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COMPARATIVE ENVIRONMENTAL EVALUATION OF PLASTIC WASTE MANAGEMENT AT NATIONAL LEVEL ON EXAMPLE OF POLISH AND AUSTRIAN SYSTEMS

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Abbreviations

ABS	–	acrylonitrile-butadiene-styrene
APC	–	air pollution control
ARA	–	Altstoff Recycling Austria AG
AWG	–	Austrian Waste Management Act
BAWP	–	Austrian federal waste management plan
BRFs	–	brominated flame retardants
C	–	carbon
Cd	–	cadmium
CEN	–	European Committee for Standardization
Cl	–	chlorine
CO	–	carbon monoxide
COBRO	–	Central Institute for Packaging Research and Development (Centralny Ośrodek Badań i Rozwoju Opakowań)
Cr	–	chromium
Cu	–	copper
DBPDE	–	decabromodiphenylether
DfE	–	design for environment
DSD	–	Duales System Deutschland AG
EC	–	European Commission
ELV	–	end-of-life vehicles
EPS	–	expanded polystyrene
EU	–	European Union
FCIO	–	Association of Austrian Chemical Industry (Fachverband der Chemischen Industrie Österreich)
GDP	–	Gross Domestic Product
GUS	–	Main Polish Statistical Office (Główny Urząd Statystyczny)
HCl	–	hydrogen chloride
HDPE	–	high density polyethylene
HF	–	hydrogen fluoride
Hg	–	mercury

HIPS	–	high impact polystyrene
IEA	–	International Energy Agency
IEOP	–	Infrastructure and Environment Operational Program
LDPE	–	low density polyethylene
MFA	–	material flow analysis
MSW	–	municipal solid waste
MSWIP	–	municipal solid waste incineration plant
n.d.	–	no data available
Ni	–	nickel
n.n.	–	not notified
NO_x	–	nitrogen oxide
NWMP	–	Polish national waste management plan
OBPDE	–	octabromodiphenylether
OPS	–	oriented polystyrene
ÖFI	–	Austrian Institute for Chemistry and Technology (Österreichisches Forschungsinstitut für Chemie und Technik)
ÖKI	–	former Austrian Plastics Institute (Österreichisches Kunststoffinstitut), at present: Austrian Institute for Chemistry and Technology (ÖFI)
ÖKK	–	Österreichischer Kunststoff Kreislauf AG
P&PW	–	packaging and packaging waste
PA	–	polyamide
PAHs	–	polycyclic aromatic hydrocarbons
Pb	–	lead
PBDPE	–	pentabromodiphenylether
PE	–	polyethylene
PET	–	polyethylene terephtalate
PMMA	–	polymethyl methacrylate
PP	–	polypropylene
PS	–	polystyrene
PUR	–	polyurethane
PVC	–	polyvinyl chloride

SAN	–	styrene-acrylonitrile
SCE	–	substance concentrating efficiency
SFR	–	solid recovered fuel
SO_2	–	sulphur dioxide
STAN	–	software for substance flow analysis
TBBPA	–	tetrabromobisphenol A
TC	–	transfer coefficient
TDF	–	tire derived fuel
WE	–	Western Europe
WEEE	–	waste electrical & electronic equipment
WFD	–	Waste Framework Directive
WM	–	waste management
Zn	–	zinc

Introduction

The use of plastic goods in everyday life seems indispensable; however the constantly increasing consumption resulting in the consequent rise in plastic waste generation constitute a major concern; leading to the related issue of the disposal of this waste having been widely discussed in recent years, not only in societies dealing with environmental and waste management problems, but also in politics and in the public domain.

In the previous decades waste management was aimed at removing waste from urban areas. However, within the last 30 years the focus has changed dramatically towards integrated waste management aimed at the prevention of waste generation and augmenting recovery [1] in relation to both environmental and economic reasons. The increasing awareness of the necessity for the development of modern integrated systems in Europe has been caused by several factors [1, 2]:

- dramatically growing quantities of generated waste,
- increasing consciousness of environmental impacts of extensive disposal,
- shortage of availability of landfill sites,
- opposition of societies,
- NIMBY (not in my backyard) effect,
- the implementation of the emerging environmental regulations intended to prevent and reduce waste generation.

After joining the European Union (EU) Poland had to adjust its legal regulations to the respective EU standards including the ones concerning the environmental policy. The need to implement the respective standards, among others the Packaging and Packaging Waste Directive [3], to the Polish law increased the awareness of the Polish policymakers to the issue of appropriate planning and development of the waste management systems.

Material and energy recovery from waste are seen as feasible solutions to the problem of growing waste amounts, also perceived as a step towards sustainable development in modern societies. However, the issues of using some hazardous substances in the production and manufacturing processes, the limitations with regards to collection and the diversified quality of the waste contribute to the complexity of the design process of appropriate waste management for plastics. Poland is still at the beginning of the route of developing its system, thus, analyzing the current situation in the waste disposal, estimating the quantities of waste generated and investigating the environmental and resource conservation issues related to the waste management of plastics seems important at this point.

This study is an attempt to analyse the state-of-art of plastics waste treatment in Poland and direct it towards fulfilling the main goals of waste management: the protection of the human being and the environment, the conservation of resources, and aftercare-free landfills. Simultaneously, a more advanced waste management system of another European Union's member state (Austria) is analysed and compared to the Polish one in order to see potential development paths for Poland. The appropriate evaluation of the current situation of plastic waste management in Poland with regards to the set goals, supported by the experience from other countries, should effectively aid the future decision processes regarding the development of a proper system in Poland, which is the main goal of the thesis. The key method used for the evaluation is the material flow analysis (MFA). Based on the results of the investigation and the conclusions drawn from it, future scenarios for Polish plastic waste management are proposed.

1 Purpose of the study

In this chapter the motivation to take up the subject of the environmental evaluation of the plastic waste management in Poland is briefly described. Consequently, the goal, the scope and the hypothesis of the dissertation is presented.

1.1 Motivation

Within a few recent decades plastics have become some of the most frequently used materials for the production of a wide range of different application goods. They are typically used in the packaging industry, for the manufacturing of parts of automotive or electronic appliances, but also for furniture or sport equipment. Their features e.g. durability, resistance, lightness, low price, contributed to the substitution of many products made of traditional materials like e.g. wood, but also allowed for the creation of different innovative products [4].

As a consequence of the constantly increasing consumption the growing quantities of the waste generated have drawn public attention [5]. Although the consumption per citizen in Poland is still significantly lower than in many other countries, especially of the Western Europe [6], it rises constantly, contributing to the necessity for the development of appropriate treatment systems for the massively growing amounts of waste.

Plastic waste, produced mainly from the products of crude oil processing, i.e. from non-renewable resources, is perceived as valuable from the material recovery viewpoint. Due to its high heating value, plastic waste is seen as interesting potential energy source. Additionally, as it decomposes very slowly, a lot of space in landfills is needed for its disposal. All those issues contribute to discussions concerning the most efficient treatment of this waste fraction from the environmental and the economic point of view.

Another important issue related to the plastic goods is the fact that various auxiliary substances and additives are used during the production of polymers and the manufacturing of products. Among them we can find stabilizers, antioxidants, flame retardants, etc. Some of them contain, or contained in the past, hazardous substances, e.g. toxic heavy metals or toxic organic compounds i.e. endocrine disrupting. Waste management is seen as a kind of filter between the anthroposphere and the environment and therefore it should remove such substances from the life cycle of products and manage them in a way that does not burden the environment or human health [7].

Simultaneously, the fact that a significant part of plastic products belongs to the group of goods with long life spans and accumulates in the anthroposphere for years must be taken into account. Even if some hazardous additives are banned or substituted by more environmentally friendly alternatives, years or decades after the goods manufactured with their application were produced, the plastics containing such substances appear in waste streams from the abovementioned long-living goods. Therefore, the knowledge concerning the stock of goods “in use” seems important for the effective design of future plastic waste management.

All the above-mentioned issues apply to plastic waste, the enormous quantities of which pollute the environment. Dynamic activities are necessary in order to solve the problem of growing waste amounts accumulated in landfill sites in Poland. All those above-mentioned issues motivated the author to investigate deeper into the subject of the evaluation of the plastics waste management system in Poland and comparing its performance with the system of a chosen EU member state (in this case Austria, which is more advanced in this field) in order to point out the crucial issues regarding the future development of plastic waste management in Poland.

1.2 Hypothesis

The starting point of this dissertation is the hypothesis that the *plastic waste management in Poland is not sustainable from the environmental viewpoint and does not fulfil the main goals of waste management regarding:*

1) *the protection of the human being and the environment,*
2) *the issue of resource conservation,*
3) *aftercare-free landfills*.

This abovementioned statement refers in particular to the following concerns:

- hazardous substances contained in plastic waste are not effectively removed from the cycles and are not consequently disposed of in safe sinks,
- resources like raw materials, energy and space are not recovered efficiently.

1.3 Goal and scope of the study

Based on the literature review of the state-of-art of plastic waste management in Poland the following goal of the thesis has been defined: a comparative evaluation of the Polish plastic waste management (WM) system and its impacts on the environment as well as the issue of resource conservation with a chosen system of another European Union member state (Austria) using the proposed goal-oriented procedure.

A proper evaluation of the existing system of plastic waste management at the national level, aided by the experience obtained in other countries with regards to the development of sustainable waste treatment, could effectively support future decision processes in the Polish plastic waste management system and the development of the appropriate system consistent with the aforementioned main goals of waste management.

In order to confirm or reject the hypothesis mentioned in the above chapter, the following detailed goals are set:

- analyzing the total flows and stocks of plastics in Poland and Austria, and their comparison,
- proposing a "well-suited" procedure for the evaluation of plastic waste management systems,
- evaluation and comparison of the WM in Poland and Austria using the proposed goal-oriented procedure.

The characterisation of plastic waste and its treatment technologies, a description of the relevant legal regulations, at the European Union level, but also in the Polish and Austrian law, and a presentation of the plastic waste management systems in Europe, with a special emphasis on the systems in the analysed countries is followed by research related to the plastic streams in both countries.

The evaluation procedure, based on the material flow analysis method and focused on the main goals of waste management for plastics, is applied. The assessment concerns the chosen aspects related to the environmental impacts and the resource conservation issues. In order to choose the suitable procedure:

- the requirements for a goal oriented evaluation method are defined,
- an appropriate set of indicators and methods is chosen.

The analysis is divided into two general parts. First, the material flow analysis method is used for the quantification of the total plastic flows (including rubber) and the related stocks of goods and waste in the analysed systems. Biodegradable plastics, due to their different features, e.g. behaviour in landfills and raw materials used in the production processes, are not included in the study. This first part of the analysis is aimed at proving the understanding of the present situation of plastic waste management. The total plastic flows in Poland and Austria in the year 2004 are quantified and compared. Additionally, the stocks of plastics and waste are estimated for the period of 1960-2004. Consequently, the results from the MFAs for the total plastic waste are analysed for more detailed studies of the goods and substances flows within the analysed waste management systems.

In the second part of the study, the chosen environmental and resource conservation aspects related to the analysed plastic waste management systems are assessed and compared using the proposed evaluation procedure. Finally, the future scenarios for the plastic waste management in Poland are proposed, based on: the Austrian experience within the period 1994-2004, plans for the development included in the new Polish National Waste Management Plan [8], information from the Polish Ministry of the Environment, and available studies concerning the abovementioned issues.

2 Characterisation of commodity plastics, plastic waste and its treatment

2.1 Plastics

The production and consumption of plastics has been increasing continually since the first half of the twentieth century. Since 1940s their worldwide production increased 100 times [9] and in 2004 it amounted to around 200 Mio. Thermoplastics, mainly polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS), polyamides (PA) and polyethylene terephtalate (PET), constitute 80% of around 50 Mio. Mg of the plastics produced in Western Europe. The remaining 20% covers thermosets, mainly polyurethanes (PUR), amino-, phenolic-, and epoxy resins [10, 11].

The growth of the production of plastics compared with the production of steel and aluminium is presented in Figure 2-1 [12]. This dynamic increase is related not only to very good features of the polymeric materials, but also to the relatively lower energy demand that is needed for its production in comparison with the traditional materials: to produce 1 kg of commonly used plastics 10 MJ of energy is required, while to produce 1 kg of steel, aluminium or bottle glass, 20-50 MJ, 60-270 MJ and 30-50 MJ, respectively [13].

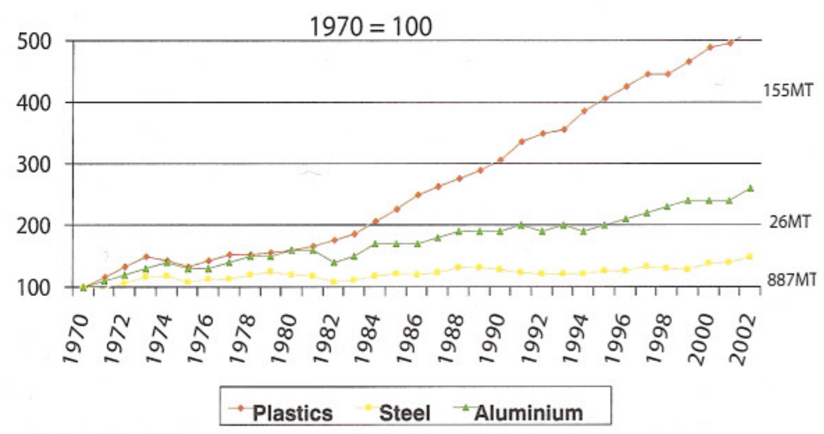

Figure 2-1 Plastic growth versus other materials

Source: [12], with permission

The consumption of plastics per capita differs significantly from country to country: in Belgium it amounts to 144 kg, in Germany and in the USA to above 100 kg, while in India only around 1 kg [9]. Due to the broad variety of polymer types and very useful features of the polymeric materials, e.g. durability, resistance, availability and relatively low production costs, the plastics cover a wide range of different applications. The use of main polymer types in different product groups is shown in the Table 2-1.

Table 2-1 Use of various polymers types in reference to application field

	Polymer type*
Packaging	LDPE, HDPE, PP, PET, PVC, PS, EPS
Building (except of pipes)	PVC, EPS, PUR
Pipes	HDPE, PP, PVC, PE, ABS/SAN
Electric/electronic	PP, PVC, HIPS, ABS/SAN, PUR
Automotive	HDPE, PP, PMMA, PA, ABS/SAN, PUR, PVC
Domestic wares	HDPE, PP
Furniture	PP, PUR, PVC

*names explained in abbreviations Source: [14]

Apart from being used in typical plastic application fields like packaging and construction materials or household and electronic products, the polymers are also applied to the production of coatings, textile fibres, adhesives and other goods. According to the estimations of the PlasticsEurope organisation around 39% of thermosets and 13% of thermoplastics are used for the manufacture of so called non-plastic application products [15]. The structure of plastics use in different application fields, with packaging and construction sectors being in the lead, is presented in Figure 2-2. The structure of their consumption by polymer type is shown in Table 2-2.

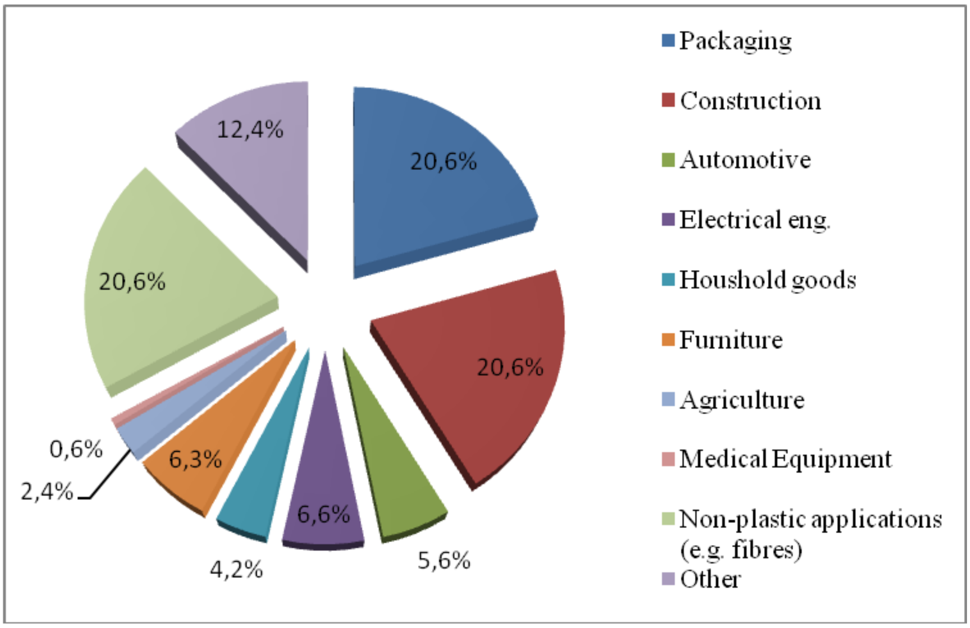

Figure 2-2 Consumption of plastics in reference to application sector in Europe

Source: based on [16, 17]

Table 2-2 Consumption of plastics in reference to polymer type in Europe

	Consultic, 2004	PlasticsEurope, 2004
	[%]	
Low density polyethylene (LDPE)	14,7	16,5
High density polyethylene (HDPE)	11,1	11,1
Polypropylene (PP)	16,2	16,1
Polystyrene (PS) Expanded polystyrene (EPS)	5,9	6,4
Polyvinyl chloride (PVC)	15	12
Polyethylene terephtalate (PET)	3,9	7,8
Polyamide (PA)	3	2,7
Polymethyl methacrylate (PMMA)	0,9	0,7
Polyurethane (PUR)	6,2	5,5
Other	23,1	21,2

Source: based on [15, 16]

The life span of plastic products differs significantly among various applications. According to Huckestein et al. [18] only 25% of plastic goods become waste within one year, while 60% have life span of eight years or even more. The construction industry products have especially long life spans, exceeding 30 years. The Association of Austrian

Chemical Industry (FCIO) estimates that around a half of all the plastic articles belongs to the so called long-living products group and is used mainly in construction and automotive sectors, as well as for electric & electronic appliances; while around one third of all plastic goods, mainly packagings, medicine articles and some office equipment, reach the end of their life cycle within one year. The rest of the plastic products is assigned to the medium-long use group – with a life span below ten years [19]. The approximate life spans of the plastic products from different applications fields are presented in Table 2-3.

Table 2-3 Approximated life spans of plastic products

	Lifespan [years]
Packaging	~ 1
Construction, building	20-50
Automotive	~ 15
Electrical engineering	5-50
Household goods	~ 5
Furniture	~ 15
Agriculture	~ 3
Medical equipment	~ 1
Non-plastic applications	5-15
Other	~ 5

Source: own assumptions for [20]

2.2 Plastic waste and related environmental concerns

The plastic waste is a very non-homogeneous group of materials that differ not only with regards to their chemical composition or previous application field, but also quality, i.e. purity or contamination level. All those issues influence the future treatment possibilities. The plastic waste constitutes 7-14% of the total mass of municipal solid waste and even up to 30% of its volume [21]. Around 70-85% of this waste originates from consumption, while the rest is generated during the production and processing of the polymeric materials to plastic products [5, 13]. The structure of the plastic waste generation is presented in Table 2-4.

Table 2-4 Structure of plastic waste by polymer resin in Europe

	[%]
Low density polyethylene (LDPE)	24,7
Polypropylene (PP)	18,2
High density polyethylene (HDPE)	16,1
Polyvinyl chloride (PVC)	8,5
Polystyrene (PS)	7,5
Polyethylene terephtalate (PET)	7,3
Expanded polystyrene (EPS)	1,1
Other thermoplastics	7,3
Thermosets	9,3

Source: [22]

Plastic waste can be classified according to various criteria. Joosten [23] divides plastic waste, depending on its origin and quality, into three groups: 1) production or processing waste (the best quality for recycling), 2) sorted post-consumption plastic waste (of medium quality), and finally 3) mixed plastic waste (low quality fraction, difficult to recycle). This waste can also be categorised in reference to the source [24], e.g. packaging, construction, and other; or depending on the type of polymer, PE, PP, PET, PVC, etc. Another classification is related to the way in which plastic waste is collected: sorted or mixed waste. From the viewpoint of the European Commission's legal regulations a practical way of classifying the plastic waste would be distinguishing between e.g. packaging waste, electric and electronic equipment waste, end of life vehicles waste, etc.

Waste can be classified in a number of ways such as: by material fraction or waste stream (organic, glass, paper), by characteristics (combustible, recyclable, hazardous), and by source (household, industrial, agricultural etc.) [24].

As mentioned in the previous section, plastic products differ with regards to its life span. Plastic packaging approach the end of their life cycle mainly within one year, while other products leave the system of consumption as waste after years or even decades of usage. In order to estimate future waste quantity and its composition, which have a direct influence on decisions concerning planning of future plastic waste management systems e.g. investments for treatment facilities, the knowledge of the structure of the stock in the process of consumption over time is very important.

The implementation of respective legislation in Western Europe (WE) contributed to the increase of recovery of plastic waste within the last years, and to simultaneous divertion of significant amounts of this waste from direct landfilling. In 1991 7% of the total plastic waste was recycled, while in 2003 it was 17%. The energy recovery increased respectively from 15% to 23% [12]. According to Huckestein et al. [18] at present 54% of the total plastic waste in WE is being recovered, around 26% of which is recycled mechanically, 26% is recovered thermally and 1,5% via feedstock recycling (taking place mainly in Germany). The recovery rates for selected WE countries are presented in Table 2-5. In Eastern Europe landfilling is still the most common option for dealing with plastic waste; however the situation improves, especially in reference to the packaging waste.

Table 2-5 Plastics recovery rates in chosen European countries

[%]	Country
85-60	Switzerland, Denmark, Norway, Netherlands
60-40	Germany, Sweden, France
40-20	Belgium, Austria, Finland, Portugal, Italy, Spain
< 20	United Kingdom, Ireland, Greece

Source: [12]

In the following chapter a few chosen environmental concerns related to the plastic waste and its management are presented.

2.2.1 Additives in plastic waste

Due to the fact that plastics are processed at high temperatures and many plastic products must be resistant to exposure to such factors like light, heat, humidity, etc., a wide variety of additives and auxiliary substances is used in production processes to improve various features of plastic goods to protect them against undesired influence, and consequently against changes in their appearance and premature mechanical failures. Amongst them, there are light- and heat-stabilizers, processing aids, antioxidants, flame retardants, lubricants, acid scavengers, anti-blocking, antistatic and antifogging additives, blowing agents, colorants, nucleating agents, and others [25, 26, 27, 28].

Additives can contain hazardous substances which are of special concern in thinking of waste management of plastics and their longer-term impacts. To name a few examples we could mention zinc, lead and cadmium, contained e.g. in stabilizers [29]; phosphoorganic plasticizers, brominated flame retardants, and others [27]. It should be emphasized that some of the migrating substances contained in additives are physically active and can influence human health, causing intoxication as well as, acting slowly, lead to chronic health problems. Due to the role of waste management, as mentioned in the Introduction, being a filter between the anthroposphere and the environment [30], the problem of appropriate treatment of plastic waste, related to the hazardous substances they contain, should be of special importance for modern societies [13].

Even though the use of some hazardous substances decreases, e.g. due to "serious toxicological and ecological concerns about cadmium and its compounds (…), it is successively replaced by other stabilizers, particularly in Europe and Japan" [25] it must be also remembered that years or even decades after discontinuing its use in the production processes, cadmium will be still present in plastic waste streams, due to long life-spans of many plastic products manufactured in the past and still accumulated in the anthroposphere.

2.2.2 Resource conservation

Energy plays a crucial role in the life cycle of plastics. Fossil fuels are used as feedstock for the production of traditional plastics and energy is required for the processes of polymerisation, for processing of polymers to plastic products, for transportation in distribution chains, in the consumption process and finally for dealing with plastic waste. At the end of the life cycle of plastic products the energy can be recovered through appropriate waste treatment. Material recycling allows for the salvation of primary materials for the production of new commodities and consequently the fossil fuels needed for the production processes, both as feedstock and energy source. Direct energy recovery through thermal treatment of plastic waste allows on the other hand for saving of conventional fuels for industrial processes (e.g. in cement industry) or for heat/power generation. Therefore, plastic waste is seen as a valuable material from the resources conservation's point of view and its appropriate waste management can contribute to sustainable development.

2.2.3 Long-term impacts of disposed plastic waste

Due to the fact that plastics have been commonly used for a few decades only "too little is known about the long-term behaviour of high polymers" in landfills conditions. However, typically plastic waste is regarded as decomposing very slowly or even as being non-degradable, however some "experts" doubt the non-degradability exists at all [31]. Scott [32] quotes that "due to absence of oxygen, plastics do not biodegrade in sanitary landfill conditions" and "properly stabilised PVC is stable almost indefinitely in anaerobic landfill and the chlorine will remain locked away without harm to the environment almost indefinitely". The author emphasizes that the problem referred to landfilling of plastic waste in developed countries refers only to the shortage of sites for disposal.

Brandrup et al. [31] presents a different point of view. The author indicates that if plastics do degrade the issue of additive behaviour in landfilling process is of special concern, as the additives, some of them being hazardous, can be released to the landfill body. Additionally the intermediate products of degradation can be hazardous.

In many studies related to the plastic waste disposal the environmental impact from its landfilling is disregarded. Mølgaard [33] claims that plastic waste does not decompose in landfill in anaerobic conditions in a temporal boundary of 100 years, however, the emissions from landfilled materials continue for a long time, of up to hundred years after disposal and the hazardous impact can restrict the utilisation of the land above and under the landfills in the long-term [34]. Finnveden & Nielsen [35] suggest that this issue must be taken into account as otherwise the impact on future generations can be neglected. Nielsen & Hauschild [34] suggest 100 years as a temporal boundary, although the emissions will continue in long-term, but the fate of the disposed materials and its behaviour is rather unpredictable.

In general, more and more common landfills are seen as the worst option for the plastic waste (justifiable only for residues, which cannot be recycled anymore) and this way of disposal is regarded as a loss of valuable material and energy resources. This issue will be revealed further in the practical part of the study.

2.3 Plastic waste management

There are a few treatment alternatives for plastic waste. Zinowicz et al. [13] divide the options of plastic waste management into two general groups. The first group refers to the disposal of plastic waste without pre-treatment in landfill sites, while the methods of plastic waste recovery are assigned to the second group. The notion of the recovery of plastic waste encompasses material and energy recovery, which can be further divided into mechanical and feedstock recycling (material recovery) respectively, direct incineration and the use of plastic waste as alternative fuel (see Figure 2-3) [12].

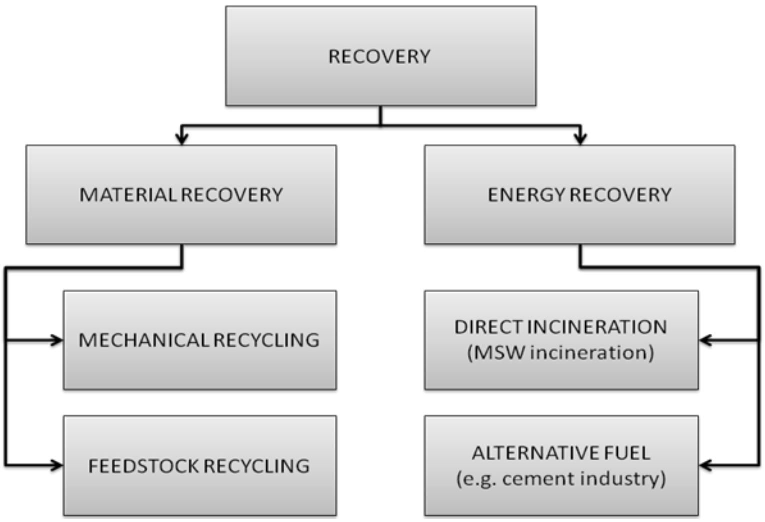

Figure 2-3 Options for plastics recovery

Source: [12]

According to the definitions agreed in 2006 by the International Standardization Organization Committee ISO TC 61 [36] mechanical recycling signifies "processing of plastic waste to secondary raw material or products without significantly changing the chemical structure of the material", feedstock recycling means "production of new materials by changing the chemical structure of plastics through cracking, gasification or de-polymerization excluding energy recovery and incineration" and energy recovery is defined as "production of useful energy through controlled combustion".

The quality of the waste stream and the collection possibilities determine or limit the decision on which kind of treatment alternative can or should be used [36]. The preferred technology should be adjusted to the type of waste and its location; e.g. litter plastics should be treated differently from separately collected waste streams. In general, clean plastic waste from production or industry should be recycled in a closed loop, the mechanical recycling is preferable for homogenous, uncontaminated waste from certain polymeric materials, and in the case of heterogeneous, mixed and dirty waste the energy recovery is the economically favoured option [32, 37].

Kozłowski [5] indicates the following issues influencing the waste management of plastics: possibilities of collection, availability of technologies and installations for recovery and disposal, market price for secondary materials from recycling, legislative requirements and economic feasibility.

2.3.1 Collection and pre-treatment

As mentioned above, the activity separate waste collection is of great importance for future treatment possibilities, but it also influences the economic dimension of recycling [38]. Williams [39] distinguishes between two general systems of separate waste collection from households: the "Bring" and the "Collect" system. The first method stands for the collection and separation of a specified type of waste from municipal solid waste (MSW) and its delivery to the central collection site. The "Collect" system involves kerb-side collection of certain wastes, which are previously segregated in households and subsequently collected by waste disposal teams. Both of these systems differ with regards to the costs they generate, convenience of treatment for households and collectors, and the level of recovery. The "Bring" system is cheaper but more demanding for households, also dependant on the ecological consciousness of the society, and therefore, on average, less efficient, than the other system whose features seem to be directly the opposite.

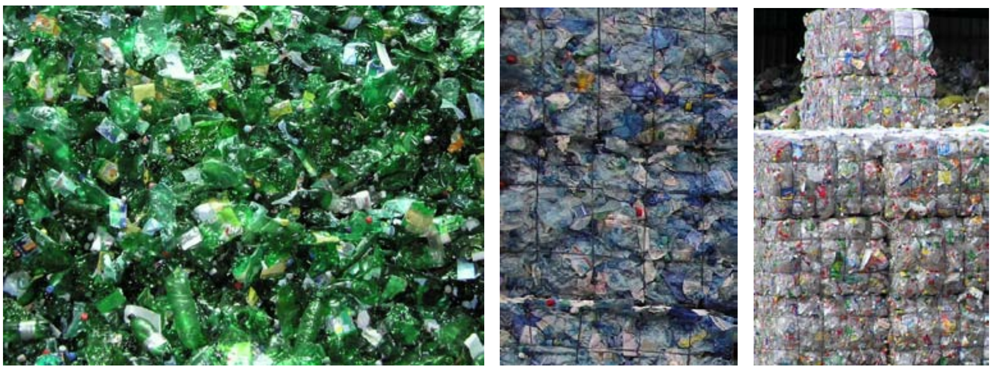

Figure 2-4 Collected plastic waste

Source: [40]

Among the processes of pre-treatment size reduction, classification, washing and drying belong to the most important ones [41]. The first of the mentioned processes is aimed at obtaining the desired shape and size of the waste material [42]. In the classification phase separation of the bulk material according to the shape and size of the particles takes place [43]. During the washing step dirt adhering to the waste material is removed and finally, the drying process reduces the moisture content of the processed material [44].

There is a range of methods used for the separation of mixed plastic waste stream into clean mono-polymer fractions relying on dissimilar properties of the polymeric materials, e.g. density, conductivity, ferromagnetism, surface properties, etc. [45]. However, due to sometimes very small differences between plastics, the separation of certain polymer types from each other is difficult and then detection techniques have to be applied. They allow, for example, to recognise chlorine-free materials from the chlorinated ones through different interaction of the analysed material with X-radiation. The methods used for polymers identification can be divided into three groups: 1) analysis of polymer molecules (using e.g. near- and middle infra-red spectroscopy), 2) analysis of fragments of polymers chains (using e.g. infrared spectroscopy), and 3) analysis of very small fragments or ions (using e.g. sliding spark spectroscopy) [46, 47].

The following methods of separation and identification of plastic waste are used [5, 37, 45, 46, 48]:

- manual sorting,
- density-based sorting in flotation tanks, hydrocyclones or on gravity separation tables,
- flotation methods,
- optical sorting with application of polarised or UV light, X-Ray transmission imaging,
- spectroscopic-based methods like Infrared, Raman, Laser Induced Plasma, X-ray fluorescence spectroscopy or Laser Induced Thermal Impulse Response,
- automated hybrid sensors – applying a combination of many separation methods,
- electrostatic methods,
- methods of sorting using the differences in melting point of different polymers,
- sorting by selective dissolution.

The choice of a certain method depends on various issues, e.g. fraction of the waste to be separated, size and form of the waste materials (e.g. manual sorting is used for larger pieces, while for the optical sorting waste material of similar size is required) or the quality (i.e. level of contamination, as some methods, e.g. spectrometric, are insensitive if the material is highly contaminated). The methods also differ with regards to the effectiveness of the separation processes [37].

2.3.2 Mechanical recycling

Mechanical recycling is aimed at reprocessing of plastic waste material by physical means to produce flakes, pellets or new end products, keeping the chemical structure unchanged [48, 49]. It covers melting, shredding or granulating of the plastic waste and subsequently producing recyclate. Also the advanced technologies including the step of purification or upgrading at extreme temperature and pressure conditions (e.g. bottle-to-bottle ultra-clean process for PET) or technologies using solvents for removal of contaminants and extracting the regenerated resins (e.g. Vinyloop® process) belong to the mechanical recycling methods [50].

In order to produce high quality products from recycling appropriate input materials, i.e. homogeneous, clean waste, must be supplied. Therefore, residual contamination or undesired plastics must be removed. Before processing the plastic waste undergoes appropriate pre-treatment [41, 26] mentioned before. One scheme for the recycling process is presented in Figure 2-5.

The mechanical recycling is well established for homogenous, type-specific, clean waste plastics i.e. of production and processing materials. In reference to post-consumer plastic waste the quality of waste is essential for the possibilities of the mechanical recycling. If the plastic waste is mixed, the possibilities of its treatment are limited, the process is less efficient and the quality of subsequent product deteriorates [51]. The recycling of mixed fractions yields the so called “thick wall applications” products, mainly non-plastic applications like pallets, cable conduits or acoustic barriers [46]. An additional disadvantage of this treatment is related to the fact that sorting and cleaning of plastic waste requires a lot of water, energy and consequently results in higher costs. Therefore, the mechanical recycling is seen as a solution only for clean, sorted and high quality plastic waste, while for the mixed fraction it is often perceived as unjustifiable from the economic and ecologic point of view [18].

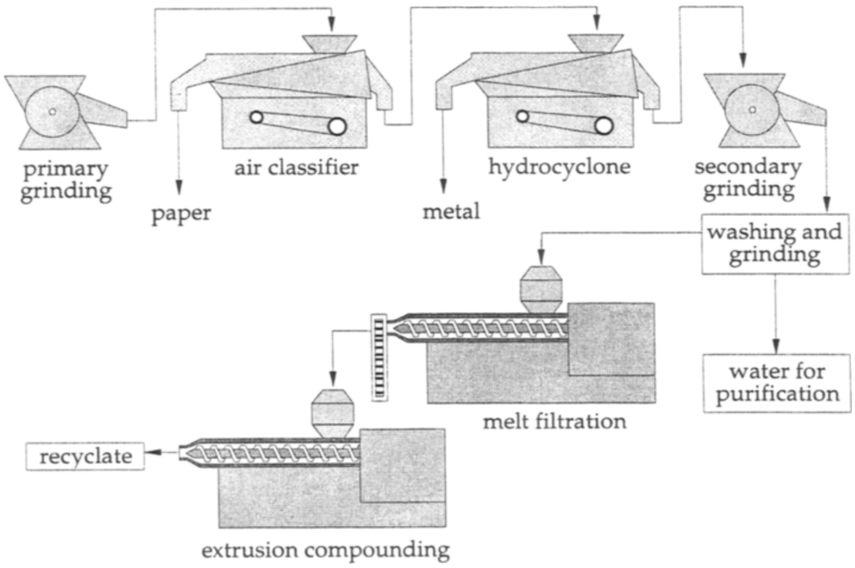

Figure 2-5 Recycling of post-consumption plastic waste

Source: [48]

The problems that the mechanical recycling is faced with refer, for example, to the incompatibility of the diverse polymers, different colours of the materials even for the same resin, as well as the fact that the plastic materials undergo degradation through UV radiation, temperature, ozone or oxygen influences, which results in the production of recyclate of lower quality [37, 52]. Additionally, it should also be remembered that the multiple recycling generally negatively influences the quality of the product obtained [48] and that eventually another disposal method, e.g. thermal treatment, must be used for the material which cannot be recycled anymore [9, 13].

Good examples of mechanical recycling application represent plastic bottles, made mainly of PET, PE, PP. According to the information from PlasticsEurope [53] around 40% of PET bottles, which were available for collection in 2006, were recycled. Multiple variations exist amount various countries in this respect. In some EU member states the recycling rate for PET bottles is below 10%, while e.g. in Austria or Belgium it amounts to nearly 70%. In many countries works toward close-loop recycling of bottles are underway, aimed at using reprocessed PET and HDPE for new bottles. However, in this case, sever requirements, especially in reference to packaging for food, have to be met.

One of the recognized problems concerning the recycling of PET bottles concerns the use of PVC shrinking sleeves. The use of PVC contributes to the degradation of PET and negatively influences recycling of the PET material [54]. The Council of PET Bottles Recycling proposed already in 2001 the “Voluntary Design Guidelines for Designated PET Bottles [55]. In one of the points abandoning the use of PVC containing labels is suggested and using PE or PET shrink sleeves printed with inks removable by hot alkaline treatment instead is recommended. The same opinion is held by Petcore [55], Europe's PET Recycling Association, a non-profit organization working on facilitating PET recycling. Recently Petcore [56] asked bottlers to also stop using oriented polystyrene (OPS) in shrink sleeve labels as this material impede recycling systems.

Lewandowska & Foltynowicz [57] emphasize the significance of the so called design for environment (DfE). Designers already in the phase of planning of a new product should take into account its whole life cycle, including future. DfE, called also sustainable product design, refers to the issues like using of highest possible amount of recyclable materials or avoiding applying composite materials, which causes problems for recycling [58]. One of the examples related to plastics concerns designing caps and other elements of bottles from materials compatible with the material of the bottle, i.e. the element for HDPE bottles should also be of this plastic and not of PP or PVC.

According to information from PlasticsEurope apart from the recycling of packaging plastics, the recycling of PVC windows and profiles is also developing dynamically [53]. In connection with the initiative program Vinyl 2010, the collection and recycling systems for the abovementioned products have been established in some European countries, e.g. in Austria, Belgium, Denmark, France, Germany, Ireland, Italy, the Netherlands, Spain and the UK. Granulate obtained from PVC recycling is used as raw material for production of new construction products.

Poskrobko & Piontek [59] emphasize that high demand for raw materials and related high prices of primary plastics and crude oil positively influence the development of mechanical recycling of plastic waste. Increasing costs of primary polymers production contribute to growing the competitiveness of recyclate prices, which was one of the most important factors limiting attractiveness of the recycled material in the past.

2.3.3 Feedstock recycling

Feedstock recycling, also called chemical recycling, covers a wide range of processes during which the polymeric structure is broken down into fairly large molecules (plastic monomers or hydrocarbon feedstock) using heat, chemical agents or catalysts [37]. Products, which are obtained in this process, can be used again in refineries, in petrochemical and chemical production substituting raw material, e.g. natural gas or oil [37, 50, 60]. There are various feedstock recycling technologies. Amongst them there are technologies of chemical depolymerisation (e.g. hydrolysis, methanolysis, glycolysis), oxidative methods like gasification, thermal degradation (including thermal and steam cracking or pyrolysis), catalytic cracking, reforming and hydrogenation or using the waste as reducing agents in blast furnaces. Huckestein et al. [18] characterise the feedstock recycling processes in reference to the use of the plastic waste in them:

1) solvolysis – is a process in which condensation polymers, e.g. polyethylene terephtalate, polyamides and polyurethanes are split into respective monomers through dissolving processes with the use of water or alcohols (methanol, glycol) [5]; these processes are applied mainly to homogenous and type-specific plastic waste,
2) thermal feedstock recycling processes – used for mixed plastic fraction consisting of e.g. polyethylene, polypropylene, polystyrene or polyvinyl chloride; these processes can be applied for dirty and lower quality plastic waste. Among them there are:
    - pyrolysis, thermolysis used e.g. for mixed packaging waste,
    - generation of synthesis gas – thermal splitting of the waste plastic material into syngas [61], suitable plastic waste from the varied sources (carried out on larger scale e.g. by the German company Schwarze Pumpe, yielding methanol from syngas [12]),
    - hydrogenation – thermal splitting with hydrogen; used among others for treatment of plastics from used electric & electronic appliances,
    - usage in the blast furnace processes – including first transforming plastic waste into hydrogen and carbon monoxide, and their consequent use in the

production of iron metals (reduction of iron oxides) as well as for heating or electricity production.

Currently, the most frequently used method of feedstock recycling is the method of using plastic waste instead of oil or coke as a reducing agent in blast furnaces [37], applied on larger scale in Germany [53]. The methods aimed at generation of synthesis gas are also of interest. Pyrolysis is used e.g. for scrap tires. Through thermo- destruction gaseous and liquid hydrocarbons can be obtained [62]. The end-of life tires become a potential source of fuels and recovery products: liquid products could be used in petroleum refinery feedstock, while carbon can be applied as carbon black or activated carbon [63].

Many thermal feedstock recycling processes have been developed in recent years however, only few of them can be applied for the plastic waste. Among them there are Union Carbide, Saarberg-Fernwaerme, Babcock-Rohrbach, LuigEco, Thermoselect and others [64]. Recently, attempts to use integrated non-ferrous metal smelter for the treatment of waste plastics from electric and electronic equipment with precious metal content have been conducted in Sweden and Belgium and the development of this recovery technology is expected [53] In these processes metals are recycled, while plastics are used as a reducing agent and a source of fuel [12]. Also, super high temperature steam gasification technology offers new opportunities for the treatment of plastic waste. In this process, the combustion of a part of synthesis gas enables obtaining steam at a temperature exceeding 1000°C, which is then used as gasifying agent [65].

Lunquist at al. [48] summarise the key points in the potential of feedstock recycling for the plastic waste treatment as follows: depolymerisation is energy intensive, which contributes to the high costs of the final product, solvolysis is sensitive to contamination therefore it can be applied mainly to "well-defined product areas with efficient collection and sorting infrastructures", on the contrary, thermolysis can be used to treat mixed plastic waste and end-of-life cars shredder residues.

Although the feedstock recycling is more tolerant to the contamination of waste and more flexible over the waste composition [37], a high variety of chemical structures of the plastic waste and its thermoplasticity can still cause some technical problems [64]. Additionally, very large amounts of waste must be used for this process to be economically justified and it is mainly the economy rather than technical reasons that determines the limited use of feedstock recycling technologies [37]. Many feedstock recycling technologies are still under development or in pilot phases, which is also influenced by the low feedstock supply and high costs. Thus, ensuring infrastructural improvements, sufficient supply and markets for the products generated, are indispensable for further development of this form of recovery [48].

2.3.4 Energy recovery

Energy recovery is aimed at using the high caloric value of the plastic waste "as a source of energy either from direct incineration or its use as alternative fuel for power generation or manufacturing process" [12]. The additional role of the incineration of plastic waste is aimed at volume reduction, inerting the solid residues and prevention of uncontrolled release of contaminants [66, 67]. The energy recovery of plastic waste can be conducted through [12, 50, 68]:

- co-incineration with other residual waste in MSW incineration plants,
- co-incineration with other low caloric waste like sewage sludge in fluidised-bed furnaces,
- use as alternative fuel in energy-intensive processes e.g. in cement industry,
- mono-incineration,
- use as solid recovered fuel (SFR) to partially substitute e.g. coal for power generation.

