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VI.5

Recycling of plastic waste, rubber waste and end-of-life cars in Germany

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VI.5.1. Introduction

Among different types of consumer waste in Germany, plastic waste, rubber waste and end-of-life cars are closely intertwined. Processing techniques applied to these types of consumer waste are identical in many cases. In this chapter, similarities are outlined and one section is devoted to each type of consumer waste as follows:

- Plastic waste (Section VI.5.2)
- Rubber waste (Section VI.5.3)
- End-of-life cars (Section VI.5.4)

It should be added that as a member state of the EU, Germany is bound by the Community law on waste. Therefore, the EC Packaging Directive (1994) and Directive on end-of-life vehicles (2000) have been adequately implemented into German national law to comply with the relevant EC regulations.

VI.5.2. Plastic waste

VI.5.2.1. Legal framework and organization

At present, regulations for plastic waste recycling only apply to private households. Regulations are limited to packaging waste with the ordinance on packaging waste being the legal provision. Recycling of packaging, remnants from production or defective production units is partially organized by producers themselves.

The packaging waste ordinance of 28 August 1998 obliges every store to take back packaging waste unless industry provides for a collection and recycling network. Furthermore, the packaging waste ordinance requires 80% of the packaging to be collected and another 80% thereof to be recycled. The distributor of packaging has to collect 100% of the packaging at the place of distribution. Thus 65% of the packaging waste has to be recycled, beginning 1 July 2001 (VerpackV, 1998).

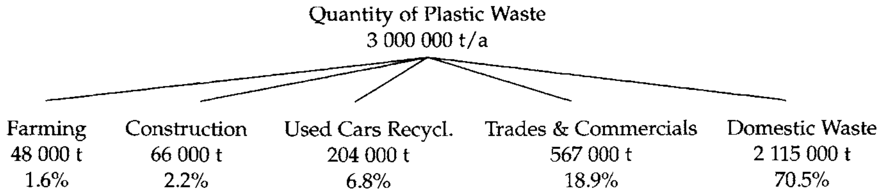


Figure VI.5.1. Origin and quantities of plastic waste (after DKR, 1995).

The German industry responded to these provisions by establishing a collection and recycling network. The Duales System Deutschland (DSD) organizes collection. The DSD entrusted the Deutsche Gesellschaft für Kunststoffrecycling (German Association for Plastic Recycling, DKR) with the recycling of packaging waste. DKR is an incorporated limited liability company, owned by the DSD (49.6%), a consortium of banks (25.2%) and the Association of Plastics Manufacturing Industry (25.2%) called "Beteiligungs- und Kunststoffverwertungsgesellschaft mbH" (DKR, 1995).

VI.5.2.2. Quantities of plastic waste

Annual volumes and percentile of plastic waste from different sources generated in 1995 in Germany are shown in Figure VI.5.1. The recovery of plastic waste according to the data of DSD and DKR (1995) are given in Figure VI.5.2.

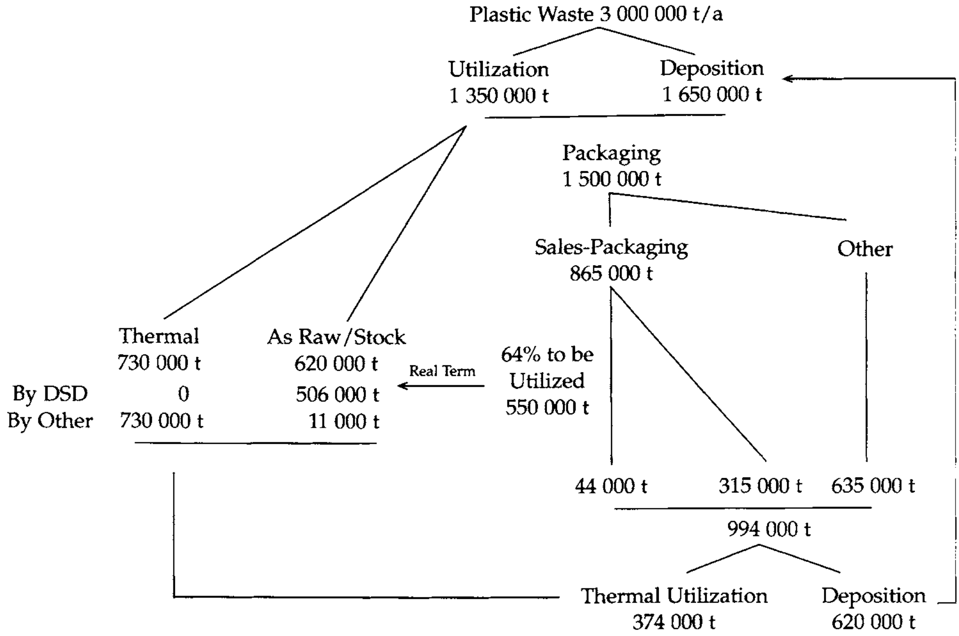


Figure VI.5.2. Recovery of plastic waste (after DKR, 1995).

Table VI.5.1. Distribution of main plastics in urban waste (after DKR, 1995).

Type of plastic	Polyolefins (PE/PP)	Polystyrene (PS)	PVC	Other
wt.%	65	20	5	10

VI.5.2.2.1. Urban waste

In 1995, out of 36 million tons (Mt) of urban waste, a total of 1.5 Mt were plastic packages that had to be taken back by trade and industry (Statistisches Bundesamt, 1996). Packaging from commercial enterprises, returnable packaging, secondary packaging and packaging for transportation purposes amounted to 635,000 t leaving 865,000 t real packaging waste to the DSD. According to the ordinance, 64% or 550,000 t had to be treated (Gesellschaft für Verpackungsmarktforschung, 1994).

Of the urban waste, 90% is composed of thermoplastics, which can easily be recycled (Table VI.5.1).

The plastic packaging waste is divided into four major categories (Fig. VI.5.3).

The fractions from sheets size A4 according to DIN (German industry standard) and bottles smaller than 5 l are made mainly of one type of plastic – either polyethylene (PE) or polypropylene. Compared to granulate from other fractions, the quality of this polyolefine granulate is the highest.

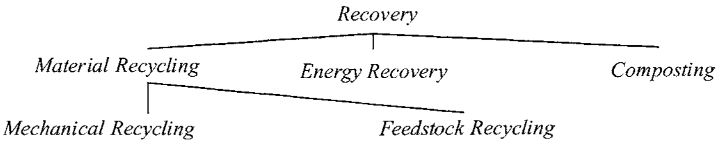
VI.5.2.2.2. Non-urban waste

The category of plastic packaging also comprises:

- commercial/industrial waste such as sheets, monobatches;
- bulky waste such as refrigerators, foams from pads or mattresses, plastic coated nog plates from the furniture industry;
- automobile parts such as molded parts, foams, shredder light fraction;
- building and construction waste such as PVC floors, tubes, roof-boarding;
- agricultural plastic sheets.

VI.5.2.3. Recovery

According to DIN and CEN standards, recovery is conceptualized as follows:



Composting of plastic waste is less important in Germany. Therefore, the emphasis will be on energy recovery, mechanical recycling and feedstock recycling.

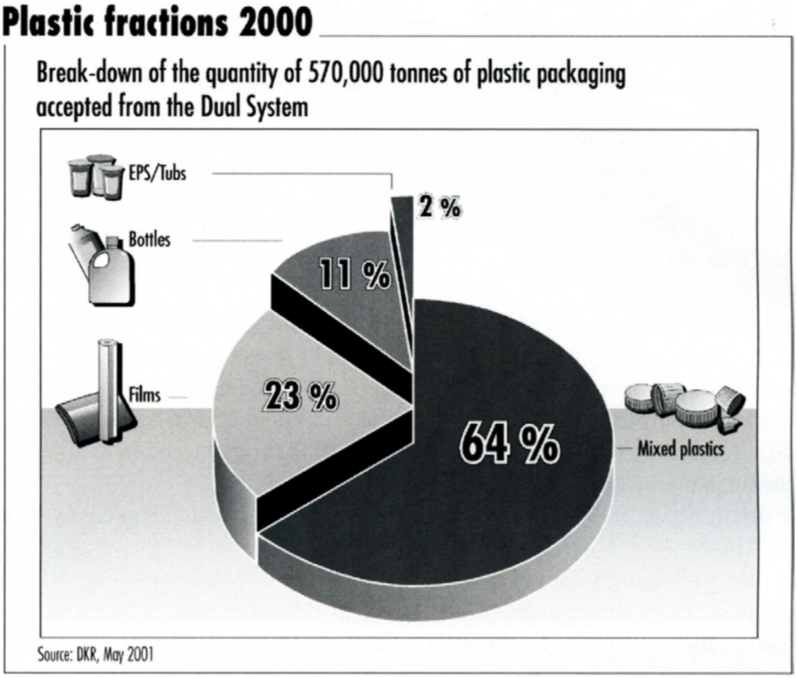


Figure VI.5.3. Distribution of plastic packaging waste according to packaging type (after DKR, 2002a).

From the three types of plastics

- thermoplasts,
- duroplasts,
- elastomeres,

only thermoplasts can be melted. Duroplasts and elastomeres are mainly disposed off by incineration or pyrolysis.

A survey of plastics recovery is shown in Table VI.5.2.

Energy recovery of plastic packaging is limited to combined heat and power stations. Combustion at waste incineration plants is forbidden according to the packaging waste ordinance. Packaging waste that cannot be submitted to mechanical recycling is usually treated by means of feedstock recycling. Packaging waste that cannot be submitted to feedstock recycling due to lack of profitability or certain regulations (e.g. plastic containers, which carried chemicals have to be treated as hazardous waste) will be treated in combined heat and power stations.

VI.5.2.3.1. Recovery pathways for plastic waste

The recycling of plastic packaging waste has increased 10-fold in the last decade (Table VI.5.3).

Table VI.5.2. Recovery – priority setting and application according to purity grade.

Recycling type	Objective	Legal provision (DSD, packaging waste only)	Application to	Permitted degree of contamination
Mechanical	Reuse material by melting and molding	65% of material recycling	Pure grade plastics	Low
			Mixed plastics	Medium
Feedstock	Depolymerize to chemical units for next synthesis	35% of material recycling	Mayor part of mixed plastics	Medium
Energy recovery	Make use of energy stored; substitute traditional fuels	>75% of energy recovery	All types, preferably if alternate recovery is too costly	High

The scheme for utilization of plastic packaging waste in Germany is shown in Figures VI.5.4 and VI.5.5.

VI.5.2.3.1.1. DSD plastic waste

In the packaging waste ordinance, a ratio of 65% mechanical recycling to 35% feedstock recycling was set to ensure a reasonable amount of feedstock recycling. However, in 1995, the ratio had rather been 81% mechanical to 19% feedstock including recycling in foreign countries. Ratio formulas are, therefore in the long run, supposed to be replaced by product

Table VI.5.3. Development of packaging waste recycling (after DSD, 1996, 2002; DKR, 2002a,b).

Year	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
(a) Quantity of packaging forwarded for recycling according to DSD (1996, 2002)											
Forwarded for recycling (in 1000 t)	20	30	40	281	461	506	532	545	548	555	548
(b) Quantity of plastic packaging accepted from DS sorting plants and forwarded for recycling according to DKR (2002a,b)											
Accepted from DSD (in 1000 t)								567	600	610	570
Forwarded for recycling (in 1000 t)								615	634	629	602

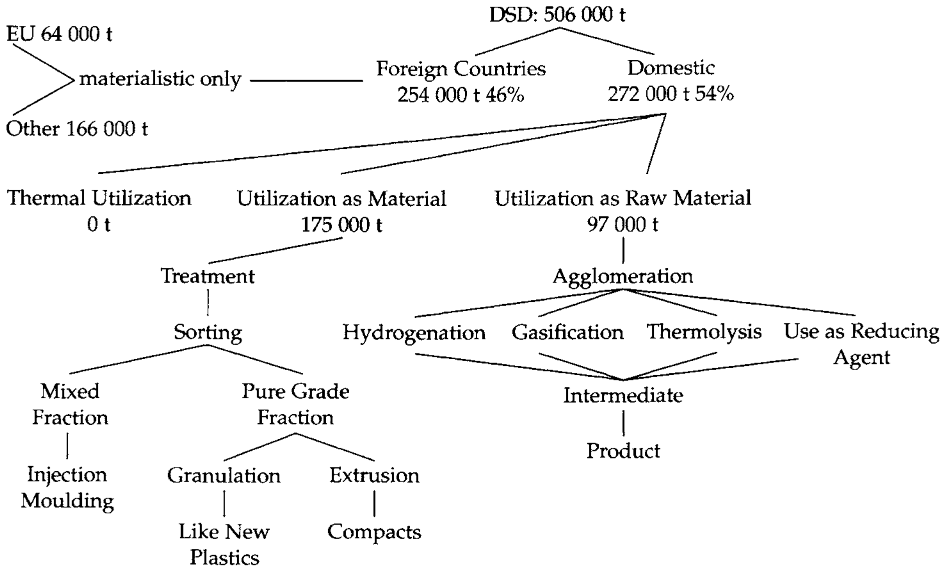


Figure VI.5.4. Flow chart for plastic packaging waste in 1995.

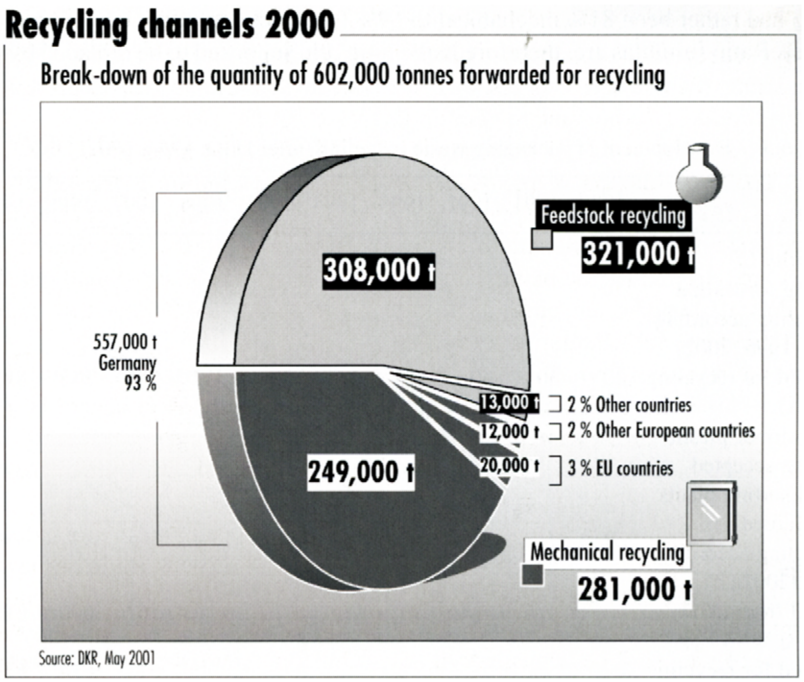


Figure VI.5.5. Destination of DSD packaging waste for recycling (plastics) (after DKR, 2002b).

specifications. If plastic waste complies with certain specifications, it follows either the pathway of mechanical recycling or feedstock recycling depending on plastic waste quality. Thus both recycling pathways are connected via a flexible switch. For instance, if there is no market for secondary plastics from mechanical recycling any more, plastic waste may also be disposed off by feedstock recycling. Recycling companies would no longer be subject to market conditions because they deliver directly to DKR. For DKR, this would mean more security in recycling (Lindner, 1996).

