# Recycling of Plastics in Germany

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## ABSTRACT

This article deals with the waste management of post-consumer plastics in Germany and its potential to save fossil fuels and to reduce $CO_2$ emissions. Since most experience is available for packaging, the paper first gives an overview of the legislative background and the material flows for this sector. Then recycling and recovery processes for plastics waste from all sectors are assessed in terms of their contribution to energy saving and $CO_2$ abatement. Practically all the options studied show a better performance than waste treatment in an average incinerator which has been chosen as the reference case. High ecological benefits can be achieved by mechanical recycling if virgin polymers are substituted. The paper then presents different scenarios for managing plastic waste in Germany in 1995: Considerable savings can be made by strongly enhancing the efficiency of waste incinerators. Under these conditions the distribution of plastics waste among mechanical recycling, feedstock recycling and energy recovery has a comparatively small impact on the overall results. The maximum savings amount to 74 PJ of energy, i.e. 9 % of the chemical sector's energy demand in 1995 and 7.0 Mt $CO_2$, representing 13 % of the sector's emissions. The assessment does not support a general recommendation of energy recovery due to the large difference between the German average and the best available municipal waste-to-energy facilities and also due to new technological developments in the field of mechanical recycling.[1]

## Introduction

Since the early 1990ies, a big effort has been made to recycle plastics in Germany. This is one element of the German federal government's long-term policy to integrate the concept of sustainable development in various fields of the economy. Good progress has been achieved in the recycling of *pre*-consumer plastics waste where there is not much scope for optimization (Consultic 1994-1996). But for *post*-consumer plastics waste the share recycled is estimated at only 20 %-25 % (see below, Table 1). Moreover, the amount of *post*-consumer plastics waste exceeds the amount of pre-consumer waste by a multiple of 3.5 to 5, and this ratio will increase considerably in the future due to waste from long-term applications. For these reasons, this article focusses on the recycling of post-consumer plastics waste.

Most experience is available for post-consumer waste from the packaging sector. In Germany, collection and sorting of packaging materials is organized by the *Duales System Deutschland* (DS, former token: DSD), whose trademark is the green dot. Within the DS framework the organisation *Deutsche Gesellschaft für Kunststoff-Recycling* (DKR) is responsible for plastics recycling. Organisations similar to the DS are gaining ground also in other

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[1] 1 Mt: 1 metric Megaton, 1 Mt = $10^9$ kg = $2.205*10^9$ lb; PJ: Petajoules, 1 PJ = 277,8 GWh

Western European countries and an equivalent may also be introduced in Japan in the close future.

There are a number of reasons why DS was introduced in Germany. First of all, packaging constitutes a considerable share of municipal solid waste (30 % by weight and 50 % by volume) and the capacities of landfills, which still represent the main disposal method in Germany, were declining rapidly. Further, environmental considerations, geological limitations, land use aspects and public pressure imposed constraints on the expansion of landfill capacity. From the year 2005 onwards, municipal waste will have to be incinerated and only landfilling of the residues will be allowed according to a federal ordinance (*TA Siedlungsabfall*). The legislative backbone of DS is the Packaging Ordinance (*Verpackungsverordnung*) and the Closed-Loop Economy Law (*Kreislaufwirtschaftsgesetz*). On the European level, there is a Packaging Directive which was passed in December 1994. National ordinances, European documents and voluntary agreements have also been passed or are being discussed in other fields of plastics use, i.e. for end-of-life vehicles, electric & electronic waste and for disposed car batteries.

The scope of this paper is recycling of post-consumer plastics originating from all fields of application; however, if specific experience is available from the packaging sector this is presented and an effort is made to translate the findings to plastics recycling in general. To start with, the paper gives an overview of the material flows in plastics recycling from the packaging sector. Second, environmental comparisons are performed for recycling processes both for waste from packaging and non-packaging applications. The ecological indicators chosen are gross energy requirements[2] and the gross $CO_2$ emissions. The sections deal with the potential application of recycling by groups of technologies and with estimates of the savings of energy and $CO_2$ at the macrolevel. The paper closes with a discussion of the results and with conclusions.

## Material flows in packaging recycling

DS is responsible for the management of all packaging materials from the private sector and small consumers, i.e. for plastics, glass, paper/cardboard, tin, aluminium and composites. Plastics packaging handled by DS amounts to about 800 kt which is equivalent to approx. 60 % of all plastics packaging materials (Umweltbundesamt 1997) and about 11 % of the total consumption of plastics products (see **Table 1**). On the waste side, DS covers 20 %-25 % of total plastics waste and it accounts for about 70 % of the total recycling of post-consumer plastics in the country (Table 1).