Williams [39] divides incineration processes into two general groups: mass burn incineration plants, where municipal solid waste is treated, and other types of incineration like e.g. fluidised bed, rotary kilns and cement kilns.

Conventionally, the incineration of waste has been used to reduce the volume of waste and to convert hazardous waste into inert residuals. It was also connected with the generation of harmful emissions which contributed to the social non-acceptance of this method. Nowadays, technologies which prevent the production of such emissions have been developed [48].

The thermal treatment with energy recovery is suitable for most plastic waste which does not contain chlorine. Incineration of PVC waste and other chlorinated polymers is problematic due to hydrogen chloride (HCl) and toxic emissions however, it can be solved e.g. by using calcium oxide to absorb HCl, if PVC is present in small amounts. High contents of heavy metals in some waste, originating e.g. from overprints also constitute a significant problem [59].

In a municipal waste incineration plant (MSWIP) plastic waste is incinerated together with other residual waste. A typical incineration plant (see Figure 2-6) consists of the following units: 1) waste delivery, bunker and feeding system, 2) furnace, 3) heat recovery, 4) pollution control and 5) energy recovery (via electricity generation and district heating). The most significant burdens resulting from thermal treatment of waste in MSWI plants are: particulate matter, heavy metals (mercury (Hg), cadmium (Cd), lead (Pb), As (arsenic), Zn (zinc), Cr (chromium), Cu (copper), Ni (nickel), etc.), acidic and corrosive gases (e.g. HCl, hydrogen fluoride (HF), sulphur dioxide (SO_2) and nitrogen oxide (NO_x)), products of incomplete combustion (carbon monoxide (CO), polycyclic aromatic hydrocarbons (PAHs), dioxins and furans) and contaminated ash. Chloride and fluoride in waste comes mainly from plastic materials like PVC, as well as from rubber. HCl emission in flue-gas is regarded to come from PVC [39, 69, 70]. However, modern incinerators (see Figure 2-6) are plants with efficient combustion systems and good quality air pollution control (APC) devices, which not only reduce the volume of waste to inert residue with a minimal pollution level but also produce energy.

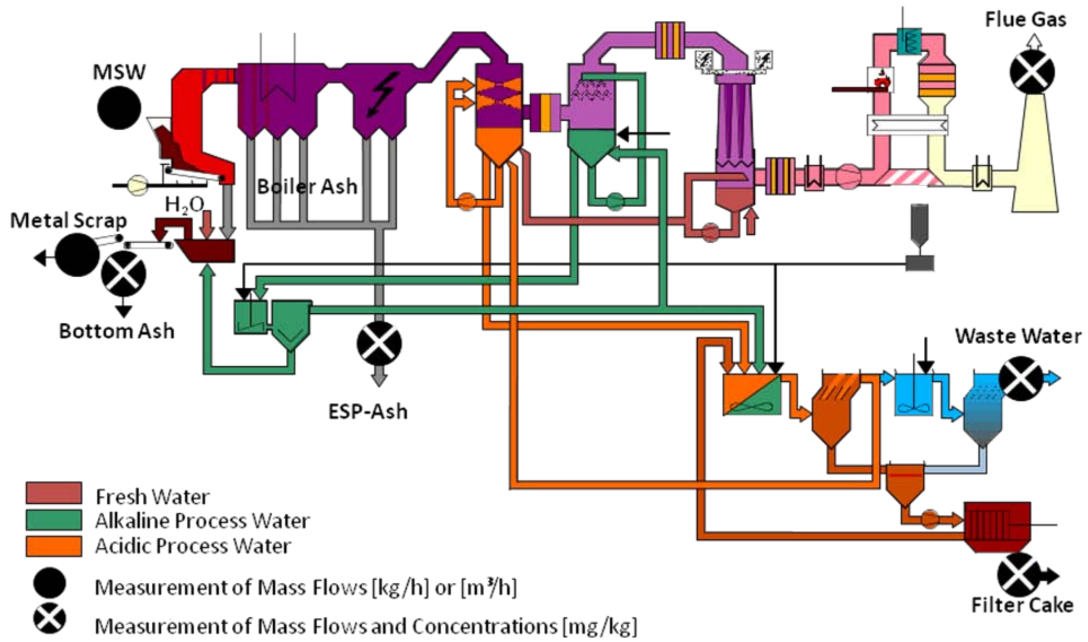

Figure 2-6 Modern MSW incinerator with state of art APC device

Source: Institute for Water Quality, Resources and Waste Management, Vienna University of Technology, with permission

Apart from thermal treatment of plastic waste in MSW incineration plants, co-incineration of this waste fraction, e.g. with waste of low caloric values in fluidised beds like sewage sludge, is conducted. Plastic waste with low ash content is suitable for this process. Fluidised beds are furnaces equipped with a wind-box through which the air for combustion passes upwards into the furnace space. The installation consists of a bed of sand (placed above the wind-box) into which the material for combustion is introduced [71, 72]. Plastic waste contains chlorine, fluorine and sometimes bromine as well as heavy metals like cadmium, zinc and lead, which means that comprehensive exhaust gas purification, is necessary in plants where they are co-incinerated [72]. Additionally, processes in MSWIP and in fluidised furnaces result in residues like filter cake and ash, which require appropriate disposal.

One of the options of energy recovery from waste is the production of solid recovered fuel (SRF) [73]. Highly calorific waste, consisting e.g. of plastics, is separated and converted into a material with defined features [74, 75]. Also the use of end-of-life tires as alternative fuel is applied. This fuel is called tire derived fuel (TDF). Both can substitute conventional fuels e.g. in cement kilns, paper mills and power plants [48].

The processes of energy recovery of scrap tyres in cement kilns are often considered as the most highly recommended methods from the abovementioned [62]. Due to the fact that the processes in the cement industry are very fuel-intensive [76], around 50% of the total manufacturing costs constitute the costs of energy. The use of plastic or rubber waste as alternative fuel allows for the conservation of primary energy sources, e.g. oil, gas or coal, and enables the reduction of the energy costs. Since 1970's, when the cost of primary fuels increased, trials with e.g. scrap tyres and rubber use have been conducted, subsequently also fuels from household waste and shredder waste, containing relatively high amounts of plastics have been tested. The processes in cement industry do not produce ash or slag for landfilling as mineral components and heavy metals contained in the alternative fuel (except of mercury) are bound to the clinker [77]. It should be added that the cement production plants co-incinerating waste materials fulfil the requirements concerning the emission standards set in the EU Directive 2000/76/EC [62, 78].

The energy recovery from plastic waste is necessary for solving the problem of plastic waste landfilling, especially observing the implementation of the emerging legislation aimed at a total landfilling ban in many countries. However, this option should not be perceived as a solution to avoid plastics recycling, but rather as an alternative to the disposal in landfill sites [48, 79]. The advantages of material recycling include the reduction of the use of virgin materials, minimization of energy consumption and consequently salvation of valuable resources and costs, as well as emission reduction [39]. The use of plastic waste as alternative fuel also has many advantages not only in the environmental dimension (e.g. saving of primary energy carriers), but also in the economic sense. From the macroeconomic point of view, the expenses for landfill construction and restoration can be reduced, while from the microeconomic perspective – the expenses for fuel use can be lowered [59]. Additionally, through the recovery processes the volume of waste which has to be land-filled is reduced, which in consequence contributes to saving land-filling space. The landfilling of plastic waste is perceived as the least desired option for plastic waste management, both from the environmental and economic point of view [13].

2.4 Legal regulations on plastics waste management

2.4.1 Legal regulations in the European Union

At the beginning of 1990's, the European policy makers noticed that the increasing generation of waste related to the continued economic growth cannot contribute to sustainable development in the long-term [12]. Hence, it was emphasized that the efforts should be made in order to prevent waste generation and to increase its recovery. Various legal acts have been developed and implemented in the countries of the European Union in order to reach those goals. Among them there are:

- Directive 94/62/EC on packaging and packaging waste [3] (P&PW); with later amendments: Directive 2004/12/EC [80] and Directive 2005/20/EC [81],
- European Commission Decision 1999/177/EC establishing the conditions for a derogation for plastic crates and plastic pallets in relation to the heavy metal concentration levels established in Directive 94/62/EC on packaging and packaging waste [82],
- Directive 1999/31/EC on the landfill of waste [83]; with later amendments,
- Directive 2000/53/EC on end-of-life vehicles (ELV) [84],
- Directive 2000/76/EC on the incineration of waste [78],

- Directive 2002/95/EC on the restriction of the use of certain hazardous materials in electrical and electronic equipment (RoHS) [85],
- Directive 2002/96/EC on waste electrical and electronic equipment (WEEE) [86]; with later amendments,
- Directive 2006/12/EC on waste – “a framework directive for coordinating waste management in the Member States in order to limit the generation of waste and to optimize the organization of waste treatment and disposal” (WFD) [87].

The Waste Framework Directive [87] defines waste as “any substance or object (…) which the holder discards or intends or is required to discard”. The hierarchy for waste treatment, as stated in WFD, is quoted below:

“Member States shall take appropriate measures to encourage:

(a) first, the prevention or reduction of waste production and its harmfulness, in particular by:

(i) the development of clean technologies more sparing in their use of natural resources;

(ii) the technical development and marketing of products designed so as to make no contribution or to make the smallest possible contribution, by the nature of their manufacture, use or disposal, to increasing the amount or harmfulness of waste and pollution hazards;

(iii) the development of appropriate techniques for the final disposal of dangerous substances contained in waste destined for recovery;

(b) second:

(i) the recovery of waste by means of recycling, re-use or reclamation or any other process with a view to extracting secondary raw materials; or

(ii) the use of waste as a source of energy” [87].

Apart from the abovementioned act, there are a few so called “process directives”. They intend to “regulate the waste management of various end-of-life-streams” [12]. The Directive 94/62/EC on Packaging and Packaging Waste [3], with later amendments, requires that the Member States take measures to set up return, collection and recovery systems to ensure the implementation of measures to prevent the packaging waste formation, e.g. to “introduce producers responsibility to minimise the environmental impact of packaging”. This regulation aims to encourage the increase of packaging waste recovery through re-use, recycling or energy recovery and minimise the disposal of packaging waste in landfill sites.

This directive also sets targets for recycling and recovery of the packaging waste for the countries of the EU. The revised Directive 2004/12/EC [80] sets the following limits for the treatment of this waste:

- recovery rate of at least 60% of the total amount,
- recycling rate of at least 55% and max 80% of the total amount,
- in reference to the recycling of plastic packaging waste "the minimum recycling target of 22,5% by weight of material that is exclusively recycled back into plastics".

The deadline for fulfilling the requirements of this directive is 31st December 2008 for all countries of the European Union, with the exception of Portugal, Greece and Ireland (the deadline is 31st December 2011) and the "new" EU member countries (there the deadlines are set within the years 2012-2015). For Poland the deadline is 31st December 2014.

Apart from the abovementioned "process directives" two important acts which concern the treatment of waste in general are in force. The Directive 2000/76/EC on the incineration of waste [78] is aimed at preventing or reducing hazards for the environment and human health caused by incineration or co-incineration of waste, establishing e.g. limits on emission to water or air for certain pollutants. The Directive 1999/31/EC [83] on the landfill of waste "has laid down strict requirements for waste and landfills to prevent and reduce as far as possible the negative effects on the environment from landfilling". It requires e.g. for the treatment of waste before its landfilling.

In 2005 seven thematic strategies were published by the European Commission (EC). Two of them, the Thematic Strategy on the Prevention and Recycling of waste [88] and the Thematic Strategy on the Sustainable Use of Natural Resources [89], are related to waste management problems and express the change of end-of-life thinking towards life-cycle thinking. The first strategy is aimed at reducing "the negative impact on the environment that is caused by waste throughout its life span, from production to disposal, via recycling". It sets out guidelines for the EU actions and proposes measures for achieving the improvement of waste management. Moreover, it introduces the approach of seeing waste not only as a source of pollution but also as a potential resource. The objective of the second strategy is to transform the European member community into "a recycling society" through the usage of waste as a resource.

2.4.2 Legal regulations in Poland

"The II National Environmental Policy" [90] states that "the guiding direction in the waste management policy is the sustainable development principle and an integrated approach to environmental protection (…). The concept of a new strategy is to involve all business and social partners (down-to-top approach). The superior waste management policy objective is to prevent generation of wastes at source, to increase raw material recovery and waste reuse, and to ensure final disposal of non-utilised wastes in an environmentally safe way".

The Act on waste from 27 April 2001 (with later amendments) [91] defines the objectives of waste management in Poland in order to ensure safety of human health and life and environmental protection, in consistency with the sustainable development rules. This act introduces the obligation to prepare waste management plans which have to be updated every 4 years. The first national waste management plan (NWMP) [92] was adopted in Poland in 2002, the second one [8] – in 2006. The plans include the description of the current situation in waste management and the changes predicted for the next few years. Tasks, activities and projects for implementation in the scope of improvement of waste management in Poland and their schedule, as well as the monitoring system are also outlined in those plans. Apart from the national waste management plan similar documents have to be prepared also at districts and community level (from 31st December 2003 and 30th June 2004, respectively) [93].

The objectives of waste management defined in the Act on Waste [91] and in the II National Environmental Policy [90] constitute the basis for the formulation of the tasks in the Polish national waste management plan. The following waste management hierarchy has been adopted in the NWMP [8]:

- "firstly, to prevent generation of waste and minimise the quantity of waste generated and reduce their hazardous properties,
- secondly, to reuse the material and energy properties of wastes and in case when it is impossible for waste to undergo recovery processes – this waste must be

disposed of, while its deposition on landfill is generally considered the least desirable method".

The waste management of plastics is regulated in Poland by a range of legal acts. Apart from those abovementioned, the most important are listed below:

- Act on Entrepreneur Duties Concerning Management of Certain Types of Waste, and on Product and Deposit Fees [94]
- Packaging and Packaging Waste Act [95]
- End-of-Life Vehicles Act [96]
- Electric and Electronic Waste Act [97]

Among these acts it is worth to mention the Packaging and Packaging Waste Act in more detail [95]. The current Polish system for the packaging waste management has been developed as a result of the transposition this European Commission P&PW Directive to the Polish law and the obligation to report to the EC the quantities of packaging waste collected and recovered. The rule of "extended producer's responsibility" imposed the obligation for producers and importers of packed commodities to achieve adequate levels of recycling and recovery of the packaging waste. If they do not reach the given targets they have to pay a product fee to the respective Marshall Office. The fee is calculated by multiplying the product fee rate and the difference between the required and achieved level of recycling and recovery [98]. In accordance with the article 25 of the Act on Waste the subject generating waste may contract another respective entity to fulfil the requirements outlined in the P&PW Directive. Apart from this act the other two "EU process Directives" concerning the used vehicles and electric and electronic appliances have been transferred into the Polish law however, the date of their implementation exceeds the temporal boundary set in this study.

2.4.3 Legal regulations in Austria

The basis for defining the objectives of waste management in Austria constitutes, like in Poland, the principle of sustainable development. The primary legal act related to waste is the Waste Management Act (AWG) [99] with later amendments. The following priorities are set in the guidelines for waste management in Austria of this act:

- protection of mankind and the environment,

- prudent use of natural resources,
- storage of emission-neutral residuals with prudent use of landfills.

The federal waste management plan (BAWP) is being prepared in Austria at least once in five years in order to implement the objectives and principles of the Waste Management Act. The first BAWP was published in 1992, followed by the plans in print in 1995, 1998, 2001 and 2006. The plans include the analyses of the current situation in reference to quantities of waste generated, collected and treated, the regional distribution of waste disposal facilities, targets for waste management derived from the abovementioned AWG and the measures necessary to achieve these targets.

Waste management of plastics is regulated further by many legal acts, the most important of them are indicated below:

- Packaging Ordinance [100],
- Ordinance on take-back and deposit charge of refillable plastics beverages packaging [101],
- Ordinance on the collection, recycling and treatment of end-of-life vehicles [102],
- Ordinance on waste prevention, collection and treatment of waste electrical and electronic equipment (WEEE Ordinance) [103],
- Landfill Ordinance [104],
- Incineration Ordinance [105].

Apart from the earlier described EC Directives: P&PW, ELV and WEEE transferred into the Austrian national law, another very important act – the new Austrian Landfill Ordinance [104] was implemented in 2004. It prohibits landfilling of waste with organic carbon content of above 5% or with a heat-value of above 6 MJ/kg without prior pre-treatment. The development of waste management recovery facilities in Austria has been significantly influenced by this regulation, especially in the field of energy recovery. This contributed considerably to the change in the waste management of plastics, mainly through a high increase of thermal treatment of waste which cannot be disposed of in landfills without pre-treatment anymore.

2.5 Plastic waste management systems

The focus in waste management in the recent decades has been changing from eliminating waste from urban areas towards an integrated approach aimed at the reduction of waste generation at source and improvement of their valorisation potential [1]. The evolution of solid waste management in Western Europe, according to Massarutto [1] is presented in Table 2-6.

Table 2-6 Evolution of solid waste management regimes in Western Europe

Regime	Time frame	Main objectives	Key actor
Public hygiene	until end of 1960s	Removing waste from urban areas	Municipality
Environmental protection	early 1970s	Minimizing environmental impact of disposal Avoiding shipment of waste towards low-standards countries	Legislator
Facing waste mountain	end 1970s – middle 1080s	Ensuring adequate disposal capacity face dramatically increasing quantities and supply shortage	Region
Prevention and closed material cycles	from 1990s	Minimizing waste flows and increasing the potential for resources recovery	National level Manufacturers Retail sale

Source: based on [1]

In recent years two important innovations have been implemented in the management of municipal waste [1]: 1) introducing regional responsibilities for disposal planning and 2) executing the producer’s responsibility which incorporates manufacturers and distributors in the chain of waste management activities. These measures have contributed particularly to the dynamical development of the waste management packaging systems in recent years. The European Commission’s Packaging and Packaging Waste Directive played one of the key roles in this process [3].

The first legal act on packaging waste was implemented in Germany in 1991 [106, 107]. It imposed the obligation for industrial subjects to collect and recycle their used packaging on their own or through other specialized entities. At the same time Duales System Deutschland AG (DSD) was established as a private-sector company to perform the activities of recovering and recycling the packaging waste, i.e. plastic, metal, compound materials, paper and glass, on license base [108, 109].

Similar legal acts concerning packaging waste were implemented in France in 1992 and in Austria in 1993 resulting in the foundation of the packaging waste collection and recovery systems, Eco-Emballages SA, respectively Altstoff Recycling Austria AG (ARA). In 1994 the EC Directive 94/62/EC on Packaging and Packaging Waste was implemented imploring the EU member countries to set up such systems [106].

The license symbol (trade mark) of the DSD system is the "Green Dot", presented in the picture. The companies introducing packaging onto the market set up agreements with DSD GmbH and pay a license fee for utilizing the symbol on their packages. In this way they are "exempt from their statutory obligations to take them back, recycle them, and to document the procedures involved". The presence of the symbol on the packagings signals that they have paid the respective fee for their future collection and treatment [107].

Figure 2-7 Green Dote license symbol

Source: [107]

The DSD GmbH does not carry out the collection and recovery on its own, but contracts disposal partners, who perform the appropriate take-back, sort and recovery activities. One of the contractors is Deutsche Gesellschaft für Kunststoff-Recycling GmbH (DKR) responsible for the recycling of plastics [110].

In 1995 the organization PRO EUROPE (Packaging Recovery Organization Europe) was founded as an "umbrella organization for the European packaging and packaging waste recovery and recycling schemes". It is the general licensor of the "Green Dot" trademark, which "has evolved into a proven concept in many countries in implementation of producer responsibility" [111]. At present this trademark is used in twenty two EU member states: Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Estonia, France, Germany, Greece, Hungary, Ireland, Latvia, Lithuania, Luxembourg, Malta, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, and Sweden, and additionally in Norway, Croatia and Turkey. PRO EUROPE also co-operates with similar organizations founded in the United Kingdom, Ukraine, Finland, Iceland and Canada [111].

The “Green Dot” systems of packaging waste, take-back and recovery differ among countries in reference to their organizational structure or the waste fraction they cover. Full-cost and share-cost systems can be distinguished. The fees also differ in various systems. The license fee for plastic packaging in Germany, amounting to 1 409 € per ton, is the highest among all countries. In Austria it is 609 € and in Poland around 440 € [106]. A detailed description of single packaging systems founded in the European countries can be found in Kozłowski [106]. A brief overview of the Polish and Austrian systems is presented in next sub-chapters.

The European systems of packaging waste management differ not only in reference to the technologies applied but also in the way the producer’s responsibility legislation affects the regional or local authorities, and the manner of financing of the systems. In Austria, Belgium, Finland, France, Germany, Luxembourg and Sweden the local authorities do not pay for the collection of various packaging waste fractions and this task is passed over onto chosen organizations, while in France, Ireland, Italy and Spain the municipalities receive payments however, they do not cover the total costs of collection. In Denmark, Greece, Netherlands and the United Kingdom no direct funding for the collection systems exist however, the municipalities are obliged to ensure the collection of packagings (e.g. in Denmark) or to achieve high recycling rates (the Netherlands) [112].

The costs of collection of recyclable fractions are “typically in the same area as those for residual waste” [112]. The costs for the plastic packaging materials are usually higher than for other waste fractions, amounting to between €200-300 per Mg however, e.g. in the UK it only amounts to around €100. The costs of plastic waste sorting amounted to e.g. €272/Mg in Austria, €183-€229/Mg in France, €127/Mg in Ireland and €30-66/Mg in the UK.

As reported by PlasticsEurope [53] the collection rate for mechanical recycling in the 25 EU member states, Norway and Switzerland in 2005 amounted to 19,1%, i.e. 2,5% more than in the previous year. It should be mentioned however, that this value refers to the quantity collected but not effectively recycled. The trend of increased cross-border movement within the EU but also sending the collected waste for recycling to destinations outside the EU e.g. China or India has been observed in the recent years. In Switzerland, Belgium and the Netherlands the share of waste imported for recycling amounts to 35-45%.

The increase of quantities recycled is mainly due to growing amounts of separately collected packages (e.g. PET bottles), industrial packaging films and PVC products. Various practices are applied in different member states: in the Netherlands and Austria the decision to resign from collecting mixed plastics has been taken, while e.g. in the UK the activities are directed towards increased recycling of the mixed plastics stream [53].

Not only the recycling systems of post-consumer plastics waste vary significantly amongst the European countries; the same refers to the energy recovery. In Switzerland, Germany, Sweden and Denmark the strategy of “diversion-from-landfill” is being implemented and nearly no waste can be disposed in landfill sites without previous pre-treatment. Recovery levels of plastic waste exceeding 80% have also been achieved in Belgium, Austria, Luxembourg and the Netherlands. The new EU member states, United Kingdom, Greece and Ireland recover only around 20% or even less [53]. In 2006 more than 30% of the total post-consumer plastics waste was recovered in the countries of the EU25, mainly due to thermal treatment in municipal waste incineration plants.

The use of plastic waste for the production of solid recovered fuel (SRF), which can partially substitute conventional fuels in cement and paper industries or in power plants is expected to increase “after the introduction of CEN [1] standards for the classification of this type of fuel”. This technology is developing especially in Germany, but new SRF-fuelled power plants are also being built e.g. in the United Kingdom and Finland [53]. It has been generally recognized in the recent years that the increase of the energy from waste is indispensable.

In the Final Report of the Directorate General Environment of the European Commission [112] are analyzed. It is emphasized that due to the fact that some countries have already implemented the ban on the land-filling of most non-pre-treated waste (e.g. the Netherlands, Austria, Germany and Denmark), the capacities of the existing thermal treatment facilities have influenced the collection and treatment methods and the respective costs, i.e. increased separate collection in countries where the treatment costs are more expensive. The data concerning the costs and revenues for energy recovery in the so called “old EU member states” is presented in Table 2-7.

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[1] European Committee for Standardization (CEN)

Table 2-7 Comparative economic data for incineration in different EU member states

	Pre-tax costs net of revenues [€/Mg]	Revenues for energy supply [€/kWh]	Costs of ash treatment [€/Mg]
Austria	326 (60 000 Mg/yr) 159 (150 000 Mg/yr) 97 (300 000 Mg/yr)	Electricity 0,036 Heat 0,018	Bottom ash 63 Flue gas residues 363
Belgium	83	Electricity 0,025	Not available
Denmark	30-45	Electricity 0,05	Bottom ash 34 Flue gas residues 134
Finland	none	For gasification, Electricity 0,034 Heat 0,017	
France	91-101 (37500 Mg/yr) 86-101 (37 500 Mg/yr) 80-90 (75 000 Mg/yr) 67-80 (150 000 Mg/yr)	Electricity 0,023	13-18 (per Mg input)
Germany	250 (50 000 Mg/yr and below) 105 (200 000 Mg/yr) 65 (600 000 Mg/yr)	Electricity 0,046	Bottom ash 28.1 Fly ash/air pollution control residues 256
Greece	none	Not known	Not known
Ireland	46 (200 000 Mg/yr) (est)	Not known	Not known
Italy	41-93 (350000 Mg/yr) depends on revenues for energy and packaging recovery)	Electricity 0,04 (market) 0,05 (green cert.)	Bottom ash 75 Fly ash and air pollution control residues 129
Luxemburg	97 (120 000 Mg/yr)	Electricity 0,025*	Bottom ash 16/Mg input waste Flue gas residues 8/Mg input waste
Netherlands	70-134**	Electricity 0.05/Mg*	
Portugal	46-76 *		Not available
Spain	34-56	Electricity 0,036	
Sweden	21-53	Electricity 0,03 Heat 0,02	
United Kingdom	69 (100 000 Mg/yr) 47 (200 000 Mg/yr)	Electricity 0,032	Bottom ash recycled (net cost to operator) Fly ash approx. 90

*estimated, ** gate fees, not costs Source [112]

The feedstock recycling still plays quite an unimportant role in the overall plastics recovery business. In 2006, a reduction of the quantities treated in this way was observed [53]. The most commonly applied technology, the use of waste plastics substituting oil or coke as a reducing agent in blast furnaces, is employed on large scale in Germany.

The organization PlasticsEurope [53] notices that the countries with high recovery rates are efficient in both material and energy recovery. The effective waste and resource management must address both of them, as achieving 100% recycling rate is not possible. Even though this organization still sees some potential for improvement in the leading countries, the increase of the recycling levels will be more challenging in the future. The modern waste management systems should be integrated structures matching the collection systems with the treatment facilities (for both separated recyclable fraction and residual waste) in order to ensure the systems' "flexibility for dynamic changes in system performance, changing waste composition and changing treatment costs" [112].

The current state of shares in municipal waste treatment and disposal methods in countries of the European Union, according to Pająk [113], is shown in Table 2-8.

Table 2-8 Shares of municipal waste management practices in EU member states

	Recycling and composting	Landfilling	Incineration
Austria	59	31	10
Belgium	52	13	35
Bulgaria	16	84	0
Cyprus	10	90	
Czech Republic	6	80	14
Denmark	41	5	54
Eastland	37	63	0
Finland	28	63	9
France	28	38	34
Germany	58	20	22
Great Britain	18	74	8
Greece	8	92	0
Hungary	12	85	3
Ireland	31	69	0
Italy	32	57	11
Lithuania	9	91	
Leland	13	83	4
Luxemburg	36	23	41
Malta	20	80	
the Netherlands	65	3	32
Poland	4,5	95	0,5
Portugal	3	75	22
Romania	19	81	0
Slovakia	14	81	5
Slovenia	14	84	2
Spain	38	55	7
Sweden	41	14	45

Source: [113]

2.5.1 Plastic waste management in Poland

The packaging waste management system, based on the "packaging chain" responsibility, has been developing in Poland since the year 2002. According to the information gathered by Poskrobko et al. [114] in 2005 this system covered 72% of citizens and 46% of communes. The first Polish recovery organization Rekopol Organizacja Odzysku S. A. was founded in the year of 2001. In 2004 there were already around 40 organizations that played an active role in the collection and recovery of the packaging waste. Such a big number of mainly small organizations and lack of consolidated action of the recovery market resulted in low efficiency of the recovery of the packaging waste in Poland [59].

Krawczyński [115] emphasizes that the economic changes in Poland in the 1990s contributed to the de-monopolisation of the waste management sector and to the foundation of a few thousands of entities dealing with waste. The lack of control of the waste management authorities and strong competition between the companies resulted in concentrating their activities on short-term profits. The necessity to reduce cost contributed in consequence to illegal or partially legal disposal of waste at lowest possible costs. The activities of the companies were not directed towards the investment in the development of sorting and recovery infrastructure. The Polish legal regulations concerning packaging waste management is consistent with the European Union system, thus failing to execute the requirements and commitments resulting from the legal acts, is the main problem [115].

The "Report from the Commission to the Council and the European Parliament on the implementation of the Directive 94/62/EC on Packaging and Packaging Waste and its impact on the environment, as well as on the functioning of the internal market" [116] states that the "information on the packaging waste management in the new member states before accession is scarce". However, due to the implementation of this directive into the Polish law the availability of respective data improves gradually in Poland [117]. Useful information concerning the current state-of-art and changes in packaging waste management in Poland are contained in Compendium on Waste and Packaging [118].

Significant barriers in the development of recycling in Poland refer to insufficient funding for the collection from households, lack of sorting facilities, low ecological consciousness of the society, and low prices for landfilling. The average costs for disposal of waste at municipal landfills are around 60-80 PLN (approx. €19-25), however, the differences between max and min prices are even around 100 PLN (approx. €30). This fact contributes to the problem of transporting and disposal of municipal waste on the landfills which charge lowest prices [114, 119].

Poskrobko et al. [114] distinguish two groups of sources for the secondary materials recovery: concentrated and non-concentrated. The first group covers the industry and commercial networks, while the second one – the systems of separate collection, sorting plants and firms buying up secondary materials. The share of the packaging waste resulting from separate collection in the overall quantity of waste directed for recycling constituted in the years 2003-2005 around 17%. The rest was obtained from concentrated sources. The same situation concerns the plastic packaging waste – the main sources for the collection are trade and industry, while the collection from households is much lower.

In Poland two methods of plastics recycling are authorized: mechanical (material) recycling used for homogeneous, polymer-specific, sorted waste fractions, mainly of PE, PP and PET, and chemical (feedstock) recycling used for olefins. Poskrobko & Piontek [59] estimate that a certain percentage of the plastic packaging waste is directed for feedstock recycling, however there is no respective data. The levels of the material recycling of the plastic packaging waste in Poland in the years 2002-2005 are presented in Figure 2-8.

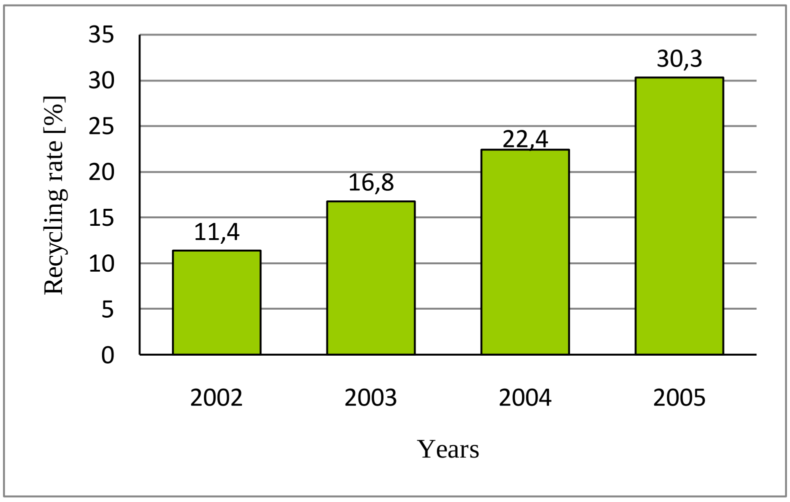


Figure 2-8 Recycling rates of plastic packaging waste in Poland in 2002-2005

Source: based on [114]

Despite the growing rate of recycling of packaging waste in order to realize the packaging waste recovery targets investments in thermal treatment of waste, i.e. building new MSW incineration plants and creating incentives for production and use of alternative fuels are indispensable in the coming years. Poskrobko et al., [114] also point out that restraining the imports of alternative fuels from abroad should be conducted. The future vision for the development of waste recovery systems [21] contains constructing a modern incineration plant with capacity between 50 000 and 250 000 Mg/year in each voivodeship, although high investment costs and unwillingness of local societies can influence and limit this process. Currently in Poland there is only one MSW incineration plant operating since 2001 within the Solid Communal Waste Utilisation Plant in Warsaw, with an annual capacity of 100 000 Mg [120]. The cost of plastic waste utilisation in ZUSOK incineration plant amounts to 650 PLN (approx. €203) pro Mg of waste [121]**.**

Some quantities of plastic waste are used in the cement industry, incinerated in medical waste incineration plants and used as reducing agents in metallurgic industry. In the year 2004 58 000 Mg of plastic and rubber waste was treated thermally in the cement kilns. 78% thereof are end-of-life tires [122]. The use of this waste fraction as alternative fuel in cement kilns in Poland is presented in Figure 2-9. The Polish Cement Association [123] plans to cover in the long term 30% of its energy demand through energy obtained from alternative fuels. Currently, the energy from the use of waste plastics and end-of-life tires covers 5% of the total energy demand.

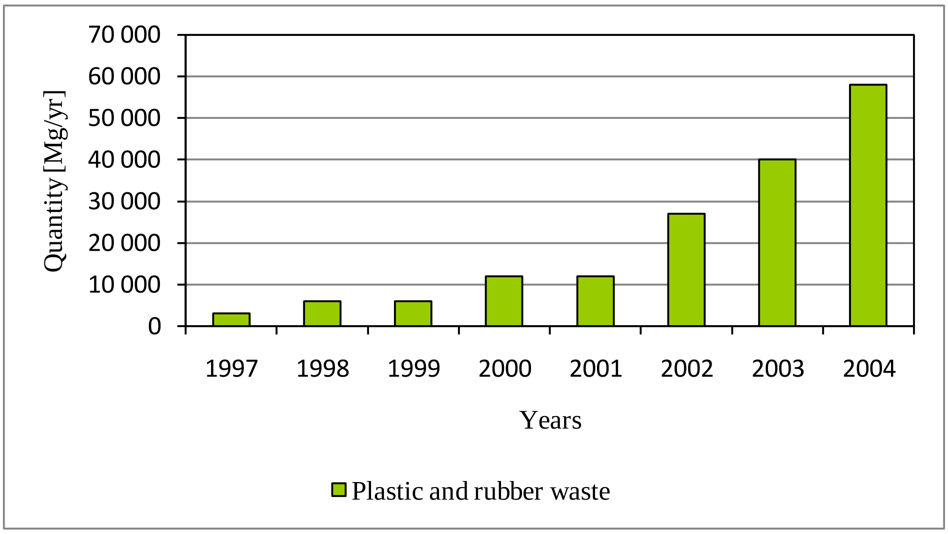


Figure 2-9 Use of plastic and rubber waste in cement industry in Poland in 1997-2004

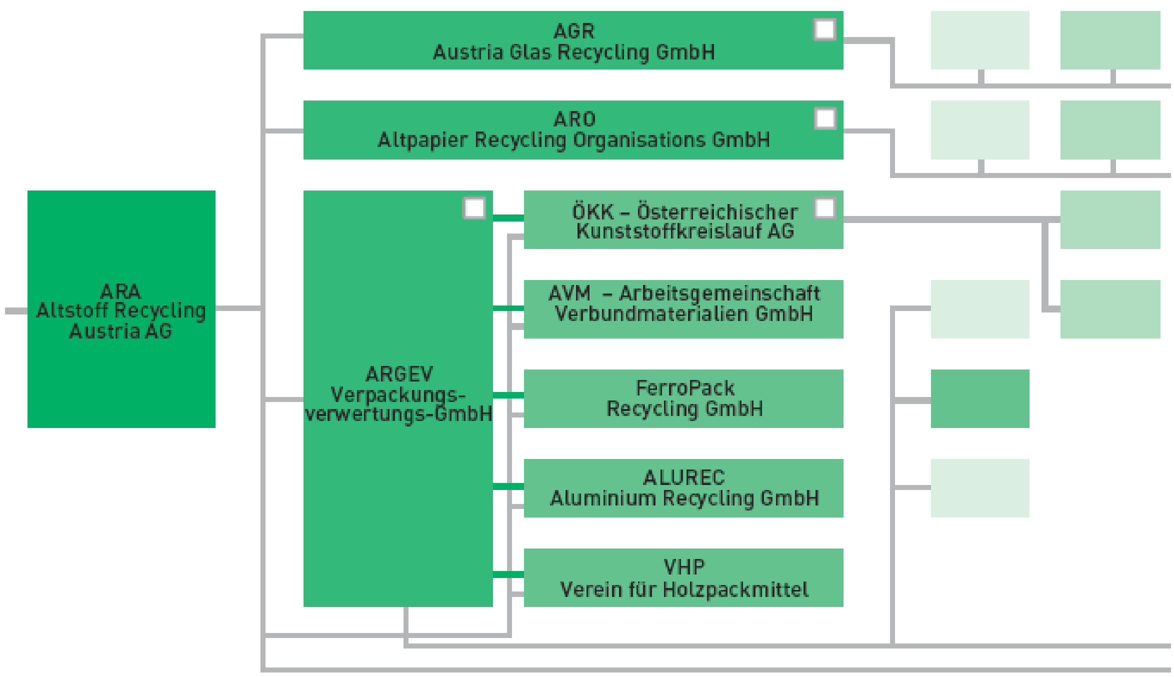
Source: [122]

In 2007 the European Commission approved the Infrastructure and Environment Operational Program (IEOP) for the years 2007-2013 [124]. Fifteen priority axes are to be implemented under this program. The activity 2.1of the second axe “Waste management and the protection of earth” refers to the projects in waste management filed. Ten projects of thermal waste treatment plants are under preparation at present with an estimated time for the initiation of the investments in 2009/2010. The Ministry of Environment [125] currently investigates the potential projects for the conformity with the formal and essential criteria. Until the year 2013 ten incineration plants should be in operation however, the information about their capacity is not available for the public yet.

2.5.2 Plastic waste management in Austria

Contrary to the Polish system for the packaging waste collection and recovery which consists of a high number of small organisations, take-back and recovery of this waste in Austria is organized within the frame of one structure called ARA System (Altstoff Recycling Austria AG). This non-profit organisation was founded in the year 1993 in relation to the implementation plan of the Packaging and Packaging Waste Directive [3]. Its activity is aimed at collecting and ensuring recovery of packaging waste from households, trade and industry. It consists of ARA AG and eight branch-associations, which are responsible for various fractions of the packaging waste. ARGEV Verpackungsverwertungs-Ges.mbH and Österreichischer Kunststoffkreislauf AG (ÖKK) with its partners are responsible for the plastic packaging waste [126]. The scheme of the system is presented in Figure 2-10.

The amounts of plastic packaging waste collected within the frame of ARA System increases each year, as shown in Figure 2-11. In 2004 nearly 132 000 Mg were collected by ARGEV, 80% of which comes from households, the rest from commerce and industry. In the year 2004 changes in the system of plastic packaging waste collection has been implemented by ARGEV in a few provinces: Vienna, Lower Austria, Upper Austria, Salzburg and Carinthia. From that date only bottles are collected separately in those regions. Other plastic packaging waste is sent for thermal treatment together with residual waste. This system change is aimed at developing a plastic recycling system only for fractions for which it is economically and ecologically justified [127]. The recycling of polymeric materials by resin is presented in Figure 2-12.



Umbrella company	Branch-recycling companies	Collecting, sorting, recovering partner companies

Figure 2-10 Structure of ARA System

Source: [128]; with permission

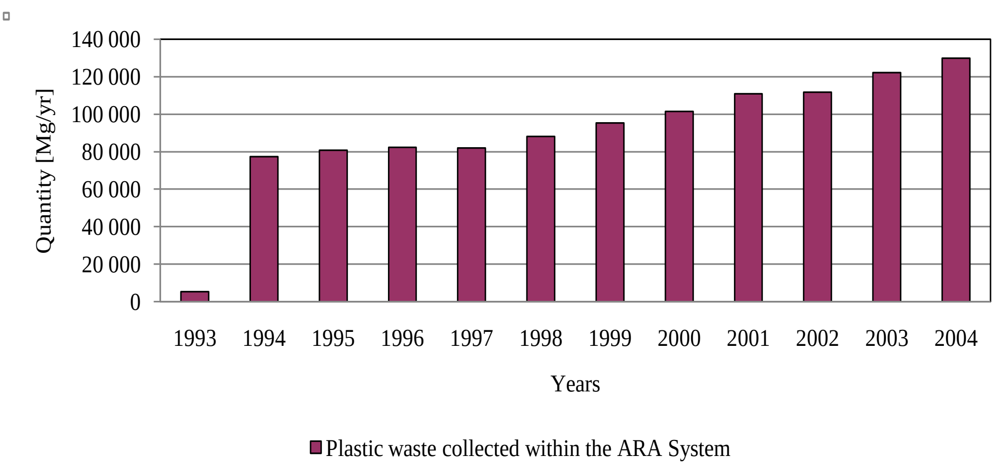


Figure 2-11 Quantities of lightweight packaging waste collected within the frame of ARA System in Austria in years 1993-200,4 Source: based on [129]

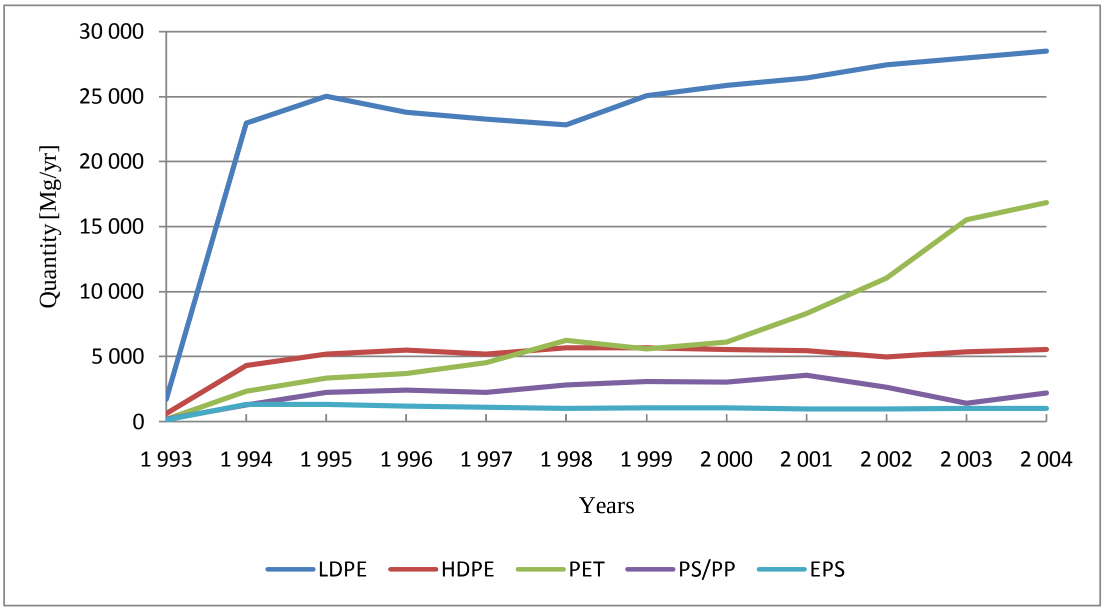


Figure 2-12 Quantities of polymeric materials recovered within the frame of ARA system in Austria in the years 1993-2004, Source: based on [130]

Based on the information from the Austrian Environmental Agency [131], there are ten installations for thermal treatment of household waste (listed in Table 2-9), compliant with the requirements of the Austrian Landfill Ordinance [104]. The quantity of municipal waste incinerated annually in Austria increased from 880 000 Mg in the year 2000 to approx. 1,8 Mio. Mg in 2005 [131].