VI.5.2.3.1.2. Other plastic waste

Plastic waste from commercial enterprises. Plastic waste from commercial enterprises is usually pure grade, for instance, large containers or monobatches. Large containers and other commercial packaging are collected and recycled by specialized providers, e.g. "Gesellschaft zur Rückführung industrieller oder gewerblicher Kunststoffverpackungen RIGK mbH"/Wiesbaden (a company collecting industrial and commercial packaging waste), Interseroh AG/Köln, "Vereinigung für Wertstoffrecycling Vfw GmbH"/Köln or "Folienverwertungsgesellschaft mbH"/Düsseldorf (a company specialized on sheets).

Moreover, a significant amount of plastic waste (1993: 382,000 t) from companies is collected as urban waste (1993: 24,203,000 t total urban waste, of which 1.6% were plastics) (Statistisches Bundesamt, 1997).

Plastic waste from bulky waste. These are foams from pads or mattresses or coated nog plates. Pure grade collection could easily be achieved by introducing special collection days. Currently, plastics from bulky waste cannot be subject to treatment other than disposal or energy recovery, for profitability reasons. Refrigerators also belong to bulky waste. Their coolants are removed before refrigerators are submitted to energy recovery. Deposition is deemed to contribute to ozone layer damaging from degassing of non-CFC-free insulating foams. Refrigerators that are collected today have been produced long before the Montreal Treaty and contain up to 13% CFC 11.

Plastic waste from used car recycling. End-of-life cars and linen goods are shredded together. The light fraction is mainly deposited. A minor portion is treated at garbage incineration plants or gasification plants. Recycling of plastics from the light fraction is not profitable yet and is only carried out to a minor extent. About 20% of polypropylene shock absorbers are recycled for the manufacturing of new shock absorbers. Small quantities of varnish do not spoil the recycling process (VW) (Schäper, 1993). Another example is duroplast granulate substituting for other fillers.

Plastic waste from electronic scrap. The metal conductors and the plastic insulation are separated. Since insulation is contaminated with about 1% metals it cannot be recycled for the same application (Masshöfer, 1989) but e.g. anti-noise sheets instead, thereby recovering 90% of the plastic. Usually, the casing is made of pure grade plastic thus rendering mechanical recycling possible in principle.

Plastic waste from buildings and construction. The plastic waste from demolition amounted to an estimated 2.4 Mt in 1989 (Kohler, 1991). The demolition of more recent constructions, in the following decades, will result in the dramatic increase of the plastic waste from this source, reflecting fast growth of plastic use for construction purposes. Most of the plastics will be deposited. In case rubble is sorted, the plastics fraction will either be left for treatment or submitted to energy recovery. Due to an initiative by the working group on PVC (Arbeitsgemeinschaft PVC Bodenbelag-Recycling), PVC floors and roofing have been collected separately since 1990 (Hofmann, 1993). The Society for Plastics Recycling (Entwicklungsgesellschaft zur Wiederverwertung von Kunststoffen) supported a recycling concept for PE from demolition waste. It is used for the manufacturing of non-compression-proof tubes with up to 30% secondary PE (Anonymous, 1993a).

VI.5.2.4. Treatment

The treatment of plastic waste comprises fragmentation, sizing, sorting, washing and drying, agglomeration and granulation. The more intense the treatment, the cleaner and purer the granulate will be matching the characteristics of new material. The latter is important since granulate from plastic recycling has to compete with new material on the market (see Section VI.5.2.12).

VI.5.2.4.1. Sorting

Sorting aims at gaining the maximum purity grades possible. It especially serves purification of mixed plastic waste. The usually applied techniques are as follows.

VI.5.2.4.1.1. Separation by float-sink processing

Plastic fragments will be stirred into a pool. According to its specific density, PE and polypropylene will float and can be decanted; PVC and polystyrene PS will sink to the bottom and will be removed using a scraper.

VI.5.2.4.1.2. Separation by hydrocyclone

In the hydrocyclone method, the washed and fragmented plastics will again be separated according to their densities. The separation is induced by centrifugation and takes place in a vortex. For instance, DSD-plastics will be separated to 99% purity. Fractions are:

- polyolefins (PE, PP)
- polystyrene and
- PVC

The separation capacity of Thyssen-Henschel-plant/Hamburg is 1 t/h.

VI.5.2.4.1.3. Separation by centrifuge

This technique is suitable even for filthy plastic waste. Plastic waste is ground, washed and stirred giving it an aqueous suspension, which is separated by three consecutive centrifuges. If DSD-plastics are supplied, the following fractions will be gained:

- polyolefins (PE, PP),
- polystyrene,
- PVC,
- metals,
- paper,
- other plastics.

The plastics suspension will be pumped into the centrifuge. The plastic particles will hit a ring of water that moistens the cylinder of the centrifuge moving with it. Lighter plastics such as PE or polypropylene will float on the surface of the water ring and are extracted by a worm conveyer. In contrast, PVC and polystyrene, which have a higher density, will sink through the water ring to the funnel-shaped cylinder of the centrifuge to the extraction site. KHD Humboldt Wedag AG/Köln has developed this process. It is called "Censor" and separates up to 99.9% purity.

With regard to DSD-plastics, sorting serves two purposes:

- separation of non-plastics;
- fractionation into
  - sheets,
  - hollows,
  - mixed fraction.

Further treatment in plastics recycling requires a constant plastics quality. This requirement is met by sorting. For instance, sheets should be sized at least DIN-A4 or the purity grade should be 92% for further processing (DSD, 1996), at the minimum.

VI.5.2.4.2. Agglomeration

Agglomeration helps to maintain quality standards of recycled plastics such as bulk density, particle size, ash content, chloride loading or residual moisture. A frequent prerequisite for further processing is the conversion of mixed plastics into a semi-finished product. This conversion can be achieved by agglomeration, e.g. in a circular die (Fig. VI.5.6). Agglomeration is a multistep process as shown in Table VI.5.4.

Plastic waste is collected by the DSD as a mixed fraction for commercial reasons (DSD, 1996). In order to recycle plastics from the mixed fraction, certain quality standards must be met. This can be achieved through agglomeration as shown in Table VI.5.5.

VI.5.2.5. Feedstock recycling

In feedstock recycling, plastics are depolymerized. The monomers gained will be used for synthesis of new products in the petrochemical industry. Feedstock recycling is a means to recover even plastics that could not be traded otherwise.

Feedstock recycling is applied to contaminated and heterogeneous plastics waste. Most of the plastics entering this process originate from the urban waste and shredding light fraction with PE, polystyrene, polypropylene and polyvinyl chloride as the main constituents. For feedstock recycling, plastics have to comply with certain minimum quality standards, which do not apply to plastics from the above-mentioned sources. Therefore, feedstock recycling is preceded by extraction of contaminants, i.e. dehalogenation and degrading extrusion to separate halogens and heavy metals contained in additives.

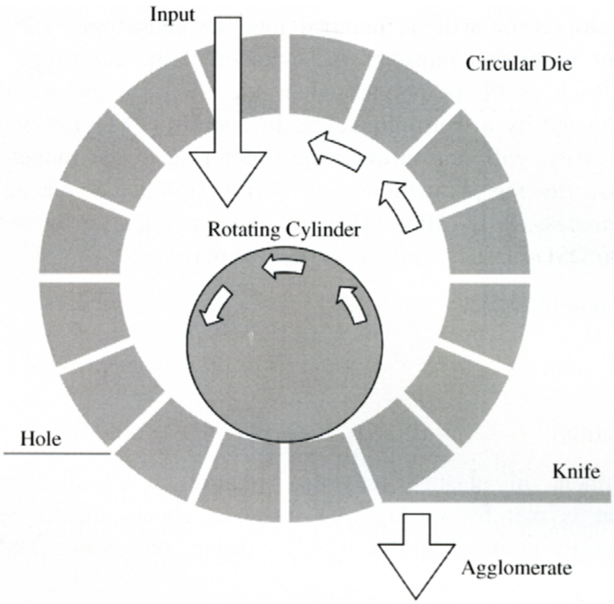


Figure VI.5.6. Circular die (after DSD, 1996).

VI.5.2.5.1. Hydrogenation (VEBA)

Hydrogenation takes place at pressures of about 250 bar requiring plastics to be liquefied before they are processed (Fig. VI.3.7). Liquefaction is achieved by heating plastics for a longer time. After compression to 250 bar in a high-pressure reactor, the plastic liquid is heated to 480°C and mixed with hydrogen. Due to heat and pressure, the carbon chains are split. Supplying hydrogen serves two purposes: carbon chains are split further by the help of hydrogen binding to the breaking points. At the same time detoxification takes place. Reaction products are gases and a synthetic crude oil called "Syncrude" (Table VI.5.6).

Table VI.5.4. Agglomeration.

Step	Remark	Corresponds to specification
Prior crushing	–	–
Segregation of contaminants	By air separator, vibrating riddle, magnet, Eddy current	Reducing of contaminants, dust, ash
Agglomeration		
Cup agglomeration	Rotating knifes producing frictional heat 140°C; caking; cut	Bulk density
Die agglomeration	Plastic particles are pressed through the hole of a die; cut	Particle size, residual moisture

Table VI.5.5. DSD quality requirements for mixed plastics waste (DSD, 1996).

Specification	Requirement
High bulk density	>300 g/l
Particle size	<50 mm
Low content in dust/ash	<4.5%
Low chloride loading	<2%
Low residual moisture	<1%

VI.5.2.6. Gasification (Schwarze Pumpe, high-pressure gasification)

Gasification aims at the production of synthetic gas for other industrial processes. Plastics are mixed with oxygen and steam at 800°C. The gases formed consist mainly of hydrogen and carbon monoxide. Heavy metals and minerals will vitrify in a second step thus forming slag. Condensable intermediates like tar or solids will then be separated for synthetic gas production by means of gasification. Synthetic gas is a basis in the chemical industry, e.g. it is used to produce methanol.

VI.5.2.7. Thermolysis (BASF)

In contrast to hydrogenation, plastics are liquefied at 300°C in vacuum. Without adding hydrogen, plastics are cracked and fractionated to petrochemical basis. Naphtha gases, alpha olefins and oil are formed.

VI.5.2.8. Reduction (Bremer Stahlwerke, blast furnace processing)

Conversion of ore into steel requires deoxygenation. Only recently the traditional reducing agent, crude oil, has partially been replaced by plastic waste in the Bremen steel factory. In principle, plastics could substitute oil completely. To date, 30% of oil is substituted.

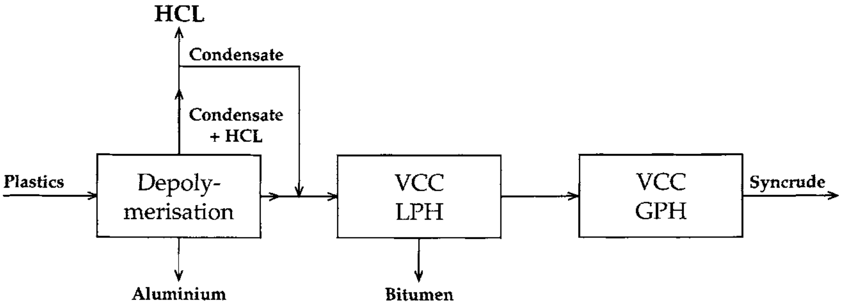


Figure VI.5.7. Recycling of plastic waste by hydrogenation (after Hecka and Niemann, 1996).

Table VI.5.6. Contents and characteristics of hydrogenation main product "Syncrude" (after Korff and Heim, 1989).

Content/ characteristic	Naphthene, paraffin	Ethyl-benzene	Sulfur	Heavy metals	Distillability
Percentage/extent	87%	13%	<0.05%	0% (crude oil: 3%)	Unlimited (crude oil: limited)

Agglomerate is blown into the melting bath at the blast furnace's bottom. Gases formed, thereafter, serve as a reducing agent (DSD, 1996).

VI.5.2.9. Mechanical recycling

In mechanical recycling, refined plastics are melted and processed forming the desired product. In some processes, contaminants and particles of poor melting quality have to be separated from the fusion in order to gain a highly homogenous polymer. If mixed plastics are supplied, e.g. by the DSD, sorting, grinding and agglomeration are required before plastification can start.

The manufacturing process is the same as for new material. Mixed and contaminated plastics are mainly melted and recycled by the following processes.

VI.5.2.9.1. Extrusion

During extrusion, mixed and ground plastic particles are melted together with their contamination forming a fusion that can directly be pressed into a mold by means of a roll extruder. After solidification the product can be taken from the mold.

VI.5.2.9.2. Injection molding

In injection molding, plastics are first melted by heating. Melted plastics are then fed into a cylinder and compressed by means of a piston. They are directly pressed into a mold, whilst the pressing force remains constant until the product is solidified.

VI.5.2.9.3. Sintering

In this process, plastic particles agglomerate in a heated mold first. They are melted due to the high pressures exerted on them. Afterwards, they are directly pressed into a mold.

VI.5.2.9.4. Coextrusion

During coextrusion, multilayer sheets can directly be produced in a single step. Usually a layer of new material will enclose a core consisting of recycled plastics. Granulate is melted first then pressed through intercalating jets. This technique is applied, e.g. to food packaging since layers of recycled plastic are not supposed to directly enclose food.

VI.5.2.10. Energy recovery

VI.5.2.10.1. Emissions from incineration of plastic waste

Compared to other material with a high calorific value, about 80% of standard plastics (PE, PP, PS) cause lower emissions in incineration plants. Only PVC increases dioxin and furan emissions due to high chloride concentrations. PVC and plastic foams (polystyrene and polyurethane) have to be supplied in a mixture with other fuels due to their negative impact on emissions (Wurm et al., 1996).

