Improving the Efficiency of Fossil Carbon Use for Materials

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ABSTRACT

This paper deals with the use of fossil carbon to manufacture materials ("products of non-energy use") and with the potential to reduce the inputs of fossil resources and the emissions of fossil carbon CO_2. The paper starts by giving an overview of the material flows in Germany in 1995. As an interesting result, recycled and re-used products still accounted for less than 10 % of the final products consumed domestically. Then the energy requirements and CO_2 emissions of all the production and waste processes related to non-energy use are calculated: it is estimated that approx. 1700 PJ of finite primary energy are consumed and 57 Mt of fossil CO_2 emissions are released (1995). Compared to the total German industry (without non-energy use) this is equivalent to nearly 44 % for energy and 18 % for fossil CO_2. The potential for future improvement is quantified by estimating the possible impact of recycling, re-use, enhanced energy recovery and the use of biomass as a feedstock. In total, the potential savings identified amount to 218 PJ of gross finite energy and 13.6 Mt of gross fossil CO_2. Compared to the total system analysed this is equivalent to savings of 12.8 % for energy and 23.8 % for CO_2. Hence, the saving potential identified on the non-energy side is comparable to the one discussed and negotiated for energy efficiency improvement.

Introduction

Fossil fuels are mainly used to provide the economy with energy, primarily in the form of liquid, gaseous and solid energy carriers and electricity. However, a significant fraction of fossil fuels is also used for "non-energy" applications. "Non-energy use" is defined as the consumption of carbon feedstocks for the manufacture of synthetic materials and chemical products, e.g. plastics, fibres, synthetic rubber, lacquers & varnishes, solvents, fertilizers, lubricants and surfactants. In principle, most of these products can be manufactured from carbon sources of both fossil and biomass origin. However, since the contribution from biomass sources for non-energy use is generally very small, it is usually neglected in energy balances. Therefore, non-energy use is usually defined as the consumption of *fossil* carbon feedstocks.

In energy terms, non-energy use, i.e. the consumption of fossil fuels as feedstocks, represents approx. 12 % of the total amount of fossil fuels for final consumption in Western Europe (EU-15, 1996). Within Europe, the share of non-energy use differs from country to country. For example, the share in the Netherlands is approx. 16 %, and hence fairly high, whereas, it is close to the European average in Germany, with a percentage of about 11 % (1996). German non-energy use in 1995, i.e. the amount of fossil carbon used as chemical feedstock, was equivalent to approx. 77 Mt[1] of CO_2 (Patel et al. 1998b). However, only a part of this is released in the short term (actual emissions), due to industrial processes (steam-cracking, methanol and ammonia production), the treatment of solid and liquid production waste, wastewater treatment and short-lived products, e.g. solvents and antifreeze agents. The remainder may be emitted in the long term, mainly due to carbon stored in plastics, synthetic rubber and bitumen (Patel et al. 1998a).

In addition, energy is also required for fuelling the processes which are in operation to convert fossil feedstocks to final products. This also leads to CO_2 emissions.

Once a final product of non-energy origin becomes waste it is a potential source for further CO_2 emissions. Products made of plastics, for example, will practically not result in any CO_2 emissions if they are landfilled but they are fully oxidised to CO_2 in the case of incineration. On the other hand, plastics incinerated in municipal solid waste incineration (MSWI) plants may substitute, to some extent, the use of fossil fuels if the plant also produces electricity and/or steam (waste-to-energy facilities). Moreover, technology for recycling and re-use may help to reduce the energy demand and the CO_2 emissions of the system. This may also be true for the increased use of biomass as a chemical feedstock.

We are currently preparing a study dealing with these issues for the German economy (Patel et al. 1998b). The goals are to

a) make an inventory of the flows of all materials made of fossil carbon ("products of non-energy use"), including the manufacture and foreign trade on the various levels of production and, moreover, the generation of waste and its management in the year 1995,
b) to determine the energy requirements of and the CO_2 emissions from this entire system,
c) to compile the most important measures applicable to improve resource efficiency and to abate CO_2 emissions within this system and
d) to estimate the potential savings of energy and CO_2 for the system analysed, assuming the state of technology in the year 2005.

This paper presents the major results of the analyses. The study does not include any assessment of the potentials related to *energy efficiency*.

Methodology

As **Figure 1** shows, the material flows, energy requirements and CO_2 emissions of carbon-based products in the production chain and in the waste management section are simulated by a set of coupled modules (see boxes in Figure 1). Within the process chain of production, four production levels are distinguished: they are represented by the modules for the production of fuels (module AB), of basic chemicals (module BC), of intermediate products/materials (module CD) and of final products (module DE). In the following service module (module EF), the in-use phase of the final products is modelled: Products consumed at one point of time return as post-consumer waste when their lifetime is over. Then the waste

[1] Mt stands for 10^6 metric tons (Megatons).

is collected, possibly segregated and pre-treated. It is then sent to the various waste treatment facilities, i.e. mainly landfilling, incineration and the various options for closing the loop, i.e. Back-to-Feedstock recycling (BTF), Back-to-Monomer recycling (BTM), mechanical recycling (Back-to-Polymer, BTP) and final product recycling (Re-Use).

