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Ecological and Economical Aspects of Polymer Recycling

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Abstract: Recycling is considered to play an essential role in developing a sustainable economy. A restrictive environmental legislation has forced German economy into extensive recycling activities. Meanwhile, German society and German industry have more than six years of practical experience with recycling of postconsumer plastic waste from household packaging due to this legislative situation. It is time to critically evaluate the situation. This paper summarizes the development in Germany and tries to show ecological impacts based on a life-cycle analysis and correlates these data with economical consequences.

INTRODUCTION

A discussion on the possible environmental benefit of recycling, on its required extent and on its contribution to a product evaluation has been going on for the last seven years in Germany and for not much less time in the rest of Europe. For plastics, the question is even more complicated since different recycling routes exist (Fig. 1). The public considers mechanical recycling as the best ecological solution since a part of the processing energy can be theoretically saved. Industry, however, stresses prerequisites for mechanical recycling like homogeneous, rather clean waste, which leads to certain limitations, and emphasizes the possibility of energy recovery from highly contaminated but high-energy products like postconsumer plastics.

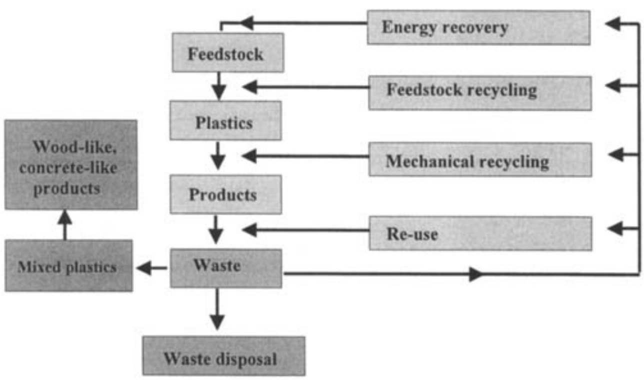

Fig. 1: Recycling strategies of plastics

Since all the energy content of the feedstock is preserved in the final product, plastics can be considered to be an environmentally beneficial recycling loop of crude oil which will be closed once the energy has been recovered. The environmental bureaucracy favoured public opinion to a large extent, which led to the corresponding legislation features:

- Quotas for material recycling in general in Germany and Europe;
- Special quotas for mechanical recycling in a more recent legislation on packaging in Germany;

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- Ongoing discussions in many European countries like Austria or Belgium to introduce quotas;
- Very restrictive emission limits when recovering energy from waste;
- Totally neglecting the energy recovery as in the most recent proposal of the European waste directive.

Initially, little information and facts were known to cope with this situation. This has changed meanwhile:
- Numerous technologies have been tested for its ability to recycle plastic waste.
- Several hundred thousands tonnes of capacities investments lead to practical experience in dealing with plastic waste.
- The costs of recycling became aware rather soon.
- The ecological benefits remained obscure until a life cycle analysis on the subject was carried out.

Today it is accepted more and more that recycling is not an independent goal but an essential part of a sustainable product development. If sustainability is the goal of a modern industrial society, this means at the same time that recycling cannot be evaluated independently as it was done in the past, but only as a part of the product "cradle-to-grave" analysis. In other words, environmental benefits during the life-time of the product and environmental burden when it became waste have to be judged together. Recycling is the goal to improve sustainability but not a goal itself. We have to check where recycling helps to achieve this goal and where not.

TECHNOLOGY AND RECYCLING CAPACITIES IN GERMANY

The German packaging ordinance requests that "... 64 % of the waste separately collected and sorted should be put into material recycling". Material recycling in 1991 – the birth year of the ordinance – meant mechanical recycling only. It soon became apparent that the quality of the plastic household waste is prohibitive to achieve this goal with mechanical recycling alone since more than 60 % of the household plastic packaging waste weighs less than 10 g and is difficult and costly to sort and to purify (Fig. 2). Both are prerequisites for mechanical recycling as is common knowledge meanwhile. Alternative material recycling routes had to be developed since energy recovery has been so far permitted only for the 36 % of remainings on the sorting band, but not for the main waste stream collected. This was the birth of feedstock recycling.

The following routes of feedstock recycling were opened:
- Hydrogenation in an existing plant for hydrogenation of coal or refinery crudes in Bottrop.
- Syngas production in existing plants based on coal conversion in SVZ / Schwarze Pumpe as well as in Rheinbraun/Köln. Both are using the syngas today for methanol production.
- The use as reducing agent in a blast furnace in Bremen. Several other plants test this route (Ecostahl, Thyssen).