VI.5.2.10.2. Combustion in incineration plants for urban waste

According to the packaging waste ordinance, combustion of plastic waste is permitted only if the efficiency of energy recovery is at least 75%. Garbage incineration plants are usually constructed for inertion of waste and not for recovering energy. Thus the efficiency of garbage incineration plants amounts to only 20% compared to 40% for power stations. To date, mechanical and feedstock recycling are subsidized with several hundreds of EURO (€) per ton. Since these recycling methods are too expensive in the long run, supplying garbage incineration plants with plastics waste is being considered. Experiments carried out at a test plant (TAMARA/Karlsruhe) have shown that (Mark et al., 1996):

- mixed plastic waste can be added up to 30% by weight;
- foams can be added up to 3% by weight;
- all halogens (e.g. chlorine from PVC) accumulate in flue gas. They are extracted by flue gas scrubbing.

One limitation arises from the high calorific value of plastic waste. The throughput is reduced by fuels with high calorific value, which could be bypassed if existing plants were modified (Lautenschlager and Mark, 1996).

VI.5.2.10.3. Combustion in cement factories

The cement manufacturing industry is one of the most energy-consuming industries. Therefore, cement factories aim to reduce the energy expenditure by selecting suitable fuels. Cement is produced in three steps: gaining raw cement flour, burning and grinding. Temperatures of about 1450°C are required for burning. Thus fuels with a high calorific value are necessary, e.g. plastic waste. Since fossil fuels became more and more expensive, other fuels have replaced them as shown in Table VI.5.7.

The ordinance on pollution control (17. BImSchV, "Bundesimmissionsschutz-Verordnung"), previously designed for garbage incineration plants only, also applies to cement factories if they are supplied with plastic waste. Threshold values according to this ordinance are fairly low thus hampering energy recovery from plastic waste in cement

Table VI.5.7. Substitution of traditional fuels in the cement industry 1979, 1991, 1997–1999, in percentage (after Knopf, 1995; Bilhard, 1997; VDZ, 1999).

Fuel	1979	1991	1997	1998	1999
Oil	61	9	2	5	6
Gas	14		2	1	1
Coal	25	75	80	75	70
Substitutes (rubber, plastics)	0	16	16	19	23

factories if no exemption permit is granted. Cement quality is not spoiled as long as the amount of plastic waste added to traditional fuels is limited.

In some cement factories, plastic waste granulate is supplied to rotary furnace kilns as fuel substitute. The particle size of the granulate is about 10 mm. Emissions from plastic waste are comparable to those of traditional fuels. However, the amounts of sulfur dioxide emissions are even less.

VI.5.2.10.4. Co-combustion in coal dust incineration plants

According to the Kreislaufwirtschaftsgesetz (German law on waste, enacted 7.10.1996), co-combustion of plastic waste in coal dust incineration plants is permitted if the calorific value of plastic waste is 11 MJ/kg or more, i.e. 30.3 MJ/kg in fact, and the combustion efficiency is at least 75%. It is not permitted according to the ratio formula for plastic waste recycling. Experiments at a test plant (IVD/University of Stuttgart) have shown that (Christill et al., 1996):

- plastics have to be ground to particle sizes between 2 and 10 mm. Additional costs for this treatment amount to 10–15€/t;
- the portion of plastics added can be up to 10% of the furnace power. This would mean energy recovery of 50,000 t plastics waste for 300 MW plants;
- corrosion of the plant does not increase because of fuels with high chlorine concentrations;
- modification of plants does not require a high investment. Operating costs amount to an additional 100€/t.

The use of fly ash and slag in building and construction industry would have to be evaluated again.

VI.5.2.10.5. Monocombustion in fluid bed kiln (rotating)

Whereas garbage incineration plants have an efficiency of 20% for energy recovery, monocombustion of plastic waste reaches up to 40% efficiency in fluid bed kilns – almost comparable to the efficiency of power stations. Compared to coal, plastic waste has a higher calorific value and higher halogen content. Halogens ought to be extracted first in order to avoid high temperature corrosion of the steam boiler, which would result in a lower proportion being converted to current. To avoid this process without dehalogenation, the maximum temperature of the steam boiler would have to be lowered to 380°C, thus lowering the proportion converted to current from 38 to 20%, at the same time. Dehalogenation reduces profitability of monocombustion. In Ahlstrom, Finland a fluid bed kiln operated at 200–300€/t rendering this process less competitive compared to other combustion technologies (Martin, 1995).

VI.5.2.11. Deposition

According to the Waste Catalogue, plastic waste may be deposited after being treated. Plastic mud or emulsions must not be deposited.

In 1991, about 1.3 Mt of plastics were deposited at landfill sites (Consultic, Marketing und Industrieberatung GmbH, 1995). In the long run, additives (stabilizers, pigments, softeners) could be washed out due to a change of pH during rotting and microbiological processes. These washouts are not considered harmful to the environment. But since the overall capacity of landfill sites is limited, deposition fees are raised, rendering deposition less profitable compared to recycling techniques.

VI.5.2.12. Economics of recycling and markets for recycled plastics

VI.5.2.12.1. General remarks

The utilization of recycling capacities indicates problems and successes in marketing recycled plastics (Table VI.5.8).

The utilization of capacities is low because prices for raw materials are low and they vary greatly due to fluctuations in the markets where raw materials are traded. Fluctuations in the raw materials market directly affect the market for secondary raw materials. Figure VI.5.8 shows the range of fluctuations for raw materials (PE, PP, PVC) in 1986–1991. A similar instability of the plastic market was also observed from 1995 to 2001 (Fig. VI.5.9).

The costs for treating plastic waste by granulation, washing and melting amount to an average of DM 1.50 (0.75€) per kg (Meimberg, 1995) for all thermoplasts. Therefore, recycling of plastics that are cheaper than DM 1.50 (0.75€) per kg is not profitable. Figure VI.5.10 depicts price relations between new and recycled thermoplasts.

Whether recycled plastics will compete successfully in the market not only depends on the price but also or even more so on quality. The higher the purity, the more the characteristics of recycled plastics will become identical with those of newly manufactured plastics and the more marketable recycled plastics will be.

Table VI.5.8. Utilization of capacities for mechanical and feedstock recycling in 1995 (after Lindner, 1996).

Type of recycling	Utilization of capacities (%)
Mechanical	39
Feedstock	45

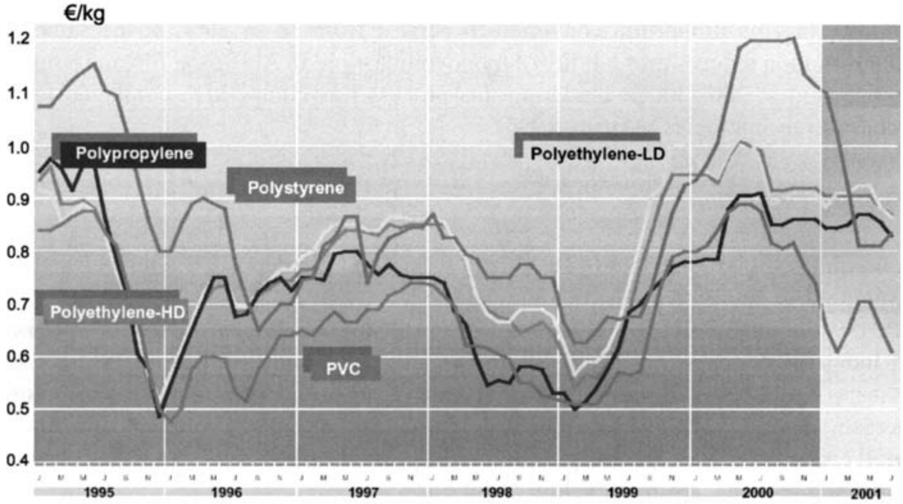


Figure VI.5.8. Price index for PE, PP and PVC 1986–1991 (after Bilitewski et al., 1991) (originally in DM; DM ≈ 0.5€).

VI.5.2.12.1.1. Case study: recycled polyethylene

High-quality recycled PE closely resembles newly manufactured PE. A low price for newly manufactured plastics limits recycling to pure grade PE fraction. During the last decade, recycled plastics were used for applications demanding lower quality standards (Table VI.5.9).

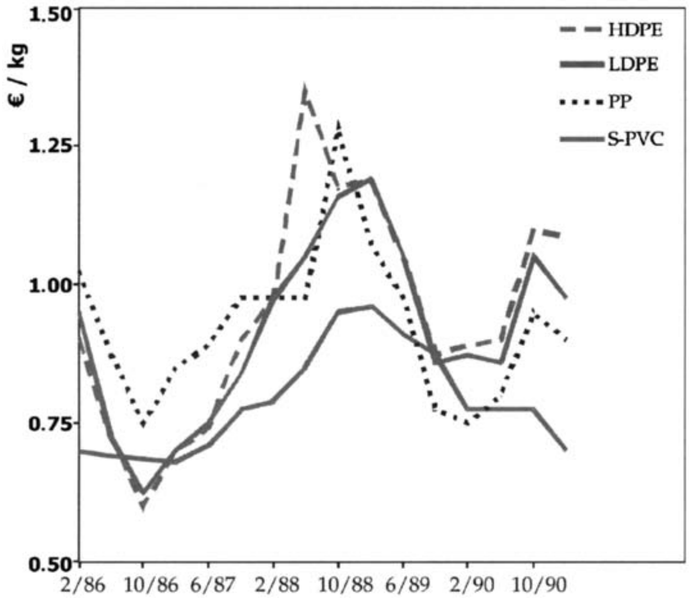


Figure VI.5.9. Price index for PE, PP and PVC 1995–2001 (after VKE, 2002) (originally in DM; DM ≈ 0.5€).

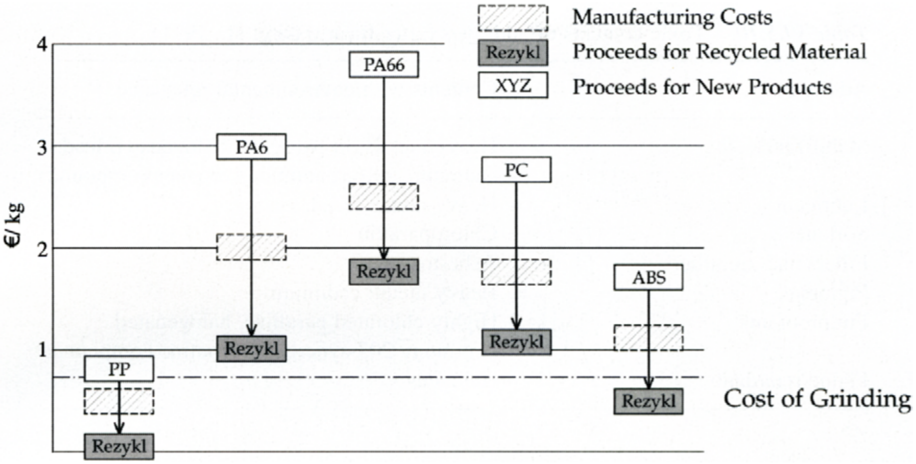


Figure VI.5.10. Proceeds for new and recycled thermoplasts as compared to manufacturing expenditures 1995 (after Meimberg, 1995) (originally in DM; DM ≈ 0.5€).

Another recycling method – coextrusion in hollows manufacturing – is less applied due to reduction of the hollows' weight.

VI.5.2.12.1.2. Influence of additives on the quality of recycled plastics

Plastics are changed by the use of additives to serve different purposes. Additives are mostly composed of halogenated or metallo-organic compounds that are harmful to the environment (Table VI.5.10).

The composition of additives is unknown, for reasons of competitiveness. Therefore, recycled plastics are banned from hygienic applications. Moreover, due to interactions between remaining and newly added additives, the characteristics of recycled plastics cannot be adapted as precise as those of newly manufactured ones. Additives pose a problem in mechanical or feedstock recycling since toxins from additives could contaminate gases.

Table VI.5.9. Application of recycled PE, 1995 (after Hanning and Raddatz, 1995).

Products/use in sector	Tons per year (1995)
Dust bin	5,000
Bottling sector without bottle boxes	10,000
Bottle boxes	35,000
Other	50,000
Sheets	
Bags	
Non-compression-proof pipes	

Table VI.5.10. Toxic contents of additives (after Bilitewski et al., 1991).

Additive	Contents with environmental relevance
Stabilizer	Heavy metals, in particular halogenated lead, cadmium, sulfur, antimony, copper compounds
Lubricant	Heavy metals: lead, zinc
Softener	Chloroparaffin
Fillers and amplifiers	Asbestos
Pigments	Heavy metal: cadmium
Fireproofants	Highly chlorated paraffins, halogenated Antimony 203-synergists, bromine compounds
Flame retardants	Halogens

Granulate from recycled plastics is used for:

- building and construction (forms, isolation, timbering, insulation);
- packaging and transportation (sheets, containers);
- industry (car manufacturers: molds).

VI.5.2.12.2. Mechanical recycling

VI.5.2.12.2.1. Products from injection molding

Injection molding allows a high extent of automation and high throughputs. Due to their fair profitability, products made of mixed plastics compete successfully against traditional materials such as wood or cement. Typical products are forms, tubes, anti-noise sheets, checker bricks or bags (see Table VI.5.15).

VI.5.2.12.3. Feedstock recycling

The basic methods of plastic waste utilization, products generated and potential markets in Germany are shown in Table VI.5.11. If feedstock recycling is preceded by agglomeration a throughput of at least 20,000–30,000 t/year is required to achieve profitability (DKR, 1995).

VI.5.2.12.3.1. Feedstock versus mechanical recycling (DSD et al., 1996)

From the environmental point of view, mechanical recycling should be chosen, if:

1. high purity grades are given;
2. a 100% substitution of primary raw material versus secondary raw material can be achieved.

For mixed plastics, feedstock recycling should be applied according to the following environmental ranking:

1. reduction;
2. thermolysis;
3. gasification.

Table VI.5.11. Feedstock recycling: processing output, products, markets.

Method	Company	Output	Possible products	Markets, reuse in
Hydrogenation	VEBA	Syncrude	Benzene, fuel, diesel fuel	Petrochemistry
		HCl	HCl	Chemical industry
		Bitumen	Asphalt component	Building and construction
Gasification	RWE (Schwarze Pumpe)	Technical gas	e.g. Methanol	Chemical industry
		Cinders	Building material	Building and construction
Thermolysis	BASF	Naphtha	Ethylene, propylene	Plastics industry (PE/PP)
		Technical gas	Various	Chemical industry
		Oil	Methanol	Chemical industry
Use as reducing agent	Steel-factory Bremen	"Reduction"	–	Steel industry

Mechanical and feedstock recyclings are comparable from an economical point of view. The DSD subsidized recycling is given in Table VI.5.12.

Subsidies serve to adapt existing plants to plastic recycling requirements. Subsidy spending will be stopped after amortization of the plants giving way to real pricing. Mechanical recycling is more profitable since it requires less treatment.

Table VI.5.12. Subsidies paid by the DSD for different types of recycling (DSD, 1996).