DS only covers sales packaging from households and small consumers. For other types of packaging (e. g. transportation packaging), no mandatory quotas have been fixed and there is no obligation to report, but the packaging materials have to be re-used or recycled as far as this is technically feasible and economically reasonable (Closed Loop Economy Law, *Kreislaufwirtschaftsgesetz*, §4 (2) and §5 (3) ).

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2 Gross energy requirements, also referred to as Cumulative Energy Demand, is defined as energy consumption in terms of primary energy for the entire system starting with the extraction of resources from the various deposits and ending with the product(s) under consideration. Gross $CO_2$ emissions are defined by analogy.

Table 1: Consumption, waste generation and recycling of all plastics products and of DS plastics packaging in Germany, 1996

| | kt |
|---|---|
| All plastic products | |
| - Consumption | ~7450 [a)] |
| - Post-consumer waste | |
| -- according to ISI | 3650 [a)] |
| -- according to Sofres | 3147 |
| - Recycling | 749 |
| -- Feedstock | 251 |
| -- Mechanical | 498 [b)] |
| DS packaging [c)] | |
| - Consumption | 792 |
| - Collected post-consumer waste | ~780 [d)] |
| - Recycling | 535 |
| -- Feedstock | 258 |
| -- Mechanical | 277 |

All values refer to the year 1996 and are given in kilotonnes.

[a)] Own estimate, based on [plstream]. Excluding chemical fibres and non-plastics.

[b)] Share of mechanical recycling over total post-consumer waste:
14% (basis: ISI) to 16% (basis: Sofres)

[c)] 'DS packaging' is a subgroup of 'All plastic products' (see upper section of table).

[d)] See footnote 2) in Table 2.

Since the enactment of the Packaging Ordinance and the subsequent establishment of DS in 1991 the total consumption of packaging materials has declined by 12 % and for plastics packaging by 4 % (by weight). The relatively small decrease for plastics is due to the fact that plastics have continued to substitute other packaging materials. Without new designs of plastics packaging - using less material for the same function - this decrease would have been even smaller. Of course, these developments are very welcome since the avoidance of material input (and waste) without losses regarding the functionality is economically and ecologically the most efficient option. Nevertheless, the changes which DS has induced on the side of waste management are by far more important than reductions in the consumption of plastics packaging. This directs attention to waste management and its economical and ecological impact which will be discussed in the following.

The data for DS plastics packaging given in Table 1 are broken down further in **Table 2**: the figures for 1997 show that the total amount of DS plastics packaging waste equalled 820 kt and that the valuable output from the sorting facilities was 567 kt, i.e. 69 %. The remaining 31 % represents the refuse rate from sorting facilities that ended up in landfills. In 1997 a total of 615 kt was recycled. This is more than the output from the sorting facilities (567 kt) due to the change of stocks. For reasons of easier comparison with the mandatory quota (see column on right hand side) the change of stocks has not been taken into account in Table 2, i.e. all the data listed refer to a total of 567 kt (amount of sorted plastics waste). 58 % (331 kt) of this was fed to feedstock recycling facilities where the polymers are split into monomers or broken down to upstream products such as substitutes for oil.

Table 2: DS recycling of plastics packaging 1996 and 1997

| | 1996 | | | 1997 | | | Mandatory quota from Jan. 1st, 1999 |
|---|---|---|---|---|---|---|---|
| | kt | % (780 kt =100%) | % | kt | % (820 kt =100%) | % | % (820 kt =100%) |
| Collected plastic waste [a)] | *780* [b)] | 100% | | *820* [b)] | 100% | | 100% |
| Sorted plastic waste | 535 | 69% | 100% | 567 [c)] | 69% | 100% | 60% |
| - Feedstock recycling | 258 | 33% | 48% | 331 | 40% | 58% | |
| - Mechanical recycling, domestic | 171 | 22% | 32% | 185 | 23% | 33% | |
| - Mechanical recycling, abroad | 106 | 14% | 20% | 51 | 6% | 9% | |
| - Incineration | 0 | 0% | 0% | 0 | 0% | 0% | |
| Mechanical recycling by waste fractions | 277 | 36% | 100% | 236 | 29% | 100% | 36% [e)] |
| - Films | 144 | 19% | 52% | 153 | 19% | 65% | |
| - Bottles (mainly PE, PP) | 48 | 6% | 17% | 51 | 6% | 22% | |
| - Cups, beakers (mainly PS, EPS) | 16 | 2% | 6% | 11 | 1% | 5% | |
| - Mixed plastics | 68 | 9% | 25% | 21 | 3% | 9% | |
| Mechanical recycling by quality of products [d)] | 277 | 36% | 100% | n.a. | n.a. | n.a. | |
| - BTP Polymer substitutes | 224 | 29% | 81% | n.a. | n.a. | n.a. | |
| - BTP Non-Polymer substitutes | 53 | 7% | 19% | n.a. | n.a. | n.a. | |
| -- for domestic use | 45 | 6% | 16% | n.a. | n.a. | n.a. | |
| -- exported | 8 | 1% | 3% | n.a. | n.a. | n.a. | |

a) Includes only plastics packaging collected by DS; other materials/products are excluded.