Table 2-9 Incineration plants for household waste in Austria

Location	Technology	Current capacity [Mg/yr]	Start up
Arnoldstein (Carinthia)	grate firing	80 000	2004
Dürnrohr (Lower Austria)	grate firing	300 000	2004
Flötzersteig (Vienna)	grate firing	200 000	1963
Lenzing (Upper Austria)	fluidised bed	150 000-300 000*	1998
Niklasdorf (Styria)	fluidised bed	100 000	2004
Pfaffenau (Vienna)	grate firing	250 000	2008
Simmeringer Haide (Vienna)	fluidised bed	110 000	1980/1992/2003
Spittelau (Vienna)	grate firing	260 000	1971
Wels I (Upper Austria)	grate firing	75 000	1995
Wels II (Upper Austria)	grate firing	230 000	2006

*depends on the calorific value Source: [131, 132]

The untreated residual waste is mainly incinerated in plants with grate firing, while the high calorific waste fraction from mechanical-biological treatment is more often used in co-incineration plants (fluidised beds). One of the examples of the model MSW incineration plants is the Viennese combined heat and power incineration plant Spittelau. It has a capacity of 260 000 Mg per year [133] and the heat generated is used for the Vienna district heating system, while the power goes for the Vienna grid. The used plastics constitute by weight approximately 10% of the feed and cover 50% of the calorific content. The plant is equipped with a very effective air-cleaning facility. Though it was not socially accepted at the beginning, a few years after the start up a comprehensive education campaign and ensuring the highest technical standards caused that the conducted survey met with wide acceptance (81% of the enquired people) of this incineration and district heating investment [53].

New incineration and co-incineration plants are under construction (Pfaffenau) or have already been commissioned (Zistersdorf) or in their respective planning stages (Frohnleiten – expected to operate in 2009/2010, Heiligenkreuz – in 2010, Linz – in 2011) or pending formal project review (Dürnrohr Line 3 – in 2009) [132]. This will result in an increase of the thermal treatment capacity of 1,4 Mio. Mg in the coming years [131].

The plastic waste is also thermally used in the cement industry. The use of plastic waste and old tires as alternative fuel substituting partially the conventional energy sources in the cement kilns began in Austria in the year 1994. The amount of this fraction has been increasing since then and the composition has been changing (see Figure a). In 2004 above 110 0000 Mg of plastics and 83 000 of old tires were used in the Austrian cement industry [134].

Additionally, in the year 2006 the company Voestalpine AG in Linz, started using the plastic waste fraction in blast furnaces. The annual capacity for the treatment of the waste fraction amounts to 220 000 Mg [135].

This fast development of the energy recovery from waste in Austria in the recent years is mainly a consequence of the implementation of the new Landfill Ordinance [104], as at present (with some exceptions until 2009) no waste with organic carbon content above 5% can be disposed of without previous pre-treatment in landfill sites in Austria.

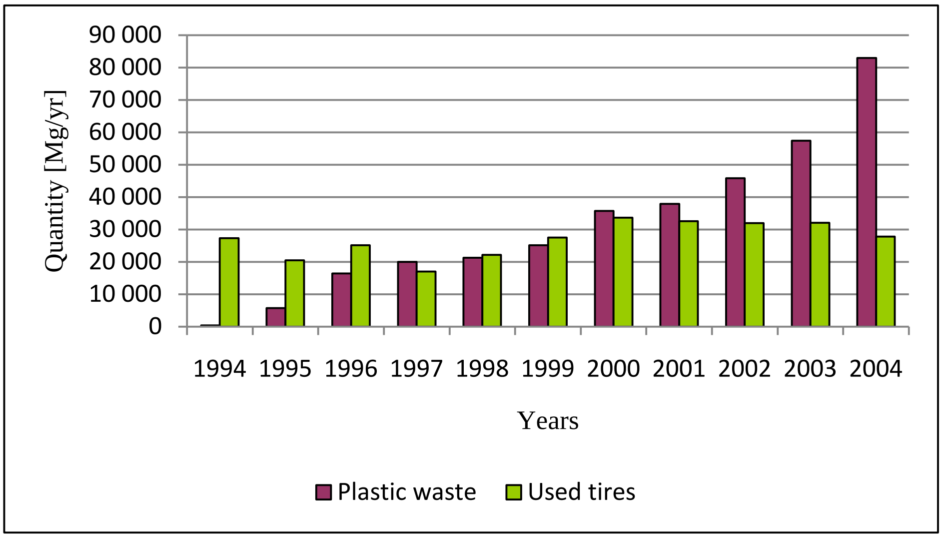


Figure 2-13 Use of plastic waste and old tires in Austria's cement industry

Source: based on [134, 136]

3 Application of material flow analysis to estimate plastic flows and stocks

In the following chapter the material flow analysis (MFA) method used in the study is presented. It is used to quantify:

- the total flows and stocks of plastics in the investigated systems,
- the total flows and stocks of plastic waste in the investigated systems,
- the flows of the selected substances from plastic waste in both WM systems.

The definition of the systems chosen for the study, the defined systems' boundaries and the selection of goods, processes and relevant substances included in the evaluation is presented in the following chapter.

3.1 MFA definition

The material flow analysis aims at describing, investigating, and evaluating the metabolism of anthropogenic and geogenic systems. Brunner & Rechberger [137] define the MFA method as "a systematic assessment of flows and stocks of materials within a system defined in space and time. It connects the sources, the pathways, intermediate and final sinks of a material". Through the act of balancing the input and output flows the identification and quantification of the respective waste flows, environmental loads and their sources is feasible. Additionally, the method allows to estimate the accumulation or depletion of material stocks and some minor changes of those stocks which are not significant enough to be measured in short-term but contribute to long-term damage.

MFA refers to an accounting of material flows expressed in physical units for defined periods of time and can be carried out on different levels: international, national and regional, but also community or even company level. The analysis is conducted based on the assumption that a mass balance exists for the material into and out of the economic systems [138, 139]. Sometimes in literature, a distinction between bulk material flow analysis and substance flow analysis (SFA) is made. The first one considers the total flows of materials, while in SFA the flows of specific substances are studied (e.g. of nitrogen compounds or heavy metals) [140, 141].

3.1.1 Main terms used in MFA

The main terms used in the MFA methodology are presented briefly below [137]:

- Substance is any chemical element or compound composed of uniform units,
- Good is an economic entity of matter with a positive or negative economic value; made up of one or several substances,
- Material stands for both substances and goods,
- Process refers to transformation, transport, or storage of materials,
- Flow (mass flow rate) is a ratio of mass per time that flows through a conductor,
- Import process is a process of origin of a flow or flux that enters the system,
- Export process is a process of destination of a flow or flux that leaves the system,
- Transfer coefficient (TC) refers to partitioning of a substance in a process,
- System is a group of elements, interactions between these elements, boundaries between these and other elements in space and time; the system can be closed or opened (interacting with the surrounding),
- The system is defined in time (temporal boundaries) and space (spatial boundaries),
- Activity is a set of all relevant processes, flows and stocks of goods and substances that are necessary to meet and maintain a certain human need.

3.1.2 Steps of MFA

Conducting the material flow analysis consists of the following steps [137]:

- Defining problems, goals and the scope of the study,
- Selecting relevant substances for the evaluation,
- Defining the system in space and time,
- Identifying the relevant processes, flows, and stocks,
- Determining the mass flows, stocks and concentrations,
- Quantifying the total material flows and stocks,
- Presentation of the results.

3.1.3 Application of MFA

The material flow analysis is used for analysis in fields like environmental protection, resource- and waste management, and economics. MFA is a tool for environmental management and engineering e.g. with regards to environmental impact statements, design of air-pollution control strategies or soil-monitoring programs. In the field of industrial ecology MFA is applied to balance industrial input and output to natural ecosystems, to systematize patterns of energy use, control pathways for materials use in industrial processes, or to balance industrial output in the creation of loop-closing industrial practices It is very useful for the observation of accumulation or depletion of resources, for investigating changes of stocks and forecasting resources scarcity. It is a cost-effective tool for determining waste composition and therefore it helps to make decisions concerning the design of future sustainable waste management systems. Moreover, it is used to investigate substance management of recycling and thermal treatment processes and facilities and thus, it supports the design of new environmentally friendly products, which is related to the so-called "design for recycling", "design for environment" and "design for disposal". The evaluation tools based on MFA enables to assess whether the goals of the investigated system, products, and facilities are achieved and which crucial points require more attention or improvement [137].

3.1.4 State-of-art of MFA application

The method of material flows analysis is not generally used in Poland yet, however some works in this direction have been initiated. In December 2006 Świerkula [142] conducted a study aimed at evaluation of possibilities of calculating indicators of material flows relying on the national data. This work can certainly contribute to the development of applicability of the material flow analysis method at national level in Poland.

On the contrary, MFA is commonly used in many other countries. European Environment Agency conducted a study concerning the use of MFA methodology in the European countries. Austria, Denmark, Germany, the Netherlands, Norway, Sweden and Switzerland are considered as countries most advanced in the field of different MFA and SFA studies [139]. To the main institutions working actively in the field of material flow analysis and accounting belong among others: Institute for Water Quality, Resources and

Waste management of Vienna University of Technology, Institute for Social Ecology and Sustainable Europe Research Institute (Austria), Charles University Environment Center in (Czech Republic), Danish Environmental Protection Agency (DEPA), Wuppertal Institute for Climate, Energy, Environment (Germany), Institute of Environmental Sciences of Leiden University (the Netherlands), Faculty of Engineering Science and Technology of The Norwegian University of Science and Technology (NTNU) in Trondheim (Norwey), Swiss Federal Institute of Technology (Switzerland), Centre for Environmental Strategy at University of Surrey (United Kingdom), and outside of Europe National Institute for Environmental Studies (Japan) or Center for Industrial Ecology at Yale University (United States of America).

The MFA studies for plastic flows at national levels have been conducted e.g. by Baccini & Diener [143] for Switzerland in 1991, Fehringer & Brunner [149] for Austria in 1997, Patel et al. [144] for Germany in 1998, Joosten et al. [145] for the Netherlands in 2000, and recently e.g. Mutha et al. [146] for India in 2006. The current study is an attempt to update the MFA for plastics in Austria and a first trial to quantify the total plastic flows in Poland, with special emphasize on waste streams.

The research field of stock modelling in MFA develops dynamically in the recent years. Comprehension of the stock dynamics and its role in the industrial metabolism is an essential, however usually least understood issue, in conducting material analysis [147]. Thus, development of appropriate, e.g. dynamic [148] modelling methods for stocks accounting will certainly be a one of the key tasks in the MFA research area in the coming years.

3.2 MFA of plastic flows

In the first part of the analysis the total flows and stocks of plastics in the investigated systems are quantified. The main questions which are to be answered during the study are as follows:

- How many plastic goods are consumed in the analysed systems?
- How much plastic waste is generated in the analysed systems?
- How many plastics are accumulated in the stocks "in use" and the landfills in the analysed systems?
- How do the plastic flows differ from one another in the investigated systems?

- How does the plastic waste management differ in the analysed systems?

This part of the analysis is a pre-study aimed at obtaining the relevant input data for more detailed quantification of the flows within the waste management systems and their subsequent evaluation.

3.2.1 System definition of total plastic flows

In this chapter the systems chosen for the analysis are presented: the spatial and temporal boundaries are set, and analysed processes, goods, and substances are briefly described.

3.2.1.1 System boundaries

Two countries – Poland and Austria – are chosen for the study. The spatial boundaries constitute their territories, each of the countries being a separate system. Poland has a territory of 312.000 km² and around 38 Mio. inhabitants, while the area of Austria is 84.000 km² and the population amounts to approximately 8 Mio. people.

Although both chosen systems differ from each other with regards to the geographical, demographical and also economic features, they have been chosen for the evaluation to compare the development of the waste management system in Austria (a country more advanced in this respect) to the Polish system, which is currently under development.

At present Poland and Austria are member states of the European Union, however Austria joined the EU ten years before Poland did. Also, the first national waste management plan has been implemented in Austria around ten years earlier than in Poland. Currently both countries are obliged to adapt to the same EU legal regulations concerning e.g. waste management (like the Packaging and Packaging Waste Directive [3]).

The first quantification of the total plastic flows using the MFA method was conducted in Austria ten years before by Fehringer & Brunner [149] for the year 1994. The situation observed by the authors at that time was much like the situation in Poland at the moment. Due to the fact that at present waste- and resource management and the related infrastructure and treatment facilities are better developed in Austria, significant differences are expected to exist between plastics waste management in both countries thus, it seems interesting to analyse the differences between the two systems and to evaluate the environmental performances of both waste management systems in order to determine which development direction Polish plastic waste management should follow in the forthcoming years. Will Poland go the same way within the next years as Austria did in the past? Can the Austrian experience be useful for future decision of Polish authorities and waste management companies in this respect?

The year 2004 is chosen as the temporal boundary for the analysis. Additionally, the estimation of the stocks of long-living goods accumulated in the anthroposphere and the stocks of plastic waste disposed of in landfills is conducted for the period 1960-2004.

3.2.1.2 Description of goods, processes, flows and stocks

The system model proposed by Fehringer & Brunner [149] (with some modifications explained later), constitutes a basis for the quantification of the plastics flows in the analysed systems in 2004. It is presented in Figure 3-1. The system covers the processes and relevant flows between them, as well as the imports and exports included in the analysis.

The processes included in the model for MFA of the total plastic flows are presented in Table 3-1. They refer to the life cycle of plastics: beginning from the plastic goods production, through consumption, the processes of collection, sorting and transport of the plastic waste generated, until the processes of treatment and final disposal in landfill sites. The respective imports and exports of polymers, semi-finished products, plastic goods and the waste are also included in the quantification.

There are two main stocks identified:

- a stock of plastic goods in the *consumption* process (so called stock “in use”),
- a stock of plastic waste in landfills.

In the first of the mentioned stocks medium- and long-living commodities used for a few years or even decades are contained. This covers e.g. household articles, construction materials, sport equipment, etc. This stock “in use” constitutes potential for the future waste and its estimation is important for the effective design of future waste management systems.

The second of the mentioned stocks containing the plastic waste disposed in landfill sites is the only sink of the MFA system. Due to the fact that plastic waste decomposes very slowly and stays in the landfills for a long time, this stock increases constantly. There is no output of the process of *landfill* within the time boundary set for the MFA of the total plastic flows.

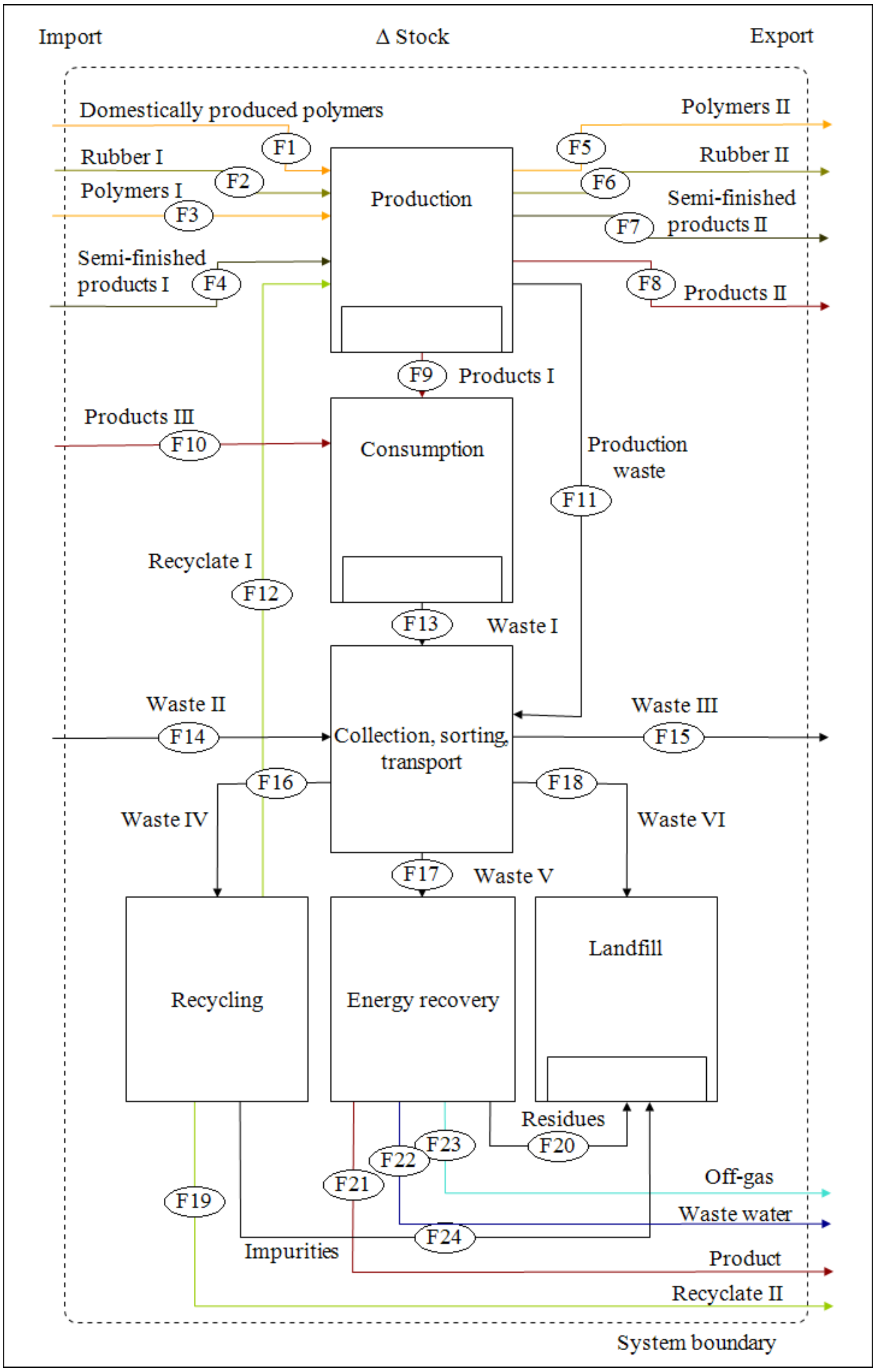


Figure 3-1 Total plastic flows and stocks

Source: based on [149]

Table 3-1 Processes for MFA of plastic flows

Process	Short description
Production	In this process plastics in primary forms are processed into semi-finished products and plastic articles; a part of which is exported from the system. The input to this process includes polymers produced domestically or imported, imported rubber, and semi-finished products processed within the system to plastic goods for final consumption. A part of the domestically produced polymers is not processed in the system, but exported. Other output from the system includes rubber, semi-finished products and plastic articles, which are produced for export.
Consumption	A process of use of short-, medium- and long-living plastic commodities.
Collection, sorting, transport	This process covers collection, sorting and transport of plastic waste to treatment facilities or landfills.
Recycling	Mechanical recycling of plastic waste: the collected plastic waste undergoes a few steps of processing including cleaning, sorting out residues, and producing recyclate, which can be either used for production of new goods at national market or exported.
Energy recovery	Thermal treatment of plastic and rubber waste in municipal waste incineration plants and fluidised beds or used as secondary fuel in cement kilns.
Landfill	Disposal of plastic waste and after-treatment residues in landfills

Source: own study for [150]

Due to a high variety of plastics and plastic goods produced, consumed and the general complexity of the system on one hand, and because of the scarcity of data on the other hand, simplifications and assumptions concerning the data used in the analysis must be made. The assumptions used for the calculations and a brief description of single flows to and from the respective processes are presented below.

Production

- The flow of *domestically produced polymers*, which covers the polymers produced in the analysed system, enters the process of *production* and is accounted for as import to the system due to the fact that upstream processes (e.g. production of polymers from primary and secondary raw materials) are excluded from the analysis. This is the main difference between the model system used in this thesis and the model proposed by Fehringer & Brunner [149]. They distinguish between the processes of *chemical industry* and *processing manufacturing* and estimated roughly the quantities of raw materials consumed for polymers production.

- The flow of *rubber I* imported to the system is used e.g. for the production of tires and various technical rubber articles,
- The input of *polymers I* and *semi-finished products I* covers the flows imported to the system for further processing,
- In this stage processing of plastics in primary forms but also of semi-finished products from import takes place. It is worth noticing that apart from the goods consisting 100% of plastics or rubber there are also commodities which consist of these materials only to a certain extent. The shares of plastic material in single product groups used in the study to calculate the total flows of plastics in imported or exported goods are presented in Table 3-2. The quantification of import and export flows is based on information from national statistics of foreign trade [175, 181].

Table 3-2 Average content of plastics in chosen articles

	Content of plastics [%]
Articles of rubber	90
Plastic yarns	90
Machines, vehicles (without street vehicles)	1
Street vehicles	7
Furniture	10
Clothes	10
Plastic clothes	100
Shoes	30
Articles of plastics	100
Sport equipment	30
Tapes	90

Source: based on [149]

- A part of the domestically produced polymers, rubber, semi-finished products and products leave the system as export flows (*polymers II*, *rubber II*, *semi-finished products II*, *products II*)

- The production waste resulting from the processing of the plastics in primary forms and semi-finished products, containing failure articles and production residue amounts to around 10% of the total production value [149]. It is assumed that a half of this fraction is recycled internally and the rest leaves the process as the flow of *production waste* for external waste treatment.
- The stock in this process is estimated approximately for four weeks of the production processes.

<u>Consumption</u>

- The flows of plastic goods from domestic production (*product I*) and from import (*product III*) enter the process of *consumption*. This process covers the use of short-, medium- and long-living plastic and rubber products. Only the articles with a life span of below one year (e.g. packaging materials, some medical equipment) leave the system as waste (as a part of the flow of *waste I*) in the analysed year, the rest (i.e. window frames, household goods, sport equipment, construction materials, etc.) accumulates in the anthroposphere in the so called stock "in use".
- The estimation of the total flow of *waste I* and the stock in the *consumption* processes is conducted by analysing the structure of the goods consumed (see Table 2-1) and the respective life spans (Table 2-3) with the application of time series, beginning from the year 1960.

<u>Collection, sorting, transport</u>

- This process covers the total flow of plastic and rubber waste collected in the systems in the analysed year, separately or mixed. A more detailed analysis of the output flows in the waste management systems is presented below. Due to the shortage of data concerning plastic waste collected and stored temporarily before its treatment it is assumed that there is neither a stock nor any change of this stock in the process of *collection, sorting, transport*.
- The waste imported to the system and exported from it is expressed as the flows of *waste II* and *waste III*, respectively. Due to the fact that very scarce or no data is available for those flows they are either excluded from the analysis (for the Polish system) or should be treated with precaution (for the Austrian system). It is explained in more details by presenting the results for the analysed systems.

Recycling

- Around 14% of the total stream of the plastic waste for recycling (the flow of *waste IV*) consists of non-plastic material and some residues, while the rest is processed into recyclate used in the plastic industry for the production processes. The output flows from the process of *recycling* are calculated in accordance with the information given in Table 3-3. In the MFAs of the total plastic flows the *impurity*, *residue fraction* and *melt filter residue* are summed up and leave the process of recycling as the flow of *impurities* directed to the *landfill* process.

Table 3-3 Average distribution of plastic waste flow on products of recycling

Output	[%] of Input
Recyclate	85,9
Impurity	5,6
Residue fraction	6,7
Melt filter residue	1,8

Source: based on [149]

Energy recovery

- The distribution of the *plastic waste V* flow on the output of the processes of co-incineration in municipal solid waste incineration plants and fluidised beds is presented in Table 3-4. *Filter ash*, *filter cake* and *bottom ash* are summed up and leave the process as the flow of *residues*. The flows of *off-gas* and *waste water* are exported from the system.

Table 3-4 Average distribution of plastic waste flow on products of waste incineration

Output		[%] of Input
Off-gas		92,1
Waste water		2,3
Landfill residue	Filter ash	1,8
	Filter cake	0,3
	Bottom ash	3,8

Source: based on [149; 157]

- Additionally, a part of the plastic and rubber waste (e.g. used tires) is applied as the secondary fuel in the cement industry. According to Fehringer & Brunner [149] around 70% of the rubber input and approximately 90% of the plastic waste input is converted into carbon dioxide and water, and leaves the process with the *off-gas* flow (summed up together with the off-gas from other energy recovery processes). The rest constitutes the ash which leaves the cement industry connected to the flow of *product* (clinker).

Landfilling

- The process of landfilling has no output in the short-term. The input flows to the *landfill* process cover the waste disposed of directly without pre-treatment (the flow of waste VI), *impurities* from the *recycling* process and the *residues* from the *energy recovery* processes.

3.2.2 Data sources for MFA of plastic flows

This part of the analysis is based on data obtained mainly from the official national statistics and also on the information from various institutions and companies dealing with plastics, available branch reports and other literature sources. The list of the main information and data sources for the MFAs of the total plastics is presented in Table 3-5.

Table 3-5 List of main data sources for MFA of plastic flows in Poland and Austria

Poland	Austria
- Central Institute for Packaging Research and Development (Centralny Ośrodek Badań i Rozwoju Opakowań – COBRO) - Main Polish Statistical Office (Główny Urząd Statystyczny – GUS) - Municipal Waste Incineration Plant in Warsaw (Zakład Utylizacji Stałych Odpadów Komunalnych - ZUSOK) - PlasticsEurope Polska - Polish Cement Association (Stowarzyszenie Producentów Cementu) - Polish Chamber of Chemical Industry (Polska Izba Przemysłu Chemicznego – PIPC) - Polish Ministry of Environment (Ministerstwo Środowiska) - Regional Marshall Offices (Urzędy Marszałkowskie) of the 16 Provinces - TRADE-STOMIL Sp. z o.o.	- Abfallbehandlung und –verwertung "Am Ziegelofen" GmbH - ARGEV Verpackungsverwertungs-GmbH - Association of Austrian Chemical Industry (Fachverband der Chemischen Industrie Österreichs – FCIO) - Austrian Environmental Agency (Umweltbundesamt) - Austrian Federal Economic Chamber (Wirtschaftskammern Österreichischs – ÖWK) - Austrian Ministry of Environment (Lebensministerium) - Austrian Research Institute for Chemistry and Technology (Österreichisches Institut für Chemie und Technik – OFI) - Borealis GmbH - Fernwärme Wien GmbH - Gabriel Chemie GmbH - Gesellschaft für umfassende Analysen GmbH (GUA) - Municipality of Vienna MA 48 (Magistrat der Stadt Wien MA 48) - National Austrian Statistical Agency (StatistikAustria) - Österreichischer Kunststoff Kreislauf AG (ÖKK) - Para-Chemie GmbH - Salzburger Abfallbeseitigung GmbH - Welser Kunststoff Recycling GmbH

Source: own study for [20]

3.3 MFA of plastic waste management

The selected results obtained in the previously described part of the study are consequently used in the quantification of the more detailed flows within the waste management systems subsequently needed for the evaluation process. The analysis is restricted to the plastic waste flows and their treatment and therefore all the other processes and flows, except for those related to the waste management, are excluded from the further analysis.

3.3.1 System definition for plastic waste management

The system of the analysis of the plastic waste flows and their treatment is presented in the following chapter: the system boundaries, the processes included in the evaluation, and the chosen goods and substances are described briefly below.

3.3.1.1 System boundaries

Consequently, as in the first part of the analysis, the territories of Poland and Austria are set as spatial boundaries. The year 2004 is chosen as the temporal boundary. Additionally, time periods of 50- , 100-, 1 000- and 10 000 years are used in the analysis of the chosen environmental aspects in the evaluation part of the study. The application of specific temporal boundaries in reference to the respective assessment issues is explained in detail in later chapters.

3.3.1.2 Description of goods, processes and flows

The model of plastic waste management system used in this part of the study for the calculation for 2004 is shown in Figure 3-2. In the evaluation the chosen longer-term aspects related to the process of landfilling also are included and explained in respective chapters. A brief presentation of single flows and processes related to this model is presented below.

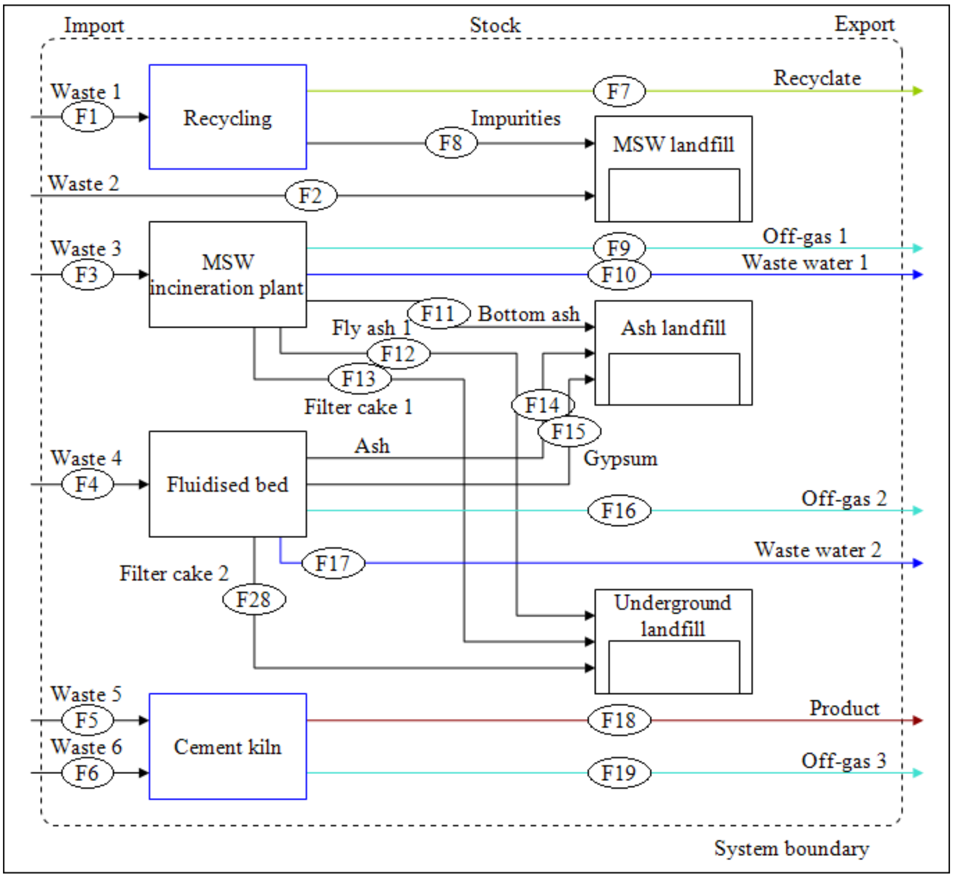


Figure 3-2 Plastic waste management system

Source: own study for [150]

The data input needed for this step of the analysis is obtained from the MFAs for the total plastic flows and from the information supplied by the respective authorities, the companies involved in the collection and treatment of the plastic waste and the available literature sources. The processes included in the system model are presented in Table 3-6.

Plastic waste is very resistant towards degradation and it stays in landfills for long periods. Leakages of e.g. additives, especially from the municipal solid waste landfills and to a lower extent from the ash landfills are expected in long-term. In reference to the underground landfills it is assumed that there is no contact of water with the disposed residues and in consequence no release of substances from the plastic waste occurs there.

Table 3-6 Processes chosen for the analysis of plastic waste management in Poland and Austria

Process	Description
Recycling	Material recycling of separately collected plastic waste
MSW incineration	Co-incineration of plastic waste with residual waste in municipal solid waste incineration plants
Cement industry	Application of plastic waste and end-of-life tires as secondary fuel in cement kilns
Fluidised bed	Co-incineration of plastic waste in fluidised beds; refers to the light-weight fraction treated this way in the Austrian system
Landfilling	Disposal of plastic waste and residues from its treatment at three kinds of landfills: - municipal solid waste landfills (disposal of non pre-treated plastic waste and residues or impurities from recycling process) - ash landfills (disposal of bottom ash from incineration) - underground landfills (disposal of filter ash and filter cake from incineration)

Source: own study for [150]

The system input and output flows are considered in the systems of plastic waste management:

- *waste 1* – the flow of waste directed for recycling,
- *waste 2* – the flow of waste landfilled directly at MSW disposal sites without pre-treatment,
- *waste 3* – the flow of waste directed for thermal treatment in MSW incineration plants,
- *waste 4* –the flow of plastic waste directed for thermal treatment in fluidised beds,
- *waste 5* – the flow of plastic waste used as alternative fuel in cement industry (excluding end-of-life tires),
- *waste 6* – the flow of end-of life tires used as alternative fuel in cement industry,
- *recyclate* – the flow of recycled material from the recycling process,
- *impurities* – the flow of non-plastic material, dirt and some other residues, from the process of recycling, calculated in accordance with the information given in Table 3-3,
- *off-gas 1* – the flow of respective residues from the process of MSW incineration in the off-gas flow,

- *waste water 1* – the flow of respective residues from the process of MSW incineration in the flow of waste water,
- *bottom ash* – the flow of bottom ash from the process of MSW incineration,
- *filter cake 1* – the flow of filter cake from the process of MSW incineration,
- *fly ash 1* – the flow of filter ash from the process of MSW incineration,
- *ash* – the flow of ash from the process of fluidised incineration,
- *gypsum* – the flow of respective residues from plastics fluidised incineration in the gypsum flow,
- *off-gas 2* – the flow of respective residues from plastics fluidised incineration in the off gas flow,
- *waste water 2* – the flow of respective residues from plastics fluidised incineration in the flow of waste water,
- *fly ash 2* – the flow of fly ash from plastics fluidised incineration,
- *product* – the flow of substances connected to clinker in the process of energy recovery from plastic waste and end-of like rubber in cement industry,
- *off-gas 3* – the flow of respective residues from the use of plastic waste and end-of-life tires as alternative fuel in cement kilns.

The processes of *recycling* and *cement kiln* have subsystems. In the process of *recycling* the calculated flows of *residue fraction* and *melt filter residue* are summed up together with *impurities* and leave the process of recycling for disposal at MSW landfill sites. In the case of the cement industry the single streams of *off-gas* and residues connected to clinker in the process of thermal treatment of the flows of *waste 5* and *waste 6* are summed up and leave the system as flows of *off-gas 3* and *product*, respectively.

In this part of the analysis the plastic waste flows and products resulting from their treatment are analysed. Due to the scarcity of required quantitative data on one hand and the very non-homogeneous character of this waste group on the other hand, the model used in the study presents a simplification of the plastic waste management system. Plastic waste differs not only with regards to its chemical composition, but also to previous application field of the plastic goods, their life spans, and the quality of waste.

All those aspects influence the generation of the plastic waste and the collection and treatment possibility contributing to the complexity of the system. The aim is however, to evaluate the overall plastic waste flows and due to the general lack of detailed data on plastic waste streams, the single fractions of various polymeric waste materials resulting from different applications fields cannot be analysed separately but are summed up and covered in total by the system model presented in Figure 3-2. Due to this fact, the results of the further evaluation should be seen as approximate and presenting a general overview of the situation in the waste management field of plastics in the analysed systems.

3.3.1.3 Choice of substances for evaluation

The substances taken into account in the analysis are selected based on their relevance for the system evaluation. Carbon is the main element contained in the polymeric materials. The importance of chlorine is related to its influence on the corrosive processes occurring in incineration facilities in the processes of the thermal treatment of waste. Heavy metals in plastics are contained in additives used in the production and manufacturing processes. Their content in the plastic goods depends e.g. on the type of polymeric material, and even to a larger extent on the kind of product [151].

The Packaging and Packaging Waste Directive [3] states that the sum of contents of lead, cadmium, mercury and chromium VI in new packaging material cannot exceed 100 mg/kg except for the kinds of packaging excluded from this obligation by respective authority regulation and packaging material produced with addition of recyclate. Sobczyńska & Korzeniowski [152] analysed the contents of abovementioned heavy metals in used packages of dairy products and they concluded that the contents were lower that the admissible ones. This study covered however only a part of packaging materials used for contact with food, where the requirements concerning the use of some substances are more restrictive.

As the plastic waste flows are analysed in total in the current study, the average values for the concentration of the selected elements in the plastic waste must be used, and therefore the amounts of the selected heavy metals in the stream of the plastic waste can be estimated only approximately. In case of conducting evaluation of separate fractions of the plastic waste (e.g. from containing higher amounts of hazardous additives waste electronic and electrical equipment) specific data must be used. However, this study is aimed at giving a general picture of the problems related to the plastic waste management and not to evaluate very accurately every selected fraction of this waste.

Three heavy metals with hazardous potential: cadmium, lead and zinc, are evaluated in this study. 26% of cadmium and 5% of lead contained in MSW comes from plastic waste. Additionally, approximately 5% of cadmium and 10% of zinc originate from used tires [153]. Therefore, the quantification and evaluation of the fate of those selected substances in the systems seems to be very important from the viewpoint of the main goals of plastics waste management.

A list and a brief description of the substances included in the evaluation are shown in Table 3-7.

Table 3-7 Substances chosen for the analysis of plastic waste management in Poland and Austria

Substance	Description
C	matrix element, indicator for efficiency of energy use, global warming potential of CO_2 emissions
Cl	volatile metal chlorides, HCl emissions, organochloride-compounds (incineration)
Cd	volatile substance with hazardous potential, toxic in low concentrations, relatively mobile in soil, depending on pH and other compounds – release of 10-50% of cadmium contained in soil [154]
Pb	hazardous, toxic potential, immobile in soil – only 1-5% of Pb can be mobilised [154]
Zn	hazardous potential, toxic in higher concentrations, relatively mobile in soil, depending on pH value and the texture of soil – 10-20% of Zn content is dissolvable [155]

Source: based on [156]

3.3.2 Data used in MFA of plastic waste management

The data input for the material flow analysis of the plastic waste management systems is obtained from the MFAs of the total plastic flows in Poland and Austria in the year 2004. Other data used in the calculations is presented in the following chapter. First of all, data related to plastic waste streams (so called good-based data) is shown and afterwards, data referring to the single waste treatment processes (process-based data) is presented.

3.3.2.1 Good-based data

It must be remembered that plastic waste is a group of very non-homogeneous materials and obtaining representative data concerning concentrations of selected substances or even the composition of this fraction is difficult. The data available in literature sources varies and often refers to some fractions of the plastic waste or to the waste from goods of different applications. In this study the plastic and rubber waste are divided into three fractions: 1) plastic packaging waste, 2) plastic non-packaging waste, 3) rubber waste. A review of the available information on concentrations of the selected elements in those three abovementioned groups is presented in Appendix 1.

Relying on the abovementioned literature review and a statistical analysis of the data found, the concentrations of the chosen elements in the plastic and rubber waste for the MFA are calculated using the standard deviation and 95 % probability (see Table 3-8).

Table 3-8 Concentrations of selected substances in plastic waste and used tires [mg/kg]

	Plastic packaging waste	±	Plastic non-pack. waste	±	Used tires	±
C	753 000	29 081,6	730 000	15 306,1	500 000	100 000
Cl	6 800	2 244,9	23 125	9 119,9	5 000	1 530,6
Cd	11,2	6,1	25,7	12,4	6,5	0,8
Pb	179,5	36	464	222,4	225,8	79,5
Zn	604	83,7	770	117,3	9 500	3 316,3

Source: own study for [150]

3.3.2.2 Process-based data

In this section the information and data used for the MFAs of the waste management systems is presented. Transfer coefficient (TC) describes the partitioning of a given substance in a process. It is calculated in accordance with Equation 1 for every output good of the process [137]. The choice of the TCs for this analysis is based on the studies conducted at the Institute for Water Quality, Resources and Waste Management of Vienna University of Technology [149, 157, 158, 159]. Transfer coefficients referring to all the analysed processed are shown in Table 3-9 to Table 3-12.

$$TC_i = \frac{X_{Output,i}}{\sum_{i=1}^{k_I} X_{Input,i}} \quad (1)$$

Where:

$X_{Output,i}$ - output flow of substance i

$X_{Input,i}$ - input flow of substance i

k_I - number of input flows

Table 3-9 Transfer coefficients for recycling process

	Goods	C	Cl	Cd	Pb	Zn
Recyclate	0,85	0,90	0,49	0,73	0,64	0,77
Impurities	0,06	0,04	0,29	0,14	0,24	0,14
Melt filter residues	0,02	0,02	0,01	0,02	0,01	0,02
Thick sludge	0,01	0	0,02	0,01	0,01	0,01
Residue fraction	0,06	0,04	0,19	0,10	0,10	0,06

Source: based on [149, 157, 159]

Table 3-10 Transfer coefficients for MSW incineration process

	Goods	C	Cl	Cd	Pb	Zn
Off gas 1	0,91	0,99	0,01	0,001	0,001	0,001
Waste water 1	0,02	0	0,53	0,001	0,001	0,001
Fly ash 1	0,01	0	0,36	0,92	0,25	0,57
Filter cake	0,01	0	0,001	0,001	0,001	0,001
Bottom ash	0,05	0,01	0,10	0,08	0,75	0,43

Source: [157,158]

Table 3-11 Transfer coefficients for fluidised bed process

	Goods	C	Cl	Cd	Pb	Zn
Ash	0,1	0,004	0,45	0,99	0,99	0,99
Gypsum	0,034	0	0	0,005	0,0039	0,005
Fly ash 2	0,002	0,002	0,005	0,005	0,005	0,0037
Waste water 2	0,001	0,001	0,5427	0,0045	0,001	0,001
Off-gas 2	0,863	0,993	0,0023	0,0005	0,0001	0,0003

Source: based on [156]

Table 3-12 Transfer coefficients for cement industry process

	Plastic waste	Used tires	C	Cl	Cd	Pb	Zn
Product	0,1	0,3	0,01	0,9981	0,9998	0,9996	0,9999
Off-gas 3	0,9	0,7	0,99	0,0019	0,0002	0,0004	0,0001

Source: based on [156]

4 Evaluation of plastic waste management

After conducting the MFAs for the total plastic waste the flows of the selected substances in the analysed systems are quantified. Subsequently, the procedure for the evaluation of the environmental and resource conservation aspects of plastic waste management is proposed. It refers to the already mentioned main goals of waste management:

1) Protection of men and the environment,
2) Conservation of resources,
3) Aftercare-free landfills.

The goal-oriented method for the evaluation of waste management should be able to assess whether the analysed systems fulfil the abovementioned goals. Therefore, first of all, the environmental criteria which should be included in the analysis are chosen and on this basis the set of evaluation indicators and methods is proposed. Finally, the results obtained from the MFAs of plastic waste are evaluated with the use of the proposed procedure.

4.1 Criteria chosen for evaluation

Based on the review of existing studies concerning the assessment of plastic waste management technologies and treatments, e.g. [149, 156, 159], the evaluation criteria which should be included in the analysis are selected. The following aspects are taken into account in the evaluation: emissions of the selected substances from treatment processes to the environment; products of treatment processes; sinks for the substances in the environment, use of resources: raw materials, energy and space; and finally long-term impacts from landfills.

The appropriate waste management system should address the following issues:

- emissions from plastic waste treatment processes should not burden human health and the environment,
- the products resulting from the plastic waste treatment, should not cause any burden in short-, medium- and long-term,

- the substances contained in plastic waste should be directed to the appropriate target processes and sinks,
- the resources should be used rationally: plastic waste management should contribute to the conservation of:
  - material resources due to material recovery,
  - energy carriers due to energy recovery,
  - space due to the reduction of the volumes of waste fractions, which require landfilling,
- the residues disposed of at the landfills should not result in long-term hazardous impacts (this point is related to the gaseous emissions and leaking of the selected hazardous substances from the landfills).

4.2 Procedure

In the following chapter the indicators and the methods chosen for the evaluation are presented.

4.2.1 Protection of human being and the environment

The first evaluation step is related to the first of the abovementioned goals: the protection of the human being and the environment. The following evaluation metrics are applied in the analysis of this step:

- critical air volume,
- appropriateness of reaching the target processes by the selected substances,
- change of the hazardous substances content in products from plastic waste treatment.