Interestingly enough, pyrolysis which has been discussed for many years as a possible route for feedstock recycling is even today not amongst industrial successful routes. It exists only one pilot project of a consortium of several industrial companies using pyrolysis at much lower temperatures than discussed in the past as an alternative to visbreaking for pretreatment of the waste for feedstock recycling routes. Researchers starting new scientific pyrolysis projects should keep this in mind.

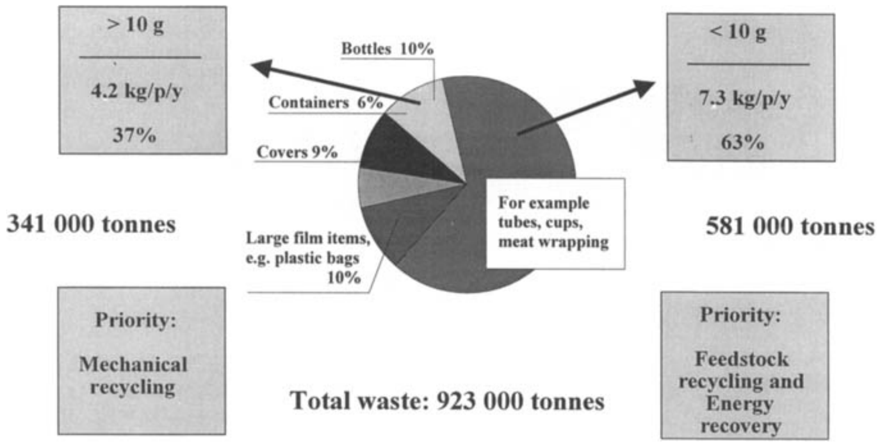


Fig. 2: Plastics packaging – domestic household use in Germany 1991 (source - GVM 1993)

This has led to the following recycling situation in Germany (Fig. 3). According to a market investigation by an independent marketing institute (Consultic), more than 1300 t of plastic waste have been collected and recycled in 1995. Comparing this with the total amount of the waste per year (3000 t) means that more than 40 % of plastic waste was generated already recycled. An enormous success for an organic product. If these figures are analyzed further, it is realized that the major amounts recycled are waste from products for production and in particular processing. Since this is a rather homogeneous waste, it is solely mechanically recycled. Public attention rests more on the postconsumer plastic waste. The major amount here is the waste from DSD household collections but approximately 80 000 t is the postconsumer waste from other areas like automotive or electro/electronic.

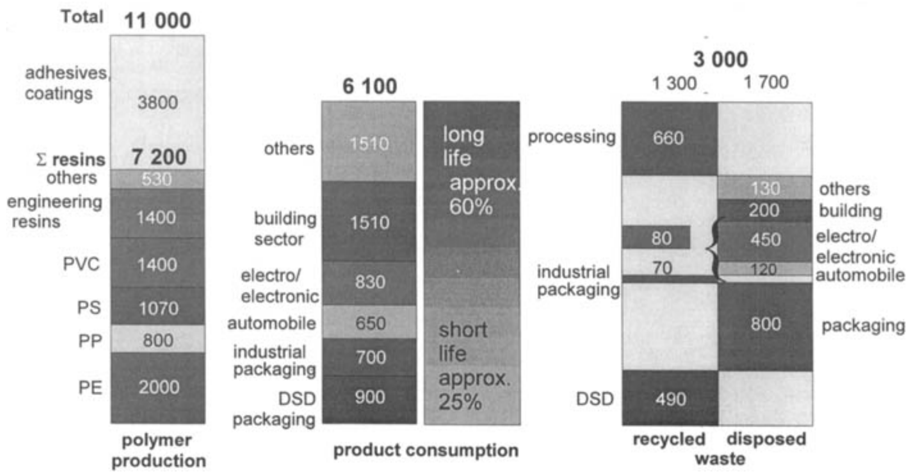
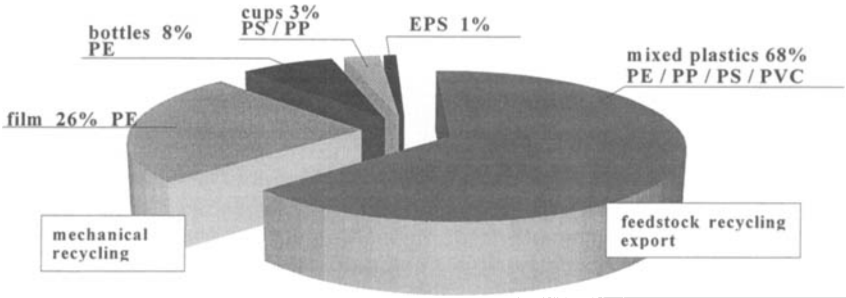