b) Own estimate of plastics packaging in the "yellow sack" (based on the collection/recovery ratio in 1995). The entries are close to the figures of DS packaging consumption in 1996 (792 kt) and 1997 (822 kt) which have been used as the reference quantity in the German Packaging Ordinance (in contrast, the licensed amount of packaging has been chosen as the reference quantity in the amendment passed by the Bundestag on August 28th 1998). The difference between the figures for collected plastics waste (820 kt in 1997) and sorted plastics waste (567 kt in 1997) gives the refuse rate from sorting units which is incinerated or landfilled.

c) In 1997 a total of 615 kt was recycled. This is more than the output from the sorting facilities (567 kt) with the difference being due to the change of stocks. For reasons of easier comparison with the mandatory quota (see column on right hand side) the change of stocks has not been taken into account in this table.

d) BTP stands for Back-to-Polymer recycling, i.e. for mechanical recycling.
The percentages for mechanical recycling by quality of products have been taken from [Brandrup]. The quantities in absolute terms (in kt) have been calculated on this basis. Even though the distinction between 'BTP Polymer substitutes' and 'BTP Non-Polymer substitutes' is bound to be relative depending on the standards chosen, the percentages give a first indication of the distribution.

e) The definition of the reference quantity chosen in the German Packaging Ordinance differs from the definition of "Collected plastic waste" chosen in this table. However, the values are very close (see footnote 2), so it is possible to compare the mandatory quota given in the last column with the achieved percentages listed in the preceding columns.

The remaining 42 % was converted by mechanical recycling where the polymer remains intact and is reprocessed. The figure given for mechanical recycling comprises the amounts exported in the form of agglomerates and regranulates representing about 9 %[3] whereas the remaining 33 % was used domestically. The mandatory quota listed in Table 2 will be valid from January 1st, 1999 onwards according to the new amendment of the pack-

3 5 % of which were exported to countries of the European Union and the remaining 4 % to other countries.

aging ordinance. Only a rough comparison is possible between the mandatory quota and the real figures also given in Table 2; for a more accurate comparison corrections would have to be made in order to account for both the change in definition of the reference quantity[4] and the change of stocks (see above). Still, the conclusion should be valid that to comply with the legal framework in 1999, the share of mechanical recycling will have to be increased (target value: 36%) whereas the percentage for sorted waste was overfulfilled already in 1997.

The achievements in Germany can also be compared to the requirements of the European Packaging Directive according to which a minimum of only 15 % of each packaging material (e.g. plastics) must be recycled. Based on total plastics packaging waste (including packaging without a green dot) this quota represents not more than 250 kt, i.e. DS exceeded the requirements for all plastics packagings by a factor of two in 1997.

Table 2 also shows a distinction between products made by mechanical recycling which is referred to as Back-to-Polymer (BTP) recycling. In the case of "BTP polymer substitutes" products, virgin polymers are replaced. "BTP Non-polymer substitutes" represent goods usually manufactured from wood or concrete. It can be assumed that these are produced mainly from the mixed waste plastics fraction.

## Environmental comparison of processes

When making environmental comparisons it must be taken into account that the various processes result in different products and therefore the benefits also vary from technology to technology. To take this aspect fully into account the methodology presented in **Figure 1** will be used: The left of Figure 1 shows that recycling of one ton of plastics waste results in a number of valuable outputs (materials) and that its operation is accompanied by energy requirements and the release of emissions. On the other hand, the same amount of plastics waste (1 ton) can be combusted in an average municipal waste incinerator, including the whole range from simple incinerators to advanced waste-to-energy facilities, this results in an output of steam and electricity (reference case, right side of Figure 1). So far the two systems are not comparable since they lead to different products. To ensure comparability, each of the two systems is complemented by the respective flows. It is assumed that these are produced in the conventional way, i.e. from fossil resources which is also referred to as virgin production or primary production [5], [6], [7].