Operation	Mechanical (€/t)	Feedstock (€/t)
Pre-treatment and sorting	300–400	150–175
Recycling	0	100–250
Proceeds	Variable	Variable
Sum of supplements	300–400	250–425

VI.5.2.12.4. Energy recovery

At present, combustion of plastic waste is forbidden according to the packaging waste ordinance. If the purpose of combustion is any other than inertization, exemption permits can be obtained. Table VI.5.13 shows limitations in thermal treatment of plastic waste.

VI.5.2.12.5. Markets relevant to the various types of plastics

Main materials in plastic waste of different origin are listed in Table VI.5.14.

Table VI.5.15 comprises major products manufactured from recycled plastics.

Table VI.5.13. Legal and economical limitations in thermal treatment of plastic waste.

Combustion in	Legally restricted by	Economics (€/t)	Done?
Garbage incineration plants	Kreislaufwirtschaftsgesetz: energy efficiency	≈ 150.-	Yes
Cement factories	Requirements 17. BlmSchV	≈ 25.-...125.- (combustion only)	Yes
Coal dust incineration plants	Packaging waste act: quoting	≈ 125.-	No
Fluid bed kiln (mono)	None	≈ 200.-...300.-	No

Table VI.5.14. Main materials in plastic waste according to sectors (after VKE and Matthews, 1995).

Origin/sector	Main materials
Farming	PE sheets
Building and construction	PVC, PP, acrylic polymers
End-of-life cars	PE, PP, PA, PVC, polyester resins
Commercials and trades	PE sheets
Domestic waste	PE, PP, PS (DSD)
Conclusion	Most important: PE, PP, PS, PVC

Table VI.5.15. Products manufactured from recycled plastics (DKR, 1995).

Sector	Products
Construction	Waste pipes, drains, sheets, bed plates, curbstones, timbering, insulating materials
Farming	Fences, fixation of river banks, horse-boxes, fish boxes
Commercial products	Bins, bags, coverings
Transportation and traffic	Pallets, noise barriers, side rails, brake pads, landing stages
Home and garden	Flower pots, benches, sand-boxes, composters

VI.5.3. Rubber waste

VI.5.3.1. Rubber

Rubber is produced by vulcanization of caoutchouc, sulfur and other substances. It is mainly used for the production of tires. Table VI.5.16 shows the typical composition of tires.

Table VI.5.16. Typical composition of tires (LENTJES LBL).

Content/characteristics	Unit	Amount
Complete tire		
Carbonization remainders	wt.%	39.0
Calorific value	kJ/kg	30.94
Fe-steel	wt.%	12 (Car-T.)
	wt.%	25 (Lorry-T.)
Rubber part only		
Loss of ignition	wt.%	7.50
C	wt.%	81.00
H	wt.%	6.70
O	wt.%	3.00
N	wt.%	0.30
S	wt.%	1.70
Cl + Br	wt.%	0.15
Cu	wt.%	0.30
Al	wt.%	0.15
Zn	wt.%	1.60
Pb	ppm	70.00
Cd	ppm	8.00

VI.5.3.2. Statistics on rubber waste

In 1994, about 1 Mt of rubber waste had to be recovered or disposed off. Some 400,000 t came from technical products, the remainder being scrapped tires (Gesellschaft für Altgummiverwertungssysteme mbH, 1996). In 2000, this number increased to about 800,000 t/year.

Table VI.5.17 lists the types of tires which are the origin of scrap tires.

VI.5.3.3. Recycling and deposition methods of rubber waste

Rubber waste is unsuitable for deposition at landfill sites because of:

- poor compressibility;
- resilient surfaces;
- extremely long rotting time;
- forming of cavities with air inclusion (scrap tires only).

Therefore, deposition decreases whereas recovery increases as shown in Table VI.5.18 for technical products other than tires.

VI.5.3.3.1. Technical products

See Table VI.5.18.

Table VI.5.17. Origin of scrap tires (after Schmidt-Burr, 1996).

Type of tire	%
Cars	63
Lorries	26
Big tires/full rubber tires	11

VI.5.3.3.2. Scrap tires

Figure VI.5.11 shows the recovery methods and disposal of scrap tires.

VI.5.3.4. Recovery technologies

VI.5.3.4.1. Mechanical recycling

VI.5.3.4.1.1. Remolding

In remolding, the abraised tread is replaced by a new one unless the carcass is damaged. Tires for small vehicles can be remolded once, while tires for larger vehicles can be remolded 3–4 times. During the process, 6 l of crude oil are used, which is one-fifth of the normal quantity required for the production of a new tire (28 l).

The most common process is the retreading by heat. In this process, a new tread and a binding plate are placed. On the carcass, vulcanization takes place at high pressures in a die heated to 160°C.

VI.5.3.4.1.2. Reclaiming

This process works with rubber flour, which is produced from rubber waste through

- cold grinding or
- hot grinding.

Table VI.5.18. Development of deposition and recovery of rubber waste in technical products (Anonymous, 1992/C).

	Amount (1000 t)				
	1990	1993	1995	1997	2000
Thereof deposition	392	400	340	190	-
Thereof utilization	30	45	125	290	500
Granulation	10	15	25	40	50
Depolymerization (e.g. pyrolysis)	–	–	50	200	350
Power stations	–	–	–	–	50
Cement factory	20	30	50	50	50
Total	422	445	465	480	500

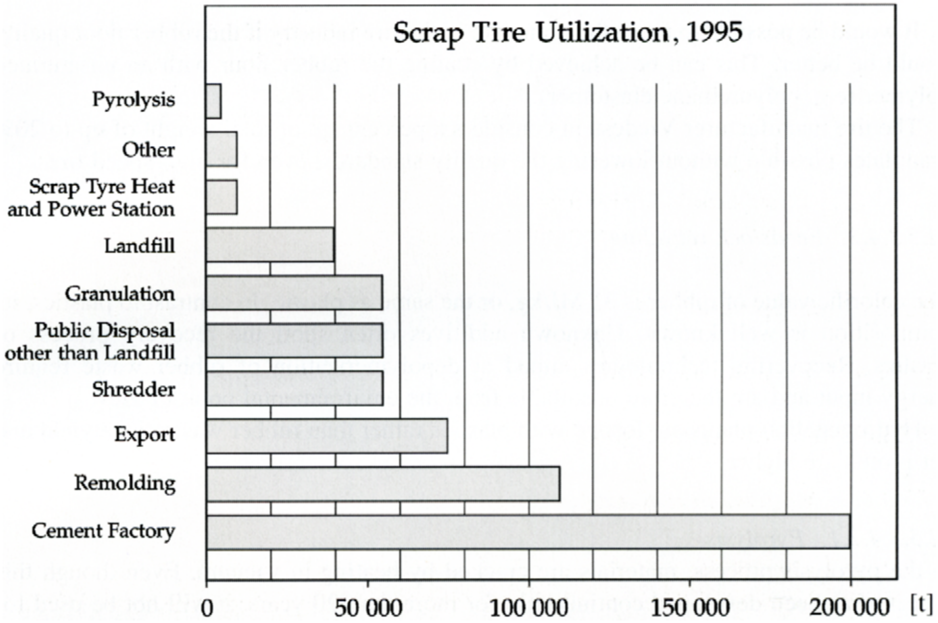


Figure VI.5.11. Utilization and disposal of rubber waste originating from scrap tires (Gesellschaft für Altgummiverwertungssysteme mbH, 1996; Schmidt-Burr, 1996).

Cold grinding process. In this process, rubber waste particles of 100 × 400 mm size are embrittled at − 100°C by addition of liquid nitrogen. Rubber flour is produced by stress impact treatment. The expenses will be higher due to the use of liquid nitrogen of about 0.5–1 kg N/kg granulate (EUWID, 1993).

In Germany, there are plants processing 15,000 t of scrap tires per year. Metals are separated with a magnet. Textiles are separated from the rubber by means of a revolving tube.

Hot grinding process. For this process, no liquid nitrogen is required. With the use of two granulators, the rubber waste is fragmented, first at a particle size of 14 mm and after separation of ferrous particles by a magnet, at a particle size between 1 and 6 mm.

Textile parts are separated by air-stream sorting. Compared to the cold grinding process, the treatment described last yields better rubber granulate quality. This process does not require liquid nitrogen and operating expenditures are even less (EUWID, 1993).

As the vulcanization process for rubber waste granulates is not well developed, it will be used for the production of less than 1% by weight of new tires. For this reason, the granulate will be used for construction mats and anti-noise sheets or sporting field surfaces. For these applications, the market for granulate is limited. Another recycling method for granulate is asphalt carpeting. However, substituting the commonly used bitumen with granulate does not make sense from the environmental point of view since bitumen cannot be cracked anymore and there are no appropriate alternative recycling methods for bitumen available (Schmidt-Burr, 1996).

It would be possible to reuse the granulate in the tire industry if the rubber flour quality would be better. This can be achieved by coating the rubber flour with an unsaturated polymer (e.g. polyurethane elastomer).

The tire manufacturer Vredestein considers a percentage of total weight of up to 20% granulates possible without lowering the quality standards, even for high-speed tires.

VI.5.3.4.2. Feedstock recycling

The calorific value of rubber is 31 MJ/kg, or the same as plastic. In contrast to plastics, its composition is well known. Unknown additives often spoil the recovery process of plastics. Recovering technologies aimed at depolymerization of rubber waste require energy input and are therefore unsuitable from the environmental point of view.

Hydrogenation plants are loaded with plastics rather than rubber waste since yield and net profits are higher.

VI.5.3.4.2.1. Pyrolysis

In the pyrolysis process, materials are cracked by heating in vacuum. Even though this process has been developed continuously for more than 20 years, it will not be used for economic reasons.

Pyrolysis yields from 1 t of scrap tires is shown in Table VI.5.19.

VI.5.3.4.2.2. Hydrogenation

Hydrogenation according to the VEBA process requires high pressures of about 250 bar. Therefore, rubber waste has to be liquefied before entering the process. Liquefaction is achieved by heating the rubber waste until elastomer chains will eventually depolymerize to smaller units. Following compression to 250 bar, the liquid material is heated to 480°C in a high-pressure reactor and hydrogen is added. By saturation with hydrogen, the carbon chains are furthermore cracked and at the same time detoxification takes place. In the process, different gases and a synthetic crude oil called "Syncrude" are produced (Table VI.5.20).

Table VI.5.19. Pyrolysis products recovered from 1 t of scrap tires (after Bilitewski et al., 1994).

Output	Amount (kg)
Soot	358
Heavy oil	186
Excess gas	121
Fuel gas	115
Steel	113
Solvents	39
Middle oil	18

Table VI.5.20. Components and characteristics of hydrogenation main product "Syncrude" (VEBA Kohleöl AG, 1996).

Constituent/characteristics	Percentage of weight (wt.%)
Naphthene, paraffin	87
Ethyl benzene	13
Sulfur	<0.05
Heavy metals	0 (crude oil: 3)
Distillability	Unlimited (crude oil: limited)

VI.5.3.4.2.3. Gasification

The main objective of gasification is the production of synthetic gas that can be used in other industrial processes. The rubber waste is mixed with oxygen and steam, at a reaction temperature of about 800°C forming a gas, which contains mostly hydrogen and carbon monoxide. Heavy metals and minerals are melted in the next phase (vitrification), thus forming a slag suitable for construction industries. In the third phase, condensable materials like tar and solid substances are gasified and turned into synthetic gas. Synthetic gas is a universal basis in the chemical industry, e.g. for the production of methanol. The process of high-pressure gasification is applied at the "Sekundärrohstoff-Verwertungszentrum Schwarze Pumpe GmbH"/Berlin.

VI.5.3.4.3. Energy recovery in cement factories

The cement industry is the most important consumer of rubber waste. It uses 236,000 t of scrap tires (26 MJ/kg calorific heat) and 290,000 t of industrial waste (plastic waste, paper, textiles, etc., 22 MJ/kg caloric heat) (VDZ, 1999). Table VI.5.21 shows a comparison of components of traditional fuels and scrap tires.

Table VI.5.21. Comparison of components of traditional fuels and scrap tires for the cement industry (PREAG Continental, 1996).

Contents	Natural gas	Fuel oil		Coal		Tires	
		Light	Heavy	Germany	S. Africa	Whole piece	Cut
C	72.90	86.40	86.30	89.00	82.30	68.00	81.00
H	24.00	13.30	10.80	1.60	5.00	5.60	6.70
O	0.50	–	–	4.00	9.30	2.50	3.00
N	2.60	0.02	–	4.80	1.90	0.25	0.30
S	<0.05	0.15	1.90	1.20	1.20	1.50	1.80
Cl + Br	0.15	–	–	0.17	0.01	0.13	0.15
Energy (kJ/kg)	40.324	42.500	40.500	29.200	25.250	28.800	34.300

In 1999, scrap tires supplied about 6% of the total fuels required (VDZ, 1999). They are fed in whole to the primary entering point of rotary kilns. If sufficient air is provided, complete combustion is achieved without increasing emissions. Sulfur dioxide is absorbed in clinker.

The cost of treatment amounts to about 100€/t rubber waste. For imported coal, the cost is about 80€/t. Therefore, the cement industry charges about 80–130€/t scrap tire to compensate for the difference (Bilhard, 1997).

VI.5.3.5. Markets for rubber waste

The "Gesellschaft für Altgummi-Verwertungssysteme" forecasts an increase in energy recovery from rubber waste, especially in cement factories and scrap tire heat, and power stations (Gesellschaft für Altgummiverwertungssysteme mbH, 1995).

An increased utilization of rubber waste in the production of new tires depends directly on the quality of the vulcanization process. The market share of reconditioned tires is 15% or 110,000 t. Of this number, 68% will be sold by tire dealers, 28% by car dealers, about 8% in gas stations and 4% in supermarkets (Schmidt-Burr, 1996). The quality of reconditioned and new tires is comparable except for high-speed applications (210 km/h or more), where reconditioned tires are not compatible any more.

The markets for insulating and anti-noise sheets are almost saturated.

VI.5.4. End-of-life cars

VI.5.4.1. Legal framework

In June 1993, the German government presented the first draft of an ordinance on end-of-life cars. Substantial issues covered by this draft were:

- the car retailers in the Federal Republic of Germany are held legally and financially responsible for the disposal of end-of-life cars;
- disposed end-of-life cars need to be recycled mechanically;
- new vehicles should be constructed with regard to recycling later on;
- the second draft of this ordinance requires retailers to take end-of-life cars back free of charge. It also stipulates special recycling quotas.

On 21.02.1996, the car manufacturers presented a declaration concerning the removal of end-of-life cars in order to avoid enacting the ordinance second draft. With this declaration, car manufacturers committed themselves to remove for free cars no more than 12 years old through certified recycling companies, to the recycling-oriented construction of new cars, to environmentally compatible disposal of end-of-life cars and to the development and optimization of both material cycles and reprocessing technologies and logistics.