Fig. 3: Production, use and waste of plastics in Germany 1995 (t/y)



	1994	1995	1996
Plastic packaging collected	**546 500 t**	**731 385 t**	-
Plastic packaging recycled	**461 100 t**	**504 000 t**	**535 000 t**
- feedstock recycling	**52 000 t**	**99 000 t**	**251 000 t**
- export	**256 000 t**	**233 000 t**	**102 000 t**

Fig. 4: Plastics packaging waste from yellow bag collections

If the DSD fraction is analyzed more in detail (Fig. 4), the following statements can be made. There is a certain part, the so-called "pick of the basket" like large bottles, large foils, which can be recycled mechanically substituting virgin resin. In addition, a certain part can be used as a substitute for wood or concrete. While the first route is waste-limited, i.e., only 24 % of the total waste collected is bottles, foils, etc., the second application, substitution of wood or concrete, is market-limited. Technical service work is needed for a further moderate growth of between 4 and 6 % per year. The main substitution routes for different waste fractions are shown in Table 1.

Table 1: Mechanical recycling of DSD/DKR waste. Substitution of virgin resin vs wood/concrete, 1996 (t/y)

	Germany		Export	
	Plastic	Wood/Concrete	Plastic	Wood/Concrete
Films	47 550	8 830	34 740	3 600
	84 %	16 %	91 %	9 %
Bottles	45 630	2 480	700	-
	95 %	5 %	100 %	
Cups	70 320	410	-	-
	95 %	5 %		
Mixed plastics	9 100	25 670	42 130	3 120
	26 %	74 %	93 %	7 %
	109 600	37 930	77 570	3 120
	66 %	34 %	91 %	9 %
Total	approx. 147 000		approx. 84 000	

The alternative material recycling route - feedstock recycling - was handicapped by limited capacities in the past. The reason for this is the valid packaging ordinance which requested the 64% goal of recycling to be achieved within five years, a time span insufficient to build up a plant. Thus, export was the outlet in the past and will be reduced in time with increasing capacities for feedstock recycling coming on stream. Feedstock recycling has to carry the major amount of postconsumer plastic waste due to quality insufficient for mechanical recycling.

Financing is a very important issue when dealing with the economic aspects of recycling. There are large areas of recycling which are profitable themselves. The actors here act like common producers and dealers. This is the case of recycling of production and processing waste. But most of the recycling requested by legal pressure is uneconomical. The main legal argument for that is the so-called requirement for internalizing of external cost so far carried by the public. In principle, industry accepts this concept to consider waste costs as part of the product total costs as long as these costs are realistic and not artificially raised by political pressure or by exclusion of marketing forces. Both has been true in Germany for the postconsumer area in the recent years.

The model for financing unprofitable waste stream from households is the so-called "Green Dot" financing system whereby a company buys a sales licence for every individual piece of packaging it sells in the German department stores or shops. The money collected is spent for waste haulers, waste sorters and, in the case of plastics, for the recycling of postconsumer packaging waste from households.
It soon became apparent that this is a very expensive system. More than 2 billion DM are spent today in order to collect approximately 750 kt and to recycle 500 kt of plastic waste. This corresponds to approx. 4 DM/kg. The market price of this product is between 1 and 2 DM/kg (Fig. 5).

