea	Date: ? Cap: ? Chl: ?	[2, p.480]
Flame process	TH Darmstadt	Technology: Liquefaction followed by partial oxidation by the spray-flame and submerged-flame process. Processing conditions: high temp., CO and H_2, O_2; Input: plastic waste; Output: gas mixture consisting of ethene, ethyne, propene, methane, synthesis gas, CO_2 and water.	Research	Date: ? Cap: ? Chl: ?	[2, p.482]

Incineration					
BSL incineration process	BSL Olefinverbund GmbH	Technology: Incineration in a rotary kiln with post combustion at 900-1200 ºC. Goal: production of energy and HCl. Start-up of plant is being planned for July 1999 with a total capacity of 45 kt/yr (incl. PVC). Input: all kinds of chlorine containing waste; Output: Steam, HCl, slag.	Pilot	Date: 1999 Cap.: 45 kt/yr (10-15 kton P VC Chl.: > 50% (i.e. PVC + other Chl. containing waste)	[30]
HT incineration process	Steinmüller, Sulzer Chemtech, Sulzer Escher Wyss	Technology: high temperature incineration in a rotary kiln. Technology developed for the thermal destruction of hazardous wastes. A feasibility study was carried out by the three companies (1993) in which a rotary kiln was used to treat PVC by oxidative cracking at 1200-1300 ºC and to recover the HCl. Around 99% of the HCl can be recovered.	Technology proven	Date: 1993 Cap: ? Chl: up to 100% PVC	[10]
Blast furnace					
Blast furnace	Stahlwerke Bremen GmbH	Replacement of heavy oil or coal by mixed plastics waste as reduction agent in the pig iron production in a blast furnace. Plastic waste with a chlorine content of up to 1,5% (ca. 3% PVC) is permitted to be used. The chlorine content should be lower than 2% to avoid corrosion problems in the gas cleaning installations. Pretreatment for HCl removal appeared not necessary.	Commercial	Date: 1995 Cap: 75,000 t/yr aggl. MPW Chl: 1,5% (ca. 3% PVC)	[5, p.415, 470, 481-485] [10] [24] [25]

Cement kilns					
BCU process	BCU (Bündner Cementwerke AG Untervaz, Switzerland), APME, KVS, ZEBA	Research commissioned by APME, BCU and KVS to explore the potential of used plastics as a fuel for co-combustion in cement kiln. Feasibility of using MPW from households or commercial/industrial operations has been successfully proven. Input quality: particle size 3-8 mm.	Technology proven	Date: 1995 Cap.: 1 – 2 t/hr, 4500 t/'96 Chl.: ?	[3][4]
EWvK process	EWvK, BASF (Germany) Heidelberg Cement, Ready Mix	MPW as primary firing fuel in cement kiln. Input: DSD fraction not suitable for mechanical recycling;	Technology proven	Date: ? Cap.: ? Chl.: ?	[3, p.8]
Enichem process	Ambiente / Enichem (Ravenna, Italy)	RDF containing HDPE and PET as primary firing fuel in cement kiln. In 1994 7000 tons fuel were substituted.	Commercial (?)	Date: 1994 Cap: 7000 t/'94 Chl: ?	[3, p.8] [4]
Gasification/ pyrolysis/cement kiln	Wietersdorfer & Pegganer Zementwerke and Baufeld GmbH (Austria)	Technology: Fuidised bed gasification / pyrolysis to produce fuel gas for cement production. In 1995 4600 tons of fuel were substituted by plastic waste.	Commercial (?)	Date: 1995 Cap: 4600 t/'95 Chl: ?	[3, p.8] [4]
	Erwitte and CC Umwelt GmbH (Germany)		Commercial		[3, p.8]
Cementa process	Cementa (Sweden)	In 1995 4600 tons of fuel were substituted by plastic waste.	Commercial	Date: 1995 Cap: 3400 t/'95 Chl: ?	[3, p.8] [4]
	ENCI (Netherlands)	Use of mechanically separated paper/plastics waste fraction as fuel in cement kiln.			[3, p.8]
	Ciments d'Obourg (Belgium)	MPW combustion of rejected DSD fractions. Start up in 1996.	Commercial	Date: 1996 Cap: ? Chl.: ?	[3, p.8] [4]

Not suitable for the processing of PVC					
PMMA depolymerisation		Most common process for the depolymerisation of PMMA in a molten metal bath (e.g. tin and lead). Process conditions: Residence time: several minutes, T= >300 ºC Input: ground PMMA; Output: 95-100% pure MMA;			[5, p.488]
Glycolysis of PET		Depolymerisation of PET with EG at higher temperatures (> 200 ºC). Acceleration with catalysts.	Commercial		[5, p.495]
Methanolysis of PET		PET treated with an excess of methanol at temperatures above 200 ºC, p > 2 MPa and a metal catalysts. Insensitive to all kinds of contaminants.	Commercial		[5, p.497]
Hydrolysis of PET		PET heated with an excess of water at higher temperatures (ca. 250 ºC) and under pressure (ca. 2-5 MPa).			[5, p.499]
Thermolysis/Hydro-lysis of PA-6		Depolymersiation with water at higher temperatures (ca. 300ºC) and higher pressures (20 - 100 bar) to caprolactam.			[5, p.502]
Acid cleavage of PA-6	e.g. BASF, Rhone-Poulenc and SNIA	Depolymerisation using for example phosphoric acid.			[5, p.503]
Depolymerisation of PA 6,6	DuPont				
Hydrolysis of PUR	Bayer General Motors	Hydrolytic process for PUR flexible foams developed as far as pilot plant stage.	Pilot		[5, p.518]
Alcoholysis of PUR		Alcohols as cracking agent.	Commercial		[5, p.520]

[1] M. Gebauer, Kunststoffe 85 (2) p. 214 (1995)

[2] Brandrup “Die Wiederverwertung von Kunststoffen”, Hanser 1995.

[3] Plastic waste – an alternative fuel source for cement production – draft version, march 1997 (by: BCU, APME).

[4] Presentation of results of project “Plastic waste – an alternative fuel source for cement production” (by ZEBA, BCU, APME).

[5] Brandrup “Recycling and recovery of plastics”, Hanser 1996.

[6] Evaluation of the Texaco-gasification process for treatment of mixed plastic household waste, report of phase 1 (October 1995) and final report of phase 1 & 2 (Febr. 1997), H. Croezen, H. Sas, Centrum voor energiebesparing en schone technologie.

[7] Chemical week jan. 31, 1996.

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