The main objective of the car industry (as stated in the declaration of 21 February, 1996) was the reduction of waste percentage by weight as shown in Table VI.5.22.

Table VI.5.22. Reduction of the percentage of waste by weight according to the Car Manufacturers Declaration of 21 February 1996.

Year	1996	2002	2015
Maximum wt.% of waste	25	15	5

The German Ministry of Environmental Affairs responded by passing a legal regulation, which came into force on 1 April, 1998. The main contents are:

- mandatory registration of each car scrapped;
- specific technical and organizational requirements for construction, technical equipment and operation of buildings such as collection stations, recycling plants and vehicle shredders;
- obligatory annual inspection of the plant by external experts (certification).

The German system has been working satisfactory over the last 4 years. However, some problems still remain.

- Mostly in the first 2 years, a considerable percentage of end-of-life cars were exported to Eastern Europe to circumvent recycling costs. This problem is nowadays partly solved by tighter legal regulations in these countries.
- The external experts used different evaluation standards to certify recycling companies.
- The surveillance by the authorities is not always sufficient: some recycling plants are still operated without permission or certification.

In September 2000, the European Community passed a directive on end-of-life vehicles, which became effective in German law in 2002. The main goals are the following:

- disposal of end-of-life cars free of charge and establishment of a suitable nationwide infrastructure;
- increased recycling rates as compared to the ordinance of 1998;
- prohibition of certain heavy metals in the construction of new cars;
- implementation of comparable and transparent evaluation standards by external experts for the certification of recycling companies.

VI.5.4.1.1. Quantities of end-of-life cars

According to the prognosis of 1991, about 3 million cars would have been disposed each year until the year 2000 (Deutsche Shell, 1991). This estimate was based on the registration statistics, rolling stock and registration of cancels. In 1999, the rolling stock amounted to about 45 million motor vehicles. This number showed an increasing trend as shown in Figure VI.5.12.

The share of cancelled registrations amounts to approximately 6.8%. Thus in 1999, 3.05 million licenses for motor vehicles had been cancelled. In other words: in 1999, 3.05 million motor vehicles were disposed off.

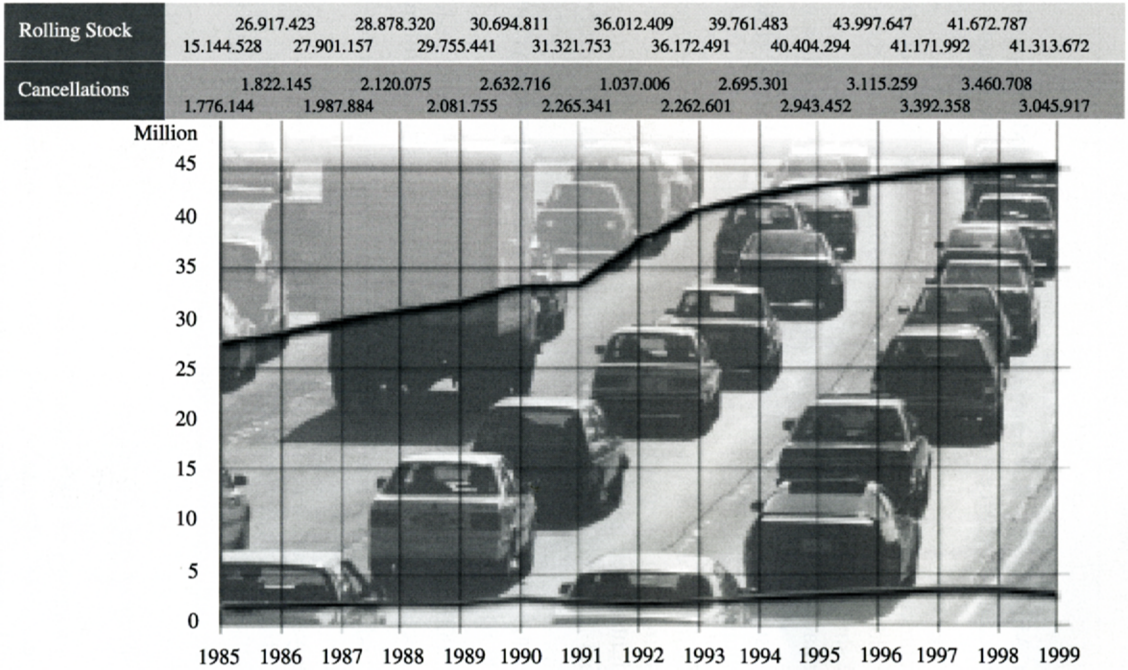


Figure VI.5.12. Rolling stock and cancellations of motor vehicles in the Federal Republic of Germany (after ARGE Altauto, 2000).

Prior to the ordinance of 1998, about 90% of end-of-life cars in Germany was disposed off by either shredding or dismantling and fragmentation. The other 10% was exported. The ADAC, the largest German automobile club, reports that 50% of end-of-life cars will be dismantled before shredding. The latter can be performed at shredding plants, which handle 85% of all disposed cars. The remainder is cut by scrap sheers and compressed in scrap presses (Schmidt, 1993). Today about 1.1–1.7 million (= 36–56% of cancellations) end-of-life cars in Germany are treated first by dismantling and fragmentation in about 1150 licensed recycling plants and, as a second step of treatment, by shredding. The rest will be exported or stolen (ARGE Altauto, 2000).

In 1993, 50 shredding plants handled 1.7 Mt of end-of-life cars (Anonymous, 1993b). Since 1993, a rising demand in shredding plants can be observed, as a shortage of capacity to handle about 200,000 t of end-of-life cars existed. In 2000, 57 licensed shredding plants (41 in Germany, 16 in other countries) were in operation (ARGE Altauto, 2000).

VI.5.4.1.2. Make up of components in end-of-life cars

The make up of the components in end-of-life cars has changed over the last years. The use of plastic instead of metal parts has increased (Table VI.5.23).

The use of plastics has notably increased, as they are not corrosive and are easier to manufacture. The development of highly stress-resistant plastics broadened the field of applications thus allowing the use of plastics in the engine compartment or for primary structures such as doors and fender wings.

Of about 40 different types of plastics used in the car industry (Fig. VI.5.13), the mainly used are given in Table VI.5.24.

As the weight percentage of plastics used in car manufacturing increases, the Automobile Industry League (VDA in German) recommended the identification of parts according to DIN 7728-Part 1, in order to improve recycling feasibility.

Table VI.5.23. Changes in the composition of end-of-life cars (after Härdtle, 1989).

Material	Year of scrapping					
	1980/85		1990/95		2000	
	kg	wt.%	kg	wt.%	kg	wt.%
Steel	560	55.1	535	53.0	465	47.0
Cast iron	142	14.0	126	12.5	109	11.0
NF metals	45	4.5	53	5.2	59	6.0
Rubber	53	5.2	51	5.0	50	5.0
Plastics	45	4.5	91	9.0	158	16.0
Glass	40	3.9	40	4.0	40	4.0
Other	130	12.8	114	11.3	109	11.0
Total	1015	100.0	1010	100.0	990	100.0

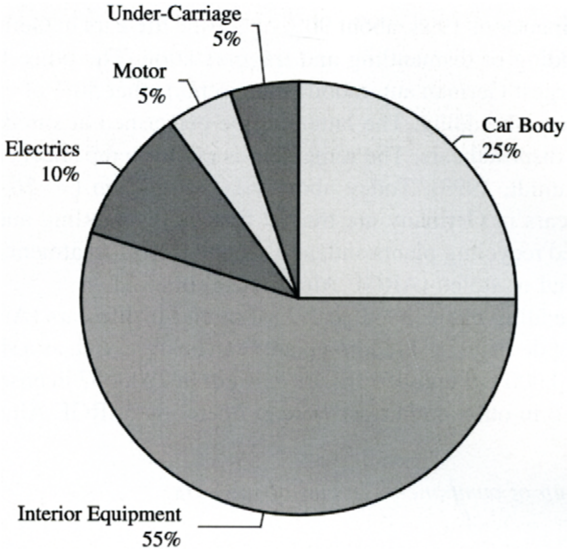


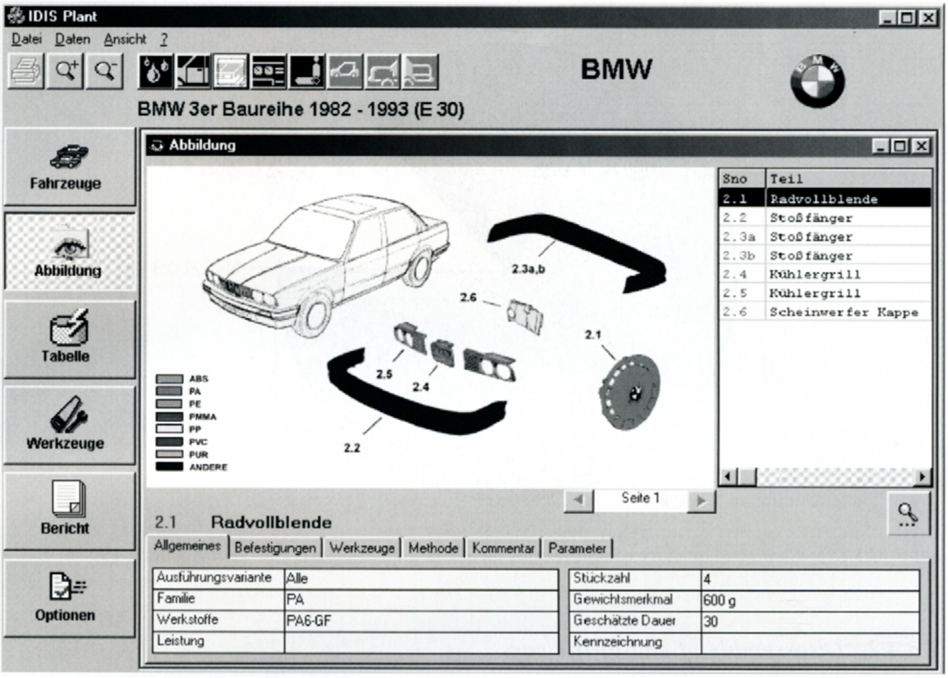
Figure VI.5.13. Use of plastics in motor vehicles: types of plastic (after Schmidt, 1992).

To improve the recycling technologies, the automobile industry developed the software tool "IDIS" (International Dismantling Information System), which contains information regarding materials and dismantling technologies for the most important types of cars. The licensed recycling plants can obtain it free of charge (Fig. VI.5.14).

Besides the above-mentioned solids, end-of-life cars contain operating fluids. Each car contains about 28 l. Because of the risk potential and danger of pollution, they have to be removed before the start of the recycling process. This has been a legal requirement since 1998. A special practical problem is posed by the resilient isolators because of the very small amount of oil and the time needed to tap it.

Table VI.5.24. Use of plastics in motor vehicles: types of plastic (after Schmidt, 1992).

Type of plastic	%	Example
PUR	22	Seats, noise isolation
PVC	23	Sheets, undersealant
ABS, PS	16	Damper, outside mirror
PP	16	Heating
PE	6	Fuel container, radiator
PA	6	Hubcap, paneling
Duroplasts	3	Motor-electrics, isolation
PMMA	2	Rear lamps



Sno	Teil
2.1	Radvollblende
2.2	Stoßfänger
2.3a	Stoßfänger
2.3b	Stoßfänger
2.4	Kühlergrill
2.5	Kühlergrill
2.6	Scheinwerfer Kappe

2.1 **Radvollblende**

Ausführungsvariante	Alle	Stückzahl	4
Familie	PA	Gewichtsmerkmal	600 g
Werkstoffe	PA6-GF	Geschätzte Dauer	30
Leistung		Kennzeichnung	

Figure VI.5.14. International Dismantling Information System (IDIS).

Table VI.5.25 shows the type and average quantity of operating fluids remaining in one used car.

In addition, end-of-life cars contain a considerable amount of non-ferrous metals (Fig. VI.5.15).

Table VI.5.25. Type and quantities of operating fluids remaining in an end-of-life car (after Bilitewski, 1992).

Operating fluid	Amount (l)
Fuels	3
Refrigerant	7
Motor oil	4
Washer water	3
Gear oil	2
Grease	1
Brake fluid	0.7
Differential oil	0.5
Total	21.2

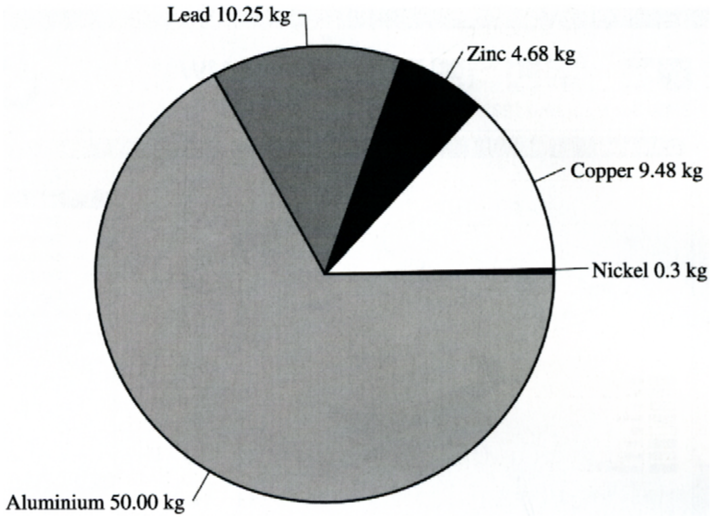


Figure VI.5.15. Share and quantity of non-ferrous metals in a middle-class car (after Schmidt, 1993).

VI.5.4.2. Disassembly of end-of-life cars

The main objective of dismantling end-of-life cars is the separation of the car's constituents into pure grade components. Thus the maximum degree of recycling is achieved. These are the advantages:

- materials and spare parts can be recycled;
- operating fluids can be removed safely during the draining;
- the amount of waste that can spoil the shredding process is reduced;
- deposition of the remaining waste at landfill sites is much easier since it is not contaminated with operating fluids (from 2005 onwards all waste to be disposed of at landfill sites will have to be pretreated thermally);
- the required energy input for shredding is less;
- the quality of the steel scrap is improved.

Figure VI.5.16 shows the main steps of dismantling.

VI.5.4.3. Shredding of end-of-life cars

The objective of shredding is the fragmentation of complete car bodies into particles sized between 50 and 150 mm. In Germany, shredding is mostly carried out using a shredder, which works like a hammer mill-crusher. Materials supplied are torn and ground until the desired particle size is obtained. Then, lighter particles will be separated by air stream sorting. Ferrous metals will be separated by a magnet. The process flow chart is shown in Figure VI.5.17.