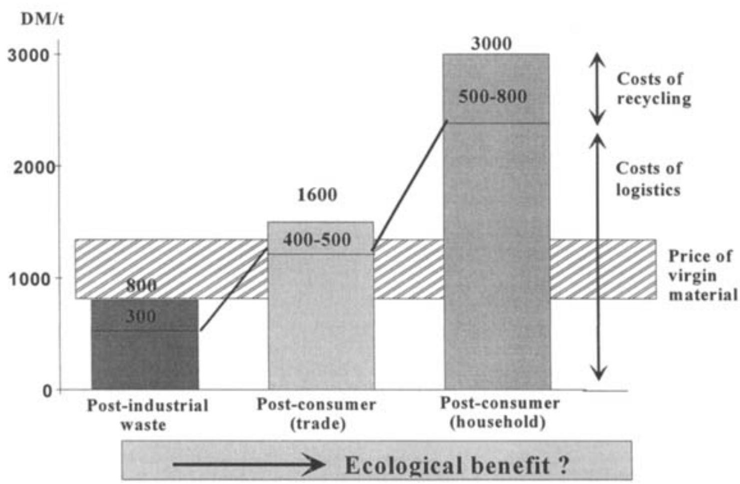


Fig. 5: Dependence of the waste management costs on the quality of waste plastics packaging

Several questions are raised immediately:

– Are these enormous waste costs the real costs of recycling which industry is prepared to accept or are they artificially high for the benefit of waste management ?

- Do more economical alternatives of the waste management exist ?
- *What are the ecological benefits which justify these enormous additional product costs ?*

It should be mentioned here that several more financing systems have been developed for industrial plastic waste like RIGK, FAF, EPSY. These organizations request significantly smaller gate fees and, interestingly enough, the customer acceptance of the system is inversely proportional to the product market price, i.e. product profitability.

ECOLOGICAL CONSIDERATIONS

Very often, the most economical process is also the best ecological process since it uses generally least energy. This could not be proved for the recycling of plastics packaging from the household waste in the past. In order to give a more specific answer to this problem, German plastics industry initiated a life cycle analysis for all presently known routes of recycling and recovery (Fig. 6) for which it gained financial support from Association of Plastics Manufacturers in Europe (APME), Verband der Chemischen Industrie e.V. (VCI) and Duales System Deutschland GmbH (DSD).

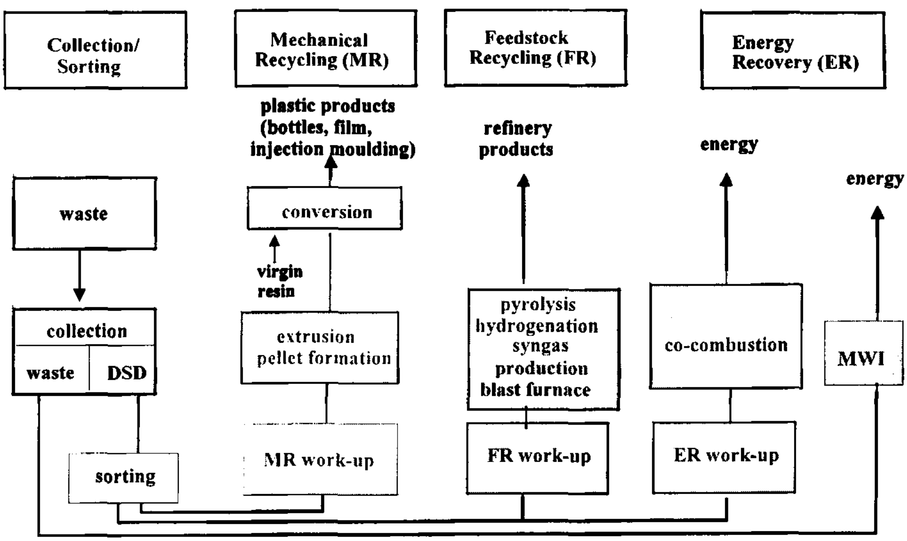


Fig. 6: Plastics recycling scenario (MWI - municipal waste incineration)

The intention was to evaluate the present day technology of plastics recycling from an environmental point of view using the instrument of life cycle analysis (LCA). Approximately twenty companies participated. This means, they were prepared to describe their process in detail and to inform on the input of resources like energy, feedstock, etc., and on the output like airborne and waterborne emissions, solid waste, heavy metals and other environmentally important products. The signing of secrecy agreement assured the companies of protection of their know-how.

The German Agency on Environment participated as guest and the German TÜV validated the individual data and their correct interpretation. The present state of ISO rules on LCA was followed as closely as possible. An independent peer review is still in progress. The life cycle analysis (LCA) was carried out by three institutes which had the tasks described in Fig. 7.