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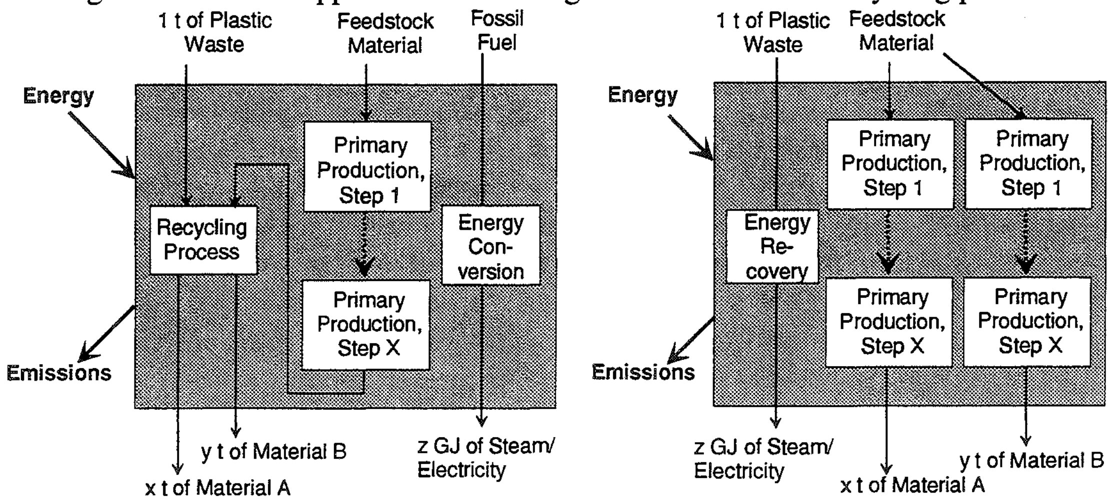
[4] See footnote b in Table 2.

[5] In detail, the calculation method is more complicated than shown in Figure 1. For example, sorting is required prior to recycling. In this study it is assumed that sorting residues are incinerated, resulting in outputs of steam and electricity. To ensure comparability, the reference case must be complemented accordingly.

[6] Own estimations of the energy demand and of $CO_2$ –emissions resulting from the logistics (collection, sorting, transport) lead to the presumption, that the burdens are more or less invariant for alternative waste inputs or collection systems except incineration and landfilling. All recycling processes were charged with the average burden (energy and $CO_2$ )of the logistics of DS plastics waste. This is a save assumption since DS plastics waste is rather commingled, consists of many small pieces and requires washing. Thus, the burden for logistics from other waste streams and other recycling processes tends to be smaller.

[7] Data for virgin production originate from own evaluations in the project (C-STREAMS), where this work is also a part of. Own energy and $CO_2$ data for virgin production are mostly smaller than those given by other authors. Therefore, the savings due to recycling and energy recovery tend to be underestimated. Furter de-

Figure 1: Method applied for the ecological evaluation of a recycling process




Using this so-called product basket-method the net effect of recycling is determined by calculating the difference between the values for each ecological indicator of the two systems. It is possible that the net effect of recycling is advantageous for one ecological indicator, and negative for the other. The ecological indicators analysed in this paper are gross energy requirements and gross $CO_2$ emissions.

As mentioned, the incineration of plastics waste in an average plant is used as the reference case on the waste management side. Other studies choose landfilling as the reference case (Heyde, Krämer 1997). In principle the results can easily be transformed into each other[8]. The choice made in this analysis originates from the fact that direct landfilling of plastics will be prohibited from the year 2005 onwards (*TA Siedlungsabfall*). In this context it must be mentioned that the standard of German municipal waste incineration plants varies greatly and that an inventory of the existing facilities including the main specifications is not available. Therefore, the data of an average plant have been estimated: about 12 % of the lower heating value, LHV[9] is sold as electricity, and another 12 % for district heating and industrial steam supply.

The recycling technologies analysed in the following include mechanical recycling and various types of feedstock recycling. In addition, energy recovery technologies are also assessed. In the case of mechanical recycling, three categories can be distinguished:

- The first comprises products which are usually manufactured from virgin polymers. Here, a distinction can be made between recycled products which serve the same purpose (e.g.

tailed explanation would by far exceed the possibilities of this paper, but more details are given in the presentation "Improving the Efficiency of Fossil Carbon Use for Materials" by M. Patel in this conference and the forthcoming article " Recycling of Plastics in Germany" (journal not yet known).