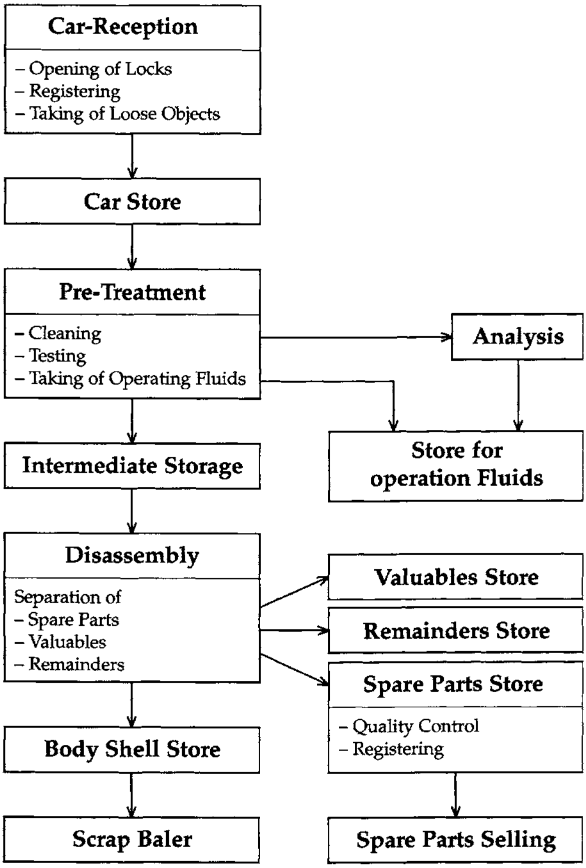


Figure VI.5.16. Dismantling steps in ELV recycling (after Bilitewski et al., 1994).

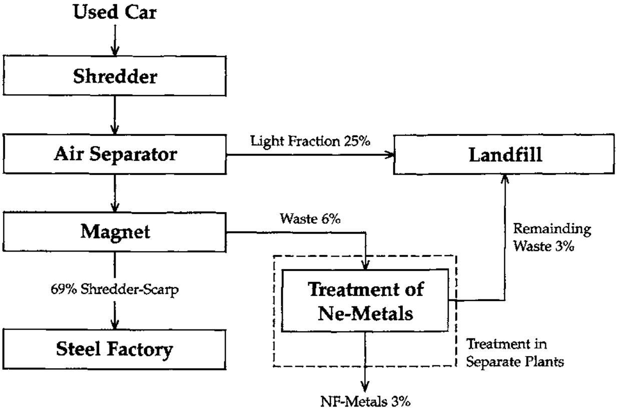


Figure VI.5.17. Flow chart of shredding ELV (after Bilitewski et al., 1994).

Table VI.5.26. Constituents of the heavy fraction (after Oetjen-Dehne and Ries, 1992).

Material	wt.%
Aluminum	41.2
Zinc	28.7
Copper	5.0
Lead	1.8
Other	23.3

After shredding, three fractions remain (weight percentages in parenthesis):

- steel scrap fraction (69%);
- heavy fraction (6%);
- light fraction (25%).

VI.5.4.3.1. Steel scrap fraction (69%)

The steel scrap complies with the requirements of the steel industry. It can be directly used. Of the end-of-life cars, steel scrap (69%) is 96% steel by weight. This presents a fair recycling share.

VI.5.4.3.2. Heavy fraction (6%)

Table VI.5.26 presents the composition of the heavy fraction.

These components can be separated by:

- separation in water;
- dry separation.

VI.5.4.3.2.1. Separation in water

First, all impurities are separated by washing. Second, the remaining ferrous metals are separated with a magnet. Third, in a float-sink process rubber, plastic and magnesium stay at the surface of ferrosilicon froth while non-ferrous metals sink. Through consecutive froth flotation, non-ferrous metals can be further separated. The separation efficiency is 93%. Although operating process waters run in closed circuits, the use of ferrosilicon requires excessive wastewater treatment, which renders this process too expensive in the long run.

VI.5.4.3.2.2. Dry separation

Dry separation is a multilevel process consisting of air-stream sorting and vibrating screens. Materials to be recovered are identified by:

- atomic emission spectroscopy,
- X-ray fluorescence analysis,

which control a sorting device.

Table VI.5.27. Composition of the light fraction (after Goldmann and Fröhlich, 1991).

Waste fraction		Light fraction	
Material	wt.%	Material	wt.%
Aluminum	41.2	Elastomeres (rubber)	23
Zinc	28.7	Cl-free thermoplasts	13
Copper	5.0	Glass, ceramics	13
Lead	1.8	Iron	13
Other	23.3	Fibers, cellulose	10
		Foams (PUR)	7
		PVC	6
		Varnish	3
		Aluminum	3
		Copper	1
		Other	8

Another means is a one-step identification and sorting by Eddy current. Eddy currents induce magnetic fields in non-ferrous metals. Since non-ferrous metals differ in their conductivity, the intensity of the magnetic field induced also differs. Hence a magnetic field of opposite direction allows the separation easily. The break-even point for sorting by Eddy current is 60,000 t/year (Sattler, 1991).

VI.5.4.3.3. Light fraction (25%)

Recycling of the light fraction is still unprofitable. Therefore, the light fraction is normally disposed at landfill sites (Table VI.5.27).

To reach the recycling rates of the European directory, it is necessary to decrease the amount of the light fraction to recover parts of it. A process for the handling of the light fraction has been developed. A pilot plant has been working since April 2000 (Fig. VI.5.18). The fractions are iron/steel, copper of a good quality, a mixture of metals and minerals and an organic fraction, which will be recovered in incineration plants.

VI.5.4.4. Treatment and recovery of remainders

VI.5.4.4.1. Remaining materials

During the dismantling process, the following materials are recovered:

- steel scrap, non-ferrous metals and noble metals;
- high-quality parts;
- plastics and polyurethane foam seats;
- tires;
- glass;
- operating fluids.

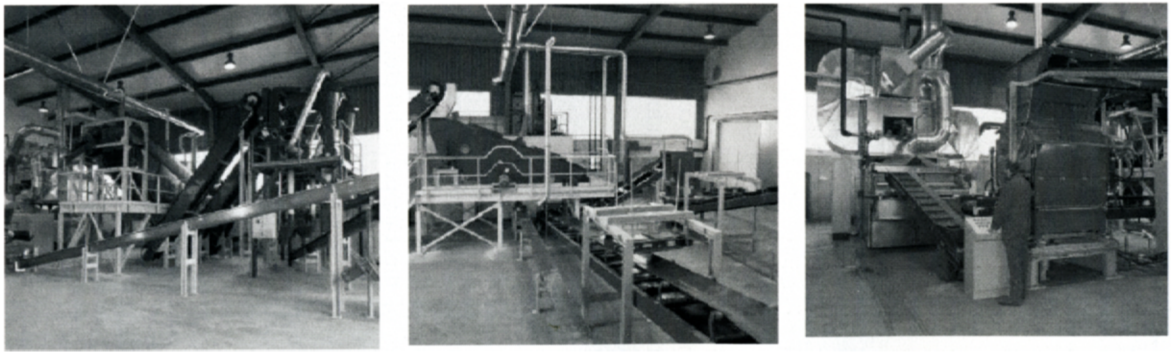
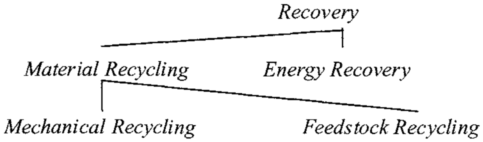


Figure VI.5.18. Pilot plant for the treatment of the shredder light fraction (ARGE Altauto, 2000).

There are several recovering options in principle:



The engines, drive trains and other valuable components can be used again after repairing and reconditioning (mechanical recycling). Plastics can be chemically recycled and reused in similar production processes (feedstock recycling).

VI.5.4.4.2. Steel scrap

The steel scrap will be used for the production of new steel. The more intense the dismantling, especially the separation of main contaminants: copper, nickel, chromium and molybdenum, the better the quality of the steel scrap. According to the Association of Iron and Steel Industries, steel scrap from end-of-life cars is classified type 4 steel-scrap index (Association of Steel Manufacturers, 1997).

VI.5.4.4.3. Non-ferrous metals

The most important components of the heavy fraction – aluminum, zinc and copper – will be 90% recyclable. These materials will be melted in special smelters. They are further used in applications with the same quality requirements as the original material. For example, aluminum will be used as secondary aluminum in the engine compartment. Copper will be reused in cable manufacturing.

VI.5.4.4.4. Precious metals and catalysts

In 1993, the regulations for vehicles emissions were changed radically in Europe. Compliance with regulations can only be achieved by using catalysts. Limited resources of precious metals and the high value of precious metals forced recycling of used catalytic converters in order to recover platinum, palladium and rhodium.

Recovery of these materials is achieved by disassembly of the catalytic ceramic unit, followed by obtaining a ceramic powder with homogenous precious metal quantities through grinding, filtration and mixing and finally by treating the ceramic powder chemically or by applying pyrometallurgy. A share of recovery up to 98% (platinum) or 80% (rhodium) can be achieved without lowering the quality of recovered precious metals (Stoll, 1991).

VI.5.4.4.5. Plastics

Plastics have been exposed to high stress (mechanical and chemical) in end-of-life cars. About 120 kg plastics of poor quality can be recovered per used car (Richter and Lotz, 1996). Plastics account for about 30% of the shredded light fraction. Since recycling does not yet pay off, these plastics are deposited at landfill sites together with other components of the shredded light fraction. Plastics recycling is therefore close to 0%.

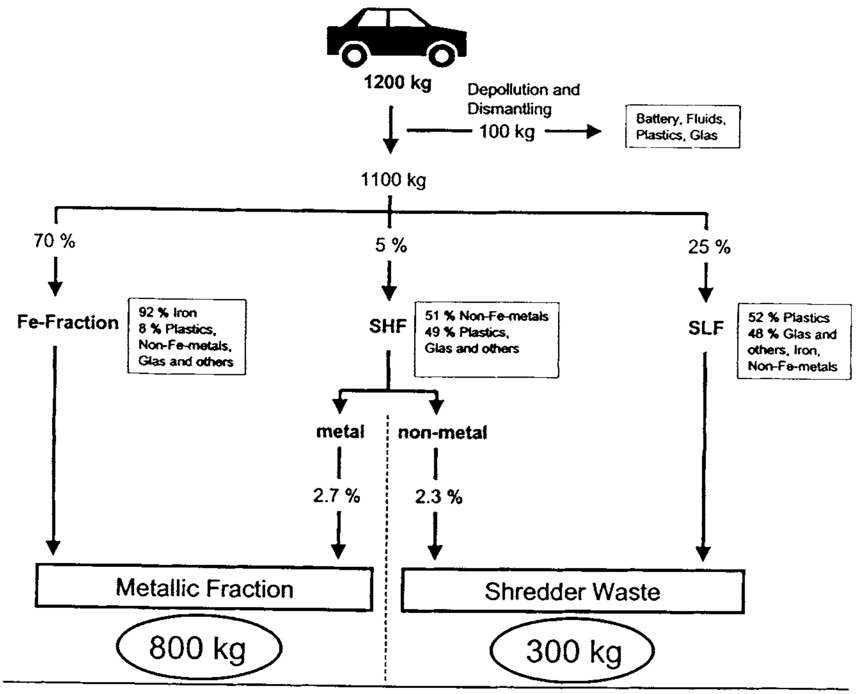


Figure VI.5.19. Material flow in the car shredding process (Lohse et al., 2001).

Although deposition of 120 kg of plastics per used car is negligible considering the total weight, shredding companies can significantly reduce deposition costs if they do not need to make use of deposition. Recycling methods depend on the purity grade of plastics (Fig. VI.5.19).

There are three basic recovery options: energy recovery, mechanical recycling and feedstock recycling. Energy recovery in gasification plants or combined heat and power stations is applied to compounds and bigger parts albeit to a minor extent. PUR-foam seats are burned in power stations replacing up to 20% of traditional fuels (Weigand et al., 1996). Costs are incurred mainly for disassembly and transportation.

Mechanical recycling and feedstock recycling require high purity grades to guarantee compatibility of secondary plastics with primary products. Advanced sorting techniques in order to gain high purity grades are not profitable yet. Figure VI.5.20 explains why.

The working group *End-of-life Cars Recycling of German car manufacturers (PRAVDA)* aims to use recycled plastics as grinding stock additives if the safety requirements allow this. As for mechanical recycling, duroplasts are ground to 2–4 mm particle size and added as filler in the duroplast manufacturing process. For instance, the plastics portions of the former GDR cars "Trabant" have been transformed into insulating sheets and anti-noise sheets using this process.

Plastics recycling is successfully applied to polypropylene shock absorbers. They are easily accessible for dismantling. They are composed completely of polypropylene, which

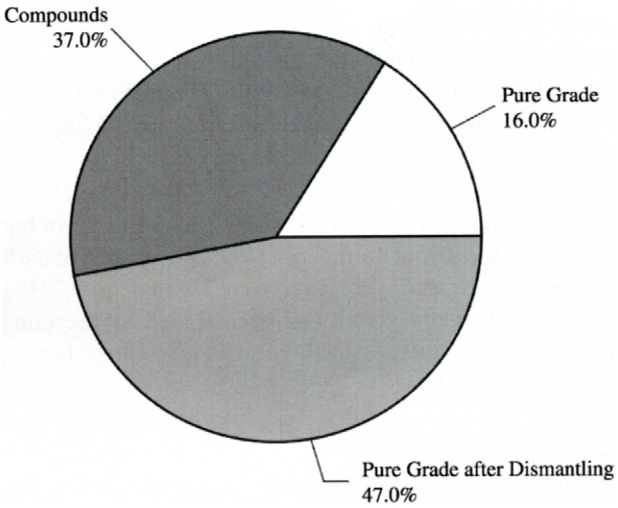


Figure VI.5.20. Purity grade of plastics from ELV after disassembly (after Richter and Lotz, 1996).

complies with high purity demands and only has to be devarnished before grinding. The same characteristics apply to petrol containers.

Nevertheless, recycling of plastics is not economical yet. Therefore, automatic detectors for the separation of the different plastic types are necessary. BMW is developing such a technique.

VI.5.4.4.6. Glass

Every year about 60,000 t of flat glass, from end-of-life cars must be processed (Anonymous, 1991). Each car contains an average of 4% of its weight or 40 kg flat glass. The main portion is deposited as waste. The rest will be used for isolation glass, hollow glass and cast glass. A secondary usage in car manufacturing is impossible due to the high-quality standards. Especially the glass of the windscreen and the side windows cannot be recovered in a common process.