4.2.1.1 Critical air volume

Critical air volume expresses the theoretical volume of air (V_{crit}) which is necessary to dilute a certain emission load of an analysed pollutant to the immission threshold value [160]. This indicator is used mainly to compare different systems or scenarios among each other and to choose the optimal one from the viewpoint of air pollution. Its calculation is conducted using the following equations:

$$V_{ik,crit.} = \frac{\text{Emission [mg] of substances i in scenario k}}{\text{Immissionsthreshold value [mg/Nm}^3\text{] of substance i}} \tag{2}$$

$$V_{k,\,crit.} = \Sigma_i \, V_{ik,crit.} \tag{3}$$

Two approaches are used in the study: 1) the critical air volume is calculated using the immission threshold values contained in respective legal standards; 2) the geogenic reference values are applied to the V_{crit} estimation. The reference values used in this study are presented briefly in Table 4-1 and with detailed literature references in Appendix 2.

Table 4-1 Reference values used for calculation of critical air volume

	Immission threshold values	Geogenic reference values
	[µg/m³]	
HCl	100	0,1
Cd	0,04	0,0002
Pb	0,5	0,02
Zn	100	0,05

Source: based on [158, 159]

4.2.1.2 Appropriateness of target processes

The fate of some chosen substances in the environment and the question of appropriateness of the target processes they reach is an important issue in the evaluation of plastic waste management systems in this study. A target process is defined as a place that a given substance reaches e.g. as a result of a treatment process. A sink is a target destination in which this substance stays in long-term (for hundreds to thousands of years), e.g. the sink for chlorine is hydrosphere. The sink is considered as appropriate if the concentration of the substance in the sink is in order with the geogenic reference value and no negative impact on the environment occurs [158, 159].

In order to evaluate the abovementioned aspect the answers for the following question must be found:

- What temporal boundaries will be considered in this evaluation step?
- Which target processes are appropriate for the analysed substances?
- What amounts of the selected substances reach the investigated target processes?

Based on the works of [149, 158] and own assumptions the following classes of appropriateness of the target process are defined:

I - appropriate target process

II - conditionally appropriate target process

III - inappropriate target process

Two time periods are chosen for the evaluation: a medium-long period (50 years) and a long period (1 000 years). The assignment of the target processes for each of the analysed substances in the medium- and long-term is presented in Table 4-2 and Table 4-3.

Table 4-2 Classes of appropriateness of target processes for selected substances for a 50-year period

	Atmo-sphere	Hydro-sphere	Use phase	MSW landfill	Ash landfill	Undergr. landfill
C	I	III	I	III	III	III
Cl	III	I	III	III	II	II
Cd	III	III	III	II	II	I
Pb	III	III	III	II	II	I
Zn	III	III	III	II	II	I

Source: based on [149, 158]

Table 4-3 Classes of appropriateness of target processes for selected substances for a 1000-year period

	Atmo-sphere	Hydro-sphere	Use phase	MSW landfill	Ash landfill	Undergr. landfill
C	I	III	II	III	III	III
Cl	III	I	III	III	III	II
Cd	III	III	III	III	II	I
Pb	III	III	III	III	II	I
Zn	III	III	III	III	II	I

Source: based on [149, 158]

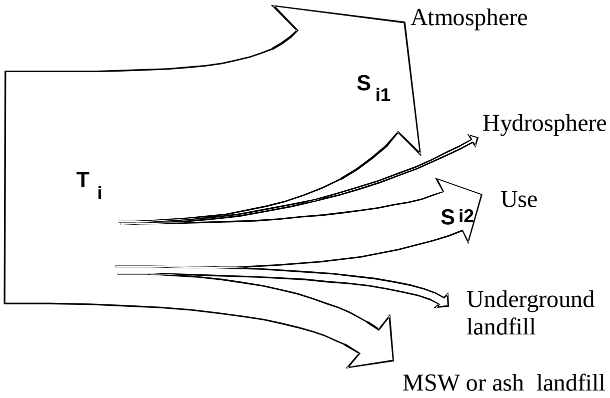
The appropriateness of landfills as sinks depends on many factors. Among others: the quality of the disposed material (i.e. if and how pre-treated it is) or the quality of the landfill sites (e.g. existence and kind of physical barriers); the geographical location and the related climatic conditions. The temporal boundaries are also of great importance for the evaluation, as some sinks may be appropriate for the period of fifty years, but are not appropriate in long term.

The following issues concerning the investigated target processes are used in this step [149, 158, 159]:

- in the medium-term, the analysed heavy metals are supposed to remain in municipal and ash landfills however, for longer periods they are expected to leak to varying extents from the landfill bodies,
- chlorides are expected to be washed out from municipal landfills, and in the long-term from ash landfills in which solidified slag from incineration is stored,
- for the underground landfills no contact with water is assumed, thus no releases of heavy metals form landfilled residues occur neither in the medium- nor in the long-term,
- hydrosphere is an appropriate target process for chlorine,
- atmosphere in this study is defined as an appropriate sink for carbon in the form of carbon dioxide (CO_2) due to the fact that the energy recovered from plastic waste (the main process of carbon dioxide generation) is assumed to substitute the respective amount of the energy generated from conventional energy carriers (fossil fuels); thus the CO_2 emissions related to the generation of the energy from primary sources are saved in this way. The issue of climate change is not revealed in the study.

In order to evaluate the appropriateness of the target processes for each of the selected substances the flows of those substances in the systems are quantified with the application of the MFA method and the use of literature values on concentrations of the analysed substances in plastic waste and the respective TCs for the treatment processes, presented in chapter 3.3.2.2.

The calculation of the efficiency grades for reaching the appropriate target processes is conducted in accordance with Equation 4 presented below:



$$\eta_i = \frac{\sum_n S_{in}}{G_i} \qquad (4)$$

n – number of the appropriate target processes for the substance i

S_{in} – substance i flow to the appropriate target process n [Mg/yr]

T_i – total flow of substance i

Figure 4-1 Example of qualitative balance for a selected substance with two appropriate target processes

Source: [158]

4.2.1.3 Products from treatment processes

The next aspect considered in the evaluation refers to the issue of the quality of products from treatment processes. The treatment of plastic waste should result in environmentally compatible products not burdening human health in short-, medium- and long-term. Therefore, the goods whose production is related to the waste management practices should be taken into account in the evaluation as they stay in the life cycle and may have further impacts.

It is difficult to investigate the aspect of the environmental impacts related to the products from the treatment processes due to a few reasons. Amongst them there are: uncertain application fields and conditions of use but also unknown final disposal of the potential goods (when their life span is over). The products may be used for short or long periods, reused or recycled several times, but also landfilled directly without any pre-treatment. All those issues would have influence on the environmental performance. Additionally, in the case of long-living goods the waste treatment technologies can change significantly in the future, contributing even more to the uncertainty of the evaluation.

Fehringer et al. [156] emphasize that the environmental compatibility of the final disposal of products resulting from the recycling of cement industry in the long-term will be dependent on the level of accumulation of the hazardous substances at the disposal point.

Taking the abovementioned issues and limitations into account it has been decided that the focus should only be maintained on the fate of the hazardous substances, contained in the plastic waste in the processes of recycling and the cement industry and the "transfer" of those substances to the products resulting from the abovementioned processes: the recyclate and the clinker.

4.2.1.3.1 Product from recycling

The evaluation of the products resulting from the recycling process is very complex due to the fact that the recycled material can be used as:

- substitute of the raw material for manufacturing of products of the same kind as the original goods from which recyclate is produced,
- substitute of the raw material for producing other plastic-application products, often of lower quality ("down-cycling"),
- substitute for non-plastic application products, e.g. wood or natural construction materials.

Due to the fact that the current study focuses on plastic waste and the associated impacts but not on the whole life cycle of plastic products, investigating the environmental impacts related to the abovementioned three groups of recyclate applications exceeds the scope of this thesis. It should be however remembered that the field of application of the recyclate influences future waste treatment possibilities however, due to the abovementioned issues and the general approach applied in this study this problem is not revealed further.

This analysis is restricted only to the investigation of the fate of heavy metals from plastic waste in the output from the process of recycling and the "transfer" of those substances to the products-recyclate. Additionally, the essential issue related to the recycling of waste electronic & electric equipment (WEEE) related to the brominated flame retardants is presented later in chapter 5.2.3.2.3.

4.2.1.3.2 Product from cement industry

The application of plastic waste and used tires as secondary fuel in the cement industry can result in the increase of the concentration of the analysed heavy metals in clinker and subsequently in cement. Above 99% of the flows of considered substances: cadmium, zinc and lead, are transferred and incorporated into the clinker.

Fehringer et al. [156] raise the question of appropriateness of cement as a sink for the heavy metals from the waste used as alternative fuel. To what extent does cement constitute an appropriate target process for the abovementioned elements? Due to the uncertainty of the fate of cement products, among others: the number of recycling-use cycles, the conditions of use, i.e. exposition, weathering, etc., the authors come to the conclusion that it is not possible to provide scientific evidence showing which additional loads of heavy metals from the waste in clinker and consequently in cement products are environmentally compatible in the long-term. However, they claim that the change of the concentration below 10% should not have any negative influence on the environment.

In this study the method of Fehringer et al. [156] is used to evaluate the influence of the use of the plastic and rubber waste on the change of the concentration of selected heavy metals in the products from the cement industry. The concentrations of cadmium, lead and zinc are calculated for the clinker produced: 1) exclusively with the use of conventional fuels (the so called reference clinker, 2) with partial substitution of the conventional fuels by the plastic waste and used tires. At the end, the changes of concentration caused by the application of plastic waste are calculated for each of the analysed metals. The inventory data used in the calculations in this step of the study are presented in Appendix 3.

4.2.2 Resource conservation

Due to the fact that the non-renewable resources (fossil fuels) are used as both feedstock and energy source for the production of plastic goods, plastic waste is seen as important material from the material resources conservation viewpoint. The high energy content of this waste contributes additionally to its image as an interesting alternative energy source. Furthermore, as plastic waste decomposes very slowly (its degradability can be almost neglected in the short- and medium-term) it occupies plenty of space in landfills which is not consistent with the goal of resources (soil) conservation either.

In this section the procedure for evaluation of the resource conservation related to plastic waste management is proposed. The following methods and indicators are used to achieve this goal:

- potential to save raw materials,
- potential to save energy carriers,
- substance concentrating efficiency (SEA),
- reduction of volume needed for landfilling.

4.2.2.1 Conservation of raw materials

In order to estimate the potential of recycling to conserve raw materials the amount of primary plastics which may theoretically be substituted by the secondary material from recycling in the production process is estimated and the energy demand for the production of primary plastics and the recyclate is compared, based on the data given by Patel [161] (presented in Appendix 4).

The composition of plastic waste recycled in Austria in 2004 within the ARA System, shown in Table 4-4, is used to calculate the energy demand for the process of recycling and for the primary plastics production.

Table 4-4 Composition of sorted plastic waste recycled within ARA System in Austria in 2004

	[%]
LDPE	52,6
HDPE	10,2
PET	31,1
PS/PP	4,1
EPS	2,0

Source: own calculation based on information from [130]

In reference to the Polish system there is a scarcity of information concerning the abovementioned composition. According to Czerkawski [162] 68% of plastics used in Poland for packaging constitute polyolefins, 21% - PET packaging. The structure of the plastic packaging waste generated in Poland in 2005 is given in Table 4-5.

Table 4-5 Structure of plastic packaging waste in Poland in 2005

	[%]
PE	42,0
PP	20,0
PET	21,0
PS	15,0
PVC	2,0

Source: [119]

Due to the lack of more detailed data concerning the recycled plastics in Poland and assuming that there are not many significant differences between both systems in this respect, the composition of the recycled plastics, as given by Paul [130], is used in the calculation of the average energy needed for the primary plastics production in Poland and Austria. This value is estimated to amount to approximately 74 MJ/kg.

Different values of energy consumption for the recycling processes are found in literature sources. Brunner et al. [159] give the energy use for the production of the recyclate amounting to 800 KWh and 18 l of fuel oil per Mg of plastic waste input. GUA [163] gives the value of 1650 KWh per Mg of input. Arena et al. [164] mentions the additional average energy demand of 0,32 MJ per kg of waste input for collection and transport processes, however, this value does not influence the results significantly. In the current study the value, calculated relying on the data from Patel [161], of 38,7 MJ/kg of waste input is used for the calculations.

The effectiveness of the substitution of the virgin material by the material from recycling is assumed to be 100%[2]. Firstly, the energy consumed by the production of the recyclate and by the production of the same quantity of the primary material is quantified and subsequently the value of energy saved through recycling is calculated. Finally, the obtained value is calculated back to the kg of crude oil equivalents in order to compare the analysed systems with each other and with the energy recovery potentials.

The calculation refers to the theoretical values due to the fact that the recycled product from one system is not necessarily used in the same system. Based on the information from recyclers in Austria [165] above 90% of the recyclate produced by some Austrian companies is exported from the country. Thus, the calculated theoretical value

[2] Some authors suggest however using the value of 90%.

for the raw materials and consequently crude oil saving due to the recycling processes does not express the real amount of these resources saved in the analysed systems but the estimated potential of the analysed plastic waste management system to conserve the raw materials.

4.2.2.2 Conservation of energy

The thermal treatment of plastic waste with energy recovery contributes to conservation of energy and consequently to saving of e.g. fossil fuels. There are two kinds of processes of the energy recovery:

- treatment of plastic waste in MSW incineration plants or fluidised beds with generation of heat and/or electricity, and subsequent substitution of the heat and/or the electricity from conventional energy carriers needed i.e. for industrial processes, heating, etc.,
- partial substitution of the primary fuels (like hard or brown coal or natural gas) by plastic waste used as secondary fuel e.g. in cement industry.

In order to evaluate the potential of energy conservation of both analysed systems the following values are estimated:

- the total amount of energy generated in the processes of plastic waste incineration in MSW incineration plants and fluidised beds,
- the amount of energy from the primary fuels which can be saved due to the use of the plastic waste used as alternative fuel in the cement kilns.

The following efficiency grades are used in the calculation: for MSW incineration net efficiency of 70% [158], for industrial incineration in fluidised beds 80% (20% of which is electric and 60% process heat) [158, 166,167], while the efficiency grade of 66% is used for the calculation of energy recovery due to the use of plastics in the cement industry [158].

It should be noticed that the energy sources for heat and electricity generation differ significantly between Poland and Austria (the structure of the heat/electricity production in both countries is presented in Table 4-6); therefore the crude oil equivalents are used in the study in order to compare the results for both countries.

Table 4-6 Structure of electricity and heat production in Poland and Austria in 2004

	Poland		Austria	
	Electricity	Heat	Electricity	Heat
Production from:	[%]			
- coal	93,1	90,8	14,2	6,5
- oil	1,6	1,8	2,8	13,6
- gas	2	6,2	17,1	47,3
- biomass	0,6	0,8	2,8	24,8
- waste	0,2	0,4	0,9	6,9
- hydro	2,4	0	60,8	0
- other sources	0,1	0	1,4	0,9

Source: [168]

The total amount of energy recovered from the thermal treatment of plastic waste is calculated separately for each of the following processes: MSW incineration plants, fluidised bed and the cement industry, based on the approach of Fehringer et al. [158]. At the end, the results obtained for each of the processes are summed up and calculated back to the crude oil equivalents, like in the raw materials conservation. The input data used for the calculations of the particular processes are presented in Appendix 4.

4.2.2.3 Substance concentrating efficiency

The method of substance concentrating efficiency (SCE), developed by Rechberger [169], evaluates "the ability of a system to concentrate or dilute substances". SCE values for the particular processes and of the whole systems are calculated according to the equations presented below:

$$H(c_{ij}, m_i) = ld(Xj) \quad \frac{1}{Xj}\sum_{i=1}^{k} m_i * c_{ij} * ld(c_{ij}) \tag{5}$$

$$Xj = \sum_{i=1}^{k} m_i * c_{ij} \tag{6}$$

$$H_{max,j} = ld(\sum_{i=1}^{k} m_{Ii}) \tag{7}$$

$$RSE_j = \frac{H(c_{ij}, m_i)}{H_{max,j}} \tag{8}$$

$$SCE_j = \frac{RSE_{I,j} - RSE_{O,j}}{RSE_{I,j}} * 100 \tag{9}$$

Where:

H – statistical entropy

c_{ij} – concentration of substance j in good i [%]

m_i – mass flow of good i

k – number of goods

RSE – Relative Statistical Entropy

I - input

O - output

In compliance with the main goals of waste management, treatment processes should lead to the concentration of substances like cadmium, lead or zinc and should direct them towards a safe disposal destination or for recycling. The appropriate waste management should prevent diffusion of those heavy metals in the environment or in products resulting from treatment processes. This is an important issue from the resources conservation and environment protection viewpoint. Therefore, the desired values of SCE for the waste management of hazardous substances contained in plastic waste are high [156, 169].

In the study, the results of the MFAs for the selected substances are used to calculate the SCE values using the above described method of Rechberger [169].

4.2.2.4 Reduction of volume needed for landfilling

The use of space for landfilling is the last aspect related to the goal of the resource conservation evaluated in this study. The appropriate waste management system should contribute to the conservation of space by reducing the volume of plastic waste, which must be disposed of in landfills.

The situation in which the total plastic waste is disposed of without any pre-treatment is set as a reference scenario, the so-called worst case scenario. The data from mass balances of plastic waste treatment and the densities of particular residual fractions (presented in Appendix 4) are used for the calculation. The value of the so-called "landfill volume reduction" is calculated in accordance with Equation 10:

$$R_v = (1 - (V_{at} / V_r))*100 \qquad (10)$$

Where:

R_v – "landfilled volume reduction" [%]

V_{af} – volume of plastic waste and residues after treatment [m^3]

V_r – volume of untreated plastic waste (reference scenario) [m^3]

It should be mentioned that goods produced with the use of the recyclate will become waste in the future too; however, this issue is excluded from further evaluation as the temporal boundary for this evaluation step is set for one year.

4.3 Long-term impacts from landfills

Due to the fact that plastic waste is commonly used for a few decades only, predicting the behaviour of the plastic waste disposed with other municipal waste in the landfills is in the long-term very difficult. Nielsen & Hauschild [34] emphasize that it is not possible to "measure product specific emissions from landfills as emissions from various waste are mixed and occur in different time periods, decades or even centuries after waste is landfilled". Additional difficulty is caused by the fact that different external conditions may influence the degradation rate of plastic waste; e.g. photo-oxidation or radiation may increase the degradation. This is related not only to the emission of carbon dioxide and methane, but also to the release of volatile organic compounds. Moreover, if additives from plastic material are lost through degradation or migration, polymers can degrade more easily [170].

Thus, little data concerning emissions and potential leaking of hazardous substances form landfilled waste is available. The scarcity of the respective data results in the fact that in most studies concerning plastic waste management long-term impacts from landfills are neglected. In some studies the temporal boundary of 100 years is chosen, like in the studies of Arena et al. [164] and Bez et al. [171]. According to those authors the landfill gas and leachate can be neglected in the assessment of the landfilling process as only 1-3 % of hydrocarbon from plastic waste may be degraded in this time frame. Finnveden et al. [170] suggest a degradation rate of 1-5 % for plastic waste, while Sundqvist et al. [172] give the following degradation rates (see Table 4-7):

Table 4-7 Degradation rates of plastic waste in MSW landfills

	Degradation rate after 30 years	Degradation rate after 150 years
	[%]	
PE, PVC	-	1-5
PS	-	1-10
PET	-	1-3
Plastics	0	0-5

Source: [172]

Brunner et al. [159] stress that the hazardous potential of the residues and waste disposed of in landfills is determined by aspects like quality of residues, the type of landfill, climatic conditions or geographic location, etc.

In the current study the following approach [149] related to the behaviour of the selected elements from plastic waste in landfill sites is used:

- although it is generally believed that the municipal solid waste landfills are not appropriate for plastic waste in long-term (e.g. risk of leaking of hazardous additives from landfill body), due to the lack of respective data concerning leaking of the abovementioned substances from the landfilled plastic waste this aspect is not revealed quantitatively in the study.

- the behaviour of the analysed substances in the ash landfills is calculated within the use of the method of Brunner et al. [159] and the respective TCs, presented in Table 4-8 and Table 4-9.

Table 4-8 Transfer coefficients for behaviour of selected substances in ash landfills in a 100-year period

	C	Cl	Cd	Pb	Zn
Landfill body	1	0,64	1	1	1
Leakage water	0	0,36	0	0	0
Gaseous emission	0	0	0	0	0

Source: [159]

Table 4-9 Transfer coefficients for behaviour of selected substances in ash landfills in a 10 000-year period

	C	Cl	Cd	Pb	Zn
Landfill body	0,98	0	0,66	0,99	0,97
Leakage water	0,02	1	0,34	0,01	0
Gaseous emission	0	0	0	0	0

Source: [159]

- it is assumed that in the underground landfills no contact of the disposed residues with water occurs in the long-term, thus, there is no potential for the release of hazardous substances.

5 Results

In this chapter the results obtained with the use of the aforementioned evaluation procedure are presented. They are shown separately for the material flow analysis part and subsequently for the evaluation, in each case, first for the Polish system, then for the Austrian one and finally compared for both analysed case studies. In most cases the result values are presented rounded.

5.1 Material flow analysis of plastics

The results of the material flow analysis of plastics are presented in the following section. The analysis was carried out within the frame of the project conducted by the author at the Institute for Water Quality, Resources and Waste Management of Vienna University of Technology [20]. The results of this study constitute a basis for further evaluation and were conducted in order to obtain information concerning waste flows in the analysed systems. A brief description of the state-of-art of the processes analysed, not presented before in the chapter concerning the waste management system in both countries, is included in this section.

5.1.1 Material flow analysis of plastics in Poland

The results obtained in the MFA of total plastic flows in Poland for the year 2004, shown in Figure 5-1, are presented below.

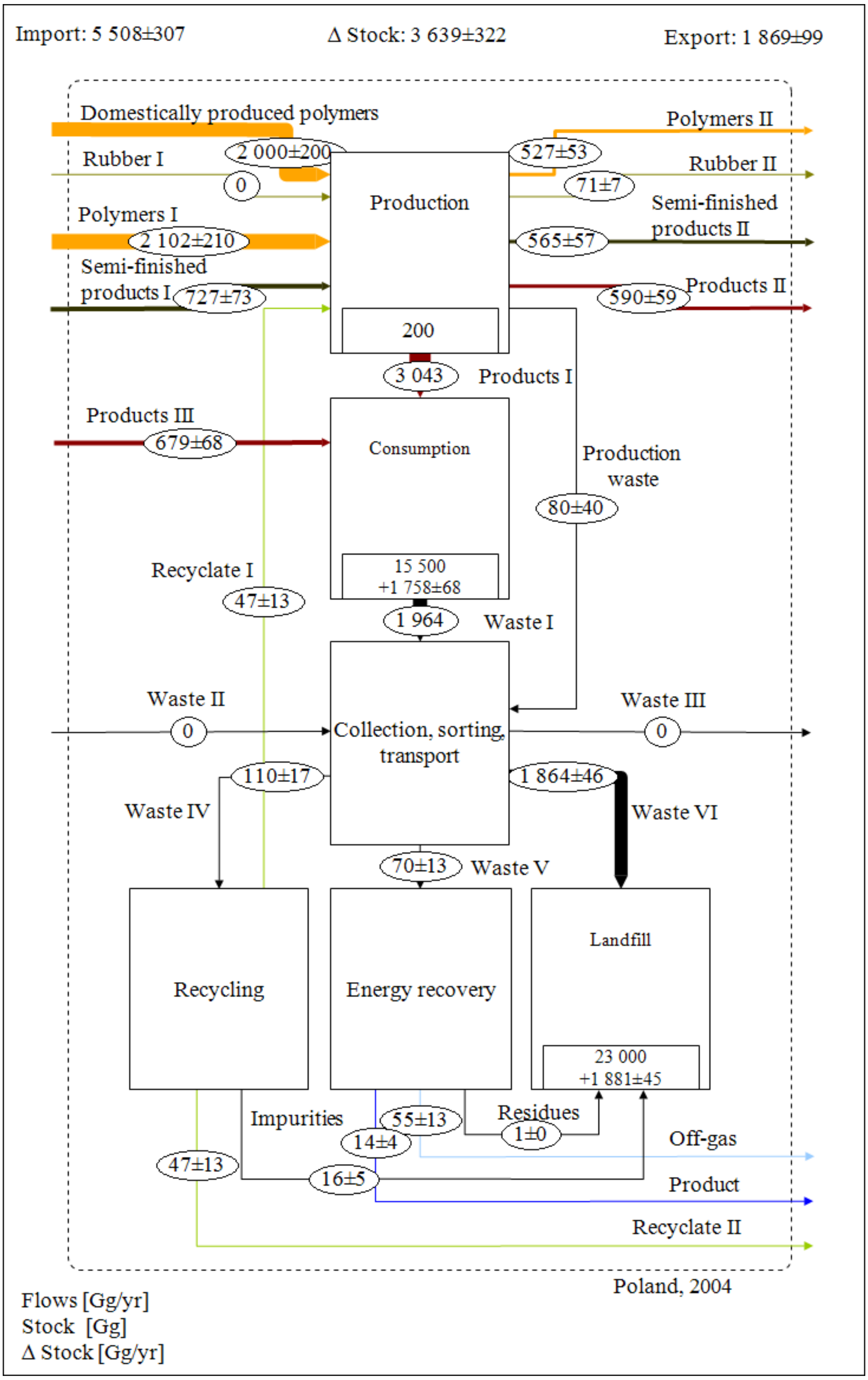


Figure 5-1 Total plastic flows and stocks in Poland in 2004

Source: own calculations for [20]

- Production

The branch of polymer industry has been developing dynamically in Poland in recent years. In 2004 the investment increase in this branch has been observed. It has already resulted in a significant growth of polymer production in Poland, especially of polypropylene (PP) and high density polyethylene, and this process is supposed to continue in the future. Thus, Poland is expected to change from the role of an importer to an exporter of those polymers [174].

In the recent years the company Basell Orlen Polyolefins Sp. z o. o. built two new installations for polyethylene and polypropylene production with the capacity of 870 000 Mg (400 000 Mg of polypropylene, 320 000 Mg of high density polyethylene and 150 000 Mg low density polyethylene) [173]. Moreover, a new factory for the production of polyethylene terephthalate (with a capacity of 120 000 Mg per year has been opened by SK Chemicals and Anwil; and the company Firma Chemiczna Dwory S. A built a new installation for polystyrene with an annual capacity of 100 000 Mg [174]. It should be however mentioned that an opposite trend has also been observed for some polymers - the production of PVC in Zakłady Azotowe Tarnów-Mościce has been closed in 2006.

Based on the data from the Main Polish Statistical Office more than 2 Mio. Mg of polymers were produced in Poland in the year 2004 (see Table 5-1). The authors of the report "Polish polymer industry in the year 2004" [174] emphasize that the domestic production of polymers amounted to 8% more than in the year 2003. Between 1990 and the year 2000 the production increased by 75%.

Table 5-1 Production of plastics in primary form in Poland in 2004

	Quantity [Mg/yr]
PVC	430 000
PE	160 000
PP	140 000
PS	100 000
PA	60 000
Other	1 140 000
Total	2 030 000

Source: [175]

The sector of plastics processing in Poland consists of a large number of small companies. There are around 13 400 firms active in this field employing around 100 000 people. 93% of the firms are of small or medium size. The structure of plastic goods production is as follows [174]:

- 22% for packaging industry,
- 24% for building & construction industry,
- 5% pipes, profiles and boards production,
- 49% other applications.

The development of this sector is even more dynamic than the polymers production. The production of rubber and plastic goods increased by 13,7% in comparison to the year 2003 and since the beginning of the nineties the processing of polymeric materials increased three times [174].

INPUT: The input flows to the *production* process were as follows: above 2 Mio. Mg [175] of plastics in their primary forms were produced in Poland in 2004 (the flow of *domestically produced polymers*) and about the same amount (the flow of *polymers I*) was imported [176]. Due to the shortage of data the share of semi-finished products and plastic goods in the flows of imported and exported products had to be estimated. Based on the statistics from the Main Polish Statistical Office [176] and own assumptions the flow of *semi-finished products I* imported to Poland amounted to 727 000 Mg. The additional input flow comes from the *recycling* process. It is presupposed that half of the recyclate produced in the system (the flow of *recyclate I* amounting to 47 000 Mg) was used by the national market and the rest was exported.

OUTPUT: According to the data from the national statistics [176] 251 000 Mg of thermoplastics, consisting mainly of polymers of vinyl chloride, other halogenated olefins and polyamides; and 276 000 Mg of duromers (mainly of amino- and phenol resins and polyurethanes) from domestic production were exported from Poland in the analysed year (the flow of *polymers II*). Additionally 71 000 Mg of rubber were exported (the *rubber II* flow) [175]. Around 80 000 Mg of *production waste* left the *production* process for further treatment. The input flows were processed at this step into products and to semi-finished products, which were either exported from the system (565 000 Mg of *semi-finished products II* and 590 000 Mg the *products II* in 2004) or entered the process of *consumption* (approx. 3 Mio. Mg – calculated as the difference between the sums of input and output flows mentioned above) assigned to the flow of *products I*.

STOCK: The stock of the process of *production* was estimated for approx. 200 000 Mg. No change of the stock occurs in this process.

The summary of the data described above is presented in Table 5-2.

Table 5-2 Balance of goods of the production process in Poland in 2004

Input	Mg/yr	Output	Mg/yr
Domestically produced polymers	2 000 030	Products I	3 043 000
Rubber I		Polymers II	527 000
Polymer I	2 101 970	Rubber II	71 000
Semi-finished products I	727 000	Semi-finished products II	565 000
Recyclate I	47 000	Products II	590 000
		Production waste	80 000
Total input	4 876 000	Total output	4 876 000
Stock [Mg]	105 000	Change of stock	0

Source: own calculations for [20]

- <u>Consumption</u>

The value of plastics consumption per capita in Poland, amounting to 95 kg is by approx. 50% lower than the values for the “old” EU member states. It should be however noticed that at the beginning of nineties this value in Poland amounted only to around 17 kg [174] and since then it has been systematically growing.

INPUT: The input to the process of consumption constitute the flow of *products I* (around 3 Mio. tons from domestic production) and additionally nearly 680.000 Mg [176] of imported articles (the flow of *products III*). The total amount of plastic and rubber goods (called further plastic goods) consumed in Poland in the years 2004 amounted to approximately 3,7 Mio. Mg.

OUTPUT: The calculation of the post-consumption waste amounts is conducted with time series and taking into account life spans of products from different applications fields. It is estimated to amount to nearly 2 Mio. Mg (the flow of *waste I*). However, it should be noticed that the abovementioned result, and consequently the calculation of the stock of plastics accumulated in the process of *consumption*, is dependent on the assumed life spans of various groups of products. The longer the life span used in the analysis the smaller the quantities of waste released at present and the higher the quantities accumulated in the stock "in use". It is discussed in greater detail when describing the uncertainties.

STOCK: Based on the abovementioned calculations the stock in the process of *consumption* amounted to approximately 23 Mio. Mg and in 2004 it increased by around 1,8 Mio. Mg of medium- and long-living goods.

The summary of the results obtained for the process of *consumption* is shown in Table 5-3.

Table 5-3 Balance of goods of the consumption process in Poland in 2004

Input	Mg/yr	Output	Mg/yr
Products I	3 043 000	Waste I	1 964 000
Products II	679 000		
Total input	3 722 000	Total output	1 964 000
Stock [Mg]	23 000 000	Change of stock	1 758 000

Source: own calculations for [20]

- <u>Collection, sorting, transport</u>

The Polish system of packaging waste collection consists of around 40 companies [114] and it is still under development. The accessibility of data is low and the Polish Ministry of Environment emphasizes the shortages in reporting data for waste collection and recovery [117]. Therefore, the data used in this part of the evaluation and the results obtained must be treated as approximate and showing only the overall situation in the system. However, due to the generally low levels of the recycling and energy recovery from plastic waste in Poland the potential lower or higher values for recovered quantities should not have significant influence on the results and consequently, the conclusions of the analysis.

INPUT: The input flows entering the process of *collection, sorting, transport* amounted to almost 2 Mio. Mg of post-consumption waste (the flow of *waste I*) and 80 000 Mg of *production waste*. Due to the lack of data concerning imported and exported plastic and rubber waste the flows of *waste II* and *waste III*, presented in Figure 3-1 are left out in the Polish system.

OUTPUT: Based on the data from the Polish Ministry of Environment [117] around 110 000 Mg of plastic packaging waste was recycled in Poland in 2004 (the flow of *waste IV*). The flow of *waste V* directed for the *energy recovery* process is calculated relying on the following information: the plastic and rubber waste have been used as secondary fuel in the cement industry in Poland since the year 1997. Based on the data from the Polish Cement Association [177] 45 000 Mg of old tires and 13 000 Mg of plastic waste was treated thermally in cement kilns in 2004. Additionally, in the municipal solid waste incineration plant in Warsaw around 85 000 Mg of waste was incinerated in the year 2004 [178]. The content of plastic waste in MSW is estimated as 14% [8], therefore the quantity of plastic waste incinerated there amounted to around 12 000 Mg. Based on this available data, the total amount of plastic and rubber waste directed to energy recovery processes was nearly 70 000 Mg.

The rest of the waste is accounted to be disposed of in landfills without pre-treatment (see the flow of *plastic waste VI*). It amounted to nearly 1,9 Mio. Mg, which constituted approx. 90% of the total flow of plastic waste generated in Poland in 2004.

STOCK: No accumulation in the stock occurs in the process of *collection, sorting, transport*.

The results obtained in this step are presented in Table 5-4.

Table 5-4 Balance of goods of the collection, sorting, transport process in Poland in 2004

Input	Mg/yr	Output	Mg/yr
Waste I	1 964 000	Waste IV	110000
Waste II	n.d.	Waste V	70 000
Production waste	80 000	Waste VI	1 864 000
Total input	2 044 000	Total output	2 044 000
Stock [Mg]	0	Change of stock	0

Source: own calculations for [20]

- Recycling

INPUT: As mentioned above, 110 000 Mg of plastic packaging waste was recycled in Poland in 2004. This value is higher than in previous years. In 2002, when the obligatory reporting of waste generation, collecting and recovery has been implemented, it was around 55 000 Mg, and in 2003 82 000 Mg [117]. However, this quantity is still much lower in comparison with the leading countries of the EU. Based on the available information on recycling from the Polish Ministry of Environment [117] it is not possible to analyse separately the recycling of sorted and mixed fractions, therefore in the analysis the total amount of plastics recycled is accounted as sorted waste. However this simplification is not expected to significantly influence the results. In Poland mainly packaging waste, consisting mostly of PE, PP and PET, is recycled mechanically [179].

OUTPUT: The output flows from the *recycling* processes are presented in Table 5-5. Due to the lack of data concerning further fate of the product from recycling it is assumed that 50% thereof, 47 000 Mg, were used by the national market (the flow of *recyclate I*) and the rest was exported (the flow of *recyclate II*). Additionally around 16 000 Mg of residues and impurities left the process and were disposed in landfills.

STOCK: The process of *recycling* has no stock.

Table 5-5 Balance of goods of the recycling process in Poland in 2004

Input	Mg/yr	Output	Mg/yr
Waste IV	110 000	Recyclate I	47 000
		Recyclate II	47 000
		Impurities	16 000
Total input	110 000	Total output	110 000
Stock [Mg]	0	Change of stock	0

Source: own calculations for [20]

- Energy recovery

INPUT: As previously described, round 70 000 Mg of plastic and rubber waste were estimated to enter the process of *energy recovery*.

OUTPUT: The output flows from the thermal treatment in MSW incineration plant are presented in Table 5-6. The fractions of filter ash, filter cake and bottom ash are summed up in one output flow of *residues*, which amounted to slightly less than 1000 Mg.

Table 5-6 Distribution of plastic mass on products of waste incineration in Poland in 2004

Output		[Mg/yr]
Off-gas		11 052
Waste water		276
Landfill residue	Filter ash	216
	Filter cake	< 100
	Bottom ash	456

Source: own calculations for [20]

After the calculation concerning the thermal recovery in the cement industry and summing up the respective output flows the results obtained for this process are shown in Table 5-7.

STOCK: There is no stock in the process of *energy recovery*.

Table 5-7 Balance of goods of the energy recovery process in Poland in 2004

Input	Mg/yr	Output	Mg/yr
Waste IV	70 000	Residues	< 1 000
		Off-gas	55 000
		Waste water	< 1 000
		Product	14 000
Total input	70 000	Total output	70 000
Stock [Mg]	0	Change of stock	0

Source: own calculations for [20]

- <u>Landfill</u>

INPUT: The process of landfilling has the following inputs: 1,86 Mio. Mg of plastic and rubber waste from the process of *collection, sorting, transport*, 16 000 Mg of *impurities* from the *recycling* process and below 1.000 Mg of *residues* from the *energy recovery* process.

OUTPUT: The process of landfilling has no output within the temporal boundary of this step of the analysis.

STOCK: The stock of plastic waste accumulated in landfill sites, calculated with the use of time series for the period between 1960 and 2004, amounts to approx. 30 Mio. Mg. and it increases permanently each year. The development of this and the stock “in use” is presented in Figure 5-2. The left axis refers to the values of flows and the right axis to the stocks. It is worth noticing that the development of the stock “in use” has been positive since 1960, however a stagnation of the increase was observed in the period between 1989 and 1995. Afterwards, a much faster increase of the stock is observed which is connected with the fast growing consumption of plastic goods in the respective time.

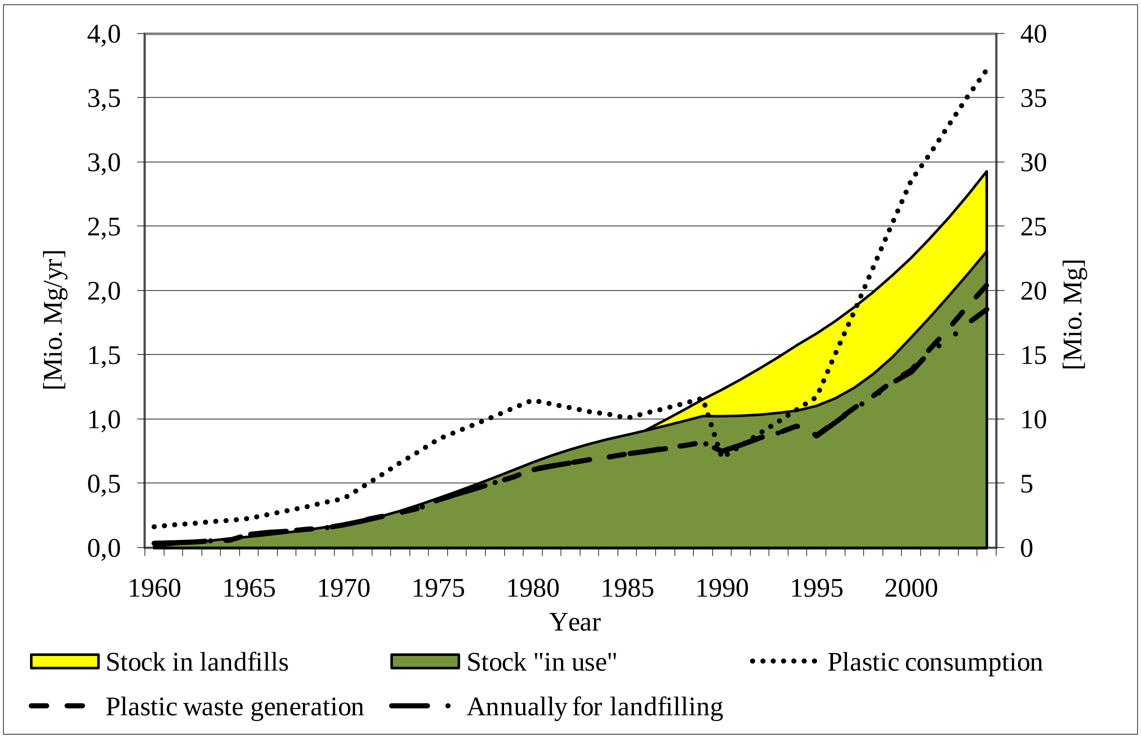


Figure 5-2 Flows and stocks of plastics and their waste products in Poland in 1960-2004

Source: based on own calculations for [20]

The summary of the results obtained for the *landfill* process is presented in Table 5-8.

Table 5-8 Balance of goods of the landfill process in Poland in 2004

Input	Mg/yr	Output	Mg/yr
Waste V	1 864 000		
Impurities	16 000		
Residues	< 1 000		
Total input	1 880 000		
Stock [Mg]	30 000 000	Change of stock	1 880 000

Source: own calculations for [20]

5.1.2 Material flow analysis of plastics in Austria

The results of MFA for plastics in Austria are presented in Figure 5-3. The explanation related to these results is presented further in this chapter.

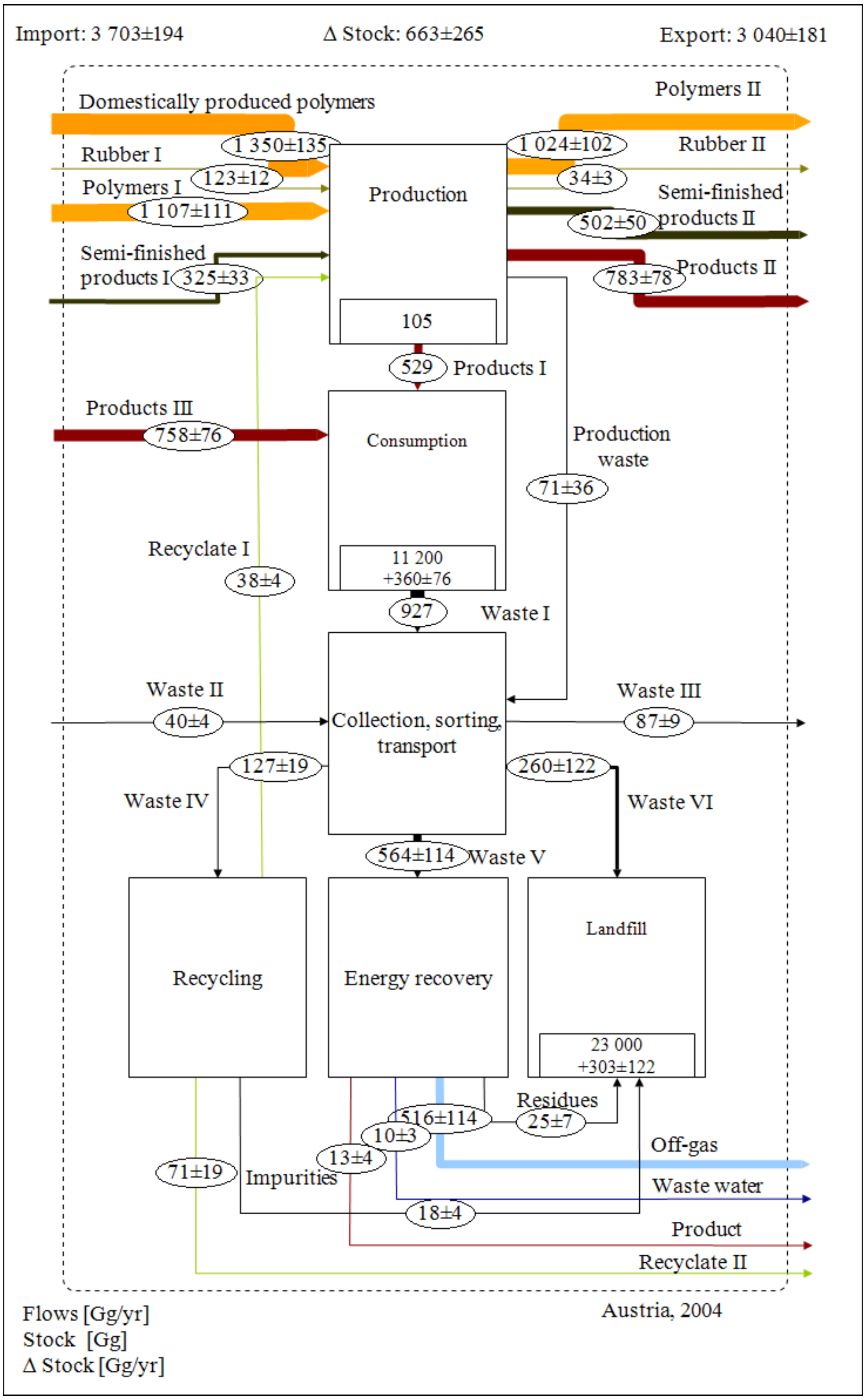


Figure 5-3 Total plastic flows and stocks in Austria in 2004

Source: own calculations for [20]

- Production

Based on the information from the Association of Austrian Chemical Industry (FCIO) [19] there are thirteen companies producing plastics in primary forms in Austria. The biggest of them, Borealis GmbH produced around 306 000 Mg of polyethylene and 426 000 Mg of polypropylene in the year 2004 [180]. The company Sunpor GmbH produces expanded polystyrene, Para-Chemie GmbH – polymethyl methacrylate, and other smaller firms - resins. Due to the fact that the number of companies producing plastics in primary form is small, and as they are usually exclusive producers of a certain polymer type in the country, the data concerning quantities produced are confidential and published neither by the firms, not by the Austrian Statistical Agency (Statistik Austria).