Recycling and re-use practically always require processes tailored to the specific waste stream and in some cases individual collection schemes are necessary (e.g. for waste bitumen). But there are also substances which are not recoverable at all, e.g. surfactants; here, the carbon fixed in the product is irretrievably lost to the environment.

The entire model comprises approx. 120 processes. For these, input-output tables depicting the supply- and demand relationships in physical terms were elaborated (Patel et al. 1998b). The datasets also include import and export data and, if relevant, the values of feedback streams (reflux) and of side products.

Overview of material flows

Figure 1 shows the material flows by modules in Germany in the year 1995. All figures represent physical flows in 1000 metric tons (kilotons, kt). The flows presented mainly contain carbon, with smaller amounts of hydrogen, nitrogen, oxygen and chlorine. The Service Module and the subsequent waste management has been studied in detail for plastics, synthetic rubber, lubricants, bitumen. All the other materials are not followed up (see arrow "Other Final Products" in Figure 1).

Most of the fuels produced in module AB are consumed in the economy as energy carriers (energy use, 446 Mt) whereas, 26.5 Mt are consumed for non-energy purposes. About 1 % of non-energy use is provided by BTF recycling of post-consumer lubricants (263 kt) and plastics (29 kt). These plastics are recycled by hydrogenation and by blast furnaces. The figure given for consumption and losses (10 519 kt) is mainly due to the refineries' energy requirements.

In the subsequent module BC, a small amount of basic chemicals was provided by the BASF plastics pyrolysis (14 kt). In the following module CD, the material flow provided by recycling (624 kt) comprises secondary materials made from post-consumer plastics (557 kt) and rubber (67 kt). A considerable share of the recycled plastics was exported in 1995.

About 715 kt of post-consumer materials were recycled back to module DE. The major part of this flow is bitumen (600 kt) which is recovered as reclaimed asphalt pavement (RAP) and is fed back to road construction. Old tyres constitute the remaining amount (115 kt) most of which is re-used by retreading.

To summarize, the total amount of materials produced by recycling or re-use corresponds to about 1650 kt (plastics, synthetic rubber, lubricants, bitumen). If compared to the total amount of final products consumed domestically in 1995 (total output of the entire module DE, 22 973 kt), this is equivalent to 7 %.

Although plastics recycling continued to increase between 1995 and 1997, recycled and re-used products still accounted for less than 10 % of the total amount of the final