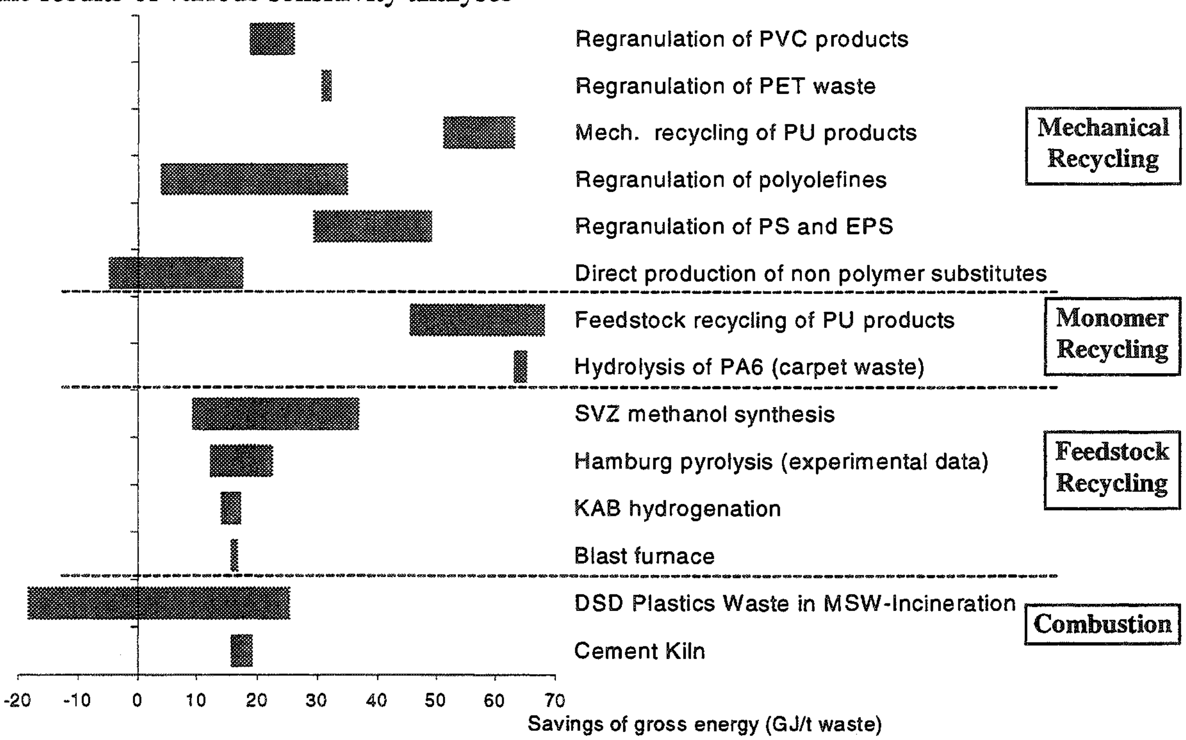
8 But further differences in assumptions, e.g. concerning the treatment of sorting residues (incineration vs. landfilling, see footnote f) and different reference quantities (plastic waste at the source vs. plastic waste after sorting), make it difficult to transform the results into each other. This is also the reason why there is only limited comparability between the results of this study and those from (Heyde, M, Kremer, M. 1997)

9 Lower Heating Value, LHV: Heating value that accounts for the evaporation of water that is generated in the combustion process (also: Net Calorific Value, NCV).

from bottle to bottle) and those which fall into a different category of application (e.g. from bottle to fibre). It must be taken into account that blending or compounding may be necessary, i.e. that a certain amount of virgin materials is also required in the recycling process (substitution factor is smaller than 100 %). In other cases it may be necessary to use more recyclates than virgin plastics to achieve the required mechanical properties. The smaller the substitution factor is, the smaller the ecological advantage compared to virgin production becomes.

- Second, there are goods which, in conventional production, are not made of plastics, e.g. fences, crates, pallets, garbage bins, sheets used in trucks and in the building sector or polyurethane particles used as an oil sorbent (instead of sand, in the case of oil spills). Within this category, the ratio of lifetimes and the ratio of in-use efficiencies are important parameters to be taken into account. Aspects which cannot be quantified in this paper are differences between conventional and recycled products concerning product properties, processability, transportability etc.
- Third, recyclates can be used to provide totally new products or services, e.g. artificial snow. It is very difficult to conduct an environmental assessment for this category, e.g.

Figure 2: Savings of gross energy due to recycling and recovery processes for post-consumer plastics. Reference case: average municipal waste incinerators; bars represent to the results of various sensitivity analyses




since a change of lifestyle may be involved which creates problems when defining primary production. Therefore, this last option will not be taken into account in this assessment.