As opposed to the small number of companies producing plastics more than 1 000 of rather small or medium size companies process them into plastic products. Only 9% of the abovementioned companies employ more than 100 people. In total, about 22 000 people works in this sector. More than a half of them work in only two provinces: Upper and Lower Austria. Based on the information from FCIO [19] approximately 40% of the production is the so-called semi-finished products, e.g. profiles, boards, films or hoses. 17% of the total production constitutes packaging and approximately the same percentage - building and construction materials.

INPUT: FCIO [19] estimates that in total around 1,35 Mio. Mg of plastics in primary forms were produced in Austria, approximately 760 000 Mg of which constituted thermoplastics and around 590 000 Mg thermosets, 70% of which for export.

Around 1,1 Mio. Mg of polymers in primary forms and above 120 000 Mg of raw rubber (the *rubber I* flow) were imported to the system in 2004. Moreover, about 325 000 Mg *semi-finished products I* from import enter the system [181]. Additional input is the product from the process of *recycling* – it amounted to 38 000 Mg.

OUTPUT: Based on the data from the national statistics [181] almost 868 000 Mg of thermoplastics were exported from Austria in 2004 and left the system, among it 275 000 Mg of polyethylene and nearly 360 000 Mg of polypropylene [180]. The quantity of exported thermosets, estimated based on the data from Statistics Austria [181], amounted to 156 000 Mg. Thus the value of the flow *polymers II* amounted to slightly above 1 Mio. Mg. Additionally, 34 000 Mg of rubber, 99% of which synthetic rubber, were exported (the flow of *rubber II*) from the system. The export of plastic products or goods containing plastic materials amounted to 783 000 Mg. Additionally around 502 000 Mg of *semi-finished products II* were exported in 2004. The flow of *production waste,* calculated based on the information from GUA [182] amounted to approx. 71 000 Mg. The *products I* flow, calculated as the difference between the input and output flows, amounted to nearly 529 000 Mg.

STOCK: The stock of the process amounted to 105 000 Mg and no change of the stock occurred in the year 2004. The summary of the results described above is presented in Table 5-9.

Table 5-9 Balance of goods of the production process in Austria in 2004

Input	Mg/yr	Output	Mg/yr
Domestically produced polymers	1 350 000	Products II	529 000
Rubber I	123 000	Polymers II	1 024 000
Polymer I	1 107 000	Rubber II	34 000
Semi-finished products I	325 000	Semi-finished products II	502 000
Recyclate I	38 000	Products II	783 000
		Production waste	71 000
Total input	2 943 000	Total output	2 943 000
Stock [Mg]	105 000	Change of stock	0

Source: own calculations for [20]

- <u>Consumption</u>

INPUT: Based on the data from the national statistics [181] and own calculations the input of plastic goods to the process of *consumption* amounted to approx. 1,3 Mio. Mg. 529 000 Mg of the commodities came from the national production (the flow of *products I*) and almost 758 000 Mg from import (*products III*).

OUTPUT: Similarly to the Polish system, the amount of plastic and rubber waste generated in Austria is calculated with time series, taking into account life spans of different product groups. It amounted in Austria in 2004 to nearly 930 000 Mg.

STOCK: According to the study of Fehringer & Brunner [149] the amount of plastic goods accumulated in the anthroposphere in the year 1994 was 7,1 Mio. Mg. Analysing the increase of consumption and waste generation in time series, beginning from in the year 1995 it is estimated that this stock has increased within the last ten years by more than 4 Mio. Mg; it means by approx. 60%. The stock increased in 2004 by around 360 000 Mg.

The summary of the abovementioned results is presented in Table 5-10.

Table 5-10 Balance of goods of the consumption process in Austria in 2004

Input	Mg/yr	Output	Mg/yr
Products I	529 000	Waste I	927 000
Products III	758 000		
Total input	1 287 000	Total output	927 000
Stock [Mg]	11 200 000	Change of stock	360 000

Source: own calculations for [20]

- Collection, sorting, transport

As mentioned in chapter 2.5.2 the collection of the packaging waste from households, trade and industry is organised within the frame of ARA System. Apart from this system there are a few other organisations dealing with other plastic waste in Austria [19]:

- Österreichischer Arbeitskreis Kunststofffenster (ÖAKF) collects PVC window frames
- Österreichisches Arbeitskreis Kunststoffrohr Recycling (ÖKR) collects plastic pipes
- Companies, which collect mainly plastic waste from commerce and industry:
    - EVA Erfassen und Verwerten von Altstoffen GmbH,
    - Bonus Holsystem für Verpackungen GmbH & CoKG,
    - GUT Galle Umwelttechnik GmbH.

INPUT: The input to the process constituted: 927 000 Mg of post-consumption flow of *waste I* from the process of *consumption*, 71 000 Mg of *production waste* from the *production* processes and 40 000 Mg of waste imported to Austria (the flow of *waste II*).

OUTPUT: Based on the information supplied by ÖKK [183] around 115 000 Mg of plastic packaging waste were directed for treatment in 2004. 47% thereof constitute the sorted polymeric fractions (54 200 Mg) for material recycling and 53% (60 500 Mg) – the mixed fraction. 6% of the mixed plastic packaging waste was mechanically recycled, 16% directed for feedstock recycling in Germany [184] and the remaining 78% was thermally treated with residual waste in MSW incineration plants [183]. It is worth mentioning that the thermal treatment of the mixed plastic waste has increased in recent years. Based on the data from the Austrian Ministry of Environment [185] around 60 000 Mg of packaging waste was thermally treated in Austria in the year 2004.

The results of calculation of output flows from the process of *collection, sorting, transport* is presented below. ÖKK and its partners received for recycling 58 000 Mg of plastic waste. The data on plastics recycled outside of the ARA system[3] were as follows: approx. 15 000 Mg for packaging waste, 4 000 Mg for non-packaging waste, as well as 50 000 Mg of production waste were recycled in Austria in 2004 [182]. That means that in total about 127 000 Mg of plastic waste were directed for recycling (see the flow of *waste IV*). The flow of *waste V* directed for the *energy recovery* amounted to approx. 564.000 Mg. A more detailed explanation is given below, when describing the process of *energy recovery*. The export of plastic and rubber waste from Austria (see the flow of *waste III*) amounted to, according to the national statistics [181], 87 000 Mg, however, it is expected that more waste was exported illegally without its registration. From the difference between the input and output values the flow of *waste VI* of waste for direct landfilling is calculated. It amounted to 260 000 Mg.

STOCK: There is no stock in the above described process.

The results described above are summarized in Table 5-11.

Table 5-11 Balance of goods of the collection, sorting, transport process in Austria in 2004

Input	Mg/yr	Output	Mg/yr
Waste I	927 000	Waste III	87000
Waste II	40 000	Waste IV	127 000
Production waste	71 000	Waste V	564 000
		Waste VI	260 000
Total input	1 038 000	Total output	1 038 000
Stock [Mg]	0	Change of stock	0

Source: own calculations for [20]

[3] Data received thanks to the courtesy of PlasticsEurope Austria

- Recycling

INPUT: As mentioned in the previous part 127 000 Mg of plastic waste entered the process of *recycling* in the year 2004 as the *waste IV* flow. Due to the fact that the feedstock recycling of plastic waste from Austria was conducted in Germany [184] and was outside of the spatial boundary of the system, and because of the small amount of plastic waste treated with the use of this method (9 700 t) this fraction is excluded from further evaluation.

OUTPUT: Based on the information from the recyclers [165], it is assumed that 35% of the recycled product, which amounted to 38 000 Mg, was used at the national market (the flow of *recyclate I*), while the remaining 71 000 Mg were exported from the system (*recyclate II*). The flow of *impurities*, also including melt filter residues and residue fraction, amounted to 18 000 Mg and was directed for the disposal in landfill sites.

STOCK: The process of *recycling* has no stock.

The results described in this chapter are summarized in Table 5-12.

Table 5-12 Balance of goods of the collection, sorting, transport process in Austria in 2004

Input	Mg/yr	Output	Mg/yr
Waste IV	127 000	Recyclate I	38 000
		Recyclate II	71 000
		Impurities	18 000
Total input	127 000	Total output	127 000
Stock [Mg]	0	Change of stock	0

Source: own calculations for [20]

- Energy recovery

INPUT: As mentioned before, the implementation of the new Landfill Ordinance [104] contributed to the increase of thermal treatment of waste. The flow of *waste V* refers to the total *energy recovery* in MSW incineration plants, fluidised beds and in industrial processes in the cement industry.

According to the information from the national waste management plan [186] the content of plastics in municipal waste is approx. 10%. Additionally, approx. 36% of textiles [187] and 20% of compound materials [188] constitute polymeric materials. A significant part of the hygienic materials also contain them. It is assumed that it sum constitutes 2,5% of the residual waste. Based on the data from waste incineration plants [189, 190] and own calculation, the amount of plastic waste used in waste incineration plants and in fluidised beds amounted to above 390 000 Mg in the year 2004. Additionally, 60 000 Mg of collected plastic packaging are treated thermally according to the information from the Austrian Ministry of Environment [185]. In the cement kilns additional 111 000 Mg, (nearly 83 000 Mg of plastic waste and almost 28 000 Mg of used tires) were used as alternative fuel [136]. The total flow of *waste V* entering the *energy recovery* process amounted to 564 000 Mg.

OUTPUT: The quantities of fractions resulting from the incineration of plastic waste (excluding the cement industry) in the year 2004 are presented in Table 5-13. The flow of *residues*, containing the filter ash, filter cake and bottom ash amounted to approx. 25 000 Mg.

Table 5-13 Distribution of plastic mass on products of waste incineration in Austria in 2004

Output		[Mg/yr]
Off-gas		417 213
Waste water		10 419
Landfill residue	Filter ash	8 154
	Filter cake	< 1 000
	Bottom ash	17 214

Source: own calculations for [20]

The thermal treatment of plastic and rubber waste in the cement industry resulted in around 79 000 Mg of *off-gas* and 4 100 Mg leaving the process with the flow of *product* (clinker).

STOCK: Analogically, like in the *recycling*, there is no stock in the process of *energy recovery*.

The results obtained in this section are summarized in Table 5-14 below.

Table 5-14 Balance of goods of the energy recovery process in Austria in 2004

Input	Mg/yr	Output	Mg/yr
Waste V	564 000	Residues	25 000
		Off-gas	516 000
		Waste water	10 000
		Product	13 000
Total input	564 000	Total output	564 000
Stock [Mg]	0	Change of stock	0

Source: own calculations for [20]

- <u>Landfill</u>

INPUT: The flow of *waste VI* from the process of *collection, sorting, transport* for landfilling was around 260.000 Mg. Additionally 18 000 Mg of *impurities* from the *recycling* process and 25 000 Mg of *residues* from the *energy recovery* were disposed of in landfill sites.

OUTPUT: The *landfill* process had no output within the temporal boundary of one year.

STOCK: Fehringer & Brunner [149] estimated the stock of plastic waste disposed of in landfill sites for the period 1960-1994 as amounting to nearly 10 Mio. Mg. The increase of this stock, beginning from the year 1995 until 2004 amounted to approx. 55% (15,5 Mio. Mg by 2004). It has been however noticed that the dynamics of this growth has slowed down in the recent years, e.g. due to the implementation of the Landfill Ordinance [104] and the Packaging and Packaging Waste Ordinance [100] and the consequent increase of thermal treatment and recycling of the plastic waste.

The change of the stock *landfill* amounted around to 300 000 Mg in the year 2004. It is supposed that this value may be lower as probably some amounts of plastic waste were incinerated in domestic furnaces or exported without registration; however, the data concerning the respective quantities was not available. The development of the plastic stocks “in use” and in landfills is presented in Figure 5-4 (the left axis on the diagram refers to the values for flows and the right axis for the stocks).

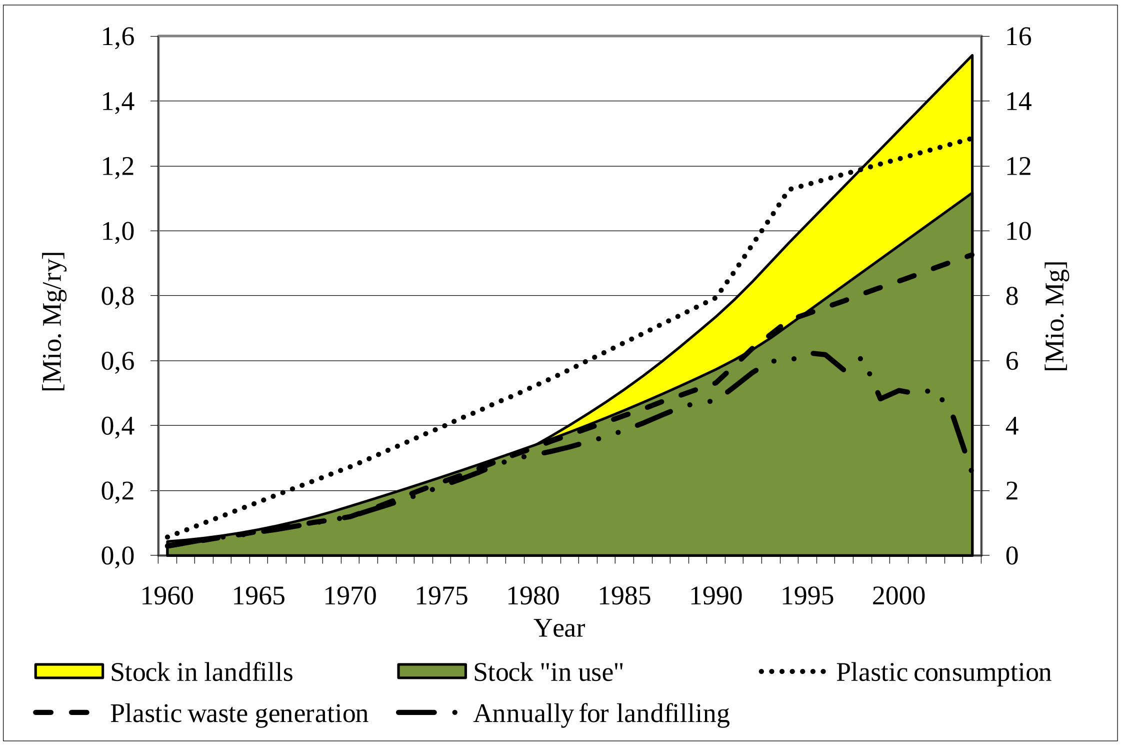


Figure 5-4 Flows and stocks of plastics and their waste products in Austria in 1960-2004

Source: own calculations for [20]

The summary of the results described above is presented in Table 5-15.

Table 5-15 Balance of goods of the landfill process in Austria in 2004

Input	Mg/yr	Output	Mg/yr
Waste VI	260 000		
Impurities	18 000		
Residues	25 000		
Total input	303 000		
Stock [Mg]	15 500 000	Change of stock	303 000

Source: own calculations for [20]

5.2 Evaluation of plastic waste management

After calculating the total flows of plastics in both systems the results concerning the plastic waste flows are used to conduct materials flow analyses for the plastic waste management systems. Additionally, relying on the data obtained from these MFAs, the evaluation of the quantified flows within the waste management systems is conducted. The evaluation concerns the selected environmental and resource conservation aspects, described in chapter 4. The results obtained are presented in the following chapters.

5.2.1 Evaluation of plastic waste management in Poland

The starting point for the evaluation of plastic waste management in Poland is the MFA of the total waste flows (see Figure 5-5) carried out based on data presented in Table 5-16.

Table 5-16 Plastic waste flows in Poland in 2004

		Poland	
		1 000 Mg/yr	kg/cap*a
Recycling		110	3
Energy recovery		70	2
thereof	MSW incineration	12	0,3
	cement industry – plastics	13	0,3
	cement industry - used tires	45	1,2
Landfilling		1 864	49
Total plastic waste		2 044	54

*values rounded; Source: own calculations for [20]

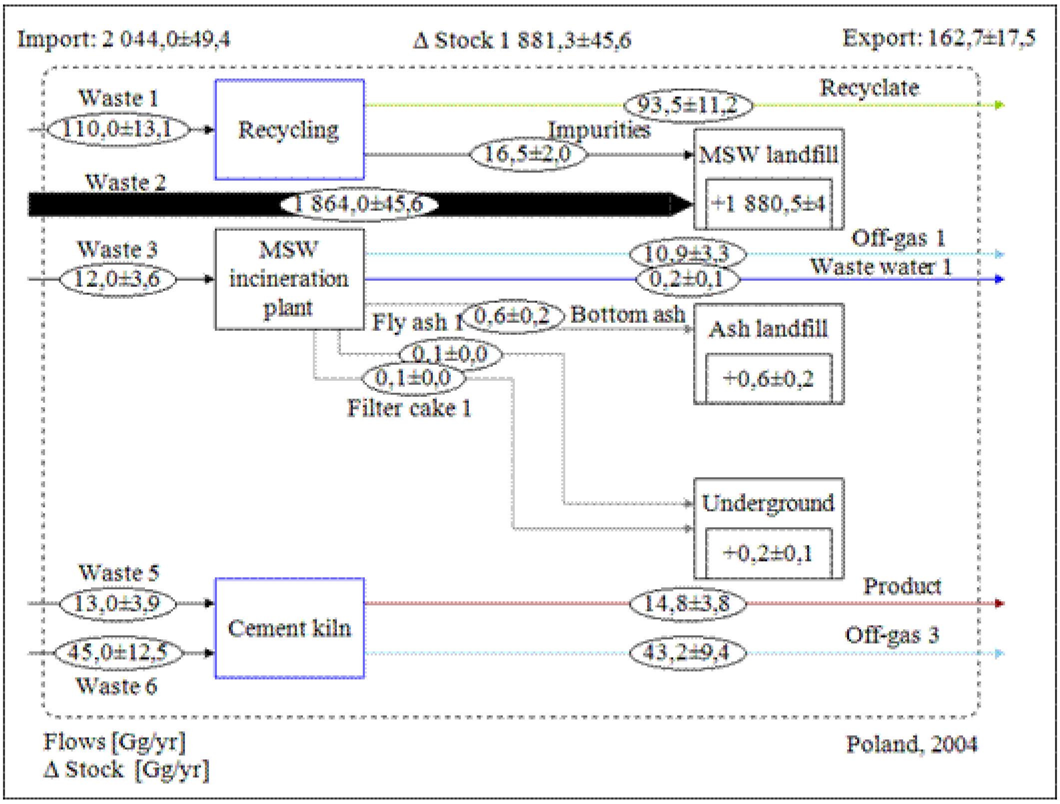


Figure 5-5 Plastic waste flows in Poland in 2004

Source: own calculations for [150]

5.2.1.1 Flows of selected substances in plastic waste management in Poland

Based on the results of the MFA for the total waste flows and using the transfer coefficients (presented in Table 3-9–Table 3-12), and concentrations of the selected substances in waste fractions (see Table 3-8) the flows of those substances in the Polish plastic waste management system are quantified. The results obtained are presented in diagrams below. The respective values calculated per capita are shown in Appendix 6.

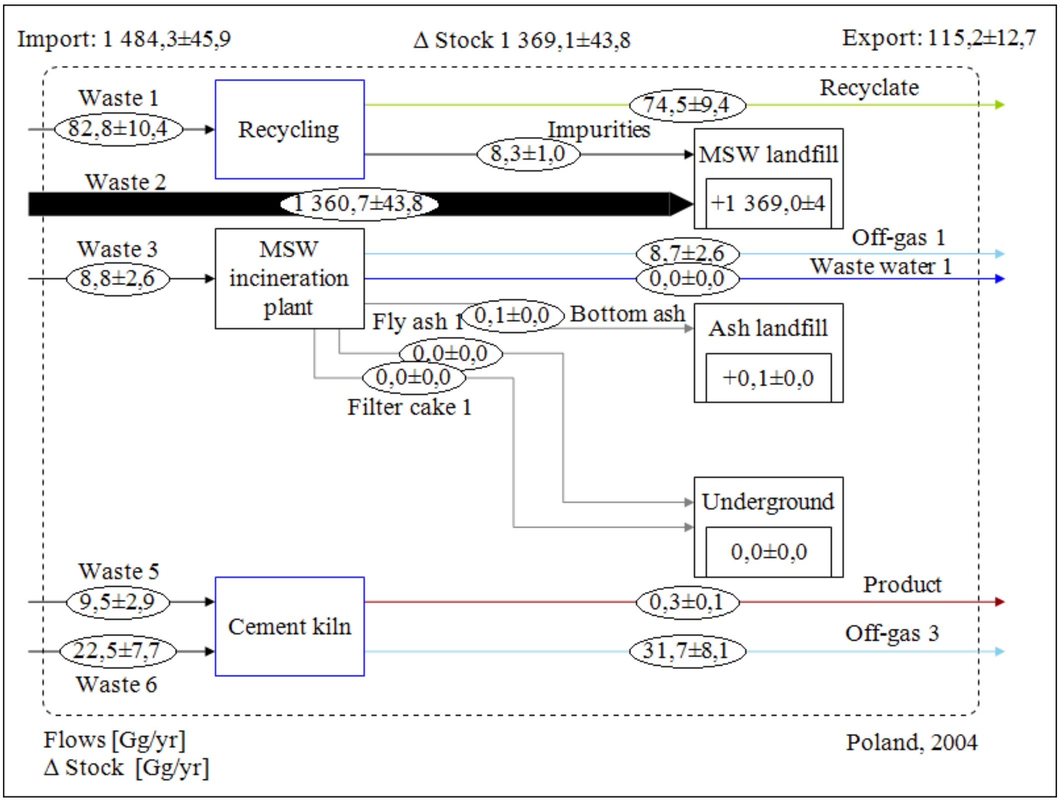


Figure 5-6 Carbon flows in plastic WM system in Poland in 2004, Source: own calculations for [150]

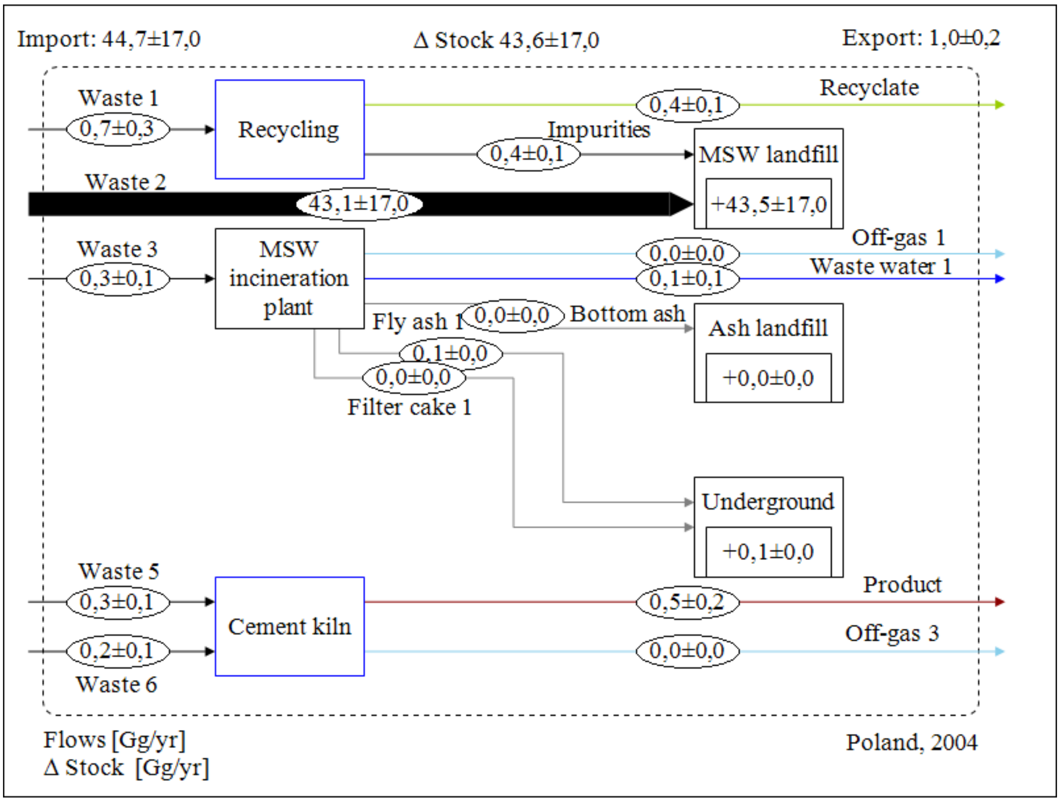


Figure 5-7 Chlorine flows in plastic WM system in Poland in 2004, Source: own calculations for [150]

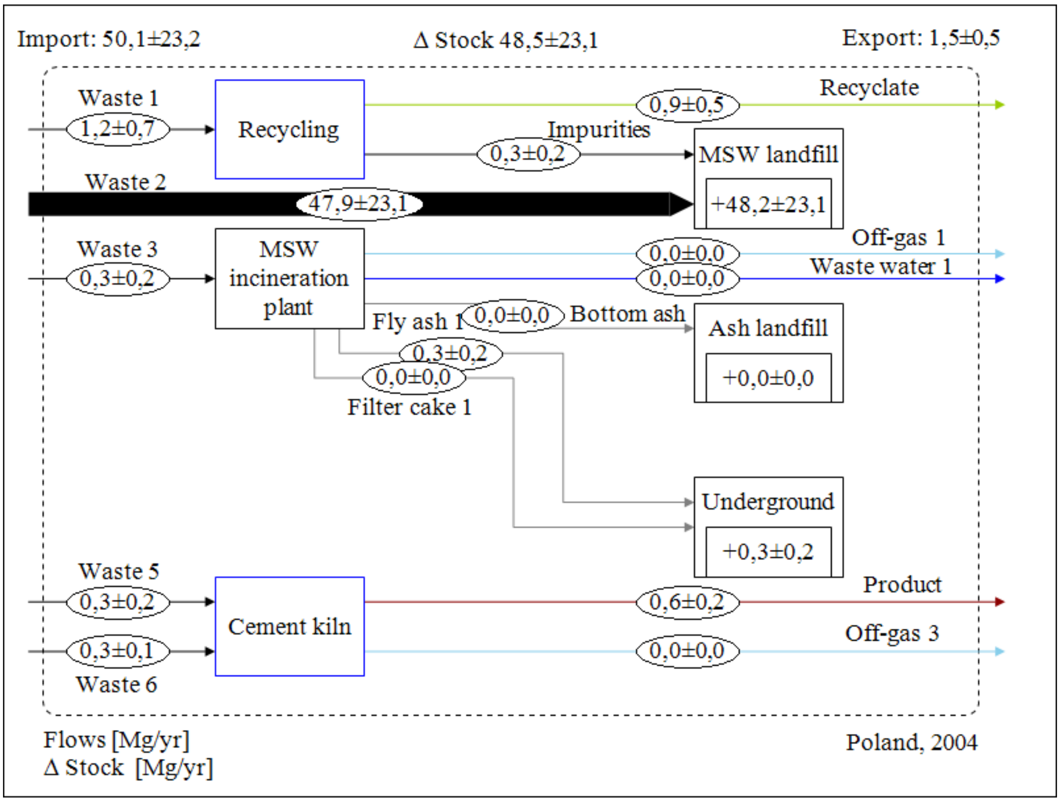


Figure 5-8 Cadmium flows in plastic WM system in Poland in 2004, Source: own calculations for [150]

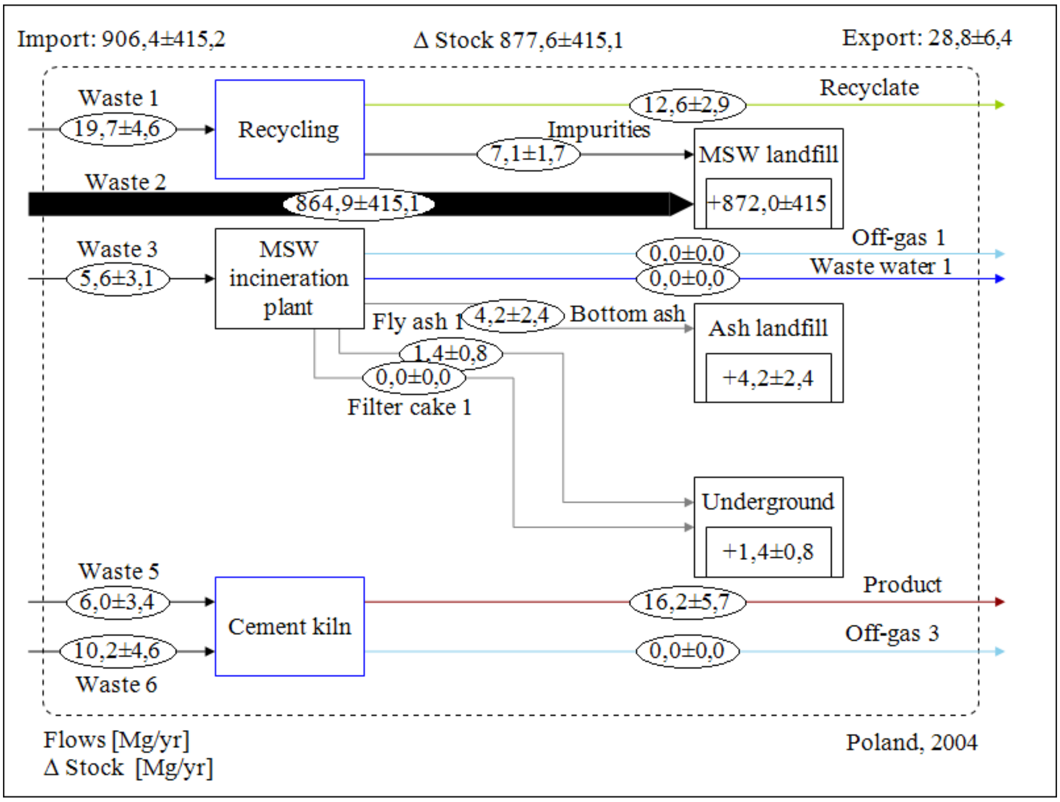


Figure 5-9 Lead flows in plastic WM system in Poland in 2004, Source: own calculations for [150]

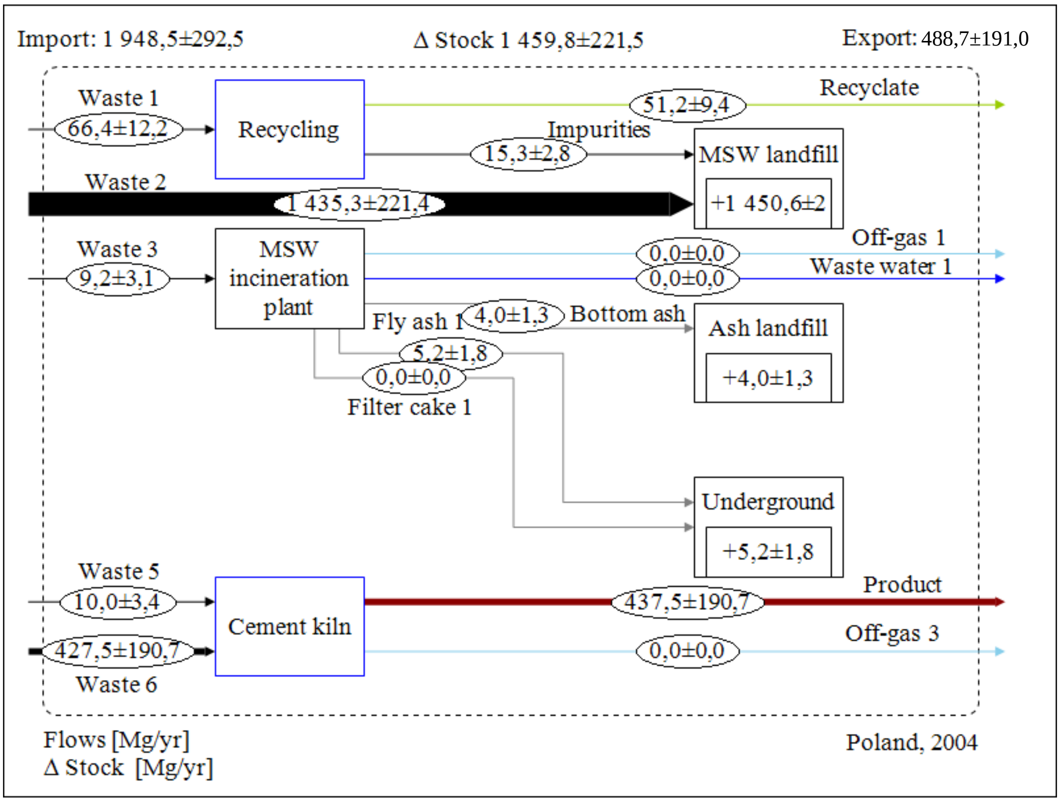


Figure 5-10 Zinc flows in plastic WM system in Poland in 2004, Source: own calculations for [150]

5.2.1.2 Fate of chosen substances in plastic waste management in Poland

The results of the calculation of the appropriateness of target processes which the selected substances from plastic waste generated in 2004 reach within a 50-year period (mean values) are shown in Table 5-17 (in Mg) and Figure 5-11 (in %).

Table 5-17 Total mass flows to various classes of target processes within a 50-year period in the Polish system

	I	II	III
	[Mg]		
C	113 990	0	1 368 960
Cl	150	100	44400
Cd	0,3	48,2	1,5
Pb	1,4	876,0	28,6
Zn	5,2	1 500	488

Source: own calculations for [150]

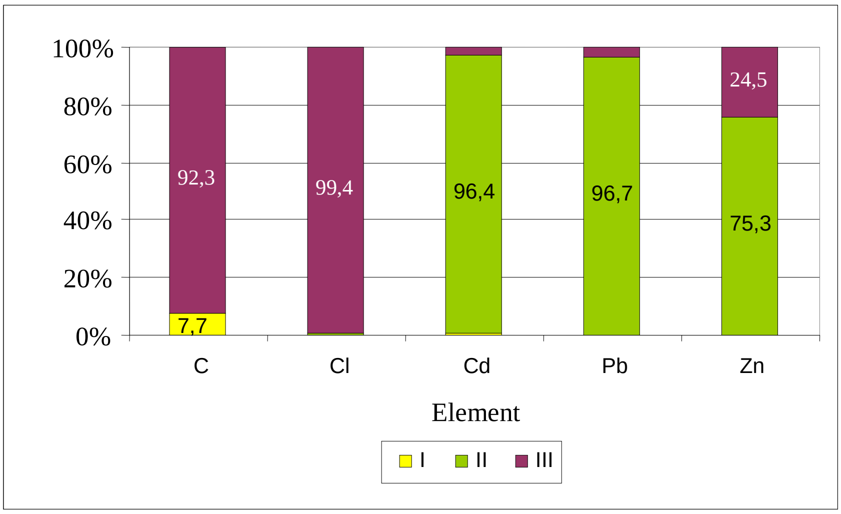


Figure 5-11 Share of total flows to various classes of target processes within a 50-year period in the Polish system, Source: own calculations for [150]

It may be summarised that around 92% of the C flow and 99% of the Cl flow did not reach the appropriate target processes in the medium-term. In reference to the flows of heavy metals it was noticed that between 75 and 97% of the total flows of the selected elements reached the conditionally appropriate target processes.

The respective results for the long-term (1 000 years) are presented in Table 5-18 and Figure 5-12.

Table 5-18 Total mass flows to various classes of target processes within a 1000-year period in the Polish system

	I	II	III
	[Mg]		
C	40 340	73 650	1 368 960
Cl	150	100	44 400
Cd	0,3	0,0	49,6
Pb	1,4	4,2	900
Zn	5,2	4,0	1 940

Source: own calculations for [150]

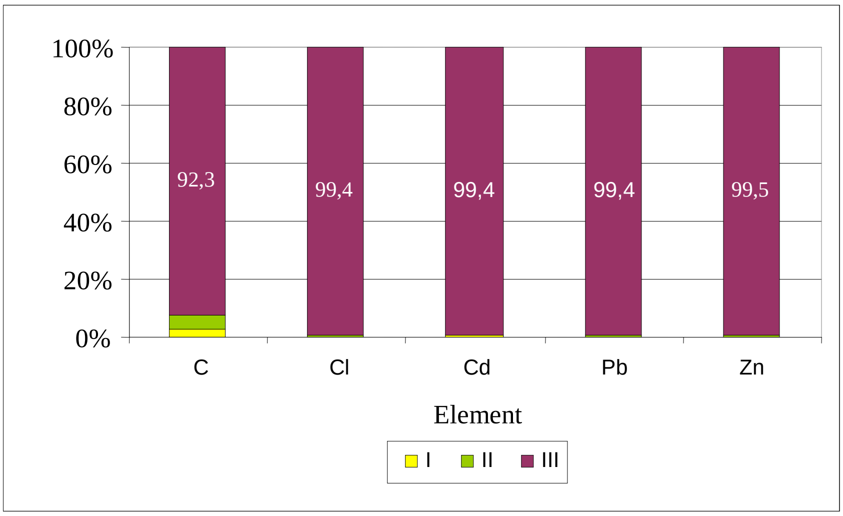


Figure 5-12 Share of total flows to various classes of target processes within a 1000-year period in the Polish system, Source: own calculations for [150]

The results obtained for C and Cl in the long-term are the same like for the above described medium-term analysis. In reference to the flows of heavy metals above 99% of them reached inappropriate target processes. Therefore, it may be concluded that in the long-term the Polish system does not meet the target of directing the analysed substances to appropriate sinks.

5.2.1.3 Product from cement industry in Poland

The concentration of the selected heavy metals produced with the use of this alternative fuel compared to the concentration in the reference clinker increased by:

- 55 % for zinc,
- 14 % for cadmium,
- 4 % for lead.

This value is the highest for zinc due to the fact that in cement industry in Poland mostly end-of-life tires, which contain significantly higher content of zinc in comparison to the plastic waste, are used as alternative fuel. A detailed presentation of the results with uncertainties is contained in Appendix 4.

5.2.1.4 Saving of raw materials in Poland

In the process of recycling around 93 000 (±12%) Mg of recyclate was produced in the Polish system in 2004. This corresponds to approximately 72 000 (±12%) Mg of crude oil, which theoretically is saved due to material recovery from plastic waste in Poland. This amount of recyclate constitutes approx. 5% of the total quantity of plastics in primary form produced in Poland. This value serves to show the theoretical potential of the system to conserve raw material-crude oil and to compare this system with the performance of the Austrian system in this respect.

5.2.1.5 Saving of energy in Poland

The results of this calculation of energy recovery from plastic waste are presented in Table 5-19. In the final step the total amount of energy which was recovered from plastics due to its thermal treatment in the MSW incineration plant and in the cement industry is calculated back to crude oil and expressed in crude oil equivalents. The uncertainty of the results is estimated to amount approx. 30%. The results obtained are, again, only theoretical values, used for the purpose of comparison of both systems, as in Poland the electricity and heat are produced mainly from hard coal, while in Austria the primary energy sources are much more diversified. Hard coal is also used in Poland as the main fuel in the cement industry. Thus, the amount of energy saved is also expressed for the Polish system in Mg of hard coal amounting to approx. 61 000 Mg in 2004.

Table 5-19 Energy recovery from plastic waste in Poland in 2004

	Unit	MSW incineration	Cement industry	Total
Total subst. potential	[GJ/yr]	277 900	1 526 260	1 804 160
Substitution of crude oil	[Mg/yr]	6 100	33 500	39 600

Source: own calculations for [150]

The energy recovery from plastic waste in Poland is accounted mainly (82%) to the use of plastic and rubber waste in the cement industry, and only to a very small extent – to the thermal treatment of this waste in MSW incineration plant (see Table 5-20). If the energy recovery from plastic waste in Poland was referred to the total amount of energy produced in the country in 2004 [168] (both expressed in Mg of crude oil equivalents) it can be noticed that it constitutes only 0,04% of the total value of energy generated. It can be concluded that the energy recovery from plastic waste is still negligible in Poland.

Table 5-20 Structure of energy recovery from plastic waste in Poland

	MSW incineration	Cement industry
	[%]	
Energy recovery	18,1	81,9

Source: own calculations for [150]

5.2.1.6 Substance concentrating efficiency of plastic waste management in Poland

The results of the calculation of substance specific SCE values for energy recovery processes and for the whole plastic waste management system are presented in Table 5-21.

Table 5-21 Substance concentrating efficiency of plastic waste management in Poland

SCE [%]	MSW incineration	Cement industry	Total system
Cd	44,1	-39,2	-0,3
Pb	29,6	-37,1	-0,5
Zn	33,8	-38,5	-8,2

Source: own calculations for [150]

The resource specific SCE_{tot} amounts to -0,4%. This small negative value can be explained by the following facts: 1) only 22% of the total plastic waste in the process of energy recovery was co-incinerated in MSW incineration plants, which resulted in the positive value of SCE; 2) however, the rest (78%) of this waste fraction was used in the process of cement industry, in which the substances are diluted in clinker and the SCE value is negative (from the viewpoint of the goals of waste management this is not a desired situation); 3) around 90% of the plastic waste was disposed of without any pre-treatment at Polish landfills. The value of substance concentrating efficiency for this process equals zero, as neither concentration nor dilution of the substances occurs in landfill sites.

5.2.1.7 Reduction of volume needed for landfilling in Poland

It is estimated that if 100% of the waste was disposed of in landfill sites without any pre-treatment, its volume would amount approx. 1,5 Mio. m³ in 2004. Due to the treatment of plastic waste this volume (including the after treatment residues) was reduced by around 8%.

5.2.1.8 Long-term impacts from landfills in Poland

Due to the lack of the information concerning the disposal of the residues from the thermal treatment of plastic waste in Poland it is assumed that this fraction is disposed of at ash landfills. The external influences, i.e. the contact with water, causes leaking of the analysed substances contained in the residues from the landfill body in the longer term. The discharge of the analysed heavy metals from the ash landfills in 100- and 10 000-year periods, calculated based on the method of Brunner et al. [159], is presented in Table 5-22 nd Table 5-23.