Over a two-year period, more than hundred persons participated in the project collecting data, evaluating and discussing them in various working groups. Here is not the place to describe this instrument of LCA in detail. Basically, all environmental inputs like resources (energy, water etc.) and outputs like water- and airborne emissions as well as waste are collected in a databank. The individual data are then grouped together and assessed in relation towards their potential influence on certain environmental effects like the ozone depletion and greenhouse effect.
In addition, a solution to the problem of comparing different processing routes leading to different products like recyclate, energy or methanol had to be developed in this specific case. The problem has been solved by defining a product basket. This basket contains all products available from reprocessing plastic waste in an amount as realized from a certain amount of waste to start with.

Mechanical recycling (Prof. Fleischer/Berlin)
bottle-to-bottle
film-to-film
film-to-cable conduit

Feedstock recycling (Prof. Ebert/Kaiserslautern)
thermolysis
hydrogenation
syngas production (fixed bed, fluidized bed)
blast furnace reduction agent

Energy recovery (Dr. Holley/München)
monocombustion
municipal waste incineration

Fig. 7: Life cycle analysis of recycling/recovery of plastics from packaging materials in household waste (Initiators: German and European Plastics Industry, German Chemical Industry, Duales System Deutschland)

The goal of the project was to fill this product basket of constant composition in the most ecological way. The argument was that the need for these products by humans is the reason for producing them in any case. If they are not obtained from waste, they have to be produced from virgin raw materials. In other words, when 1 kg of plastic waste is turned into 1 kg of recyclate, the energy needed for this basket has to be produced from primary fuel and vice versa.

The results could be simplified further when comparing each alternative route with one standard route. The traditional economy of producing all products in the basket from virgin resources and putting all waste to landfill was taken as this standard route of filling the basket. The results are shown as differences from this standard route and immediately show an ecological improvement or deterioration for this recycling route.

As demonstrated in Fig. 8, all routes of feedstock recycling or energy recovery show an improvement if comparing energy consumption, but to a different extent. Energy consumption and energy related effects like the global warming potential or the ozone depletion potential as well as landfill deposits were shown to be the most relevant environmental categories. Other categories like acidification potential, for instance, showed no or only very small differences between different routes of filling the basket of benefit and are not discussed here.

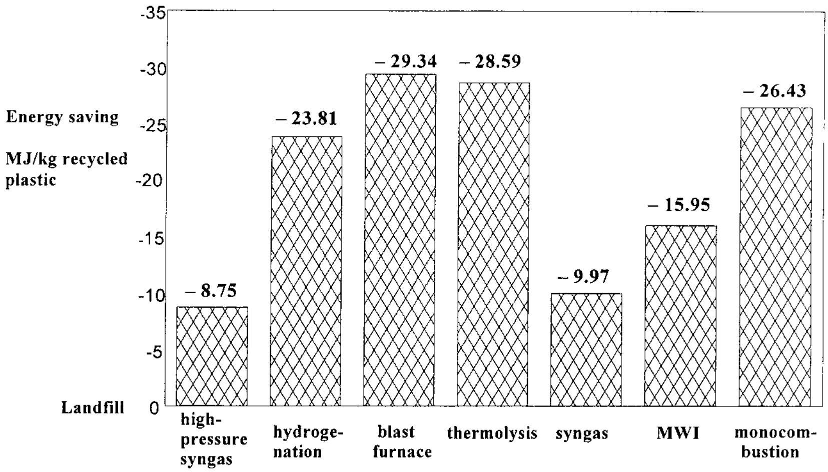


Fig. 8: Saving energy by feedstock recycling in comparison with landfill

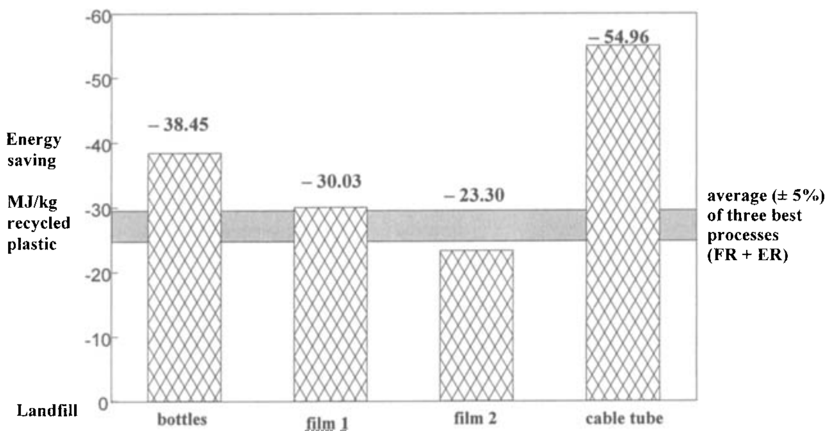


Fig. 9: Saving energy by mechanical recycling in comparison with best feedstock recycling processes