VI.5.4.4.7. Operating fluids

VI.5.4.4.7.1. Oil

Oil from oil changes or operating fluids taken during end-of-life cars disassembly, comply with the requirements for processing as second class refine according to used oil ordinance/category I. Processing and retailing is carried out by the recycling industry and petrol industry.

An important part of the used oil is recovered as a carrier of carbon and is used as energy in blast furnaces in the steel producing industry.

VI.5.4.4.7.2. Fuels

The fuels taken are sometimes contaminated by either solvents or water. In this case, they cannot be recycled and thus have to be disposed off. The main portion of recovered fuel, however, can be used in vehicles of the recycling plant after having been tested.

VI.5.4.4.7.3. Coolant

A few years ago, coolants had to be disposed off in special plants. In recent years, a new process for the recovery of the glycol portion of coolants by means of a film evaporator has become more and more important. Glycol is recovered with up to 99.5% purity. Therefore contracts on delivery of secondary glycol had been signed by recycling companies and coolant manufacturers. Today more than 90% of the coolant is recycled in several specialized plants.

VI.5.4.4.7.4. Brake fluid

Previously, brake fluids were burned in hazardous waste incineration plants. Since 1992, they can be re-esterified in a plant in Schleswig-Holstein, where the boron portion of the glycol ether is separated to distill the glycol ether in a second step. Eventually, the separated boron portion and the distilled pure glycol ether are esterified into brake fluid again. The treatment procedure recovers 95% of the brake fluids' main components (Bilitewski et al., 1994). Nowadays the most important part of the brake fluid is recovered in similar plants.

VI.5.4.4.8. High-quality spare parts from end-of-life cars

Spare parts from end-of-life cars have long been recycled. Especially abrasive parts are exchanged for repaired spare parts from end-of-life cars, e.g.:

- engine, gears, axle;
- starter, generator;
- carburetor, fuel pump;
- radiator, wheels.

Spare part sales are still the most important source of revenue for recycling plants.

VI.5.4.4.9. Batteries

The average life span of batteries is about 5 years. 90% of worn batteries are recycled. First, the sulfuric acid is removed and recycled. Then the battery is crushed in a roller crusher. Ferrous particles are extracted by a magnet, plastics separated by sink-float sorting. The lead portion gained thereby is refined and sold as commercial lead. This technique is both economically and ecologically acceptable.

VI.5.4.4.10. Waste flows in used car recycling

Figure VI.5.21 shows the waste flow in end-of-life cars' recycling (new techniques for the handling of the shredder light fraction are not considered yet).

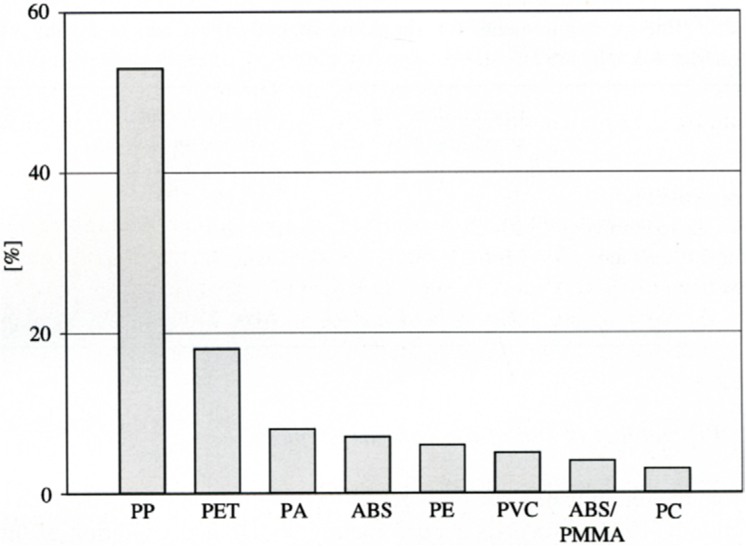


Figure VI.5.21. Distribution of types of plastics in the "high purity grade fraction" (after Richter and Lotz, 1996).

VI.5.4.5. Economics of end-of-life car recycling

VI.5.4.5.1. Basic considerations

The profitability of end-of-life car recycling depends directly on the age of vehicles. The older a spare part or material, the less its value. Usually, a market for recycled spare parts exists as long as the type of vehicle is still manufactured. The size of the market depends on its rolling stock. That does not apply to spare parts limited to a special type of vehicle, for instance, starters or generators. Also technical development accounts for reduced profitability of spare parts recovery and retailing, apart from wear and corrosion.

In theory, profitability could be raised if waste flows are scaled up in a recycling alliance. Nevertheless, high-quality recycling would result in losses up to DM 300–400 (150–200€) per car according to an investigation (ORG-Consult, 1992). Limiting factors are the extent of disassembly and recovery.

Recovery could principally be performed with or without disassembly preceding shredding. For energetic reasons, disassembly became a standard recovery step and a legal requirement as explained in Table VI.5.28.

It can be concluded that through prior disassembly about 2–13 kW h of energy per ton can be saved. Besides the energy saving aspect, removing the light fraction is quite costly, whereas retailing spare parts is considered profitable. Expenditure for light fraction removal is even higher if shredding is not preceded by disassembly, rendering the light fraction much more contaminated (Table VI.5.29).

But to get this system working, economical ways for the recovery of plastics, glass, rubber and other non-metal materials have to be developed and established.

Table VI.5.28. Energy requirements for shredding of end-of-life cars with and without prior disassembly (after Adolph, 1992).

Shredding	Energy demand shredding (kW h/t)	Energy demand processing (kW h/t)	Savings
With prior disassembly	25–28	10–13	
Without prior disassembly	20–23	8–10	
Energy savings if cars are disassembled first	Min. 2	Min. 0	$\sum$Min. = 2
	Max. 8	Max. 5	$\sum$Max. = 13

VI.5.4.5.2. Profitability of end-of-life cars disassembly

Proceeds from the retailing of spare parts are estimated to reach DM 270–300 (135–150€) per car (Schmidt, 1993). Proceeds depend mainly on age and condition of the vehicles. Disassembly time is 180 min on average (Fig. VI.5.22).

The graph also applies to the disassembly of other materials. Figure VI.5.23 shows disassembly expenditures of different recycling companies.

The costs range between DM 250 (125€) and DM 400 (200€) per vehicle. They depend on the vehicle's age and state and the number of end-of-life cars processed.

VI.5.4.5.3. Profitability of shredding

Treatment expenditures for shredding are distributed as shown in Table VI.5.30.

In 1991, shredding expenditures amounted to an average of DM 130 (65€) per ton. Main expenditures and main proceeds in used car recycling are summarized in Table VI.5.31.

VI.5.4.5.4. Steel scrap

Proceeds from steel scrap depend on its quality. The quality is related to the extent of the necessary disassembly, the latter being the most expensive step in end-of-life cars' recycling. This limits the profitability. Interdependencies of steel scrap retailing are shown in Figure VI.5.24.

Profitability was found the best at 60% extent of disassembly (UMBERA, 1992).

Table VI.5.29. PCB loading of shredding waste depending on prior treatment (UBA, 1991).

Shredding	PCB loading, mg/kg of shredding waste
Without prior disassembly	150
With prior disassembly	< 10

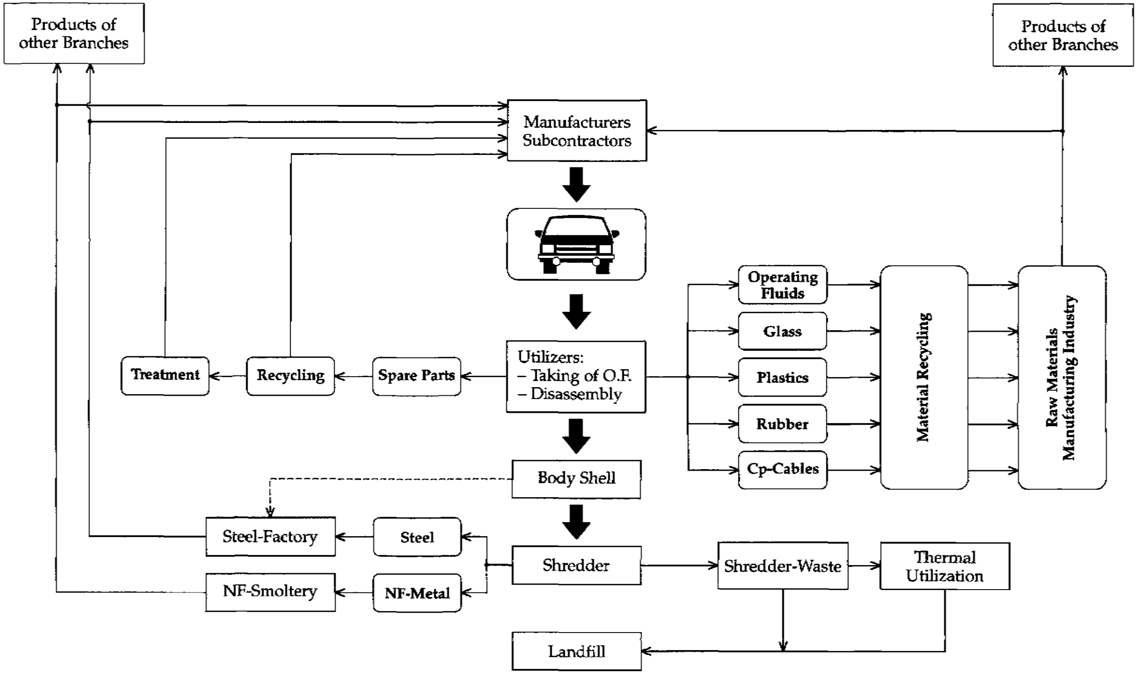


Figure VI.5.22. Waste flow in recycling (after Bilitewski et al., 1994).

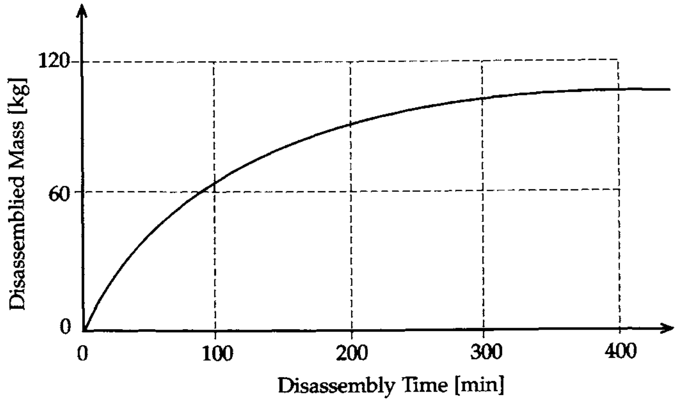


Figure VI.5.23. Correlation between disassembly time and yield (after Richter and Lotz, 1996).

VI.5.4.6. Markets

VI.5.4.6.1. Steel scrap

In 1992, 39.8 Mt of raw steel was manufactured with almost one-third or 12.8 Mt generated from steel scrap. Steel scrap originates from end-of-life cars recycling, demolition waste, incineration plants, steel swarf and sheet scrap (Bundesverband deutscher Stahlunternehmen, 1993) (Fig. VI.5.25).

VI.5.4.6.2. Non-ferrous metals

Aluminum is the most important non-ferrous metal recovered in used car recycling. As the share of aluminum in the car bodies will be increasing and 95% of the energy can be saved in contrast to producing primary aluminum by using secondary aluminum with its low melting point of 660°C, the automobile industry appears to be a promising market.

Table VI.5.30. Distribution of treatment expenditures: shredding (Anonymous, 1992).

Item	Percentage of total expenditure (%)
Disposal of remaining waste	30–40
Plant maintenance	22
Personnel	15
Energy consumption	10
Others	10–23

Table VI.5.31. Main expenditures and main proceeds in end-of-life car recycling.

Process	Main expenditures	Main proceeds	Variable
Disassembly	Personnel	Spare parts	Extent of disassembly
Shredding	Disposal R-waste	Steel scrap	Extent of disassembly → purity Separation of NE metals

VI.5.4.6.3. Plastics

See Section VI.5.2.

VI.5.4.6.4. Precious metals from catalytic converters

Precious metals from catalytic converters can be used again in the manufacturing of new catalytic converters. About 0.3 g of rhodium and 1.5 g of platinum are required per catalytic converter. Due to improved emission rules in the European Union, an estimated additional 20 million catalytic converters will be produced.

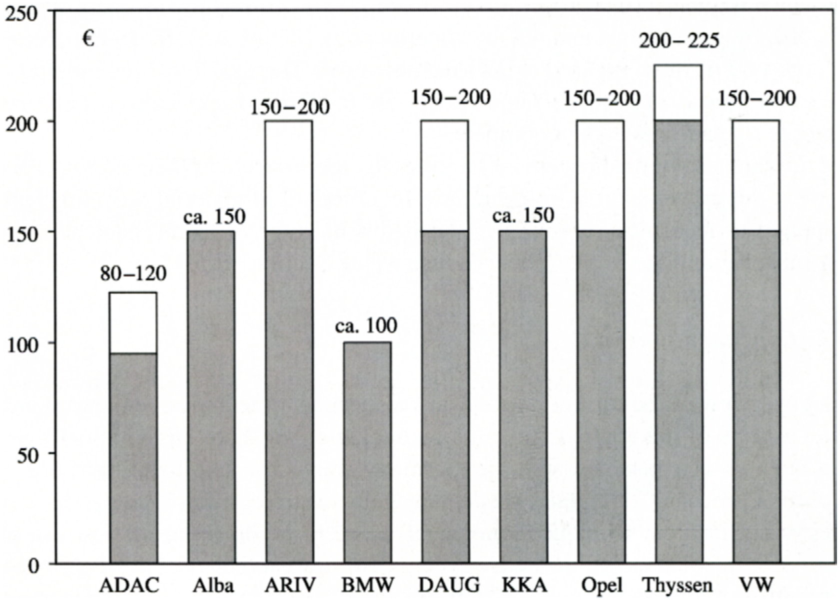


Figure VI.5.24. Main expenditures and main proceeds in end-of-life car recycling (originally in DM; DM ≈ 0.5€).

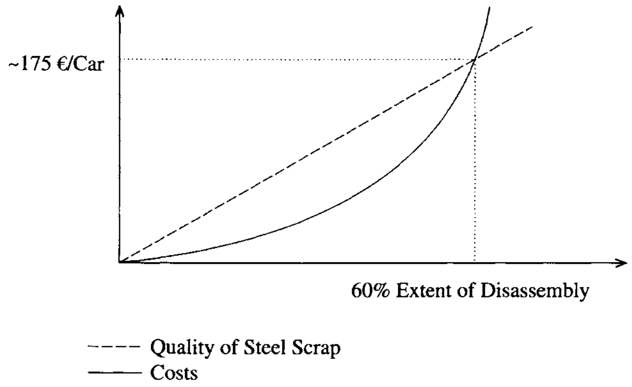


Figure VI.5.25. Profitability of steel scrap recycling related to steel scrap quality and extent of disassembly.