Table 5-22 Behaviour of selected substances in ash landfills in Poland in a 100-year period

	Mass [Mg]	Landfill body [Mg]	Leakage water [Mg]
Cd	0,025	0,025	0,0
Pb	4,2	4,2	0,0
Zn	4,0	4,0	0,0

Source: own calculations for [150]

Table 5-23 Behaviour of selected substances in ash landfills in Poland in a 10 000-year period

	Mass [Mg]	Landfill body [Mg]	Leakage water [Mg]
Cd	0,024	0,016	0,008
Pb	4,16	4,12	0,04
Zn	3,97	3,85	0,12

Source: own calculations for [150]

Due to the fact that very small quantities of plastic waste were treated in MSW incineration plants the respective releases are very small and this impact may be neglected. This issue should however be taken into account if the infrastructure for this thermal treatment develops in Poland in the coming years and the amounts of these residues from incineration increase.

5.2.2 Evaluation of plastic waste management in Austria

The input data used for the MFA of plastic waste management in Austria is presented in Table 5-24.

Table 5-24 Plastic waste flows in Austria in 2004

		Austria	
		1000 Mg/yr	kg/cap*yr
Recycling		127	16
Energy recovery		564	71
thereof	MSW incineration	227	28
	Fluidised bed	228	29
	Cement industry – plastics	83	10
	Cement industry - used tires	28	4
Landfilling		260	33
Total plastic waste		952	119

*values rounded; Source: own calculations for [20]

Based on them the MFA for the waste flows was conducted. The results obtained are presented in Figure 5-13.

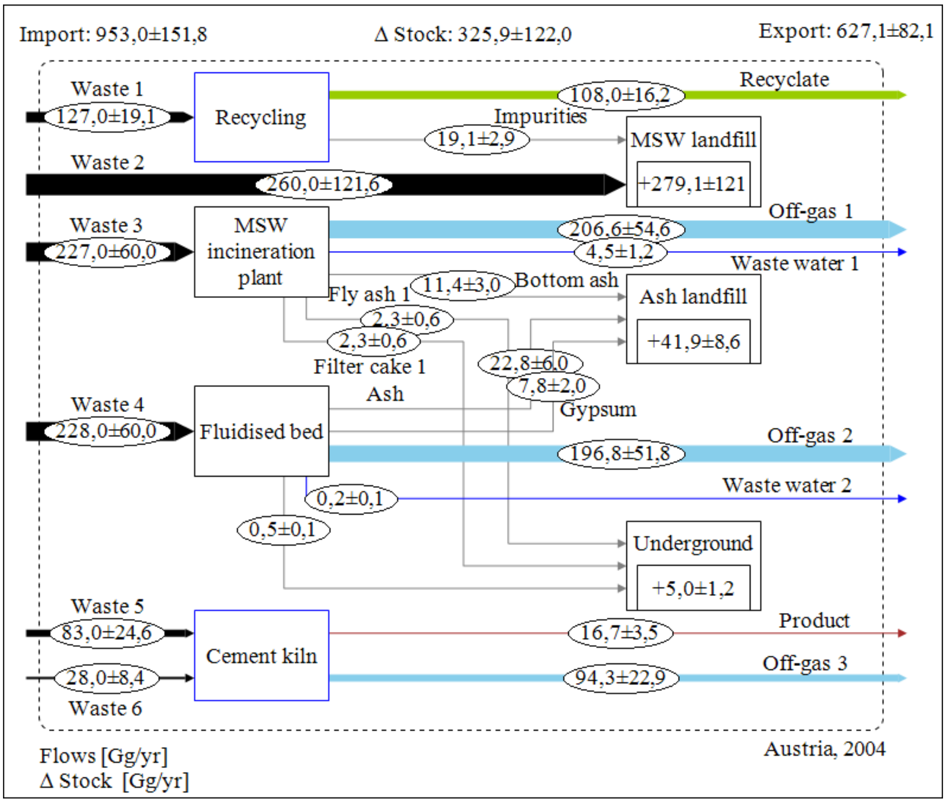


Figure 5-13 Plastic waste flows in Austria in 2004, Source: based on own calculations for [150]

5.2.2.1 Flows of selected substances in plastic waste management in Austria

The results obtained for the MFA of the selected substances are presented in graphical form in the following figures. Together with the results obtained for the total waste streams they constitute a basis for the further evaluation.

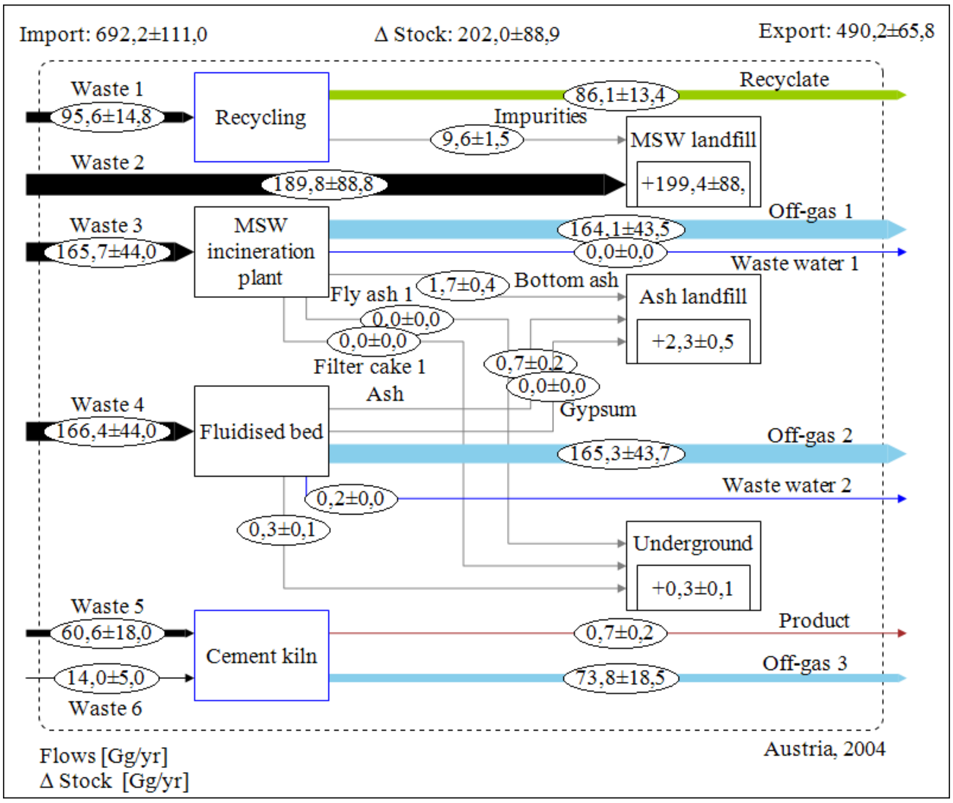


Figure 5-14 Carbon flows in plastic WM system in Austria in 2004, Source: own calculations for [150]

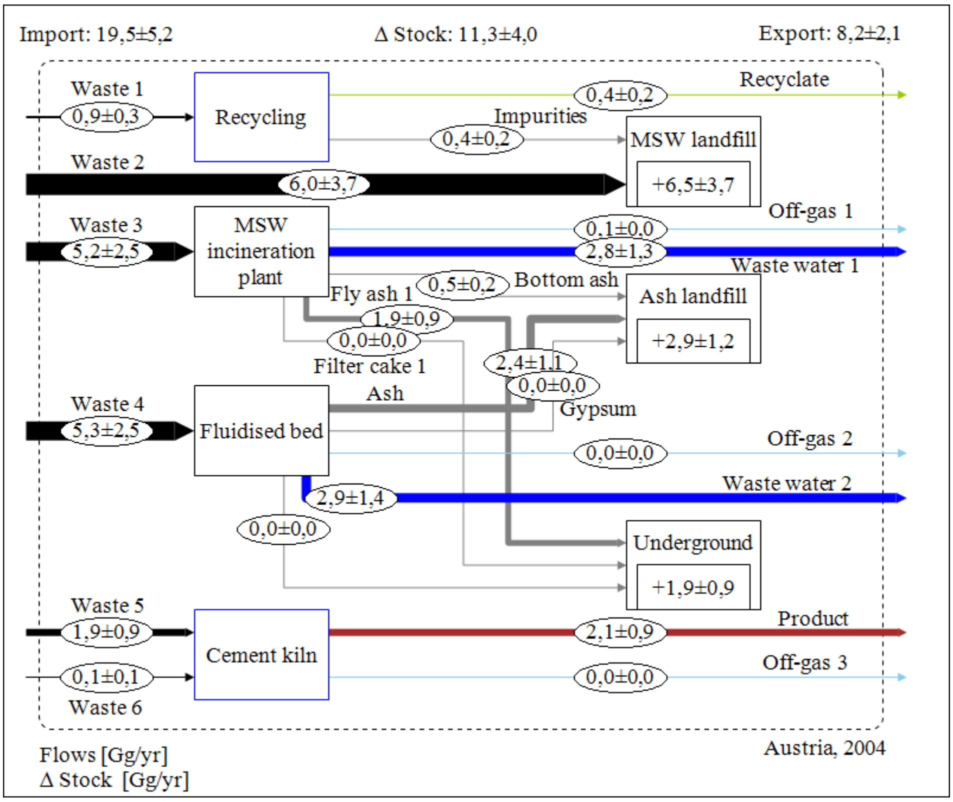


Figure 5-15 Chlorine flows in plastic WM system in Austria in 2004, Source: own calculations for [150]

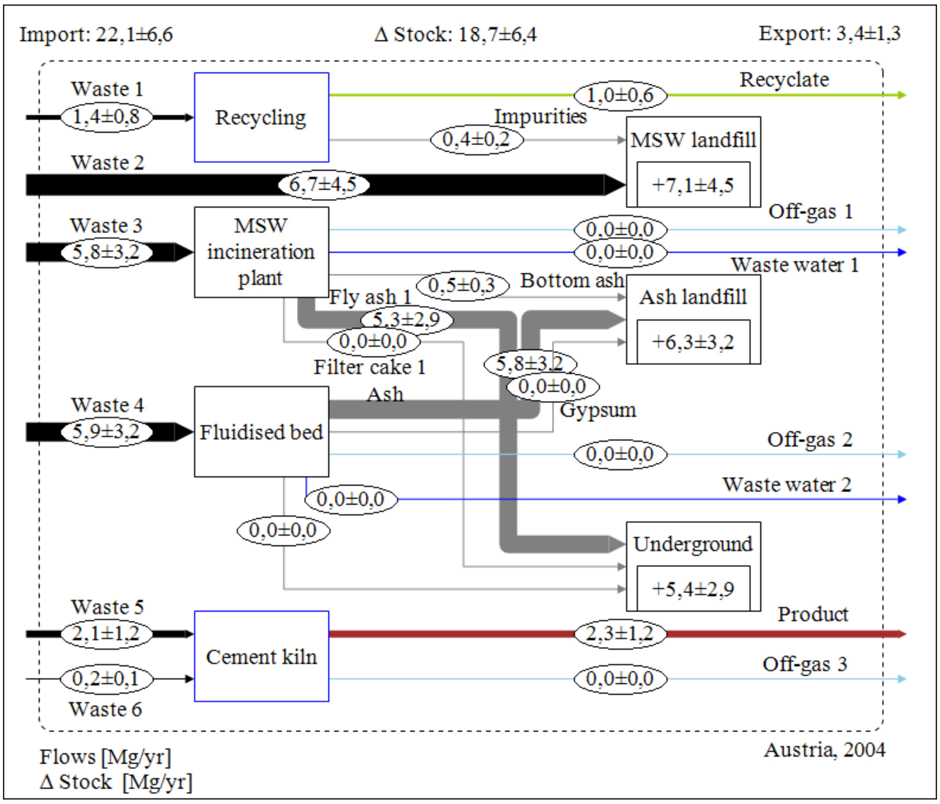


Figure 5-16 Cadmium flows in plastic WM system in Austria in 2004, Source: own calculations for [150]

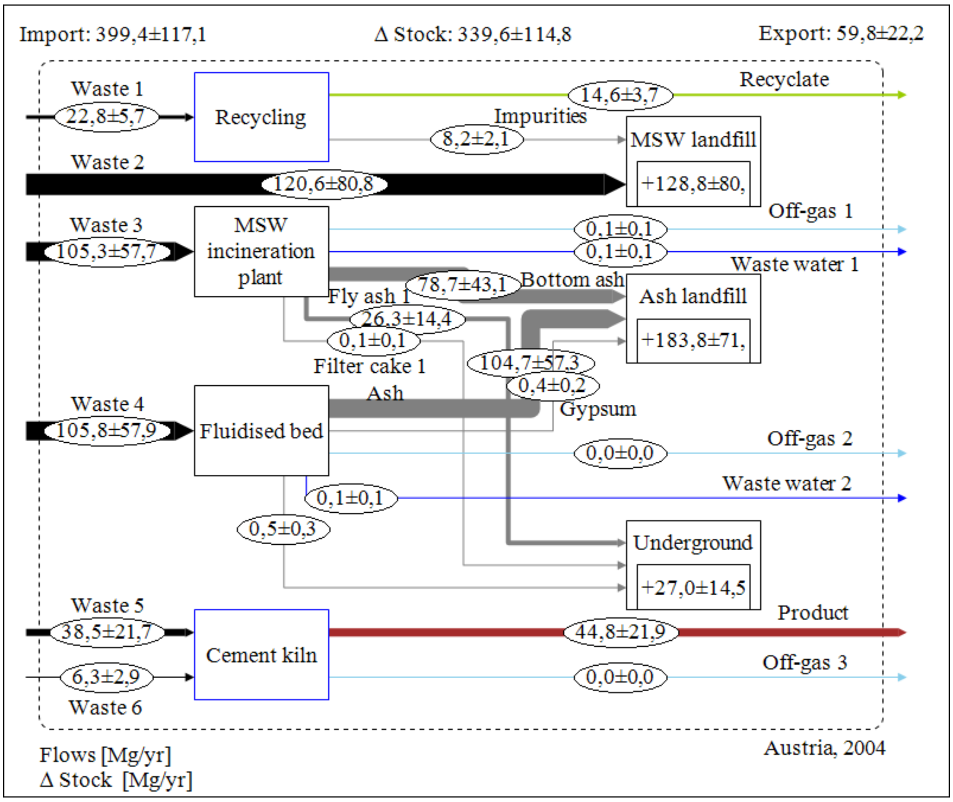


Figure 5-17 Lead flows in plastic WM system in Austria in 2004, Source: own calculations for [150]

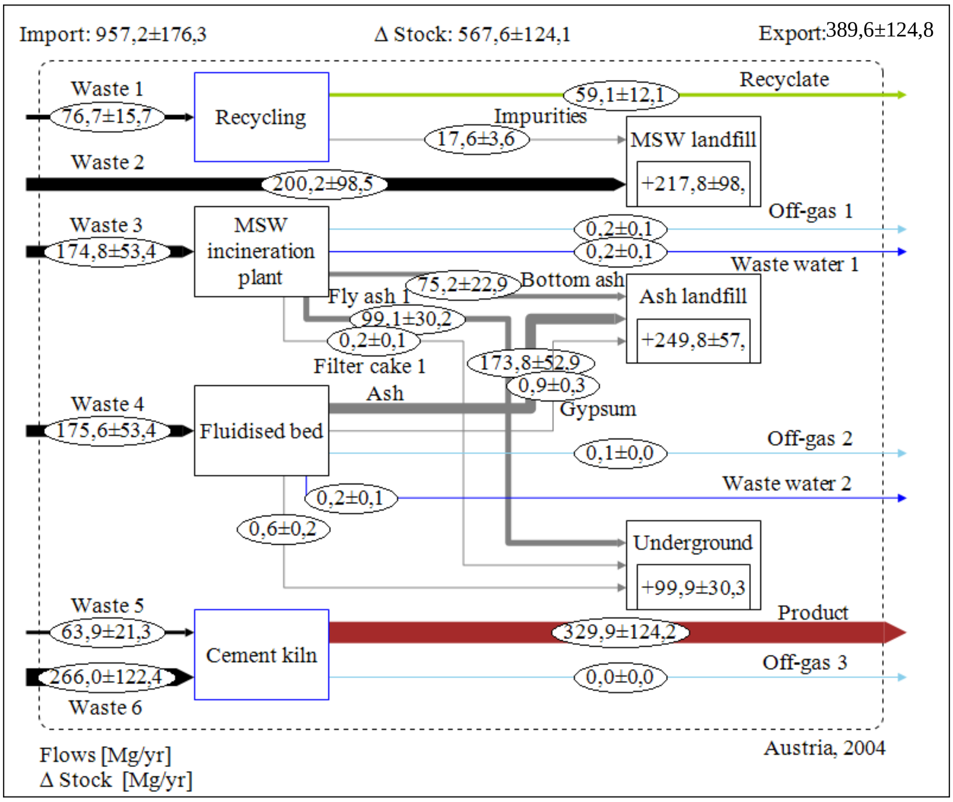


Figure 5-18 Zinc flows in plastic WM system in Austria in 2004, Source: own calculations for [150]

5.2.2.2 Fate of chosen substances in plastic waste management in Austria

Based on the data obtained from MFAs of the selected substances the appropriateness of target processes, which the analysed substances from plastic waste generated in 2004 in Austria reach, is evaluated. The results for the medium-term are presented in Table 5-25 (in Mg) and Figure 5-19 (in %). It may be noticed that, except for carbon, the chosen substances, to a significant extent, do not reach the appropriate target processes.

Table 5-25 Total mass flows to various classes of target processes in a 50-year period in the Austrian system

	I	II	III
	[Mg]		
C	490 100	0	89 140
Cl	5 650	2 480	6 480
Cd	5,4	13,3	3,4
Pb	27	313	60
Zn	100	470	390

Source: own calculations for [150]

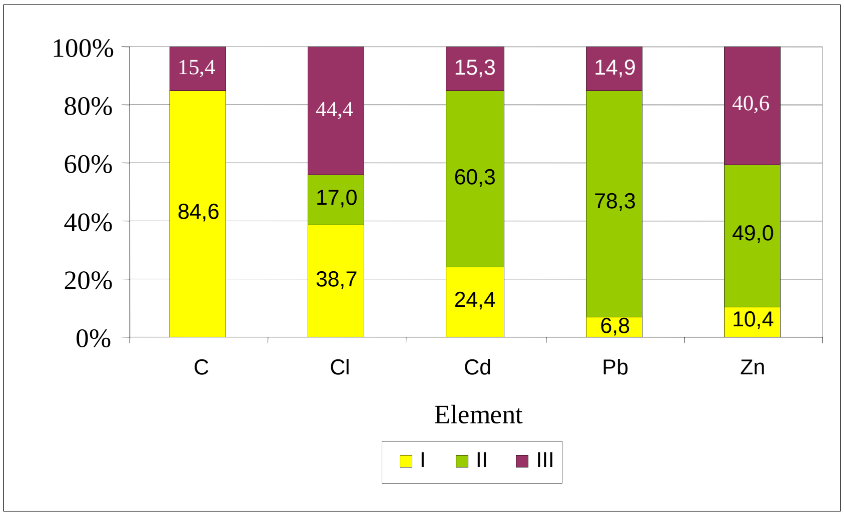


Figure 5-19 Share of total flows to various classes of target processes in a 50-year period in the Austrian system, Source: own calculations for [150]

The results of the analysis conducted for the 1 000-year period are presented in Table 5-26 and Figure 5-20. It is obvious that the goal of reaching the desired target process is achieved even to a lower extent than for the medium-term, e.g. due to the hazard of leaking of heavy metals from municipal landfill bodies in the long-term.

Table 5-26 Total mass flows to various classes of target processes in a 1000-year period in the Austrian system

	I	II	III
	[Mg]		
C	403 290	86 810	200 090
Cl	5 650	1 920	11 920
Cd	5,4	6,3	10,5
Pb	27	180	190
Zn	100	250	610

Source: own calculations for [150]

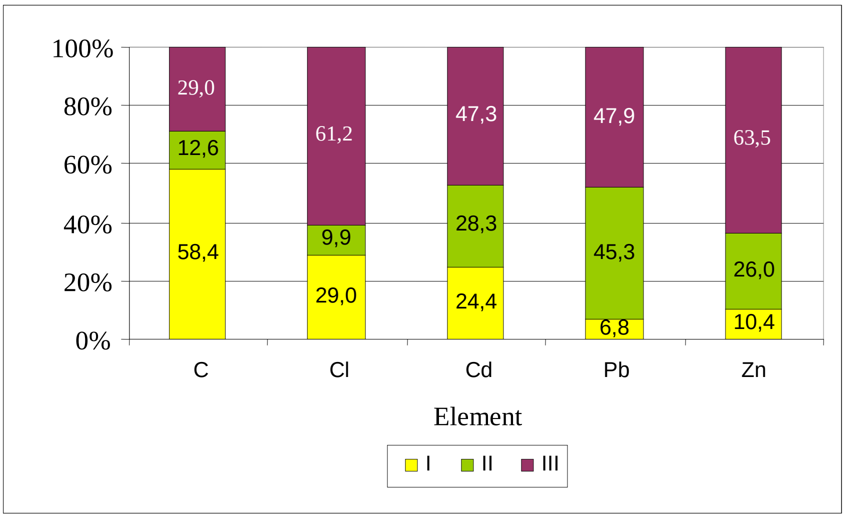


Figure 5-20 Share of total flows to various classes of target processes in a 1000-year tern in the Austrian system, Source: own calculations for [150]

5.2.2.3 Product from cement industry in Austria

The average concentration of the chosen heavy metals in clinker, calculated using the same approach as for the Polish system, increased as follows:

- by 170 % for cadmium,
- by 125 % for zinc,
- by around 40 % for lead.

Contrary to the results obtained for the Polish system, the highest increase is observed for cadmium. This is related to the fact that long-living plastic goods contain significant amounts of this metal and this waste is used mainly in the cement industry in Austria. At present in new goods cadmium-additives are replaced by other substitutes and consequently the concentration of cadmium is expected to decrease, however this heavy metal is still contained in various long-living goods accumulated in the anthroposphere and it will appear for years in the waste stream.

5.2.2.4 Saving of raw materials in Austria

Nearly 110 000 (±15%) Mg of recycled material was produced in Austria in 2004. It is estimated that theoretically approx. 95 000 (±15%) Mg of crude oil for primary plastics production could be saved thanks to this process. This amount of recyclate constitutes around 8% (±1%) of the total quantity of primary plastics produced in Austria. However, it must be remembered that the major part of recyclate was exported from the country and did not directly contribute to the crude oil saving in the analysed system. The calculated value gives only theoretical information on the potential of the system to save raw materials.

5.2.2.5 Saving of energy in Austria

The results of the energy saving due to thermal treatment of plastic waste in Austria in 2004 are presented in Table 5-27, the uncertainty amounts ±30%.

Table 5-27 Calculation of energy recovery from plastic waste in Austria in 2004

	Unit	MSW incineration	Fluidised incineration	Cement industry	Total
Total subst. potential	[GJ/yr]	5 264 500	6 035 200	2 927 300	14 227 000
Subst. of crude oil	[Mg/yr]	115 400	132 400	64 200	312 000

Source: own calculations for [150]

In the final stage the total amount of energy saved was calculated back to crude oil equivalents. As mentioned before, the heat and electricity generation in Austria and Poland differs significantly (see Table 4-6) and therefore this unit serves for comparing the systems from the viewpoint of the potential to save energy. The structure of energy recovery from plastic waste is shown in Table 5-28. The thermal treatment of the plastic waste in fluidised beds and MSW incineration plants contributes mostly to the energy recovery from plastic waste in Austria.

Table 5-28 Structure of energy recovery from plastic waste in Austria

	MSW incineration	Fluidised incineration	Cement industry
	[%]		
Energy recovery	37,0	42,4	20,6

Source: own calculations for [150]

The quantity of energy saved due to the thermal use of plastic waste constitutes around 1% of this total production of electricity and heat in Austria in 2004 calculated in crude oil equivalents.

5.2.2.6 Substance concentrating efficiency of plastic waste management in Austria

The results of the calculation of substance specific SCE values for energy recovery processes and for the whole Austrian system are presented in Table 5-29. The resource specific SCE_{tot} amounted to 8,9%.

Table 5-29 Substance concentrating efficiency of plastic waste management in Austria

SCE [%]	MSW incineration	Fluidised bed	Cement industry	Total system
Cd	33,6	17,5	-29,9	9,5
Pb	22,5	18,2	-29,2	7,0
Zn	25,7	18,1	-36,7	-2,9

Source: own calculations for [150]

From the environmental and resource conservation point of view the hazardous substances should be concentrated in the system and in this form recycled or disposed of in safe sinks, and not diluted in the environment or in products from the treatment processes. The treatment of plastic waste in fluidised beds and MSW incineration plants contributed mostly to the increase of the SCE value, while their use in the cement industry resulted in negative values of SCE. It can be explained as follows: the mass of clinker is higher than the mass of the plastic waste used for the production of clinker and more than 99% of the heavy metals analysed are connected into the clinker, and consequently diluted in the product of this treatment process. However, as the fraction of waste directed for recovery in cement kilns constituted only 20% of the total amount of this waste treated thermally and the rest 80% was treated in processes, which resulted in the increase of the SCE, the total value for the entire system is positive.

5.2.2.7 Reduction of volume needed for landfilling in Austria

If the total plastic waste generated in Austria in 2004 was landfilled there, the volume of nearly 716 000 m³ would be occupied in landfill sites. Due to the treatment of plastic waste this volume was reduced by around 60%.

5.2.2.8 Long-term impacts from landfills in Austria

The estimated discharge of the analysed heavy metals from the ash landfills in Austria in 2004 in the 100- and 10 000-year periods is presented in Table 5-30 and Table 5-31.

Table 5-30 Behaviour of selected substances in ash landfills in a 100-year period in Austria

	Mass [Mg]	Landfill body [Mg]	Leakage water [Mg]	Gaseous emission [Mg]
Cd	6,3	6,3	0,0	0,0
Pb	183,9	183,9	0,0	0,0
Zn	249,9	249,9	0,0	0,0

Source: own calculations for [150]

Table 5-31 Behaviour of selected substances in ash landfills in a 10 000-year period in Austria

	Mass [Mg]	Landfill body [Mg]	Leakage water [Mg]	Gaseous emission [Mg]
Cd	6,3	4,1	2,1	0,0
Pb	183,9	182,1	1,8	0,0
Zn	249,9	242,4	7,5	0,0

Source: own calculations for [150]

It should be noticed that cadmium especially would leak from the landfill body in the longer term, while in the shorter term all analysed substances, accordingly to the model developed by Brunner et al. [159], are supposed to stay in landfills.

5.2.3 Discussion of results and comparison of Polish and Austrian systems

5.2.3.1 With regards to flows and stocks of plastics and their waste products

The chosen results obtained in MFAs for the Austrian and Polish systems are presented in Table 5-32 and the main findings are briefly pointed out in this chapter.

- The consumption of plastics in Poland in 2004 was around 3,7 Mio. Mg and 98 kg/capita. In Austria it was 1,3 Mio. Mg respectively 161 kg/capita. It is worth noticing that an average inhabitant of Austria consumed 65% more plastic goods than a Polish citizen. However, the consumption in Poland has been growing more dynamically over the last ten years and this discrepancy is expected to decrease gradually in the coming years.
- The stock of plastic goods accumulated in the anthroposphere, which constitutes a significant potential for future waste, was in total values almost twice as big in Poland, per capita however around 60% smaller.
- The quantity of post-consumption waste in Poland amounted, in total, to 1,9 Mio Mg and approx. 50 kg/capita. In Austria the respective values were as follows: 927 000 Mg and 116 kg/capita.
- Nearly 6% of the total plastic waste generated in Poland in 2004 was recycled, 4% thermally treated and approx. 90% disposed of in landfill sites. The respective values for Austria were as follows: 14% for the recycling, 60% for the thermal treatment 26% for the landfilling. It should be however added that there is no reliable data concerning the amounts of waste incinerated in domestic furnaces as well as imported and exported, which might influence the value referred to the disposal in landfill sites.
- The total stock of plastic waste accumulated in landfills was twice as high in Poland, however per capita it is almost 2,5 times higher in Austria.

Table 5-32 Comparison of plastic flows and stocks in Austria and Poland in the year 2004

	Poland		Austria	
	Total [1000 Mg/yr]	kg/cap	Total [1000 Mg/yr]	kg/cap
Plastic consumption	3 722	98	1 287	161
Plastics to stock "in use"	1 759	46	359	45
Total plastics in stock "in use"	23 000	605	11 200	1 400
Total plastic waste flow	2044	54	952*	119*
Plastic waste flow to recycling	110	3	127	16
Plastic waste flow to energy recovery	70	2	564	71
Plastic waste flow to landfills	1864	49	260	33
Total plastic stock in landfills	30 000	789	15 500	1 938

*incl. import-export of waste Source: own calculations for [20]

5.2.3.2 With regards to evaluation of plastic waste management

The results obtained in the evaluation of the Polish and Austrian plastic waste management systems are compared in this part of this study.

5.2.3.2.1 Critical air volume of plastic waste management in Poland and Austria

The results of the calculation of critical air volume values, calculated with the application of immission threshold values and geogenic reference values are presented in Figure 5-21 and Figure 5-22.

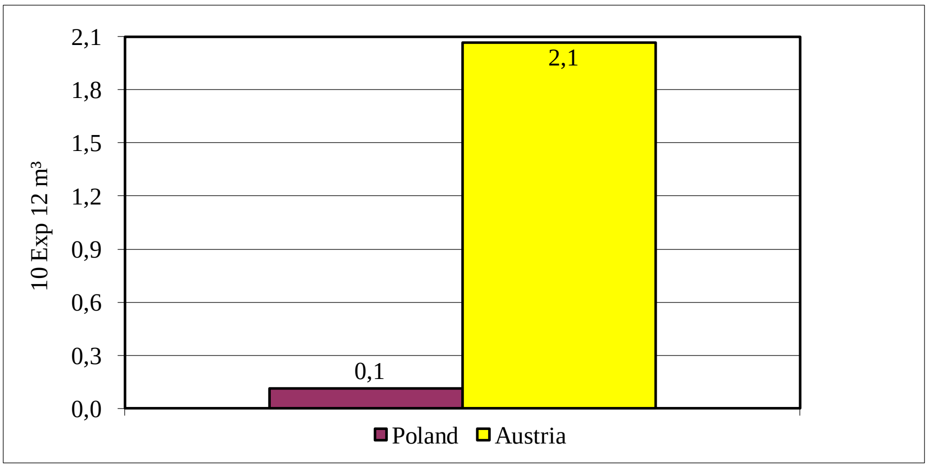


Figure 5-21 Critical air volume (immission threshold values) for Polish and Austrian systems in 2004

Source: own study for [150]

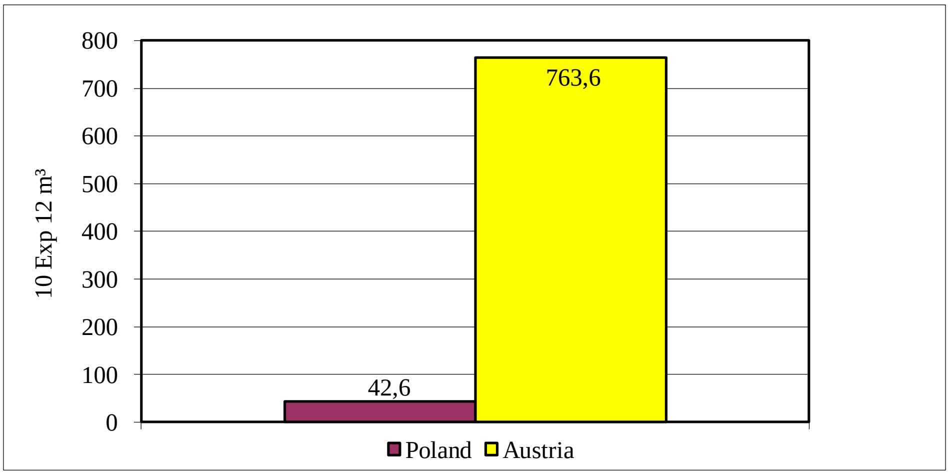


Figure 5-22 Critical air volume (geogenic reference values) for Polish and Austrian systems in 2004

Source: own study for [150]

The value of critical air volume is approx. 20 times lower for the Polish system than for Austria. It is caused by the fact that significantly less (only 70 000 Mg) of the plastic waste was thermally treated in Poland, while in Austria this value was around 8 times higher (564 000 Mg). Additionally, 80 % of plastic and rubber waste were used in Poland as alternative fuel in the cement kilns. In this process heavy metals from plastic waste up to around 99 % of their flow are transferred and connected into clinker and do not contribute to air emissions considered in the critical air volume calculation.

5.2.3.2.2 Fate of chosen substances in Polish and Austrian systems

The comparison of the results (mean values) obtained in the evaluation of the appropriateness of target processes of the analysed systems is presented in the following figures. The first two rows refer to the medium-term (50 years) and the last two rows – to the long-term (1 000 years), A stands for the Austrian system and Pl for the Polish one.

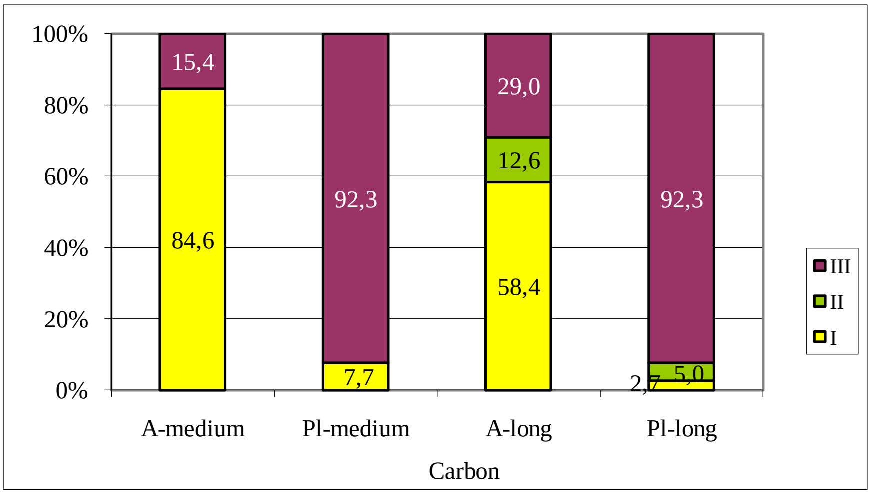


Figure 5-23 Appropriateness of target processes for carbon in Polish and Austrian systems in 2004

Source: own calculations for [150]

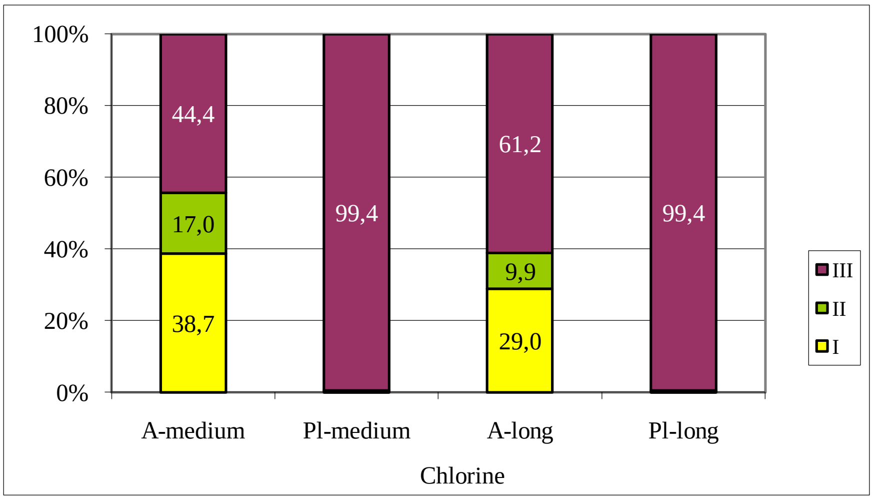


Figure 5-24 Appropriateness of target processes for chlorine in Polish and Austrian systems in 2004

Source: own calculations for [150]

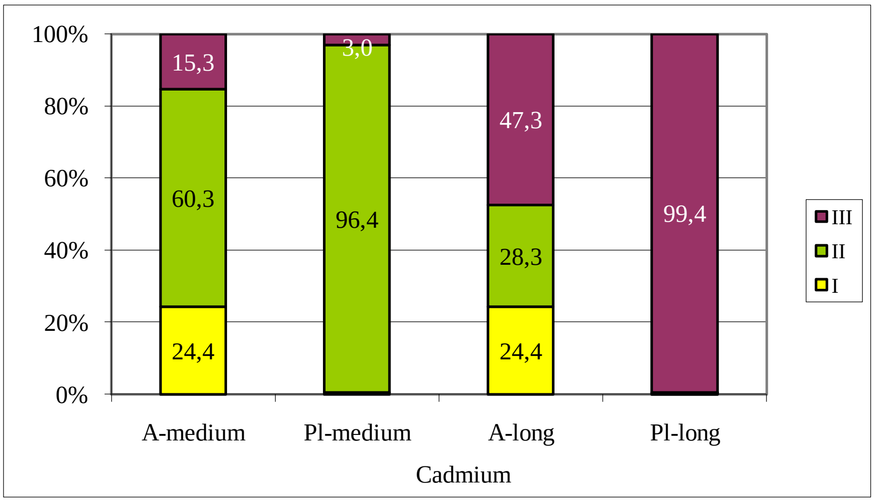


Figure 5-25 Appropriateness of target processes for cadmium in Polish and Austrian systems in 2004

Source: own calculations for [150]

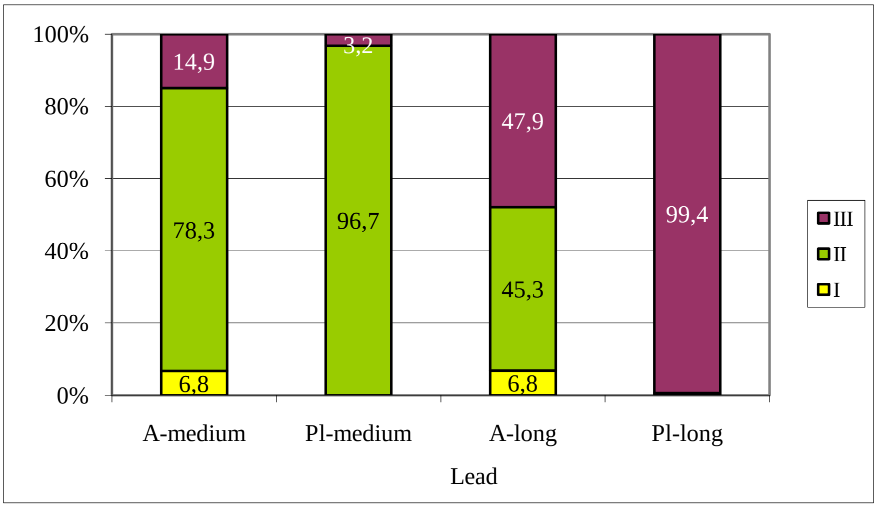


Figure 5-26 Appropriateness of target processes for lead in Polish and Austrian systems in 2004

Source: own calculations for [150]

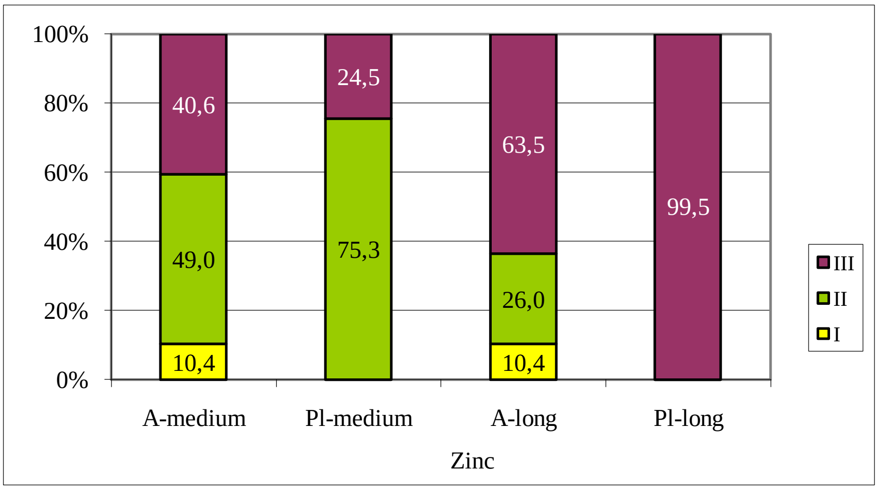


Figure 5-27 Appropriateness of target processes for zinc in Polish and Austrian systems in 2004

Source: own calculations for [150]

It may be observed that from the point of view of directing the analysed substance to appropriate target processes the Polish system does not fulfil the goals of waste management and that there is a very significant potential for, and to a smaller extent for the Austrian system too:

1) in the short-term in Poland around 92% of carbon and 99% of chlorine reach inappropriate target processes, and above 96% of cadmium and lead, and 75% of zinc flow reach the conditionally appropriate target processes. In Austria approximately 15% of carbon, cadmium and lead, 40% of zinc and chlorine reach the inappropriate target processes, while the conditionally appropriate ones are reached by around 60% of cadmium, 78% of lead and 50% of zinc.
2) in the long-term in Poland, 92% of carbon and above 99% of all other analysed substances reach inappropriate target processes; while in Austria this class reach 50% of lead and cadmium, and more than 60% of chlorine and zinc.

5.2.3.2.3 Product from recycling

As previously mentioned, the evaluation of the products from the recycling process is difficult due to the fact that future application fields, terms of use, life spans, and also final fate of the future goods containing recyclate are unknown and difficult to predict. Additional difficulty is related to the fact that recyclate in some systems e.g. in Austria, is to more than 90 % exported and applied in other countries to products which will be again exported or consumed domestically.

The transfer coefficients for the recycling process show however that the selected heavy metals to a high extent are not removed from the cycle but 77% of the total amount of zinc, 73% of cadmium and 64% of lead, contained in the plastic waste directed for recycling, are transferred to recyclate and re-enter the cycle. This is not consistent with the main goals of waste management, as there is a risk of accumulation of hazardous substances in products from multiple cycles. Morf et al. [191, 192] emphasize the shortage of knowledge regarding the efficiency of recycling processes and the quality of the secondary materials, thus this field requires further investigation.

Besides the abovementioned heavy metals, also other hazardous substances contained in plastic goods are important when analysing recycling process. Among them there are persistent brominated flame retardants (BFRs). Morf et al. [191] investigate the fate of BRFs from plastic waste electrical & electronic equipment. The following substances are considered in this study:

- Pentabromodiphenylether – PBDPE
- Ocatbromodiphenylether – OBPDE
- Decabromodiphenylether – DBPDE
- Tetrabromobisphenol A – TBBPA

The global use of flame retardants has been growing in recent years, which contributed to the increase of the stock of these additives in the anthroposphere. After the life time of the products containing BFRs is over, these substances reach waste management. There is not sufficient information regarding the stock of BFRs in the anthroposphere and its role emission source. SRU [193] emphasize that critical substances, among them BFRs, having burdening influence on human health, should be separated from the cycle and kept away from the environment. The processes of recycling are beneficial from the viewpoint of resources conservation; however, the hazardous substances are neither damaged nor concentrated and removed from the secondary material.

Brominated flame retardants bio-accumulate in organisms and have harmful impact on human health. The authors point out the study of Sjödin et al. [194], in which the results of investigations showed higher concentrations of BRFs in air inside of recycling facilities and in workers' blood. Due to high persistence of these substances, the hazard of accumulation and ubiquitous allocation in the anthroposphere is emphasized [192]. Thus, the treatment of plastic waste containing e.g. BRFs and other persistent hazardous substances requires further investigation.

The present study focuses on the evaluation of the total plastic flows and is not aimed at analysing single fractions, e.g. the abovementioned WEEE and therefore this aspect is not evaluated quantitatively in the study. However, if only a specific plastic fraction containing such persistent hazardous additives was to be analysed from the environmental and human health protection point of view, the issues described above should certainly be considered.