While the methods of feedstock recycling or energy recovery are able to deal, in principal, with all kinds of waste, sometimes after some pretreatment, mechanical recycling can be used only for certain less contaminated, but especially for rather homogeneous fractions. If we now compare four different cases of mechanical recycling (twice film-to-film, bottle-to-bottle and bottle-to-tube) with the ecologically best available technology from the other routes (Fig. 9), we realize that mechanical recycling is not (as assumed by public) always the best resource-saving recycling route.

As can be seen, mechanical recycling is able to save in certain cases also a part of the processing energy of plastic waste and hence it is in these cases the ecologically preferred process. But, there are also examples of mechanical recycling which save less energy than the best universal processes. In these cases, feedstock recycling is the ecologically preferred process. The positioning of this break-even point depends on the efficiency with which recyclate is able to replace virgin resin (Fig. 10).

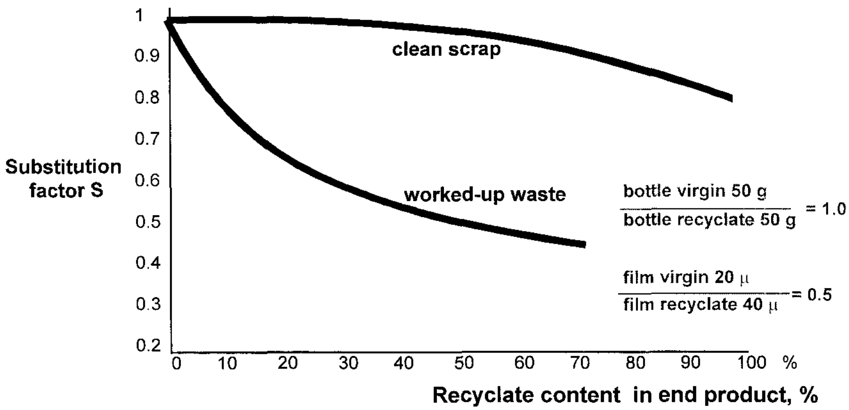


Fig. 10: Possible dependence of substitution factor on amount of recyclate in product ($S_{equal\ functionality}$ = kg virgin resin/kg recyclate)

If 1 kg of recyclate is able to substitute 1 kg of virgin resin and the final products fulfil the same practical functions, the substitution factor of 1. If, on the other hand, a bag has to be 30% thicker in order to have the same impact strength as a bag made from the virgin material, the substitution factor only equals 0.77. The substitution factor certainly varies with the ratio between recyclate and virgin material in the final product.

It will mostly be unity at low percentages of recyclate and drops drastically with increasing percentage of recyclate in the final product. Two limiting cases can be assumed in theory, one where the clean scrap substitutes virgin resins up to 100% with only a certain drop in properties and one where the worked-up waste substitutes virgin resin only up to a certain content and this with a much larger drop in properties.

The critical substitution factors or break-even points comparing mechanical recycling and feedstock recycling, i.e., when the ecological effects of mechanical recycling are identical to those of the best feedstock processes, have been calculated for the ecological categories considered for all the four routes of mechanical recycling investigated (Table 2).

Table 2: Ecological critical substitution factors resulting from a comparison of mechanical recycling and feedstock recycling

Input		**Best feedstock process**	**Bottle**	**Film 1**	**Film 2**	**Tube**
Energy total	(MJ)	blast furnace	0.922	0.682	x	0.648
Energy renewable	(MJ)	municipal waste incineration	x	0.567	x	0.644
non-renewable	(MJ)	blast furnace	0.923	0.687	x	0.651
Water	m^3	hydrogenation	0.797	0.055	0.284	0.239
Output						
Waste	(kg)	municipal waste incineration	x	x	x	x
Special waste	(kg)	blast furnace	0.603	x	x	0.050
Eutrophication	(mol PO_4)	thermolysis (BASF)	0.747	0.278	x	0.259
Acidification	(mol H^+)	thermolysis (BASF)	0.740	0.258	x	0.261
GWP	(kg CO_2)	blast furnace	0.939	0.485	x	0.573

x - worse than feedstock recycling; 0.9 - better than feedstock recycling above the substitution factor given

Mechanical recycling processes differ tremendously. In addition, different polymers like PP, PS, PET, PVC, etc. can be recycled. Hence, a general route of mechanical recycling does not exist; instead, individual cases have to be considered. The procedure developed in this project enables us to position all of them if the environmental data are available.