**Figure 2** shows the savings of gross energy for the various processes. For gross $CO_2$ emissions the results are in the main similar. Some of the processes have already been proven on the large scale whereas others are still in the development stage. Practically all options show a better environmental performance compared to plastics waste treatment in an average municipal waste incinerator (reference case). There is a large difference between advanced waste-to-energy facilities, which use up to 80 % of the LHV[10], and an average facility. The Back-to-Feedstock recycling technologies (BTF) are clearly preferable to an average incinerator, but the average of the resulting savings are only about half of those of a highly efficient waste incinerator. Recycling back to monomers (BTM) is very attractive for some engineering plastics (see footnote in Figure 2), but the collectable volumes of the respective waste streams are relatively small. Mechanical recycling (BTP) resulting in "Non-polymer substitutes" shows a particularly wide range of values since the environmental impact of primary production differs greatly depending on the material substituted and the subsequent finishing process. Moreover, it is not always clear what to assume for primary production, so the results are more uncertain. The evaluations are also prone to quickly become outdated since many of these products are also attractive for other recycled materials, e.g. recycled cardboard. Finally, mechanical recycling (BTP) leading to "Polymer substitutes" shows the highest ecological advantages, with the exception of BTM recycling for certain types of plastics. Mechanical recycling substituting virgin polymers is a feasible option particularly when a waste stream can be used which contains only one type of polymer.

## Scenarios on the Macrolevel

In this section scenarios for the effects of recycling and energy recovery concerning energy consumption and $CO_2$ emissions at the macrolevel are presented. In a first step the feasible penetration of the various options is assessed. **Table 3** shows the estimates for Germany by the year 2005. In the baseline scenario (Scenario A) an average rate of 22 % over all application areas was assumed for mechanical recycling. If mechanical recycling within DS is excluded, this is equivalent to 12 % which in turn, falls into the range of the rates which can be derived from other studies (Chem Systems 1991; Sofres Conseil, TNO 1998). The 22 % estimate is also very close to the figure which can be determined from a recent Austrian study (24 %). Table 3 also contains the estimates for the waste flows to be processed by feedstock recycling and incineration. In Scenario A, the *average* energy efficiency of today's municipal waste incinerators in Germany was assumed (see section "Environmental comparison of processes"). Compared to the best available units, this average is rather inefficient. In contrast, advanced waste-to-energy facilities have been assumed for the Scenarios B and C (among the best which are in operation in Germany, compare Figure 2). In addition, it has been presumed that only half of the plastics waste which is not recycled mechanically, is incinerated whereas the other half is fed to feedstock recycling facilities. In Scenario C, larger amounts of plastics waste are recycled mechanically (36 %), representing the upper technical potential by the year 2005 (own estimates based on various sources, e.g.). It has not been investigated whether this would exceed the absorption capacity of the recyclate market.

In Table 3 the rates for mechanical recycling have a special importance for the definition of the scenarios. There are a number of obstacles to mechanical recycling, but there are also ways to overcome them to some extent. Examples for obstacles to mechanical recycling are difficulties in recent sorting caused by the low weight of many plastics items (e.g. 60 %

10 Currently only very few plants reach this standard, but it is probable that future incinerators will have better possibilities to sell heat to industry or to district heating systems.

of plastics packagings weigh less than 10 grammes). Moreover, the contamination of post-consumer plastics, the poor miscibility of many types of plastics and the deterioration of material properties due to additives and softeners cause problems. Examples for barriers on the demand side are limitations in the use of recyclates for food and overspecifications in standardisation for some products, e.g. non-pressure pipes, garbage bins and cable ducts.

Examples for measures which improve the chances of mechanical recycling are the automation of sorting technology, design for disassembly and recycling and a trend towards single-resin systems which can be observed in some areas, e.g. in automobile interiors. Further potentials are also available by co-extrusion, compatibilisation, blending, use of reinforcing agents and stabilizers and innovative technology for purification and processing.

The factors mentioned above determine the potential of mechanical recycling which differs from sector to sector (see Table 3). For example, the data for the automotive sector are based on the results of a project dealing with the techno-economic potential of disassembling plastics components. In the case of electrical and electronic plastics waste one third is suitable for mechanical recycling according to a joint APME/VKE project.

Table 3: Shares for recycling and energy recovery for post-consumer plastics waste in Germany by the year 2005

| Application | Sector's share of total plastics waste | Percentage of total waste per recycling/recovery technology | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Scenario A: Low recycling & average incineration | | | Scenario B: Low recycling & BTF & efficient incineration | | | Scenario C: High recycling & BTF & efficient incineration | | |
| | | BTP | BTF | Incin. | BTP | BTF | Incin. | BTP | BTF | Incin. |
| Automobiles & mech. engineering | 16% | 14% | 0% | 86% | 14% | 43% | 43% | 29% | 36% | 36% |
| E&E equipment[1)], precision eng. | 10% | 6% | 0% | 94% | 6% | 47% | 47% | 34% | 33% | 33% |
| Packaging | 35% | 37% | 0% | 63% | 37% | 31% | 31% | 41% | 29% | 29% |
| Building | 13% | 11% | 0% | 89% | 11% | 45% | 45% | 40% | 30% | 30% |
| Agriculture | 7% | 40% | 0% | 60% | 40% | 30% | 30% | 49% | 26% | 26% |
| Household | 6% | 9% | 0% | 91% | 9% | 46% | 46% | 22% | 39% | 39% |
| Furniture | 5% | 13% | 0% | 87% | 13% | 44% | 44% | 21% | 40% | 40% |
| Other | 8% | 20% | 0% | 80% | 12% | 44% | 44% | 26% | 37% | 37% |
| Average (weighted) | 100% | 22%[2)] | 0% | 78% | 22%[2)] | 39% | 39% | 36%[3)] | 32% | 32% |