In order to obtain a high quality secondary material only clean waste fraction containing low amounts of hazardous additives should be processed. Substituting the hazardous additives with more environmentally friendly alternatives is also a solution, which is discussed widely, however it is not always possible to be realised at present. The quality control of recyclate is needed in order to guarantee that the hazardous substances from the plastic waste are excluded from the cycle and that only safe, high quality recyclate is produced and applied.

5.2.3.2.4 Product from cement industry in Poland and Austria

The change of mean concentrations of the analysed heavy metals in clinker produced with the use of plastic waste and used tires in comparison to the reference clinker is presented in Table 5-33 (the values with uncertainties are shown in Appendix 4). The respective values are much higher for the Austrian system than for the Polish one. This is a consequence of the fact that for the production of one ton of clinker, six times more of this alternative fuel was used in Austria than in the cement industry in Poland.

Table 5-33 Change of concentration of heavy metals in clinker produced with use of plastic waste and used tires as alternative fuel in relation to reference clinker in Poland and Austria in 2004

	Poland	Austria
	[%]	
Cd	15,3	170,8
Pb	3,6	38,1
Zn	55,3	124,7

Source: own calculations for [150]

Additionally, due to the differences in the shares of plastic waste and end-of-life tires used in the cement industry (in Poland the plastic waste constituted only 22% [177], while in Austria 75% [134]) the change of zinc concentration was the most important in the Polish system (due to a high share of tires, where zinc is contained in higher concentration), on the contrary to the Austrian system where the change of the concentration of cadmium was of greatest importance (as the plastic waste contains more cadmium).

It can be concluded that lower amounts of heavy metals were diluted in the clinker in the Polish system, which is seen as an advantage from the viewpoint of the main goals of waste management.

5.2.3.2.5 Saving of raw materials in Poland and Austria

The amount of recyclate produced per capita in Poland in 2004 was 2,4 kg, while in Austria it was 13,5 kg. The comparison of the resources conservation due to the material recovery calculated in crude oil equivalents is presented in Table 5-34.

Table 5-34 Potential to save crude oil due to recycling of plastic waste in Poland and Austria in 2004

	Crude oil saving	
	[Mg/yr]	[kg/cap.*yr]
Poland	73 000	1,9
Austria	95 000	10,6

Source: own calculations for [150]

The amount of crude oil theoretically saved due to the recycling of plastic waste in Poland constitutes 85 % of the amount saved in Austria. However, per capita it is only around 18 %. Thus, it can be said that the Austrian plastic system fulfils the goal of raw materials conservation to a much higher extent, and in Poland there is still a significant potential for improvement.

5.2.3.2.6 *Saving of energy in Poland and Austria*

The energy recovery from plastic waste is significantly higher in Austria than in Poland. The amount of energy recovered from plastic waste or saved due to its application in cement kilns constituted in Poland in 2004 only around 13 % of the respective value in Austria. The structure of the thermal use of the plastic waste and the energy savings per capita are shown in Table 5-35. The total energy recovery per capita was approx. 40 times higher in Austria.

Table 5-35 Contribution of selected processes to energy recovery from plastic waste in Poland and Austria in 2004

	Poland		Austria	
	kg/cap*yr	%	kg/cap*yr	%
MSW incineration	0,2	18,1	15,4	37,0
Fluidised bed	-	-	17,7	42,4
Cement industry	0,9	81,9	8,6	20,6
Total	1,1	100,0	41,6	100,0

Source: own calculations for [150]

It should be mentioned that the energy recovery in Austria has increased in the recent years in Austria mainly due to the implementation of the new Landfill Ordinance [104]. Ten years before around seven times less plastic waste was thermally treated there.

It may be concluded that the system in Austria fulfils the goal of resource (energy) conservation to a much higher extent than the Polish system where a high potential for improvement still exists. It is also worth noticing that introducing appropriate legal regulations, like the abovementioned ordinance could effectively support this process.

5.2.3.2.7 *Substance concentrating efficiency of Polish and Austrian systems*

The results of the calculation of the SCE are presented in Table 5-36. The SCE_{tot} value for the Polish system is a very small negative number (-0,4%), while the respective value for Austria is nearly 9%. This means that the Austrian plastic waste management system fulfils the goal of resource conservation in this point to a limited extent. The evaluation of the Polish system is negative in this aspect. The analysed substances were not concentrated and disposed of in safe sinks, as they should have been in compliance with the main goals of waste management, but they were even to a very small extent diluted in the system.

Table 5-36 Substance concentrating efficiency in Polish and Austrian systems in 2004

	Poland	Austria
	SCE [%]	
Cd	-0,3	9,5
Pb	-0,5	7,0
Zn	-8,2	-2,9
SCE_{tot}	-0,4	8,9

Source: own calculations for [150]

The abovementioned results may be explained by the following facts:

- In Poland approx. 90% of plastic waste was disposed of in landfill sites without pre-treatment. This process neither contributed to the concentration nor to the dilution of the substances.
- The most important process of energy recovery from plastic waste in Poland was the use in the cement industry, which contributed to the dilution of the substances in the products from the treatment and consequently to the decrease of the SCE_{tot}.
- 46% of the total plastic waste generated in 2004 was treated thermally in MSW incineration plants and fluidised beds in Austria. This contributed significantly to the increase of the substance concentrating efficiency and fulfilling the goals of environmental protection and resource conservation. The use of plastic waste in cement industry caused the decrease of SCE value, however only 12% of total plastic waste was used in cement kilns.

The values of SCE for zinc are negative for both Polish and Austria system. It is related to the fact that end-of-life tires, used as alternative fuel in cement industry, contain a significant amount of zinc, which is diluted in the product of the process (clinker). The SCE values for two other heavy metals are positive for the Austrian system and negative for the Polish one, which is connected with the abovementioned different shares of energy recovery: a high use of plastic waste in incineration plants and fluidised beds in Austria and very low – in Poland. The obtained results show that in Poland there is a high potential for improvement in this area, as energy recovery in incineration plants is almost negligible at the moment.

5.2.3.2.8 *Reduction of volume needed for landfilling in Poland and Austria*

The per capita volumes of the plastic waste and residues from its treatment, which had to be disposed of in landfill sites in 2004, are shown in Figure 5-28. The total volume needed for landfilling was reduced due to the treatment processes by approx. 60% in the Austrian system and by nearly 8% in the Polish one.

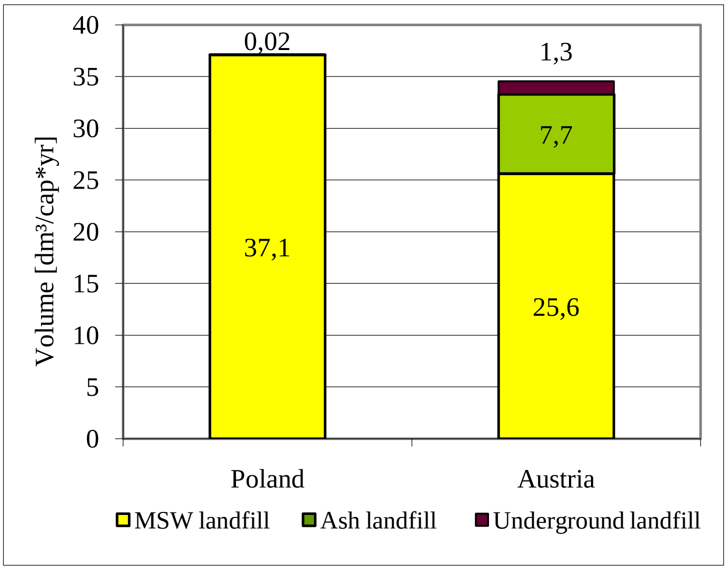


Figure 5-28 Volumes of plastic waste and after-treatment residues landfilled in Poland and Austria in 2004

Source: own calculations for [150]

Based on the results obtained the following conclusions may be drawn: The Austrian system fulfils the goal of space conservation to a much higher extent than the Polish system. The high value for Austria is certainly a consequence of the implementation the new Landfill Ordinance [104] in the year 2004. In Poland there is still a very significant potential for improvement in this respect, as around 90 % of the total plastic waste generated is still disposed of without any pre-treatment.

5.2.3.2.9 *Long-term impacts from landfills in Poland and Austria*

The releases of the selected heavy metals from residues of the thermal treatment disposed of at ash landfills, calculated according to the method of Brunner et al. [159] are presented for both case studies (in values per capita) in Table 5-37 and Table 5-38.

Table 5-37 Behaviour of selected substances in ash landfills in a 100-year period in Poland and Austria

	System	Mass	Landfill body	Leakage water
		[g/cap]		
Cd	Poland	0,001	0,001	0
	Austria	0,8	0,8	0
Pb	Poland	0,1	0,1	0
	Austria	22,4	22,4	0
Zn	Poland	0,1	0,1	0
	Austria	30,5	30,5	0

Source: own calculations for [150]

Table 5-38 Behaviour of selected substances in ash landfills in a 10 000-year period in Poland and Austria

	System	Mass	Landfill body	Leakage water
		[g/cap]		
Cd	Poland	0,0006	0,0004	0,0002
	Austria	0,8	0,5	0,3
Pb	Poland	0,109	0,108	0,001
	Austria	22,4	22,2	0,2
Zn	Poland	0,105	0,101	0,003
	Austria	30,5	29,6	0,9

Source: own calculations for [150]

Due to negligible amounts of plastic waste treated in MSW incineration plants the potential of long-term impacts from ash landfills was in Poland by a few orders of magnitude lower than in Austria.

On the other hand, it must be remembered that around 90 % of the total plastic waste was disposed of at municipal landfills in Poland in 2004 (in Austria only 26 %) and the long-term burden from MSW landfills was significantly higher for the Polish system, however, due to the lack of respective data and approaches for calculation, they are not analysed quantitatively in this study.

5.2.4 Development of plastic waste management in the coming years in Poland

In the new National Waste Management Plan [8] the necessity of expanding the technical infrastructure for collection, e.g. of packaging waste, end-of-life tires, for sorting and recycling of packaging waste and developing the infrastructure for energy recovery from waste is emphasized.

The implemented Directive on Packaging and Packaging Waste [3] waste has already contributed to increased collection and recycling of plastic waste, however, the system of separate collection from households must be improved, as at present the capacities of treatment facilities (estimated as 250 000 Mg) are higher than the amount of the separately collected packaging waste fraction [195]. Thus, the main obstacle for the plastic packaging waste treatment is the insufficient level of its collection. Additionally, the product from recycling is not competitive in comparison with primary material. However, the high crude oil prices, the international markets can also stimulate the increase of profitability of plastic material recovery [196].

It is worth mentioning that in the coming years the collection from households will play a more significant role in the process of obtaining recovery levels required by the directive [80] due to the fact that the available concentrated sources, i.e. industry, trade and services are already fully utilized. The collection from households covers at present only 16% of the total quantity of separately collected plastic waste [196]. The collection from households covers at present only 16% of the total quantity of separately collected plastic waste [196]. Thus, the development of the collection systems from households is crucial and must cover the whole population. However, the higher contribution of household collection will result in the increase of respective costs as it is more cost-intensive to take-back the waste from households than from concentrated sources. Poskrobko et al. [196] assume that the development of the system for collection and recovery will have evolutional character and the mass of packaging waste directed for recycling will increase by 10% per year.

In reference to the thermal treatment it must be stated that the energy recovery from plastics is low in Poland. Poskrobko & Piontek [59] estimate that the realization of the obligations of recovery of packaging waste and reducing the quantities of biodegradable waste disposed in landfills in the period 2006-2020 will require constructing fourteen incineration plants with average annual capacity of 400 000 Mg by the year 2020.

At present only one municipal waste incineration plant with a limited capacity of 100 000 Mg per year exists in Warsaw [195]; and even this capacity is not fully used. The potential of waste incineration in Poland was in 2007 ten times lower than required [59]. It is difficult to estimate the future development of thermal treatment in Poland; however the annual increase rate of 10% for thermal treatment of packaging waste (mainly through co-incineration) is expected [196]. As described in chapter 2.5.1 ten new incineration plants should be built in Poland and begin to operate in 2013 [125], however more detailed information concerning e.g. their capacity is not publically available yet, making the predictions concerning the future development of energy recovery from waste in Poland more uncertain.

Besides the municipal waste incineration plant in Warsaw, the plastic waste is also co-incinerated in ten cement plants. Additionally, some small amounts are thermally treated in incineration plants for medical waste or used as a reducing agent in metallurgic industry; however there is no respective quantitative data. The Polish Cement Association [123] plans to cover, in the long term, 30% of its energy demand for cement production through energy from alternative fuels. At present only 10% of the energy derives from alternative energy sources, 5% of which originates from plastic waste and end-of-life tires. Thus, there is still a potential for the increase of energy recovery from plastic and rubber waste in the cement industry in Poland.

Due to many uncertainties regarding expanding the infrastructure for future treatment of plastic waste and the dynamics of the recovery growth in Poland, it is not easy to foresee how the main goals of waste management will be fulfilled by the Polish system in the coming years. Austria experienced significant changes in its plastic waste management in the period 1994-2004. The development of plastic streams and stocks and the improvement in the waste management practices in this period is analysed and presented in the chapter below. Consequently, based on the Austrian experience, the prognoses from the abovementioned reports and own assumptions, potential future scenarios for Poland for the years until 2014 are proposed.

5.2.4.1 Change in plastic waste management in Austria in the years 1994-2004

Fehringer & Brunner [149] analysed the state-of-art of plastic waste management in Austria in the year 1994. It is worth noticing that it was quite similar to the current situation in Poland. In 1994 only 7% of the plastic waste was recycled there, while 10% was thermally treated and 83% – disposed of in landfills without pre-treatment. In Poland in 2004 the respective values were around 6% - for recycling, 4% - for energy recovery and 90% for landfilling. The comparison of the flows and stocks values regarding consumption, waste generation and its management in Austria in 1994 and 2004 is presented below.

Table 5-39 Comparison of plastic flows and stocks in Austria in the years 1994 and 2004

	1994		2004	
	Total 1000 Mg/yr	kg/cap/yr	Total 1000 Mg/yr	kg/cap/yr
Plastic consumption	1 128	141	1 287	161
Plastics to stock “in use”	405	51	359	45
Total plastics in stock “in use”	7 100	888	11 200	1 400
Plastic waste flow (incl. import-export)	751	94	952	119
Plastic waste flow to recycling	49	6	127	16
Plastic waste flow to energy recovery	71	9	564	71
Plastic waste flow to landfills	589	74	260	33
Total plastic stock in landfills	9 700	1 213	15 500	1 938

Source: based on [149] and own calculations for [20]

It can be seen that in this period:

- the consumption increased by 14%,
- the value of the stock “in use” increased by nearly 60%,
- the quantity of post-consumption waste generated in Austria increased by approx. 27%,
- significant change took place in waste management: the recycling rate increased twice and the energy recovery rate – six times,
- despite the continuous reduction of the quantity of the plastic waste landfilled the values of the stock of waste in landfill sites increased by around 60%.

The improvement of waste management in Austria has been influenced by the implementation of the Packaging Ordinance [100] and the new Landfill Ordinance [104] which contributed to the construction of new waste treatment facilities for the recovery of waste. Assuming that Poland will follow the Austrian experience in the improvement of the system for the treatment of the plastic waste within the next ten years, the separate collection systems must be extended and significant investments in the facilities for both material and especially energy recovery are needed.

5.2.4.2 Scenarios of future plastic waste management in Poland

Poskrobko at al. [196] estimate the increase of packaging amounts for the period 2005-2014 assuming that the yearly growth rate will be similar to the value of 80% of the average yearly growth rate of Gross Domestic Product (GDP) set in the documents of the National Development Strategy [197] for this period. This assumption is based on experiences of the European countries [196]. According to this prognosis the average yearly growth rate of GDP in the period 2006-2010 will amount to 5,1% and in the period 2011-2015 – to 5,2%. Based on the abovementioned information, three yearly plastics consumption growth rates (CR) of 3%, 4% and 5% (60%, 80% and 100% of the GDP growth rate) are assumed for scenarios with less dynamic, moderate and more dynamic growth of plastic consumption.

It should be added that an especially dynamic growth of plastic consumption was observed in Poland in the middle of 1990s, while since 2001 it has been more stabilised and decreased slightly from the yearly growth rate of 7% to 6% in 2004. The values assumed in this study are lower, however the consequent saturation of the market is assumed to occur in the future and no such dynamic growth as in the previous years is expected. The same process was also observed in plastics consumption pattern in Austria in the recent years.

Based on the MFA model for total plastic flows used in the previous part of the study, applying calculations with time series, including the estimation of the mass of plastic goods accumulated in and discarded from the stock “in use”, the quantities of waste for each of the scenarios for the period 2005-2014 are calculated. The results concerning the amounts consumed and the quantities of post-consumption waste generated are presented in Figure 5-29.

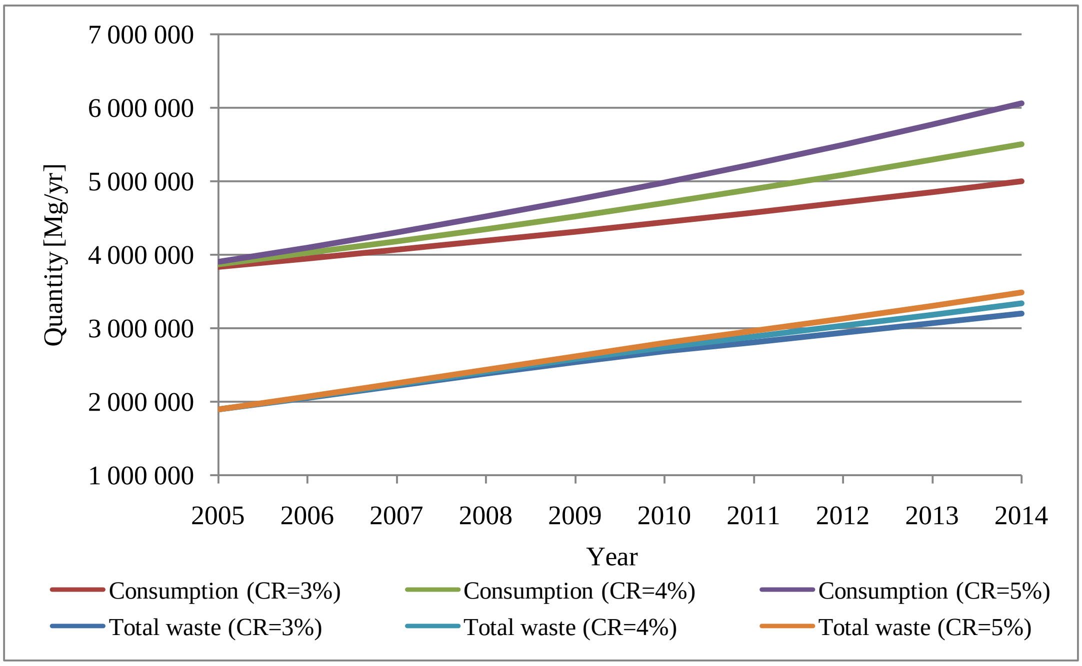


Figure 5-29 Estimated consumption and waste generation in Poland in the years 2004-2014 calculated the application of three assumed yearly consumption growth rates, Source: own calculations

The amounts of plastics consumed and waste generated in 2014 obtained for each of the scenarios are presented in Table 5-40.

Table 5-40 Estimated quantities of plastics consumed and waste generated in Poland in 2014

Yearly consumption growth rate	Consumption	Total waste
	[Mg/a]	
3%	5 002 600	3 204 900
4%	5 510 000	3 341 600
5%	6 063 400	3 487 600

Source: own calculations

It is worth noticing that the increase of plastics consumption does not result in an equal increase of the quantity of waste generated in the analysed period. This is a consequence of a delay in discarding the waste from the stock "in use" (the growing amounts of long-living products consumed in this period will become waste in later years, thus increasing waste generation may be expected in the future even when the consumption level will not increase anymore or will even decrease). Elshkaki et al. [198] defined the outflow from the stock due to discarding by the following equation:

$F^{out}(t) = F^{in}(t-L)$ (11)

Where:

$F^{out}(t)$ - is the outflow of goods at time t,

F^{in} - is the inflow of goods,

L - is the life span.

It is emphasized that the delay is determined by the life span of the products [198].

In the following study the discarding of products from the stock “in use” is quantified with the use of Matlab simulation. Based on the results for waste generation, which doesn’t differ much for each of the analyzed consumption growth rates (the quantitative results obtained for the more and less dynamic growth rates compared to the moderate growth rate do not exceed ±6%) only the scenario assuming the yearly consumption growth rate of 4% is used in the further analysis.

The following scenario types are chosen in the study [199]: Business As Usual (BAU) scenario, which is related to the situation where the waste management practices are conducted according to the status quo, with no attempt to improve and implement any changes in the current system; and Mitigation (MIT) scenarios, where additional actions are undertaken in order to improve the situation of plastic waste management in the future, thus contributing to the annual increase of the plastic waste amounts mechanically and thermally treated. These actions include the expansion of the infrastructure for separate collection and consequent increase of recycling, broadening the use of plastic waste as alternative fuels e.g. in cement industry, developing the infrastructure for energy recovery from plastic waste.

The following scenarios with assumed recovery rates are defined for the period 2005-2014:

- BAU scenario – no significant investments in the development of the infrastructure for collection and treatment of the plastic waste occur, thus the growth rates of recycling and energy recovery are the same as in the year 2004: the recycling rate remains at the level of 6% of the total amount of waste generated in Poland, the energy recovery remains at the level of 4%, and the rest of the plastic waste is land-filled.
- MIT1 scenario – yearly recycling growth rate of 4% and yearly energy recovery growth rate of 10%,

- MIT2 scenario – yearly recycling growth rate of 6% and yearly energy recovery growth rate of 15%,
- MIT3 scenario – yearly recycling growth rate of 8% and yearly energy recovery growth rate of 20%.

The estimated quantities of plastic waste recycled and thermally treated in the abovementioned scenarios are shown in Figure 5-30 and Figure 5-31.

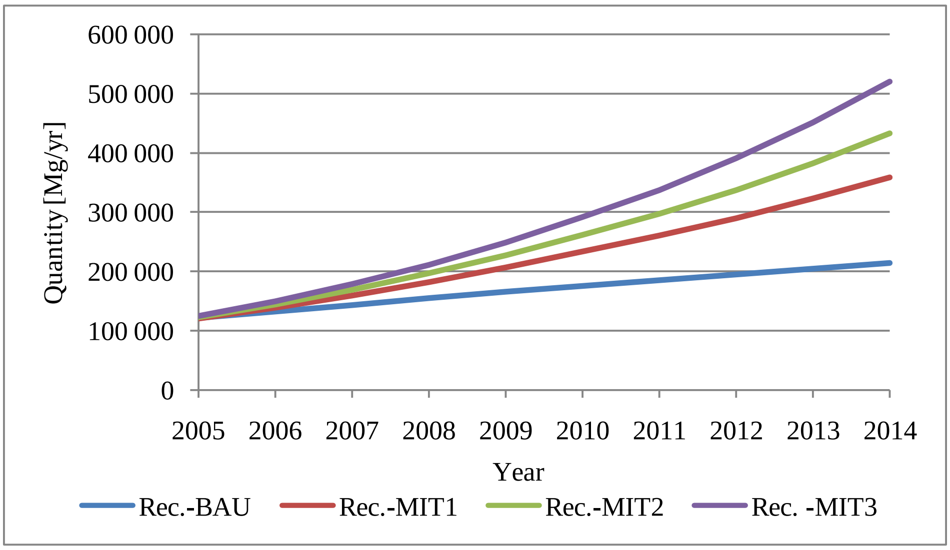


Figure 5-30 Estimated quantities of plastic waste recycled in the analysed scenarios in Poland in 2005-2014
Source: own calculations

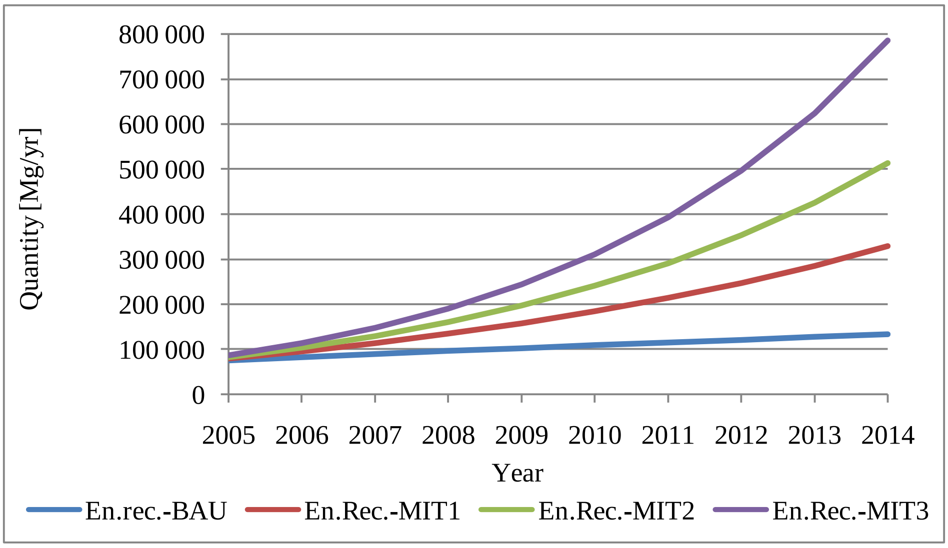


Figure 5-31 Estimated quantities of plastic waste thermally treated in the analysed scenarios in Poland in 2005-2014, Source: own calculations

Consequently, the amounts of post-consumption waste which are still directly land-filled for each scenario are calculated. Additionally, the situations where recycling growth develops more dynamically than energy recovery or the opposite are analysed combining all assumed yearly recycling growth rates (RR) and yearly energy recovery growth (ERR) rates (scenarios MIT4-MIT9). The results obtained are presented in Figure 5-32.

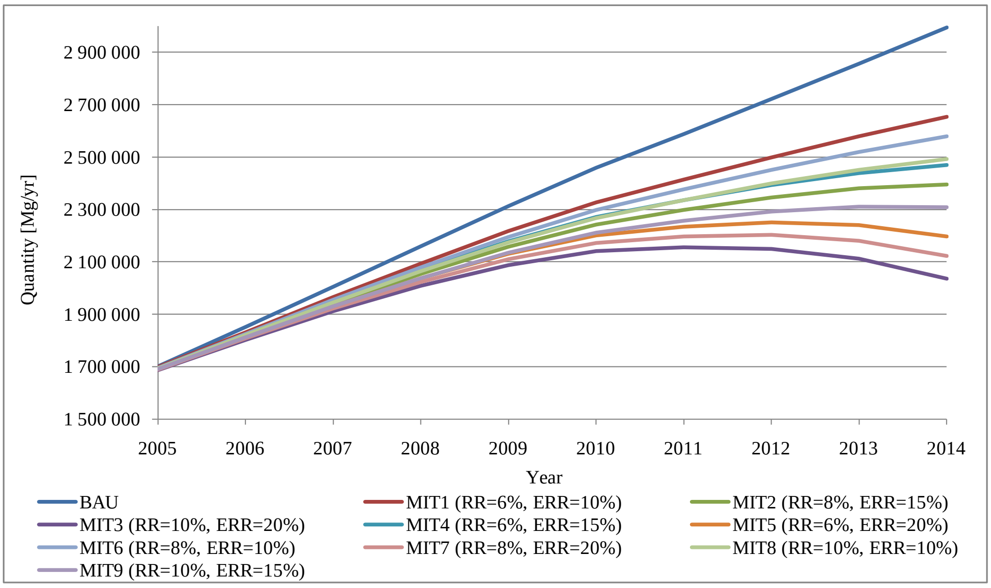


Figure 5-32 Quantities of plastic waste landfilled in the analysed scenarios in Poland in 2004-2014
Source: own calculations

The most optimistic scenario MIT3 results in the amount of non-pre-treated pos-consumption plastic waste disposed directly in landfill sites, which will amount to around 2 Mio. Mg in the year 2014, while the less optimistic BAU scenario results in the respective value amounting to nearly 3 Mio. Mg. Both of those values are above the current values for the disposal of the plastic post-consumption waste in Polish landfills, due to the increasing consumption and consequently growing waste amounts, and because of the increasing discarding of goods with long life spans (consumed already years ago) from the stock "in use".

The analysis of the results obtained shows that in the case of the highest assumed yearly recycling growth rate of 8% the material recovery level exceeds in Poland in 2014 the level which Austria had in 2004 (14%). However, in reference to energy recovery, even at the highest assumed yearly energy recovery growth rate only 24% of the total plastic waste would be thermally treated in Poland in 2014, which is significantly below the value obtained in Austria in 2004 (60%). The respective results for the four main analysed scenarios are shown in Table 5-41. More detailed results for the calculations of the future scenarios for Poland are presented in Appendix 7.

Table 5-41 Comparison of recycling and energy recovery rates in future scenarios for plastic waste management in Poland in 2014

	Share [%] of total plastic waste:	
	recycled	thermally treated
BAU	6	4
MIT1	11	10
MIT2	13	15
MIT3	16	24

Source: own calculations

Summarizing this simplified future scenario analysis for the development of the Polish plastic waste management in the coming years, it is evident that in the case of recycling, approaching the level of material recovery similar to the current level in the Austrian system can be achieved by extending the separate collection, sorting and recycling infrastructure in the way that the yearly recycling growth rate amounts to 8%. In reference to the energy recovery much more effort must be made in order to reach the recovery levels comparable to the values for the Austrian system. Constructing the aforementioned, ten new incineration plants until the year 2013 could effectively contribute to the improvement of this situation, however at present, the increased use of plastic waste in cement industry seems to be the main solution for the improvement of the level of energy recovery from this waste in Poland, and thus the values for thermal treatment of plastic waste are expected to stay much below the levels of more advanced, in this respect, European countries until these new waste incineration plants are in operation.

5.3 Uncertainty analysis

Uncertainties in the following study concern the models used and the assumptions applied to them, the input data for calculations, and in consequence, the results obtained. As mentioned in the goal and scope of the study, the analysis covers the total plastic flows and the flows of waste on a national level in both analysed countries. It means that a highly aggregated approach is used in the study in order to give an overview of the state-of-art of plastic waste management in the analysed systems and that the study is not focused on any specific product fractions. Due to the abovementioned issues the results obtained should be treated as approximate ones.

5.3.1 Uncertainty in MFA

The quality of data used in the MFA studies to quantify flows and stocks differs very often [200] due to the fact that some data originates from official statistics and other is based on actual measurements (e.g. concentration of a substance in a good or material) or estimations (e.g. structure of consumption). Additionally, data from various sources is often combined and used together in order to quantify values which are not available. Seyhan [201] notices that one of the problems in evaluating the uncertainty in material flow analyses are related to the fact that many mass flow data are recorded as single values (e.g. in statistics) and evaluation of its uncertainty range is not easy, if possible at all. Estimating uncertainty for data on e.g. substance concentrations is usually easier, as normally it is available in literature sources as records of analytical measurements. Thus, the "uncertainty in MFA arises from dealing with uncertain or conflicting data, variability of certain flows or concentrations, and unaccounted flows, which can only be roughly estimated" [201]. It can diminish the value of the MFA interpretation as the initial uncertainties are spread throughout the whole system leading to uncertain results [202].

Therefore, the handling of uncertainties is important while conducting the MFA studies. There are several methods that can be applied to carry out this task. If uncertainties of input variables are given, the Gauss's Law can be used under condition that the variables are distributed normally and the uncertainties are small. Another method, which can also be used for other distributions and higher uncertainties, is the Monte Carlo simulation [202]. The sensitivity analysis constitutes another approach [203]. In this method the estimation of the influence of one parameter on the value of other parameters is evaluated. Hedbrandt & Sörme [204] proposed a method to deal with data with unknown uncertainty in the MFA. In this approach the source of singular data is used to assign an uncertainty interval to the data (as presented in Table 1). The probability of comprising the actual value by the interval is 95% [205].

Table 5-42 Uncertainty intervals with information sources

Level	Information source
1 (interval */1,1)	official statistics, measurements
2 (interval */1,33)	official statistics on national/regional level experts' information
3 (interval */1,5)	modelled data for municipality information on request from authorities
4 (interval */2)	official statistics on national level downscaled to local level information on request from authorities, estimations
5 (interval */4)	information on request values in general for flows (from literature)

Source: based on [204]

5.3.2 Uncertainty sources in the study

In this chapter the sources of potential uncertainties are described and the approach for uncertainty assessment used in the study is presented.

Due to limited availability of quantitative data of some material flows the assumptions had to be made in order to conduct the calculations for the total flows of plastics in the analysed systems. The assumptions concern the following aspects:

- share of waste resulting from production of plastic goods,
- contents of plastic materials in various groups of goods,
- life spans of plastic goods,
- shares of recycled material exported or used at domestic market.

The input data used for the first MFA calculation originates mainly from the official statistics for imports, exports and production of both, polymers and polymeric products. The data concerning various groups of polymers and their products are summed up respectively to obtain values for the total flows of them. In order to calculate the stock values, the data were collected for Poland for the period of 1960-2004 and for Austria for the years 1995-2004 (as the previous data were available from Fehringer & Brunner [77]).

It should be mentioned that within the analysed periods the statistical classifications were changed several times, which required additional adjustments in order to obtain the needed total values. Moreover, in some periods some data was confidential and the estimations based on the available data from previous and later years had to be used together with the estimation of the annual growth of e.g. production of a given polymer.

Due to the scarcity of data and information, also in the second system model (concerning the waste management of plastic streams) assumption had to be made, e.g. in reference to the way of disposal of after-treatment residues. In this part of the study, besides the calculated waste flows values and related uncertainties, data from available literature sources concerning transfer coefficients for the analysed processes and concentration values for the selected substance in the plastic waste is used.

The abovementioned data shortage and the assumptions used contribute to the uncertainty of the results obtained the final stage of the study. However, site- and process-specific data is, in many cases, not available at all (e.g. transfer coefficients for the analysis of the processes in the Polish system), or is not publically accessible (e.g. some data on produced polymers are confidential). Additional difficulties refer to the quality of data concerning the treatment of waste in Poland. Little data is available on recycling or energy recovery of specific waste groups, e.g. reports concerning packaging waste recycling and recovery have been conducted in Poland only since 2002 and values for the year 2006 were published by the EC in summer 2008 first. Moreover, the Ministry of Environment [117] emphasizes some problems with data reporting related e.g. to double counting of amounts recycled or lack of reporting activities from some, especially smaller companies, however the quality of reported data is expected to improve recently.

Thus, it should be explicitly emphasized that the results obtained must be regarded as approximate, showing the overall situation of the waste management of plastics in the analysed countries, Poland and Austria, presenting weaknesses or issues of concern and consequently – potentials for improvement, but not very accurate values. However, despite the abovementioned uncertainty sources the results obtained in the study characterise the state-of-art of waste management in both countries and allow for drawing general conclusions about the analysed environmental aspects. Nevertheless, if exact results concerning specific plastic waste fraction were needed then product-, process-, and/or location-specific data would be necessary.

5.3.3 Uncertainty calculation in the study

The uncertainties in this study are calculated in reference to the following issues:

- flows of goods and analysed substances,
- estimation of values for stocks "in use" and quantities of post-consumption waste (depending on the assumed life spans) associated with them,
- evaluation of chosen environmental issues (related to the uncertainties of the waste flows directed to various treatment and disposal processes).

For the calculation of the flows of goods in the MFAs of total plastics to each input data, which comes mainly from the official statistics (being either a singular number or deducted from summing up all the quantities in respective category, e.g. import of various polymer types) an uncertainty range is assigned, based on the modified approaches of Hedbrant & Sörme [204] presented in Table 5-43. The calculations of the results and related uncertainties are conducted using STAN software.

Table 5-43 Used uncertainty intervals depending on information source

Information source	Uncertainty range (with 95% confidence interval)
official statistics	± 10%
official statistics on regional level experts' information information on request from authorities	± 30%
estimations from literature*	± 50%

* concerning the share of production waste

In the calculation of the analysed substances in waste management systems the values from the first MFA (mean waste values including calculated uncertainties) and the literature concentration values (with estimated uncertainty ranges) are used for calculations, using again STAN software. The results obtained (including uncertainties) are used together with the literature data concerning analysed environmental aspects (e.g. heating values of conventional and alternative fuels, energy demands for primary production and for recycling, densities of plastic waste and after-treatment residues or efficiencies of the processes of energy recovery from waste) in the evaluation part of the study. The estimation of the uncertainty of discarding the goods from stocks "in use" has been calculated comparing the results obtained in the calculation with the use of average life spans with the situation described as follows: it is assumed that 50% of the goods leave the stock at the average life span; the rest leaves the stock within assumed ranges of years, as given in Table 5-44. The assumed shares of the total amount consumed in a given year and discarded before and after the average life span is over are presented in Table 5-45 (the value in bold indicated the value of average life span). The uncertainty results obtained for the analysed period showed a mean difference of ±3% from the reference situation, which does not influence the results of the evaluation to a significant extent.

Table 5-44 Average life spans and assumed ranges for discarding of plastic goods from the stock "in use" before and after reaching the average life span

Application field	Average life span [years]	Uncertainty range [years]
Packaging	< 1	0
Construction	30	± 10
Automotive	15	± 5
Electrical eng.	30	± 10
Household goods	5	± 2
Furniture	15	± 5
Agriculture	3	± 1
Medical Equipment	<1	0
Non-plastic applications	10	± 3
Other	5	± 2

Source: own assumptions

Table 5-45 Shares of the plastic good discarded from the stock "in use"

Average life span	Deviation	Shares of the plastic good flows discarded from stock "in use" before and after reaching the average life spans [%]																				
[years]																						
3	± 1	25	**50**	25																		
5	± 2	10	15	**50**	15	10																
10	± 3	5	8	12	**50**	12	8	5														
15	± 5	1	3	5	7	9	**50**	9	7	5	3	1										
30	± 10	1	1	2	2	2	3	3	3	4	4	**50**	4	4	3	3	3	2	2	2	1	1

Source: own assumptions

The results of uncertainty analysis have been shown in all MFA diagrams (in the text the average values are presented) and when discussing the chosen singular results obtained in the evaluation step.

6 Conclusions

The proposed procedure for the evaluation of plastic waste management systems has been applied to compare two systems at the national level, taking into account the environmental and resource conservation issues. The input data used in the study includes mean values, e.g. concentrations of analysed substances in plastic waste, or data originating from the national statistics (for MFA studies), often available as singular numbers only. Additionally, a range of assumptions had to be made in situations where respective data was not accessible. Therefore, the results obtained should be treated as approximate but appropriate to give an overview of the evaluated systems. However, in the case of the evaluation of any specific plastic waste fraction, e.g. from waste electric & electronic appliances, containing higher amounts of hazardous substances, more specific data is necessary.

Based on the results obtained in the study the following conclusions have been drawn:

1) The Polish plastic waste management system does not comply, to a significant extent, with the main goals of waste management: the protection of human being and the environment, conservation of resources and after-care free landfills.
2) There is a significant potential for improvement in this system, particularly in reference to directing the hazardous substances contained in plastic waste to appropriate sinks.
3) Large amounts of valuable material and energy resources from plastic waste are not recovered in Poland and the quantity of waste which requires landfilling is not reduced a lot through waste treatment practices.
4) The Polish system is evaluated as superior to the Austrian system with regards to the aspects of air emissions and the growth of concentration of hazardous substances in products from cement industry. This is a consequence of the fact that very small amounts of plastic waste undergo thermal treatment in Poland in comparison to the system in Austria.
5) The Austrian plastic waste management system fulfils the goals of material and energy recovery to a much higher extent than the Polish system. It also performs

better, although to a limited extent, with regards to the substance concentrating efficiency and in directing the analysed substances to the appropriate sinks.

6) The Austrian system has improved a lot within the last decade, mainly due to the implementation of the new regulations on waste: Landfill Ordinance and Packaging Ordinance. This process is expected to continue, as e.g. new thermal treatment plants are under construction or ready to operate.
7) In general, trade-offs between various evaluated aspects have been noticed while conducting the assessment. An increase of energy recovery from waste allows for saving valuable energy sources and contributes to a higher concentration of the hazardous substances and directing them towards appropriate sinks, but on the other hand, results in increased air emissions.
8) Mechanical recycling allows for the conservation of resources for primary production (which results in a consequent limitation of related emissions from raw materials extraction and polymers production), but the fate and burdens related to some hazardous substances contained in plastic waste, e.g. briminated flame retardants, in products from recycling should be taken into consideration.
9) Mechanical recycling is advisable for clean, homogenous waste fractions but it can only cover a part of the plastic waste treatment. Therefore, an integrated system, which covers both recycling and energy recovery, and last but not least, proper landfill sites where the waste which cannot be recycled or thermally treated and the residues from thermal treatment processes can be safely disposed of with appropriate aftercare ensured, should be implemented in Poland.
10) There is a high demand for plastic waste treatment facilities and collection infrastructure, especially with regards to separate collection from households in Poland, since this is the main bottle neck for material recovery in this system. The existing capacities exceed the possibilities of supplying sufficient amounts of waste material for recovery.
11) The development of separate collection infrastructure should be followed by expanding the recycling facilities in order to fulfil the future requirements of the Packaging and Packaging Waste Directive in Poland.
12) The development of the facilities for energy recovery is indispensable in the upcoming years, in order to divert large quantities of plastic waste from landfills.

Ten projects concerning those investments are being currently reviewed by the Polish Ministry of Environment, providing an insight into the future strategy of Polish policymakers regarding the development of this system.

13) The growth of energy recovery share in recent years has been observed not only in Austria, but also in the main West European countries, in parts of which a complete ban for landfilling has been gradually introduced, which is consistent with the EU regulations concerning the reduction of quantities of waste disposed of there.

14) The process of expanding the energy recovery from waste is expected to follow in Poland as well. However, a proper information campaign for the society is needed in order to enhance the social consciousness about real advantages and disadvantages of thermal treatment.

15) The implementation of legal acts similar to the Austrian Landfill Ordinance could effectively support the process of the development of plastic waste management towards the set goals in Poland.

Based on the results obtained in the study, future scenarios for plastic waste management in Poland have been proposed. However, due to the lack of appropriate data concerning the costs and revenues related to the waste management of plastics in Poland, and especially due to the reluctance of companies dealing with plastic waste recovery to enable access to their data, the study is limited to the environmental evaluation and the economic aspects are barely touched, but the appropriate costs analysis could not be conducted.

New aspects of this study include a better understanding of the state-or-art of the total flows of plastics in Poland, including the aspects of accumulation of goods in the stock “in use” and the delayed discarding of products from it, and a comprehensive evaluation of the total plastic waste management in Poland with the use of the material flow analysis (MFA) method, which could be effectively applied as a tool for the analysis of other waste fractions supporting decision makers in the processes of developing holistic, integrated waste management systems.

It may be concluded that there are many challenges for policymakers, municipalities, recycling and recovery companies and other responsible entities in the field of adjusting the plastic waste management in Poland so that it complies with the main goals of waste management and the requirements of the sustainable development, nevertheless the first steps have been already taken. The proposed evaluation procedure, based on the material flow analysis, and aided by the experience from other countries could support the future planning and development of the appropriate plastic waste management in Poland.

Summary

This PhD thesis, aimed at evaluating the state-of-art of plastic waste management in Poland by use of a proposed goal-oriented procedure based on material flow analysis, should aid future development of appropriate system directed towards fulfilling the main goals of waste management. It ought to ensure insight into weaknesses of the current plastic waste disposal and indicate potential for improvement. In order to fulfil this goal also a more advanced Austrian system has been compared with the Polish one.

Firstly, the general issues concerning plastic waste have been presented and methods for its treatment have been described. The further part concerns the legal situation related to plastic waste management and consequently, various systems and strategies applied in different European countries.

In the second part of the study the total flows of plastics in the analysed countries are quantified and the respective waste management systems are evaluated taking into consideration the aspects of environmental protection and resource conservation. The results obtained show that great efforts must be made in aim to adjust the Polish plastic waste management system, in which still above 90% of waste is disposed of without any pre-treatment in landfills, to the challenges of modern environmental policy and the requirements of sustainable development.