An interesting aspect is to check the ecological relevance of substituting wood or concrete (the famous "park bench" products) instead of substituting virgin resins as considered so far. Without mentioning here all the scientific details of this additional investigation, the results shown in Fig. 11 clearly indicate:

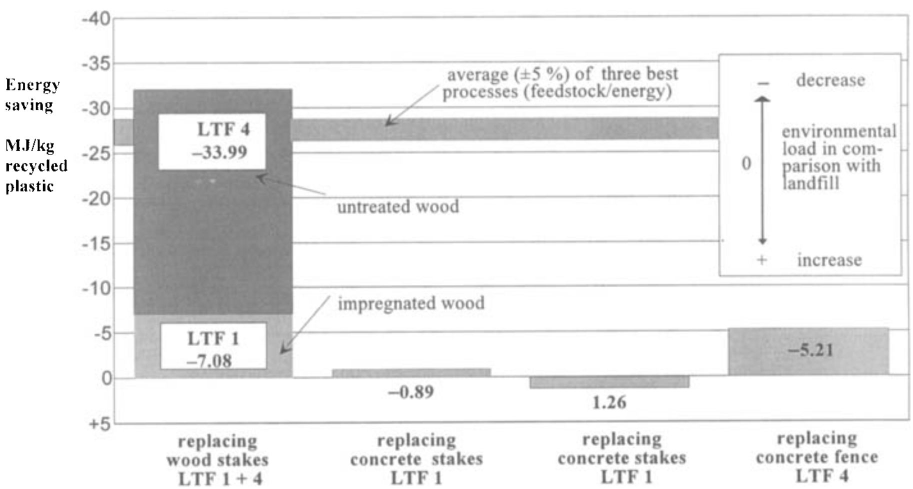


Fig. 11: Energy saving in mechanical recycling of mixed plastics (DSD-system) in comparison with landfilling (LTF = life time factor)

- The substitution of wood by the plastic recyclate has an ecologically positive contribution to energy preservation only in the case of large differences of product life-times, i.e., if the plastic products last much longer than the wooden products.
- The substitution of concrete by plastic products is always ecologically meaningless in comparison with alternative feedstock recycling or energy recovery routes.

What are the general conclusions of this work? The decisive factors in an ecological assessment are: Which processes (fed by primary resources) and which pre-products are substituted by a waste recovery process chain and what ecological expenses are needed for the substitution process. For instance, mechanical recycling is an ecologically more efficient process than feedstock recycling if the ecological expenses for mechanical recycling are low. If they are excessive – and this investigation has provided examples for this – the feedstock recycling or energy recovery may be the ecologically more preferred processes.

This leads to the final conclusion that there is not only one preferred process for recycling plastics from household packaging but an ecologically sensible recovery strategy has to combine mechanical and feedstock recycling as well as energy recovery routes taking into account both ecological and economical aspects.

ECONOMICAL CONSIDERATIONS

Economical considerations require establishing a correlation between ecology and economy. In order to do this, we have to correlate the ecological data with the amounts of waste treated and to evaluate the costs associated with each recycling route. The saving of energy was chosen for comparison. Assuming for feedstock recycling the best available average (29 MJ/kg) and for mechanical recycling the top value obtained (54 MJ/kg), we arrive at the data shown in Fig. 12.