[1)] Electrical and electronic equipment

[2)] Thereof: 12.5% Polymer substitutes, 9.7% Non-Polymer substitutes

[3)] Thereof: 22.1% Polymer substitutes, 13.5% Non-Polymer substitutes

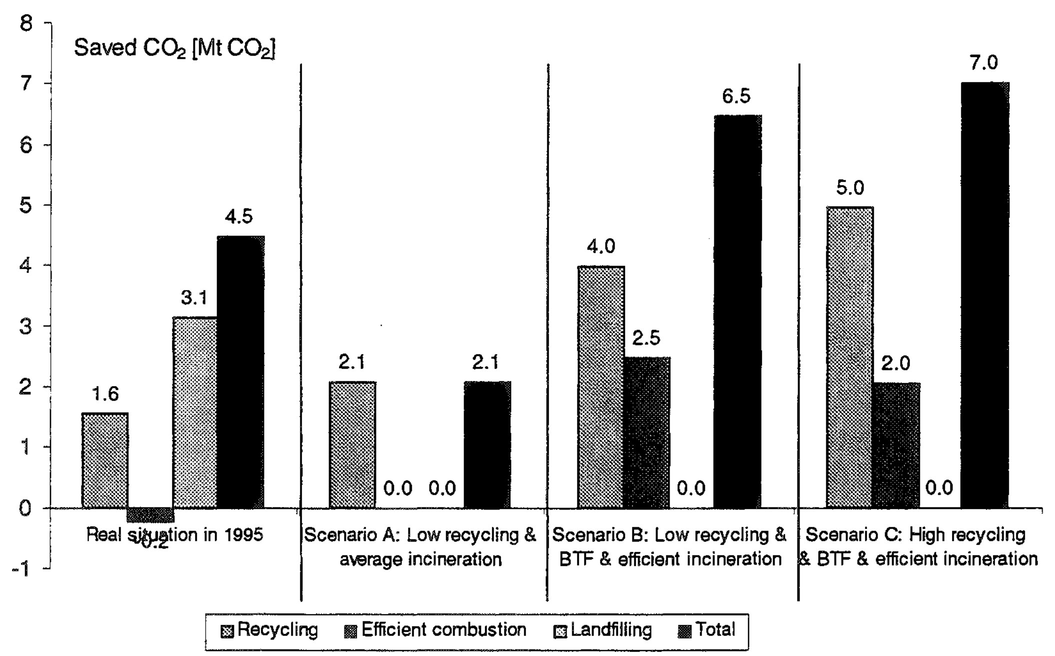
By combining the results of the environmental assessment of the recycling and energy recovery technologies with the rates described in the last section, the contribution of a Closed-Loop policy to energy saving and $CO_2$ abatement can be determined. All comparisons are based on the total amount of plastics waste in the year 1995 [11] (3.65 Mt, without fibres). In **Figure 3** the real situation in 1995 and three scenarios are shown. Only the shares of landfilling, recycling and efficient incineration are varied and the aggregated results are compared. Landfilling which was still available in 1995 avoids $CO_2$ emissions, but energy is wasted. Considerable savings could be made by the year 2005 by stepping from the Business-as-Usual path (Scenario A) to a waste management system with advanced waste-to-energy facilities (Scenario B and C). Under this precondition an enhanced share of mechani-

[11] However, the fractions of waste arisings by applications refer to the year 2005 (see Table 5, second column).

cal recycling increases the total gross $CO_2$ savings by about 8 % (from 6.5 to 7.0 Mt) whereas total gross energy savings remain practically constant (+1.5%, from 73.0 PJ to 74.1 PJ).

To put these data into perspective, they can be compared with the gross energy requirements and gross $CO_2$ emission of the chemical sector (without non-energy use) which roughly equalled 800 PJ and 52 Mt $CO_2$ in 1995 (own calculations). Hence, in the two scenarios B and C, an equivalent of about 9 % of the chemical sector's energy demand and about 13 % of its $CO_2$ emissions could be saved. The *real* environmental benefits by improving the current recycling and recovery of post-consumer plastics will be even higher (also higher than stated in Figure 3) since the amount of plastics waste will continue to rise in the future (Patel, Jochem, Radgen, Worrell 1998).