VI.5.4.6.5. Spare parts

In Germany, approximately 250 companies are involved in recondition and retail spare parts from end-of-life cars. The market for spare parts is consolidated.

VI.5.4.6.6. Tires

Remolded tires compete with new tires in the market. They hold a 15% share of the market, which is about 110,000 tires. Of this, 68% will be sold by tire retailers, 28% by car retailers, 8% by gas stations and 4% by supermarkets (Schmidt-Burr, 1996). Retreading requires only 6 l of oil compared to 28 l for new tires. The quality of retread and newly manufactured tires is almost the same except for high-speed applications (210 km/h or more) where retread tires cannot compete.

Used tires are also burned in cement factories in order to recover their energy. There are even special tire power stations in operation. If submitted to material recycling, tires are either applied to feedstock recycling in the petrol industry or to mechanical recycling, yielding rubber granulate in the rubber industry (see Section VI.5.3).

VI.5.4.7. Concluding remark

This brief overview of the current practice and assessment of technical, environmental and economic aspects of the applied recycling technologies for three large and still growing complex streams of consumer waste in Germany shows, on one hand, that one of the targets of the European Community waste management strategy that is complete or partial waste recycling in order to reduce amount of waste to be disposed off and use of raw materials, and, in some cases, to recover energy from waste material through using it as a fuel, might be successfully pursued. On the other hand, these technologies should be economically viable and competitive in the market. For this, further legal and economic structural arrangements are needed, both at the Community and the national level.

References

Adolph, M., 1992. Einsatz von Shredderanlagen zur Aufbereitung von Autokarosserien, Leichtschrott und NE-Metallschrott. In: Thomé-Kozmiensky, K.J. (Ed.), Recycling International 1992, EF-Verlag, Berlin (in German).

Anonymous, 1991. Glasindustrie. Sekundär-Rohstoffe Nr. 6, 192–193 (in German).

Anonymous, 1992. Schrottwirtschaft. Sekundär-Rohstoffe Heft, 1, 4 (in German).

Anonymous, 1993a. Abfall zum Werkstoff – Aufbereitungstechnik beim Verwerten von Kunststoffen. 20 Jahrestagung Aufbereitungstechnik, 24/25 November in Neu-Ulm, VDI-Verlag, Düsseldorf (in German).

Anonymous, 1993b. Shredderanlagen in Deutschland. Recycling Nr. 2, 32–33 (in German).

ARGE Altauto – Arbeitsgemeinschaft Altauto, 2000. 1. Monitoringbericht gemäß Punkt 3.6 der Freiwilligen Selbstverpflichtung zur Umweltgerechten Selbstverpflichtung von Altfahrzeugen (Pkw) im Rahmen des Kreislaufwirtschafts-/Abfallgesetz. Frankfurt (in German).

Association of Steel Manufacturers (Stahl-Vereinigung), 1997. Personal communication.

Bilhard, H., 1997. Personal communication. Spenner-Zement, Bad Lippspringe.

Bilitewski, B., 1992. Demontagetechnik von Altautos. In: Thomé-Kozmiensky, K.J. (Ed.), Materialrecycling durch Abfallaufbereitung, EF-Verlag, Berlin (in German).

Bilitewski, B., Härdtle, G., Kijewski, K., Marek, K., 1991. Recycling von Kunststoffabfällen. Beihefte zu Müll und Abfall Heft 27, Erich-Schmidt-Verlag, Berlin (in German).

Bilitewski, B., Gorr, C., Härdtle, G., Marek, K., 1994. Altautoverwertung. Beihefte zu Müll und Abfall Nr. 32, Erich-Schmidt-Verlag, Berlin (in German).

Bundesverband deutscher Stahlunternehmen, 1993. Zukunftsperspektiven angedacht. Rohstoff Rundschau Nr. 22, pp. 861–868 (in German).

Christill, M., et al., 1996. Mitverbrennung von Kunststoffen in Kohlestaubfeuerungen; Halbtechnische Versuche und Möglichkeiten der Großtechnischen Anwendung. VDI-Berichte 1288: Verwertung von Kunststoffabfällen, VDI-Verlag, Düsseldorf, p. 281 (in German).

Consultic, Marketing und Industrieberatung GmbH, 1995. Statistik zu Kunststoffabfällen 1994 (in German).

DKR – Deutsche Gesellschaft für Kunststoff-Recycling mbH (Ed.), 1995. Recycling von Verkaufsverpackungen aus Kunststoffen. Köln (in German).

DKR – Deutsche Gesellschaft für Kunststoff-Recycling mbH (Ed.), 2002a. Plastic Fractions 2000. Web site: www.dkr.de.

DKR – Deutsche Gesellschaft für Kunststoff-Recycling mbH (Ed.), 2002b. Recycling Channels 1998; 1999; 2000. Web site: www.dkr.de.

DSD – Duales System Deutschland GmbH (Ed.), 1996. Wandlungen – Kunststoffrecycling Heute. Köln (in German).

DSD – Duales System Deutschland GmbH (Ed.), 2002. Geschäftsberichte 1997–2000. Bilanz/Kennzahlen. Köln. Web site: www.gruener-punkt.de (in German).

DSD – Duales System Deutschland GmbH, VCI – Verband der Chemischen Industrie, VKE – Verband Kunststofferzeugende Industrie, Association of Plastic Manufacturers in Europe (Eds.), 1996. Ökobilanzen zur Verwertung von Altkunststoffen und Verkaufsverpackungen. Informationsbroschüre des DSD, Köln (in German).

EC: European Parliament and Council Directive 94/62/EC of 20 December 1994 on packaging and packaging waste. OJ L 365, 31.12.1994, pp. 10–23 with derogations OJ L 014, 19.01.1999 and OJ L 056, 04.03.1999.

EC: Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of-life vehicles – Commission Statements. OJ L 269, 21.10.2000.

EUWID – Europäischer Umwelt-Wirtschafts-Informationsdienst, 1993. Neues Verfahren für das Altreifenrecycling Nr. 2.

Gesellschaft für Verpackungsmarktforschung, 1994. Wiesbaden, 3.

Gesellschaft für Altgummiverwertungssysteme mbH (Ed.), 1995. Altgummiverwertung in Deutschland. Statusbericht 1995. Frankfurt (in German).

Gesellschaft für Altgummiverwertungssysteme mbH (Ed.), 1996. Kurzbericht zur Altgummiverwertung Juli 1996. Informationsbroschüre. Frankfurt (in German).

Goldmann, D., Fröhlich, G., 1991. Mechanische Aufbereitung von Shredderleichtmüll und Demontageteilen aus der Altautoverwertung. VDI-Berichte 934, VDI-Verlag, Düsseldorf (in German).

Hanning, N., Raddatz, E., 1995. Eigenschaften und Anwendungen von Rezyklaten aus Polyethylen-HD. In: Brandrup, J., Bittner, M., Michaeli, W., Menges, G. (Eds), Die Wiederverwertung von Kunststoffen, Carl Hanser Verlag, München, Wien (in German).

Härdtle, G., 1989. Vermeidung, verwertung und entsorgung von Abfällen aus Altautos. In: Thomé-Kozmiensky, K.J. (Ed.), Abfallvermeidung in der Metallindustrie 1, EF-Verlag, Berlin (in German).

Hecka, C.h., Niemann, K., 1996. Die hydrierende Aufarbeitung von Kunststoffen. VDI-Berichte 1288: Verwertung von Kunststoffabfällen, VDI-Verlag, Düsseldorf (in German).

Hofmann, V., 1993. Recycling von Alt-PVC-Bodenbelägen in der AgPR. Kunststoff-Recycling. Tagungshandbuch Umweltfachkonferenz am 10/11. Mai 1993 in Frankfurt (in German).

Kohler, G., 1991. Recyclingpraxis Baustoffe, Verlag TÜV Rheinland, Köln (in German).

Korff, J., Heim, K.-H., 1989. Hydrierung von synthetisch organischen Abfällen. Erdgas, Erdöl, Kohle, Heft, 5 (in German).

Lautenschlager, G., Mark, F.E., 1996. Co-Verbrennung von Kunststoff-Abfällen in Hausmüllverbrennungsanlagen. VDI-Berichte 1288: Verwertung von Kunststoffabfällen, VDI-Verlag, Düsseldorf, p.245 (in German).

LENTJES LBL: Arbeitsgemeinschaft für Altreifenentsorgung. Information Ad.

Lindner, W., 1996. Status Quo der Verwertung von Kunststoffen aus dem Consumer-Bereich. VDI-Berichte 1288: Verwertung von Kunststoffabfällen, VDI-Verlag, Düsseldorf, p. 16 (in German).

Lohse, J., Sander, K., Wirts, M., 2001. Heavy Metal in Vehicles II. Final report compiled for the EC DG Environment, Nuclear Safety and Civil Protection. Ökopol – Institut für Ökologie und Politik GmbH, Hamburg, Germany, July 2001, downloaded from www.europa.eu.int/comm/environment/waste/facts_en.htm.

Mark, F.E., Vehlow, J., Wanke, T., 1996. Co-Verbrennungsversuche von Kunststoffabfällen und Hausmüll – Basisversuche in der Testanlage TAMARA. VDI-Berichte 1288: Verwertung von Kunststoffabfällen, VDI-Verlag, Düsseldorf, p. 263 (in German).

Martin, R., 1995. Monoverbrennung von Kunststoffen. In: Brandrup, J., Bittner, M., Michaeli, W., Menges, G. (Eds), Die Wiederverwertung von Kunststoffen, Carl Hanser Verlag, München, Wien, p. 887 (in German).

Masshöfer, D., 1989. Wiederaufbereitung von Kunststoffabfällen aus der Kabelzerlegung. Verfahrenstechnik Heft, 12 (in German).

Meimberg, G., 1995. Werkstoffliche Grundlagen des Kunststoff-Recyclings. In: Brandrup, J., Bittner, M., Michaeli, W., Menges, G. (Eds), Die Wiederverwertung von Kunststoffen, Carl Hanser Verlag, München, Wien, p. 13 (in German).

Oetjen-Dehne, R., Ries, G., 1992. Aufbereitung von Autowracks. In: Thomé-Kozmiensky, K.J. (Ed.), Materialrecycling durch Abfallaufbereitung, EF-Verlag, Berlin (in German).

ORG-Consult, 1992. Automobilrecycling im Verbund. Studien-Kurzfassung der ORG-Consult im Auftrag des Ministeriums für Mittelstand und Technologie des Landes Nordrhein-Westfalen (in German).

PREAG, Continental, 1996.

Richter, E., Lotz, H.-R., 1996. Kunststoffrecycling aus Elektronikschrott und Automobilabfällen. VDI-Berichte 1288: Verwertung von Kunststoffabfällen, VDI-Verlag, Düsseldorf (in German).

Sattler, P., 1991. Schrottsortieren mit Laser – ein automatisches Aufbereitungsverfahren für vermischte NE-Metalle von Automobilshredder. VDI-Berichte 934, VDI-Verlag, Düsseldorf, pp.23–66 (in German).

Schäper, S., 1993. Statusbericht polymerrecycling im Rahmen des Großversuchs der deutschen automobilindustrie zur Altfahrzeugverwertung. VDI-Tagung: Kunststoffe im Automobilbau, Mannheim, März/April 1993 (in German).

Schmidt, J., 1992. Recycling von Kunststoffen aus Automobilen. In Stand und Entwicklungstendenzen beim Kunststoff-Recycling. Seminar des Deutschen Industrieforums für Technologie, Würzburg, 6–7 Mai, 1992.

Schmidt, J., 1993. Automobil-Recycling international gesehen: Konzepte und Lösungswege in verschiedenen Ländern. Praxis-Forum Tagung Nr. 11, 23–66 (in German).

Schmidt-Burr, P., 1996. Innovative Kreislaufwirtschaft für Altreifen am Projektbeispiel Berliner Reifenwerk. VDI-Berichte 1288: Verwertung von Kunststoffabfällen, VDI-Verlag, Düsseldorf (in German).

Statistisches Bundesamt (Ed.), 1996. Statistisches Jahrbuch 1996 für die Bundesrepublik Deutschland, Metzler-Poeschel, Stuttgart (in German).

Statistisches Bundesamt (Ed.), 1997. Jahresstatistik 1997, Metzler-Poeschel, Stuttgart (in German).

Stoll, P., 1991. Recycling von Autoabgaskatalysator. EP-Spezial Nr. 1, 29–32 (in German).

UBA – Umweltbundesamt (Ed.), 1991. Schadstoffentfrachtung von Shredderrückständen. Jahresberichte des Umweltbundesamtes. Berlin, p. 281 (in German).

UMBERA, 1992. Umweltverträgliche Entsorgung von Altfahrzeugen mit dem Ziel maximaler stofflicher Wiederverwertung. Vorstudie im Auftrag des Bundesministeriums für Wissenschaft und Forschung der Republik Österreich. St. Pölten (in German).

VDZ – Verein deutscher Zementwerke e. V., 1999. Umweltdaten der deutschen Zementindustrie. Düsseldorf. Web site: www.vdz-online.de/pub/pub.html (in German).

VEBA Kohleöl AG, 1996.

VerpackV, Verordnung über die Vermeidung und Verwertung von Verpackungsabfällen vom 27, August 1998. BGBl I 1998 S. 2379; 1999 S. 2059; 2000 S. 1344; 2001 S. 2331 (in German).

VKE – Verband Kunststofferzeugende Industrie e.V., 2002: Plastics. Business Data and Charts. Frankfurt. Web site: www.vke.de (in German).

VKE – Verband Kunststofferzeugende Industrie e.V., Matthews, V., 1995. Die europäische Situation bei Kunststoffaufkommen und -entsorgung. Ein statistischer Überblick. In: Brandrup, J., Bittner, M., Michaeli, W., Menges, G. (Eds), Die Wiederverwertung von Kunststoffen, Carl Hanser Verlag, München, Wien, p. 543 (in German).

Weigand, E., Wagner, J., Waltenberg, G., 1996. Energetische Verwertung im Industriekraftwerk - ein neuer Weg für Schaumstoffe aus Altautositzen? VDI-Berichte 1288: Verwertung von Kunststoffabfällen, VDI-Verlag, Düsseldorf (in German).

Wurm, G., Wurst, F., Willitsch, F., 1996. Erfahrungen mit der thermischen Verwertung von Kunststoffabfällen im Werk Wietersdorf der W und P-Zementwerke in Kärnten. VDI-Berichte 1288: Verwertung von Kunststoffabfällen, VDI-Verlag, Düsseldorf, p. 159 (in German).