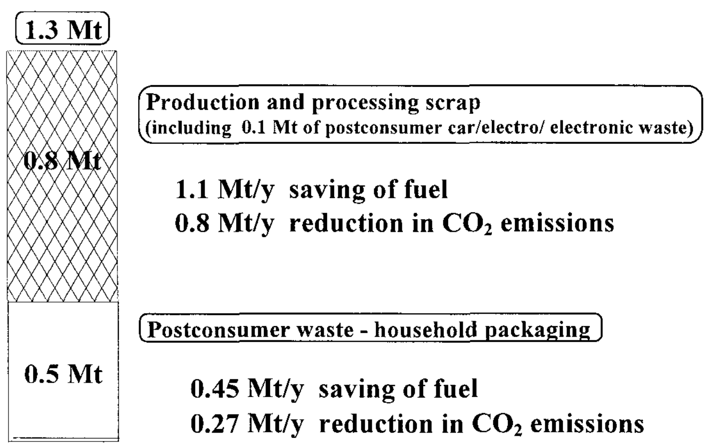


Fig. 12: Ecological consequences of recycling of plastics in Germany 1995

Approximately 1.3 Mt/y of fuel and 1.1 Mt/y CO_2 emissions are saved every year by recycling plastics already in Germany. The major contribution comes from recycling processing waste and certain better defined postconsumer waste streams, while postconsumer plastics waste from household contributes less. If we now consider the fact that the latter costs the national economy approx. 2 billion DM/y while the former is profitable, we have to ask the question how we could improve the situation. In order to do that, four major hypothetical scenarios have been investigated for comparison:

Case 1 – All DSD plastics waste of approx. 500 kt is not separately collected but left in municipal waste and treated in a municipal waste incinerator.
Case 2 – Plastic waste is collected separately via DSD and all of that is fed into a feedstock recycling process like blast furnace. This allows savings in sorting and in collection (for instance, higher compression possible).
Case 3 – Plastics waste is collected separately and all of that is manually sorted into bottles, films, cups and mixed plastics. 25 %, mainly the first three fractions, is used for mechanical recycling substituting virgin resin only and 75 % is feedstock recycled.
Case 4 – The percentage of mechanical recycling in Case 3 is raised to 50 %.

The calculated ecological benefits for each scenario were set in comparison with the corresponding total costs for the respective scenario making certain assumptions for collection, sorting and recycling. The results are presented in Fig. 13.

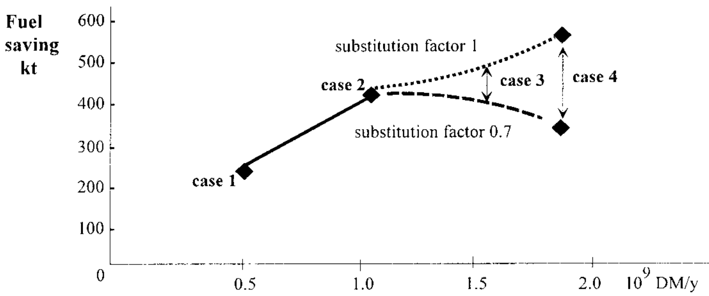


Fig. 13: Ecology vs economy for different strategies of recycling and recovery (case 1 - municipal waste incineration, case 2 - blast furnace, case 3 - mechanical recycling and feedstock (25:75 %), case 4 - mechanical recycling and feedstock (50:50 %)

It clearly shows ecological benefits for Case 2 and Case 3 in comparison with Case 1. But the costs incurred are tremendous. If the percentage of mechanical recycling is increased even further (Case 4), ecological benefits become dubious because an efficient substitution of virgin material by the products obtained becomes doubtful. It was neglected totally in this consideration, for instance, that a major part of the mechanically recycled waste originating from the DSD/DKR systems and not the virgin resin substitute wood or concrete today as shown earlier.

The German ordinance on packaging presently being discussed in the Parliament requests that 40 % of the waste collected should be recycled mechanically. The possible national savings of 120 t/y of fuel due to this in comparison with the 100 % energy recovery of the amount of 500 t/y require an expensive separate collection and sorting system where we pay more than five times the market price for the resources we have saved. There are more efficient routes to save comparable amounts of resources. Therefore, the actual conclusion is that also in ecological evaluations, the economic aspect has to be considered. The money spent here cannot be used for potentially higher ecological benefits somewhere else.

CONCLUSION

The actual discussion we have to start with is what are important ecological aspects for a sustainable development of our society and how financial resources can be directed towards these priorities.

Summarizing present experience in Germany, it can be concluded:

- Recycling should not be considered isolated. Recycling is an environmental goal and part of a sustainable development of a product.
- Recycling should be valued as part of the cradle-to-grave approach. Environmental benefits/burden of the product life time should be compared with waste or recycling issues and judged together.
- Products satisfy human needs. The life cycle analysis helps to find the most sustainable way to do it.
- Ecological benefits and economic costs have to be in balance. Recycling costs have to be taken into consideration when evaluating a situation.
- Sustainability means to consider ecological, economical and social aspects of recycling.