Figure 3: Impact of recycling and energy recovery on gross $CO_2$ emissions - Results for Germany, 1995 (average municipal waste incinerator)




Note: All calculations are based on the total amount of plastics waste in 1995. In the three scenarios, different rates have been assumed representing the technical potential by the year 2005.

## Discussion and conclusions

In this paper gross energy requirements and gross $CO_2$ emissions have been chosen as indicators to analyse the environmental impacts of various waste management strategies for plastics waste. Focussing on these two indicators is definitely a limitation, i.e. the inclusion of other types of impacts and other indicators, such as the savings of mineral resources, could lead to different findings.

An aspect which should be recalled is the fact that the results of the environmental comparison describe the advantages or disadvantages relative to today's standard primary production in Germany (manufacture of virgin materials) and relative to an average incineration plant (reference case). This is considered to be the major source of uncertainty since unfortunately, an inventory of German municipal waste incineration plants including their fuel mix, efficiencies and energy recovery data does not exist.

The choice of reference processes is difficult to handle. For example, in the case of the SVZ methanole synthesis the production of methanole from natural gas and from the feedstock mix as used in Germany, where a large share of heavy fuel oil is used, was taken as the reference. It should be kept in mind that the results can be influenced decisively by the regional boundaries and moreover, by the chosen timeframe and technological standard (C-STREAMS 1999). Therefore, the results must be handled with caution.

The recycling shares assumed are determined by a whole range of parameters many of which are difficult to estimate (e.g. the general economic development and that of the plastics sector). The shares used for the calculations are considered to be ambitious, but feasible. Developments which are expected to increase the potential of recycling in the long term have not been taken into account. Examples could be the design for recycling in automobiles in the near future which will return as end-of-life vehicles only after the year 2005, and an increased market share of plastics which show specific advantages in recycling.

In spite of the limitations listed, the following findings are considered to be robust:

- In general, recycling and efficient incineration of plastics waste clearly contribute to the goals of saving energy and curbing carbon dioxide emissions. The only exception is mechanical recycling (BTP) where non-polymers are substituted: here the savings *can* be negative, but this is not necessarily the case (see Figure 2).
- In current plastics waste management, there is large scope for improvement both in environmental and in economic terms.
- Recycling should be given preference over energy recovery in an average municipal waste incineration plant in Germany in the mid 90-ies.
- Among those recycling technologies which are applicable for bulk waste plastics streams, mechanical recycling generally yields a high environmental benefit. However, a distinction must be made between mechanical recycling resulting in products where virgin polymers are substituted and other applications which are usually manufactured from wood or concrete. In the first case the ecological advantages are among the highest of all processes studied and there is only little uncertainty about this result; in the second case, however, the result depends strongly on the specific situation.
- To ensure that as many high quality products as possible are manufactured by mechanical recycling the efforts should be continued to segregate plastics waste streams which are as pure and as uncontaminated as possible. The same strategy should be followed in order to exploit the saving potential of BTM recycling as far as possible.
- BTF recycling is clearly preferable to an average mid 90-ies waste incinerator.
- Modern waste-to-energy facilities show clear advantages over average incineration facilities. They even exceed BTF recycling (see Figure 2).

Consequently, this assessment of the net effects for energy consumption and $CO_2$ emissions does not support a general recommendation of energy recovery as it is sometimes put forward in the discussions on plastics waste management. There is no doubt that incineration is advantageous in terms of cost effectiveness. But only in the case of a high technological standard of incineration with energy recovery and with yields which are clearly better than the current average in Germany, incineration becomes competitive in terms of energy saving and $CO_2$ abatement.

The current state of plastics recycling still suffers from major drawbacks from the economic and the ecological point of view. Firstly, it is still very expensive. For this reason, up to now large amounts of post-consumer plastics are deposited in landfills. As a further problem mechanical recycling in the past has in some cases led to low-value products which are difficult to market and the ecological benefits of which are sometimes dubious.

It is interesting to observe that DS, being the protagonist of plastics recycling in Germany, has tackled both the economic and the ecological aspect of plastics recycling. Not only is the DS about to cut costs by enhancing the competition among recyclers; it has also become a strategic goal to correct the imbalance between supply and demand by creating high-value applications for plastics recyclates which, as this paper indicates, will very probably have a positive impact on the ecological evaluation.

The conclusions of this article are subject to changes in technologies and practices. It is very probable that costs will decline over time as result of the R&D activities in the plastics recycling business. Life-cycle analyses, including further environmental indicators, should be performed to assess the potential of new options and to evaluate various waste management policies. Such investigations will help to make the right choices in closing the loops. This is a precondition for the straightforward development and implementation of sound strategies towards more sustainable industrial systems.

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