The analysis of future scenarios for Poland illustrate how important is a prompt dynamic expanding the existing recovery infrastructure, especially in reference to thermal waste treatment, in order to create in the coming years a system similar to the systems of more advanced, in this respect, countries, consistent with the emerging European Union regulations and able to divert the constantly growing amounts of plastic waste from landfills.

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Electronic appendix

Appendix 1 Concentration of chosen substances in plastic waste and used tires

Table 6-1 Concentration of carbon in plastic waste and used tires

	Concentration [mg/kg]	Source
Plastic non-packaging waste	760 000	[149]
	701 000	[166]
Plastic packaging waste	810 000	[149]
	696 000	[166]
Used tires	500 000	[158]

Table 6-2 Concentration of chlorine in plastic waste and used tires

	Concentration [mg/kg]	Source
Plastic non-packaging waste	5 250	[206]
	17 000	[151]
	27 000	[151]
	41 000	[149]
	10 090	[158]
	11 700	[158]
	10 800	[156]
	18 800	[166]
Plastic packaging waste	2 400	[149]
	11 200	[166]
Used tires	2 000	[158]
	8 000	[158]

Table 6-3 Concentration of cadmium in plastic waste and used tires

	Concentration [mg/kg]	Source
Plastic non-packaging waste	1,8	[206]
	36,0	[151]
	50,0	[151]
	50,0	[149]
	6,0	[158]
	1,3	[158]
	6,0	[156]*
	21,7	[166]
	9,7	[29]*
	9,6	[29]*
	23,1	[207]
	35,6	[153]*
Plastic packaging waste	21,0	[149]
	15,9	[166]
	0,9	[29]*
	0,5	[29]*
	1,3	[29]*
	1,8	[153]*
Used tires	8,0	[158]
	5,0	[156]*
	7,0	[207]
	5,1	[153]*

*mean value

Table 6-4 Concentration of lead in plastic waste and used tires

	Concentration [mg/kg]	Source
Plastic non-packaging waste	28	[206]
	650	[151]
	90	[151]
	450	[149]
	92	[158]
	94	[158]
	92	[156]*
	359	[166]
	206	[29]*
	221	[29]*
	92	[207]
	427	[153]*
Plastic packaging waste	250	[149]
	234	[166]
	150	[153]*
	51	[29]*
	82	[29]*
	109	[29]*
	219	[29]*
Used tires	70	[158]
	250	[156]*
	70	[207]
	382	[153]*

* mean value

Table 6-5 Concentration of zinc in plastic waste and used tires

	Concentration [mg/kg]	Source
Plastic non-packaging waste	82	[206]
	540	[151]
	700	[151]
	700	[149]
	114	[158]
	95	[158]
	114	[156]*
	317	[166]
	949	[29]*
	960	[29] *
Plastic packaging waste	580	[149]
	440	[166]
	768	[29]*
	558	[29]*
	875	[29]*
	730	[29]*
Used tires	16000	[158]
	16 000	[156]*
	3000	[153]*

* mean value

Appendix 2 Reference values used for calculation of critical air volume

Table 6-6 Immission threshold values used for calculation of critical air volume

	Immission threshold values [µg/m³]*	Source
HCl	100	[208]
Cd	0,04	[209]
Pb	0,5	[210]
Zn	100	[211] cited in [158]

Table 6-7 Geogenic reference values used for calculation of critical air volume

	Geogenic reference values [µg/m³]	Source
HCl	0,1	[212] cited in [156]
Cd	0,0002	
Pb	0,02	
Zn	0,05	

Appendix 3 Evaluation of substance concentrations in product from cement industry

Due to the lack of the data on the consumption of energy by the Austrian cement industry in 2004 the proportion of use of conventional fuels from the year 2003 [134] is used in the calculation, as no significant changes are expected to occur in this respect within one year in Austria (see Table 6-8). Due to scarcity of the respective information for Polish cement industry and relying on information from Polish Cement Association [177] it is assumed that only hard coal is used as conventional fuel in 2004 in Poland

Table 6-8 Consumption of conventional energy carriers in cement industry in Austria in 2003

	Mass [Mg/yr]/[1000 m3]
Hard coal	70500
Brown coal	56800
Petroleum coke	50100
Light fuel oil	550
Heavy fuel oil	11500
Natural gas	8600
Total	198050

Source: [134]

Concentration of selected substances in raw materials and conventional fuels is presented in Table 6-9 and in alternative fuel in Table 6-10.

Table 6-9 Substance concentration in raw material mix and conventional fuels

	Concentration [mg/kg]				
	Raw materials	Hard coal	Brown coal	Petroleum coke	Heavy fuel oil
Cd min	0,03	0,1	0,1	0,04	0,02
Cd mean	1,0	1,0	0,3	1,0	1,0
Cd max	0,15	10,0	2,4	3,0	2,0
Pb min	1,7	10	1	6	1
Pb mean	15	80	5	50	10
Pb max	42	250	9	102	34
Zn min	10	20	1	16	2
Zn mean	37	85	25	100	20
Zn max	108	200	70	220	80

Source: [156]

Table 6-10 Substance concentration in alternative fuel

	Concentration [mg/kg]	
	Plastic waste	Used tires
Cd min	13,23	5,8
Cd mean	25,7	6,5
Cd max	38,07	7,3
Pb min	241,6	146
Pb mean	464	226
Pb max	686	305
Zn min	653	6184
Zn mean	770	9500
Zn max	887	12816

Source: own calculation based on review of available literature

Table 6-11 Concentration of selected substances in clinker produced with use of only hard coal and with partial substitution of coal by plastic waste and used tires in the Polish system in 2004

	Concentration in clinker [mg/kg] produced with	
	Hard coal	Conventional fuels
Cd min	0,12	0,17
Cd mean	0,4	0,5
Cd max	2,8	2,86
Pb min	7,0	8,0
Pb mean	36,9	38,2
Pb max	100,2	101,3
Zn min	29,4	59,0
Zn mean	81,1	126,0
Zn max	209,3	269,1

Source: own calculations for [150]

Table 6-12 Concentration of selected heavy metals in clinker produced with use of only hard coal, current primary fuel mix and with partial substitution of primary fuels by plastic waste and used tires in Austrian system in 2004

	Concentration in clinker [mg/kg] produced with		
	Hard coal	Conventional fuels	Addition of pl. waste and used tires
Cd min	0,05	0,14	0,5
Cd mean	0,2	0,4	1,1
Cd max	1,7	2,32	3,2
Pb min	2,8	7,5	15,0
Pb mean	24,8	34,0	47,0
Pb max	69,6	87,3	104,4
Zn min	16,2	31,8	103,9
Zn mean	60,2	82,6	185,7
Zn max	175,3	208,6	341,5

Source: own calculations for [150]

Transfer coefficients for substances originating from raw material mix and fuels are presented in Table 6-13.

Table 6-13 Transfer coefficients for substances originating from raw material mix to clinker

	Cl	Cd	Pb	Zn
for subst. originating from raw material	0,9654	0,9997	0,9993	0,9997
for subst. originating from fuel	0,9889	0,9998	0,9996	0,9999

Source: [156]

Heating values of conventional and alternative fuels used in the study are presented in Table 6-14 and Table 6-15.

Table 6-14 Heating values of conventional energy sources

	Heating value [MJ/kg],[MJ/m3]	Source
Hard coal	29,7	[156]
Brown coal	21,9	
Petroleum coke	31,6	
Light fuel oil	41,4	
Heavy fuel oil	40,7	
Natural gas	36,3	

Table 6-15 Heating values of alternative energy sources

Waste fraction	Heating value [MJ/kg]	Source
Plastic waste	30	[207]
	ca. 25-35	[213]
	27	[164]
	26,5	[134]
Used tires and rubber waste	28	[207]
	ca. 25-35	[213]
	31	[214] cited in [215]
	26,3	[134]

*the values given by Mauschitz [134] are used in the calculations

Appendix 4 Input data for evaluation of aspects of resource conservation

Energy demand for the primary plastic production is shown in Table 6-16.

Table 6-16 Average energy demand for production of virgin plastics

	Energy demand [MJ/kg]
PE	64,6
PET	59,4
PMMA	77,7
PS	70,8
PUR	78,0
PVC	53,2
PA6	122,7

Source: [161]

Data concerning efficiency grades of energy recovery from is shown in Table 6-17.

Table 6-17 Average eefficiency grades of energy recovery processes

	Efficiency grade	Source
MSWIP (only electricity production)	20%	[158]
	20%	[167]
	25%	[166]
MSWIP with combined heat and power generation (CHP)	80% (68%-electr.,12%-heat)	[166]
District heat plant	70-80%	[158]
Industrial recovery - fluidised bed	80%	[167]
	80% (ca. 20%-electr., 60% process heat)	[158]

Data concerning densities of plastic waste and after-treatment residues are shown below:

Table 6-18 Densities of plastic waste and after treatment residues

Input to landfill	Density [t/m³]	Source
Plastic waste in MSW landfill	0,75*	[149]
After-treatment residues (ash)	1,5*	[216]
	1,7	[158]
	1,4	[217] cited in [159]
	1,4-1,7	[218] cited in [159]
Filter cake and filter ash in underground landfill	2,1*	[219] cited in [159]

* values used in the calculations

Appendix 5 Selected results from MFAs for total plastics

Table 6-19 Production of plastics in Poland in 1960-1990

Production in Poland	1960	1965	1970	1975	1980	1985	1989	1990
	[Mg/yr]							
Polymers	76 000	118 000	269 000	431 000	549 000	603 000	846 000	627 000
Semifinished products + products	n.d.	n.d.	n.d.	n.d.	n.d.	998 000	794 000	743 000
Total	76 000	118 000	269 000	431 000	549 000	1 601 000	1 640 000	1 370 000

Source: own calculation based on statistical data for [20]

Table 6-20 Production of plastics in Poland in 1995-2004

Production in Poland	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
	[Mg/yr]									
Polymers	735 000	953 000	1 171 000	1 390 000	1 608 000	1 826 000	1 877 000	1 929 000	1 980 000	2 030 000
Semifinished products + products	1 150 000	1 203 000	1 366 000	1 166 000	1 187 000	1 186 000	1 145 000	1 144 000	1 403 000	1 554 000
Total	1 885 000	2 156 000	2 538 000	2 555 000	2 795 000	3 012 000	3 023 000	3 073 000	3 383 000	3 585 000

Source: own calculation based on statistical data for [20]

Table 6-21 Import of plastics to Poland in 1960-1990

Import to Poland	1960	1965	1970	1975	1980	1985	1989	1990
	[Mg/yr]							
Polymers	n.d.	17 000	26 000	118 000	157 000	97 000	105 000	55 000
Semifinished products + products	48 000	78 000	74 000	344 000	584 000	548 000	530 000	512 000
Total	48 000	94 000	100 000	462 000	740 000	644 000	635 000	567 000

Source: own calculation based on statistical data for [20]

Table 6-22 Import of plastics to Poland in 1995-2004

Import to Poland	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
Polymers	419 000	559 000	699 000	839 000	979 000	1 120 000	1 308 000	1 496 000	1 684 000	1 872 000
Semifinished products + products	476 000	568 000	661 000	754 000	847 000	939 000	1 056 000	1 172 000	1 289 000	1 405 000
Total	895 000	1 127 000	1 360 000	1 593 000	1 826 000	2 059 000	2 364 000	2 668 000	2 973 000	3 277 000

Source: own calculation based on statistical data for [20]

Table 6-23 Export of plastics from Poland in 1960-1990

Export from Poland	1960	1965	1970	1975	1980	1985	1989	1990
	[Mg/yr]							
Polymers	0	6 000	21 000	3 000	14 000	77 000	119 000	221 000
Semifinished products + products	1 000	21 000	20 000	100 000	156 000	187 000	203 000	218 000
Total	1 000	27 000	40 000	103 000	170 000	264 000	321 000	439 000

Source: own calculation based on statistical data for [20]

Table 6-24 Export of plastics from Poland in 1995-2004

Export from Poland	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
	[Mg/yr]									
Polymers	161 000	212 000	264 000	315 000	366 000	418 000	445 000	472 000	500 000	527 000
Semifinished products + products	249 000	320 000	391 000	462 000	534 000	605 000	742 000	880 000	1 017 000	1 155 000
Total	410 000	532 000	655 000	777 000	900 000	1 023 000	1 188 000	1 352 000	1 517 000	1 682 000

Source: own calculation based on statistical data for [20]

Table 6-25 Estimation of values of stocks "in use" and in landfills in Poland in 1960-1990

	1960	1970	1975	1980	1985	1990
	[Mg/yr]					
Consumption	162 000	380 000	844 000	1 148 000	1 009 000	700 000
Waste generated (incl. production waste)	35 000	157 000	337 000	564 000	680 000	712 000
Annual change of stock "in use"	128 000	223 000	507 000	584 000	329 000	-12 000
Stock "in use" [Mg]	128 000	1 822 000	3 857 000	6 643 000	8 786 000	10 233 000
Annual material recycling	0	0	0	0	0	0
Annual thermal treatment	0	0	0	0	0	0
Total treatment	0	0	0	0	0	0
Annual landfilling	35 000	180 000	370 000	609 000	730 000	749 000
Stock in landfills [Mg]	35 000	1 062 000	2 467 000	5 013 000	8 433 000	12 318 000
Stock in antrophosphere [Mg]	162 000	2 884 000	6 324 000	11 657 000	17 220 000	22 551 000

Source: own calculation for [20]

Table 6-26 Estimation of values of stocks "in use" and in landfills in Poland in 1995-2004

Plastics	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
	[Mg/yr]									
Consumption	1 174 000	1 509 000	1 839 000	2 187 000	2 524 000	2 862 000	3 065 000	3 295 000	3 512 000	3 722 000
Waste generated	814 000	916 000	1 017 000	1 122 000	1 231 000	1 320 000	1 479 000	1 641 000	1 806 000	1 964 000
Waste (incl. production waste)	872 000	977 000	1 087 000	1 181 000	1 292 000	1 381 000	1 538 000	1 701 000	1 878 000	2 044 000
Annual change of stock "in use"	360 000	593 000	822 000	1 065 000	1 293 000	1 542 000	1 587 000	1 654 000	1 706 000	1 759 000
Stock "in use" [Mg]	11 036 000	11 629 000	12 451 000	13 516 000	14 809 000	16 351 000	17 938 000	19 592 000	21 297 000	23 056 000
Annual material recycling	0	0	0	0	0	0	0	55 000	82 000	108 000
Annual thermal treatment	0	0	3 000	6 000	6 000	12 000	15 000	32 000	46 000	70 000
Total treatment	0	0	3 000	6 000	6 000	12 000	15 000	87 000	128 000	178 000
Annual landfilling (incl.post-treatment residues)	872 000	977 000	1 084 000	1 175 000	1 286 000	1 369 000	1 523 000	1 622 000	1 762 000	1 881 000
Stock in landfills [Mg]	16 684 000	17 557 000	18 534 000	19 617 000	20 793 000	22 079 000	23 447 000	24 971 000	26 592 000	28 355 000
Stock in antrophosphere [Mg]	27 720 000	29 185 000	30 985 000	33 133 000	35 602 000	38 430 000	41 385 000	44 562 000	47 890 000	51 411 000

Source: own calculation for [20]

Table 6-27 Production of plastics in Austria in 1960-1994

Production in Austria	1960	1970	1980	1990	1992	1993	1994
	[Mg/r]						
Polymers	29 000	179 000	488 000	914 000	947 000	981 000	1 014 000
Semifinished products	20 000	93 000	186 000	272 000	293 000	297 000	302 000
Products	9 000	50 000	109 000	241 000	305 000	331 000	358 000
Total	63 000	350 000	852 000	1 553 000	1 681 000	1 750 000	1 821 000

Source: own calculation based on statistical data for [20]

Table 6-28 Production of plastics in Austria in 1995-2004

Production in Austria	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
	[Mg/yr]									
Polymers	1 048 000	1 081 000	1 115 000	1 148 000	1 182 000	1 216 000	1 249 000	1 283 000	1 316 000	1 350 000
Semifinished products	306 000	311 000	324 000	336 000	344 000	365 000	388 000	462 000	477 000	430 000
Products	385 000	411 000	503 000	548 000	500 000	602 000	588 000	601 000	591 000	611 000
Total	1 891 000	1 961 000	2 113 000	2 210 000	2 203 000	2 373 000	2 421 000	2 551 000	2 592 000	2 600 000

Source: own calculation based on statistical data for [20]

Table 6-29 Import of plastics to Austria in 1960-1994

Import to Austria	1960	1970	1980	1990	1992	1993	1994
	[Mg/yr]						
Polymers	23 000	141 000	339 000	624 000	698 000	768 000	839 000
Semifinished products	9 000	22 000	45 000	91 000	99 000	138 000	178 000
Products	1 000	18 000	84 000	148 000	182 000	287 000	392 000
Total	36 000	189 000	482 000	883 000	1 003 000	1 220 000	1 437 000

Source: own calculation based on statistical data for [20]

Table 6-30 Import of plastics to Austria in 1995-2004

Import to Austria	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
	[Mg/yr]									
Polymers	840 000	1 215 000	933 000	963 000	995 000	1 098 000	1 099 000	1 137 000	1 159 000	1 107 000
Semifinished products	199 000	266 000	202 000	214 000	233 000	266 000	283 000	277 000	293 000	325 000
Products	518 000	508 000	541 000	573 000	613 000	650 000	709 000	696 000	719 000	758 000
Total	1 558 000	1 990 000	1 675 000	1 749 000	1 841 000	2 014 000	2 091 000	2 110 000	2 170 000	2 190 000

Source: own calculation based on statistical data for [20]

Table 6-31 Export of plastics from Austria in 1960-1994

Export from Austria	1960	1970	1980	1990	1992	1993	1994
	[Mg/yr]						
Polymers	9 000	128 000	336 000	592 000	713 000	771 000	830 000
Semifinished products	0	8 000	41 000	127 000	154 000	204 000	255 000
Products	1 000	13 000	53 000	117 000	156 000	250 000	344 000
Total	11 000	161 000	468 000	910 000	1 112 000	1 333 000	1 554 000

Source: own calculation based on statistical data for [20]

Table 6-32 Export of plastics from Austria in 1995-2004

Export from Austria	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
	[Mg/yr]									
Polymers	711 000	870 000	912 000	927 000	975 000	956 000	1 030 000	1 038 000	1 012 000	1 024 000
Semifinished products	283 000	275 000	312 000	335 000	343 000	355 000	376 000	417 000	447 000	502 000
Products	521 000	551 000	553 000	588 000	649 000	706 000	664 000	702 000	720 000	783 000
Total	1 647 000	1 842 000	1 931 000	2 010 000	2 136 000	2 191 000	2 249 000	2 344 000	2 368 000	2 508 000

Source: own calculation based on statistical data for [20]

Table 6-33 Estimation of values of stocks "in use" and in landfills in Austria in 1995-2004

Plastics	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
	[Mg/yr]									
Consumption	1 143 000	1 159 000	1 174 000	1 190 000	1 206 000	1 222 000	1 238 000	1 253 000	1 269 000	1 285 000
Waste generated	743 000	764 000	784 000	805 000	825 000	845 000	866 000	886 000	907 000	927 000
Waste (incl. production waste, imp-exp of waste)	774 000	801 000	824 000	844 000	828 000	886 000	903 000	924 000	937 000	933 000
Annual change of stock "in use"	399 000	395 000	390 000	386 000	381 000	376 000	372 000	367 000	363 000	358 000
Stock "in use" [Mg]	7 786 000	8 181 000	8 571 000	8 957 000	9 338 000	9 714 000	10 086 000	10 453 000	10 816 000	11 174 000
Annual material recycling	56 000	63 000	70 000	77 000	84 000	91 000	98 000	105 000	112 000	127 000
Annual thermal treatment	107 000	132 000	196 000	169 000	274 000	300 000	320 000	320 000	413 000	564 000
Total treatment	164 000	195 000	266 000	246 000	358 000	391 000	419 000	426 000	525 000	690 000
Annual landfilling (incl.post-treatment residues)	623 000	619 000	577 000	616 000	494 000	521 000	512 000	527 000	446 000	286 000
Stock in landfills [Mg]	10 923 000	11 543 000	12 120 000	12 736 000	13 230 000	13 750 000	14 262 000	14 789 000	15 235 000	15 522 000
Stock in antrophosphere [Mg]	18 710 000	19 724 000	20 691 000	21 692 000	22 567 000	23 464 000	24 348 000	25 242 000	26 051 000	26 695 000

Source: own calculation for [20]

Table 6-34 Results of MFA of total plastics in Poland in 2004

Flow	Flow value	± flow value	Flow value	± flow value
	[Mg/yr]		[kg/cap*yr]	
Domestically produced polymers	2 000 030	200 000	52,6	5,3
Semi-finished products I	727 000	72 700	19,1	1,9
Recyclate I	47 000	14 100	1,2	0,4
Products II	590 000	59 000	15,5	1,6
Semi-finished products II	565 000	56 500	14,9	1,5
Production waste	80 000	40 000	2,1	1,1
Waste V	70 000	21 000	1,8	0,6
Waste IV	110 000	33 000	2,9	0,9
Waste VI	1 864 000	45 589	49,1	1,2
Residues	1 000	30	0,03	0,001
Off-gas	55 000	16 500	1,4	0,4
Product	14 000	4 200	0,4	0,1
Impurities	16 000	4 800	0,4	0,1
Recyclate II	47 000	14 100	1,2	0,4
Products III	679 000	67 900	17,9	1,8
Polymers I	2 101 970	210 000	55,3	5,5
Rubber II	71 000	7 100	1,9	0,2
Products I	3 043 000	317 268	80,1	8,3
Waste I	1 964 000	67 900	51,7	1,8
Polymers II	527 000	52 700	13,9	1,4

Source: own calculations for [150]

Table 6-35 Results of MFA of total plastics in Austria in 2004

Flow	Flow value	±flow value	Flow value	±flow value
	[Mg/yr]		[kg/cap*yr]	
Domestically produced polymers	1 350 000	135 000	168,8	16,9
Semi-finished products I	325 000	32 500	40,6	4,1
Recyclate I	38 000	3 800	4,8	0,5
Products II	783 000	78 300	97,9	9,8
Semi-finished products II	502 000	50 200	62,8	6,3
Production waste	71 000	35 500	8,9	4,4
Waste V	564 000	169 200	70,5	21,2
Waste VI	260 000	121 594	32,5	15,2
Waste IV	127 000	38 100	15,9	4,8
Residues	25 000	7 500	3,1	0,9
Off-gas	516 000	154 800	64,5	19,4
Rubber I	123 000	12 300	15,4	1,5
Product	13 000	3 900	1,6	0,5
Impurities	18 000	4 400	2,3	0,6
Recyclate II	71 000	21 300	8,9	2,7
Products III	758 000	75 800	94,8	9,5
Waste III	87 000	8 700	10,9	1,1
Polymers I	1 107 000	110 700	138,4	13,8
Rubber II	34 000	3 400	4,3	0,4
Products I	529 000	228 276	66,1	28,5
Waste I	927 000	75 800	115,9	9,5
Waste water	10 000	3 000	1,3	0,4
Waste II	40 000	4 000	5,0	0,5
Polymers II	1 024 000	102 400	128,0	12,8

Source: own calculations for [150]

Appendix 6 Selected results from MFAs of total plastic flows

Table 6-36 Results of MFA for plastic waste management system in Poland in 2004

Level	Flow	Flow value	± flow value	Flow value	± flow value
		[Mg/yr]		[kg/cap*yr]	
Good	Waste 1	110 000	13 140	2,895	0,346
	Waste 2	1 864 000	45 590	49,053	1,200
	Waste 3	12 000	3 600	0,316	0,095
	Waste 5	13 000	3 900	0,342	0,103
	Waste 6	45 000	12 500	1,184	0,329
	Recyclate	93 500	11 169	2,461	0,294
	Impurities	16 500	1 971	0,434	0,052
	Off-gas 1	10 920	3 276	0,287	0,086
	Waste water 1	240	72	0,006	0,002
	Bottom ash	600	180	0,016	0,005
	Fly ash 1	120	36	0,003	0,001
	Filter cake 1	120	36	0,003	0,001
	Product	14 800	3 770	0,389	0,099
	Off-gas 3	43 200	9 428	1,137	0,248
	Residue fraction	6 600	788	0,174	0,021
	Thick sludge	1 100	131	0,029	0,003
	Impurity	6 600	788	0,174	0,021
	Melt filter residue	2 200	263	0,058	0,007

Source: own calculations for [150]

Table 6-37 Results of MFA for carbon in plastic waste management system in Poland in 2004

Level	Flow	Flow value	± flow value	Flow value	± flow value
		[Mg/yr]		[kg/cap*yr]	
C	Waste 1	82 830,0	10 398,7	2,180	0,274
	Waste 2	1 360 720,0	43 835,9	35,808	1,154
	Waste 3	8 760,0	2 634,4	0,231	0,069
	Waste 5	9 490,0	2 853,9	0,250	0,075
	Waste 6	22 500,0	7 701,5	0,592	0,203
	Recyclate	74 547,0	9 358,8	1,962	0,246
	Impurities	8 283,0	1 039,9	0,218	0,027
	Off-gas 1	8 672,4	2 608,1	0,228	0,069
	Waste water 1	0,0	0,0	0,0	0,0
	Bottom ash	87,6	26,3	0,002	0,001
	Fly ash 1	0,0	0,0	0,0	0,0
	Filter cake 1	0,0	0,0	0,0	0,0
	Product	319,9	82,1	0,008	0,002
	Off-gas 3	31 670,1	8 131,1	0,833	0,214
	Residue fraction	3 313,2	415,9	0,087	0,011
	Thick sludge	0,0	0,0	0,0	0,0
	Impurity	3 313,2	415,9	0,087	0,011
	Melt filter residue	1 656,6	208,0	0,044	0,005

Source: own calculations for [150]

Table 6-38 Results of MFA for chlorine in plastic waste management system in Poland in 2004

Level	Flow	Flow value [Mg/yr]	± flow value [Mg/yr]	Flow value [g/cap*yr]	± flow value [g/cap*yr]
Cl	Waste 1	748,0	262,6	19,68	6,91
	Waste 2	43 105,0	17 032,3	1 134,34	448,22
	Waste 3	277,5	137,5	7,30	3,62
	Waste 5	300,6	149,0	7,91	3,92
	Waste 6	225,0	93,0	5,92	2,45
	Recyclate	366,5	128,7	9,65	3,39
	Impurities	381,5	133,9	10,04	3,52
	Off-gas 1	2,8	1,4	0,07	0,04
	Waste water 1	147,1	72,9	3,87	1,92
	Bottom ash	27,5	13,6	0,72	0,36
	Fly ash 1	99,9	49,5	2,63	1,30
	Filter cake 1	0,3	0,1	0,01	0,00
	Product	524,6	175,3	13,80	4,61
	Off-gas 3	1,1	0,4	0,03	0,01
	Residue fraction	142,1	49,9	3,74	1,31
	Thick sludge	15,0	5,3	0,39	0,14
	Impurity	216,9	76,2	5,71	2,00
	Melt filter residue	7,5	2,6	0,20	0,07

Source: own calculations for [150]

Table 6-39 Results of MFA for cadmium in plastic waste management system in Poland in 2004

Level	Flow	Flow value [Mg/yr]	± flow value [Mg/yr]	Flow value [mg/cap*yr]	± flow value [mg/cap*yr]
Cd	Waste 1	1,2320	0,6869	32,4	18,1
	Waste 2	47,9048	23,1433	1 260,7	609,0
	Waste 3	0,3084	0,1752	8,1	4,6
	Waste 5	0,3341	0,1898	8,8	5,0
	Waste 6	0,2925	0,0889	7,7	2,3
	Recyclate	0,8994	0,5015	23,7	13,2
	Impurities	0,3326	0,1855	8,8	4,9
	Off-gas 1	0,0003	0,0002	0,0	0,0
	Waste water 1	0,0003	0,0002	0,0	0,0
	Bottom ash	0,0247	0,0140	0,6	0,4
	Fly ash 1	0,2828	0,1607	7,4	4,2
	Filter cake 1	0,0003	0,0002	0,0	0,0
	Product	0,6266	0,2096	16,5	5,5
	Off-gas 3	0,0	0,0	0,0	0,0
	Residue fraction	0,1232	0,0687	3,2	1,8
	Thick sludge	0,0123	0,0069	0,3	0,2
	Impurity	0,1725	0,0962	4,5	2,5
	Melt filter residue	0,0246	0,0137	0,6	0,4

Source: own calculations for [150]

Table 6-40 Results of MFA for lead in plastic waste management system in Poland in 2004

Level	Flow	Flow value	± flow value	Flow value	± flow value
		[Mg/yr]		[mg/cap*yr]	
Pb	Waste 1	19,745	4,609	519,6	121,3
	Waste 2	864,896	415,093	22 760,4	10 923,5
	Waste 3	5,568	3,148	146,5	82,9
	Waste 5	6,032	3,411	158,7	89,8
	Waste 6	10,161	4,557	267,4	119,9
	Recyclate	12,637	2,950	332,5	77,6
	Impurities	7,108	1,659	187,1	43,7
	Off-gas 1	0,006	0,003	0,1	0,1
	Waste water 1	0,006	0,003	0,1	0,1
	Bottom ash	4,159	2,352	109,5	61,9
	Fly ash 1	1,392	0,787	36,6	20,7
	Filter cake 1	0,006	0,003	0,1	0,1
	Product	16,193	5,692	426,1	149,8
	Off-gas 3	0,000	0,000	0,0	0,0
	Residue fraction	1,975	0,461	52,0	12,1
	Thick sludge	0,197	0,046	5,2	1,2
	Impurity	4,739	1,106	124,7	29,1
	Melt filter residue	0,197	0,046	5,2	1,2

Source: own calculations for [150]

Table 6-41 Results of MFA for zinc in plastic waste management system in Poland in 2004

Level	Flow	Flow value	± flow value	Flow value	± flow value
		[Mg/yr]		[mg/cap*yr]	
Zn	Waste 1	66,440	12,156	1 748,4	319,9
	Waste 2	1 435,280	221,447	37 770,5	5 827,6
	Waste 3	9,240	3,109	243,2	81,8
	Waste 5	10,010	3,368	263,4	88,6
	Waste 6	427,500	190,715	11 250,0	5 018,8
	Recyclate	51,159	9,360	1 346,3	246,3
	Impurities	15,281	2,796	402,1	73,6
	Off-gas 1	0,009	0,003	0,2	0,1
	Waste water 1	0,009	0,003	0,2	0,1
	Bottom ash	3,973	1,337	104,6	35,2
	Fly ash 1	5,239	1,763	137,9	46,4
	Filter cake 1	0,009	0,003	0,2	0,1
	Product	437,510	190,745	11 513,4	5 019,6
	Off-gas 3	0,0	0,0	0,0	0,0
	Residue fraction	3,986	0,729	104,9	19,2
	Thick sludge	0,6644	0,122	17,5	3,2
	Impurity	9,302	1,702	244,8	44,8
	Melt filter residue	1,329	0,243	35,0	6,4

Source: own calculations for [150]

Table 6-42 Results of MFA for plastic waste management system in Austria in 2004

Level	Flow	Flow value	± flow value	Flow value	± flow value
		[Mg/yr]		[kg/cap*yr]	
Good	Waste 1	127 000	19 100	15,875	2,388
	Waste 2	260 000	121 590	32,500	15,199
	Waste 3	227 000	60 040	28,375	7,505
	Waste 4	228 000	60 040	28,500	7,505
	Waste 5	83 000	24 560	10,375	3,070
	Waste 6	28 000	8 390	3,500	1,049
	Recyclate	107 950	16 235	13,494	2,029
	Impurities	19 050	2 865	2,381	0,358
	Off-gas 1	206 570	54 636	25,821	6,830
	Waste water 1	4 540	1 201	0,568	0,150
	Bottom ash	11 350	3 002	1,419	0,375
	Fly ash 1	2 270	600	0,284	0,075
	Filter cake 1	2 270	600	0,284	0,075
	Ash	22 800	6 004	2,850	0,751
	Gypsum	7 752	2 041	0,969	0,255
	Off-gas 2	196 764	51 815	24,596	6,477
	Waste water 2	228	60	0,029	0,008
	Product	16 700	3 517	2,088	0,440
	Off-gas 3	94 300	22 871	11,788	2,859
	Residue fraction	7 620	1 146	0,953	0,143
	Thick sludge	1 270	191	0,159	0,024
	Impurities	7 620	1 146	0,953	0,143
	Melt filter residue	2 540	382	0,318	0,048
	Filter cake 2	456	120	0,057	0,015

Source: own calculations for [150]

Table 6-43 Results of MFA for carbon in plastic waste management system in Austria in 2004

Level	Flow	Flow value	± flow value	Flow value	± flow value
		[Mg/yr]		[kg/cap*yr]	
C	Waste 1	95 631,0	14 849,0	11,954	1,856
	Waste 2	189 800,0	88 849,9	23,725	11,106
	Waste 3	165 710,0	43 966,7	20,714	5,496
	Waste 4	166 440,0	43 967,9	20,805	5,496
	Waste 5	60 590,0	17 973,8	7,574	2,247
	Waste 6	14 000,0	5 043,6	1,750	0,630
	Recyclate	86 067,9	13 364,1	10,758	1,671
	Impurities	9 563,1	1 484,9	1,195	0,186
	Off-gas 1	164 052,9	43 527,0	20,507	5,441
	Waste water 1	0,0	0,0	0,000	0,000
	Bottom ash	1 657,1	439,7	0,207	0,055
	Fly ash 1	0,0	0,0	0,000	0,000
	Filter cake 1	0,0	0,0	0,000	0,000
	Ash	665,8	175,9	0,083	0,022
	Gypsum	0,0	0,0	0,000	0,000
	Off-gas 2	165 274,9	43 660,1	20,659	5,458
	Waste water 2	166,4	44,0	0,021	0,005
	Product	745,9	186,7	0,093	0,023
	Off-gas 3	73 844,1	18 481,3	9,231	2,310
	Residue fraction	3 825,2	594,0	0,478	0,074
	Thick sludge	0,0	0,0	0,000	0,000
	Impurities	3 825,2	594,0	0,478	0,074
	Melt filter residue	1 912,6	297,0	0,239	0,037
	Filter cake 2	332,9	87,9	0,042	0,011

Source: own calculations for [150]

Table 6-44 Results of MFA for chlorine in plastic waste management system in Austria in 2004

Level	Flow	Flow value	± flow value	Flow value	± flow value
		[Mg/yr]		[g/cap*yr]	
Cl	Waste 1	863,6	313,3	107,95	39,16
	Waste 2	6 012,5	3 678,1	751,56	459,77
	Waste 3	5 249,4	2 492,7	656,17	311,59
	Waste 4	5 272,5	2 500,3	659,06	312,54
	Waste 5	1 919,4	946,3	239,92	118,29
	Waste 6	140,0	60,0	17,50	7,50
	Recyclate	423,2	153,5	52,90	19,19
	Impurities	440,4	159,8	55,05	19,97
	Off-gas 1	52,5	24,9	6,56	3,12
	Waste water 1	2 782,2	1 321,1	347,77	165,14
	Bottom ash	519,7	246,8	64,96	30,85
	Fly ash 1	1 889,8	897,4	236,22	112,17
	Filter cake 1	5,2	2,5	0,66	0,31
	Ash	2 372,6	1 125,1	296,58	140,64
	Gypsum	0,0	0,0	0,00	0,00
	Off-gas 2	10,5	5,0	1,32	0,63
	Waste water 2	2 863,0	1 357,7	357,87	169,71
	Product	2 055,3	946,3	256,91	118,29
	Off-gas 3	4,1	1,9	0,51	0,24
	Residue fraction	164,1	59,5	20,51	7,44
	Thick sludge	17,3	6,3	2,16	0,78
	Impurities	250,4	90,9	31,31	11,36
	Melt filter residue	8,6	3,1	1,08	0,39
	Filter cake 2	26,4	12,5	3,30	1,56

Source: own calculations for [150]

Table 6-45 Results of MFA for cadmium in plastic waste management system in Austria in 2004

Level	Flow	Flow value	± flow value	Flow value	± flow value
		[Mg/yr]		[mg/cap*yr]	
Cd	Waste 1	1,422	0,804	177,80	100,46
	Waste 2	6,682	4,490	835,25	561,23
	Waste 3	5,834	3,210	729,24	401,25
	Waste 4	5,860	3,221	732,45	402,61
	Waste 5	2,133	1,207	266,64	150,92
	Waste 6	0,182	0,059	22,75	7,37
	Recyclate	1,038	0,587	129,79	73,34
	Impurities	0,384	0,217	48,01	27,12
	Off-gas 1	0,006	0,003	0,73	0,40
	Waste water 1	0,006	0,003	0,73	0,40
	Bottom ash	0,467	0,257	58,34	32,10
	Fly ash 1	5,350	2,944	668,71	367,95
	Filter cake 1	0,006	0,003	0,73	0,40
	Ash	5,801	3,189	725,13	398,58
	Gypsum	0,0	0,0	0,00	0,00
	Off-gas 2	0,003	0,002	0,37	0,20
	Waste water 2	0,026	0,014	3,30	1,81
	Product	2,315	1,209	289,39	151,10
	Off-gas 3	0,0	0,0	0,00	0,00
	Residue fraction	0,142	0,080	17,78	10,05
	Thick sludge	0,014	0,008	1,78	1,00
	Impurities	0,199	0,113	24,89	14,06
	Melt filter residue	0,028	0,016	3,56	2,01
	Filter cake 2	0,029	0,016	3,66	2,01

Source: own calculations for [150]

Table 6-46 Results of MFA for lead in plastic waste management system in Austria in 2004

Level	Flow	Flow value	± flow value	Flow value	± flow value
		[Mg/yr]		[mg/cap*yr]	
Pb	Waste 1	22,80	5,71	2 849,6	714,3
	Waste 2	120,64	80,79	15 080,0	10 098,4
	Waste 3	105,33	57,66	13 166,0	7 207,7
	Waste 4	105,79	57,86	13 224,0	7 232,0
	Waste 5	38,51	21,69	4 814,0	2 711,7
	Waste 6	6,32	2,92	790,3	365,4
	Recyclate	14,59	3,66	1 823,7	457,2
	Impurities	8,21	2,06	1 025,8	257,2
	Off-gas 1	0,11	0,06	13,2	7,2
	Waste water 1	0,11	0,06	13,2	7,2
	Bottom ash	78,68	43,07	9 835,0	5 384,1
	Fly ash 1	26,33	14,42	3 291,5	1 801,9
	Filter cake 1	0,11	0,06	13,2	7,2
	Ash	104,73	57,28	13 091,8	7 159,7
	Gypsum	0,41	0,23	51,6	28,2
	Off-gas 2	0,01	0,01	1,3	0,7
	Waste water 2	0,11	0,06	13,2	7,2
	Product	44,83	21,89	5 604,3	2 736,2
	Off-gas 3	0,00	0,00	0,0	0,0
	Residue fraction	2,28	0,57	285,0	71,4
	Thick sludge	0,23	0,06	28,5	7,1
	Impurities	5,47	1,37	683,9	171,4
	Melt filter residue	0,23	0,06	28,5	7,1
	Filter cake 2	0,53	0,29	66,1	36,2

Source: own calculations for [150]

Table 6-47 Results of MFA for zinc in plastic waste management system in Austria in 2004

Level	Flow	Flow value	± flow value	Flow value	± flow value
		[Mg/yr]		[mg/cap*yr]	
Zn	Waste 1	76,71	15,69	9 588,5	1 960,9
	Waste 2	200,20	98,47	25 025,0	12 308,3
	Waste 3	174,79	53,35	21 848,8	6 668,8
	Waste 4	175,56	53,41	21 945,0	6 676,2
	Waste 5	63,91	21,27	7 988,8	2 658,8
	Waste 6	266,00	122,37	33 250,0	15 296,6
	Recyclate	59,07	12,08	7 383,1	1 509,9
	Impurities	17,64	3,61	2 205,4	451,0
	Off-gas 1	0,17	0,05	21,8	6,7
	Waste water 1	0,17	0,05	21,8	6,7
	Bottom ash	75,16	22,94	9 395,0	2 867,6
	Fly ash 1	99,11	30,25	12 388,2	3 781,2
	Filter cake 1	0,17	0,05	21,8	6,7
	Ash	173,80	52,88	21 725,6	6 609,4
	Gypsum	0,88	0,27	109,7	33,4
	Off-gas 2	0,05	0,02	6,6	2,0
	Waste water 2	0,18	0,05	21,9	6,7
	Product	329,91	124,21	41 238,8	15 526,0
	Off-gas 3	0,00	0,00	0,0	0,0
	Residue fraction	4,60	0,94	575,3	117,7
	Thick sludge	0,77	0,16	95,9	19,6
	Impurities	10,74	2,20	1 342,4	274,5
	Melt filter residue	1,53	0,31	191,8	39,2
	Filter cake 2	0,65	0,20	81,2	24,7

Source: own calculations for [150]

Appendix 7 Chosen results of calculations carried out for future scenarios of plastic waste management in Poland

Table 6-48 Quantity of plastic goods consumed in Poland in 2005-2014 depending on the assumed yearly consumption growth rate for this period

Yearly consumption growth rate	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
	[Mg/yr]									
3%	3 834 100	3 949 100	4 067 600	4 189 600	4 315 300	4 444 700	4 578 100	4 715 400	4 856 900	5 002 600
4%	3 871 300	4 026 100	4 187 200	4 354 700	4 528 900	4 710 000	4 898 400	5 094 300	5 298 100	5 510 000
5%	3 908 500	4 103 900	4 309 100	4 524 600	4 750 800	4 988 400	5 237 800	5 499 700	5 774 600	6 063 400

Source: own calculations

Table 6-49 Quantity of plastic waste generated in Poland in 2005-2014 depending on the assumed yearly consumption growth rate for this period

Yearly consumption growth rate	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
	[Mg/yr]									
3%	1 898 100	2 057 600	2 220 900	2 384 100	2 544 800	2 690 300	2 813 700	2 943 400	3 074 000	3 204 900
4%	1 898 100	2 065 500	2 237 200	2 410 300	2 581 700	2 744 600	2 886 700	3 036 300	3 188 100	3 341 600
5%	1 898 100	2 073 400	2 253 700	2 437 100	2 619 600	2 800 800	2 962 700	3 133 800	3 309 000	3 487 600

Source: own calculations

Table 6-50 Quantity of plastic waste recycled in Poland in 2005-2014 in analysed scenarios

Recycling	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
	[Mg/yr]									
Rec.-BAU	121 478	132 192	143 181	154 259	165 229	175 654	184 749	194 323	204 038	213 862
Rec.-MIT1	120 720	139 240	159 870	182 580	207 290	233 600	260 430	290 360	323 180	359 060
Rec.-MIT2	123 000	144 550	169 090	196 750	227 600	261 320	296 840	337 200	382 390	432 860
Rec. -MIT3	125 270	149 950	178 660	211 740	249 470	291 730	337 520	390 510	451 050	520 040

Source: own calculations

Table 6-51 Quantity of plastic waste recycled in Poland in 2005-2014 in analysed scenarios

Energy recovery	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
	[Mg/yr]									
En.rec.-BAU	75 924	82 620	89 488	96 412	103 268	109 784	115 468	121 452	127 524	133 664
En.Rec.-MIT1	79 339	94 970	113 150	134 100	158 000	184 760	213 760	247 330	285 660	329 360
En.Rec.-MIT2	82 946	103 800	129 300	160 200	197 320	241 240	291 790	352 950	426 190	513 710
En.Rec.-MIT3	86 552	113 020	146 900	189 930	244 110	311 420	393 050	496 110	625 100	786 240

Source: own calculations