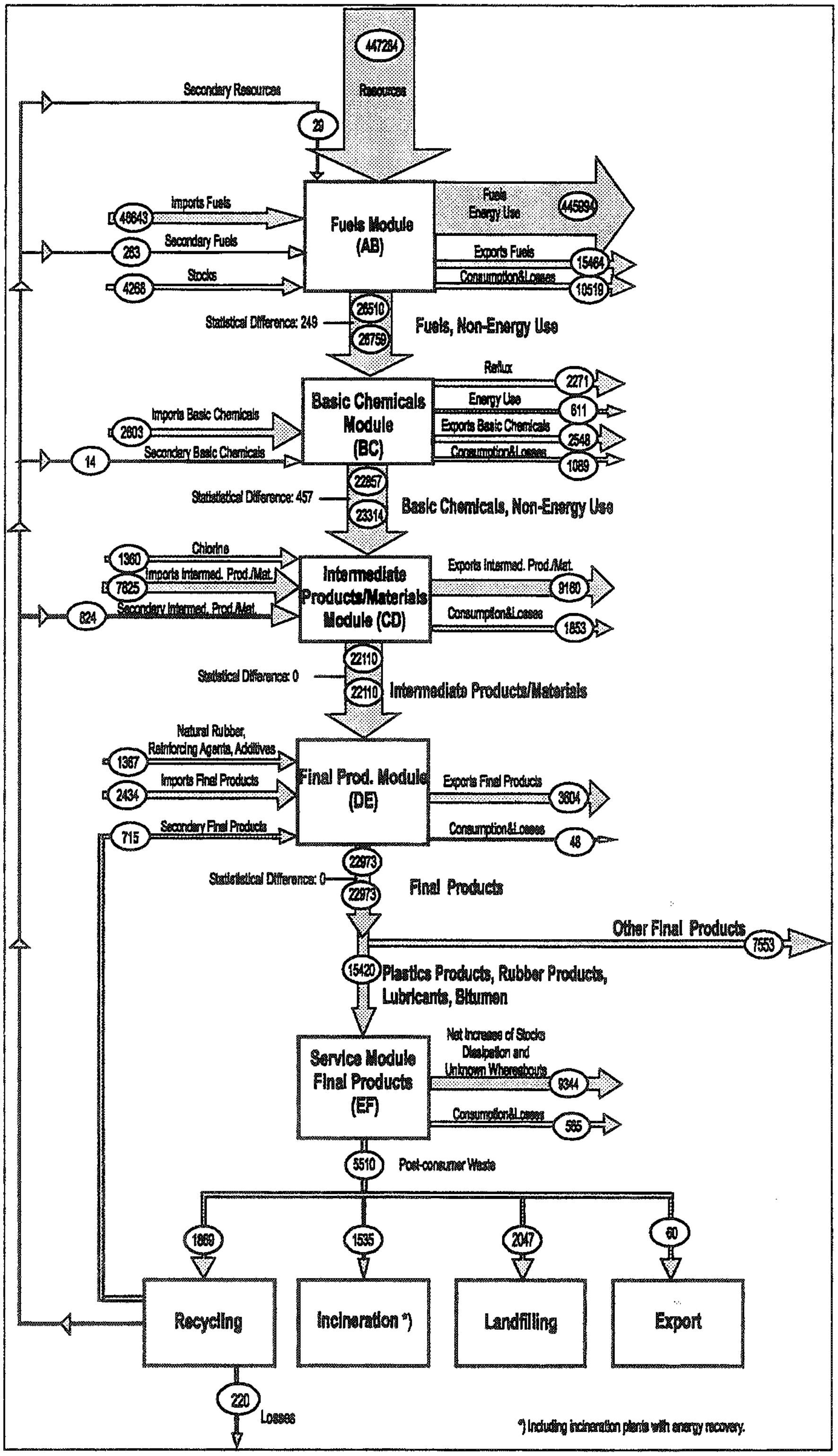

Figure 1. Mass Flows (in metric kilotons, kt) of Materials Made of Fossil Carbon in Germany, 1995

products consumed domestically in 1997[2]. The reasons for this low percentage are that considerable amounts of waste are landfilled and incinerated and more importantly, that there is a large increase of stocks. For example, in the case of plastics products, the increase of stocks represents 58 % of the consumption of final products (Patel forthcoming). This is due to the large share of plastics used in long-lived products: it has been estimated for Germany that about 70 % of the total consumption of plastics products are in use for more than 3 years and about 30 % for even more than 11 years (Patel et al. 1998c). Since direct landfilling of waste containing organic carbon will be prohibited in Germany from the year 2005 onwards and since the material flows in the economy will gradually reach a steady state, the amounts available for recycling and re-use will rise in the future. For the longer term, the potential is enormous. Two reasons can be given for this: Firstly, the amount of post-consumer plastics waste, being the largest stream of the materials studied, would increase by a factor of 2.4 if the net increase of stocks were zero (based on data for 1995, according to (Patel forthcoming)). And secondly, the use of some materials - again especially plastics -, will continue to rise in the future which will also result in larger amounts of waste.

Energy & CO_2 Analysis for virgin material production

In the petrochemical industry there is a close relationship between energy and materials: to produce the bulk chemicals methanol, ammonia and olefins, a part of the feedstock is used as a fuel. Moreover, the production waste that is not suited for recycling is usually incinerated and some of the energy is recovered for steam raising and electricity generation. Finally, due to imperfect yields, a part of the carbon feed ends up in wastewater and requires treatment. All of these processes lead to immediate CO_2 emissions. In **Figure 2** the energy and material flows and the CO_2 emissions for virgin material production are shown. On the left hand side, the upper stream represents the direct energy use in the modules AB to DE (290 PJ fuels, 90 PJ electricity; 37 Mt CO_2), whereas the lower stream represents the non-energy use of fuels, i.e. the input of feedstocks (1066 PJ); of the latter, a total of 239 PJ[3] is oxidised, leading to 16.3 Mt of CO_2[4]. This demonstrates that the immediate emissions of non-energy origin are not negligible, i.e. that they have to be included in any emission inventory prepared for the chemical/petrochemical sector.

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2 It may not be considered as appropriate to choose the total amount of the final products consumed domestically as the reference quantity. The reason is that recycling/re-use is not possible for some of the products due to their dissipative way of use (e.g. surfactants). If the these products are excluded the percentage increases by about 50 %. Hence the percentage recycled and re-used is still close to 10 %.

3 This is the total of the following figures given in Figure 2: 87 PJ for steam crackers, 112 PJ for NH_3/CH_3OH, 31 PJ for solid and liquid waste and an equivalent of 9 PJ of organics in wastewater.

4 This is the total of the following figures given in Figure 2: 5.5 Mt CO_2 from steam crackers, 7.6 Mt CO_2 from NH_3/CH_3OH, 2.2 Mt CO_2 from solid and liquid waste and 0.95 Mt CO_2 from organics in wastewater. The captive use of CO_2 in urea and calcium ammonium nitrate (0.9 Mt CO_2) is not included in this total because these amounts of CO_2 are fixed in fertilizers and are released as a part of agricultural activity, but not of chemicals production.

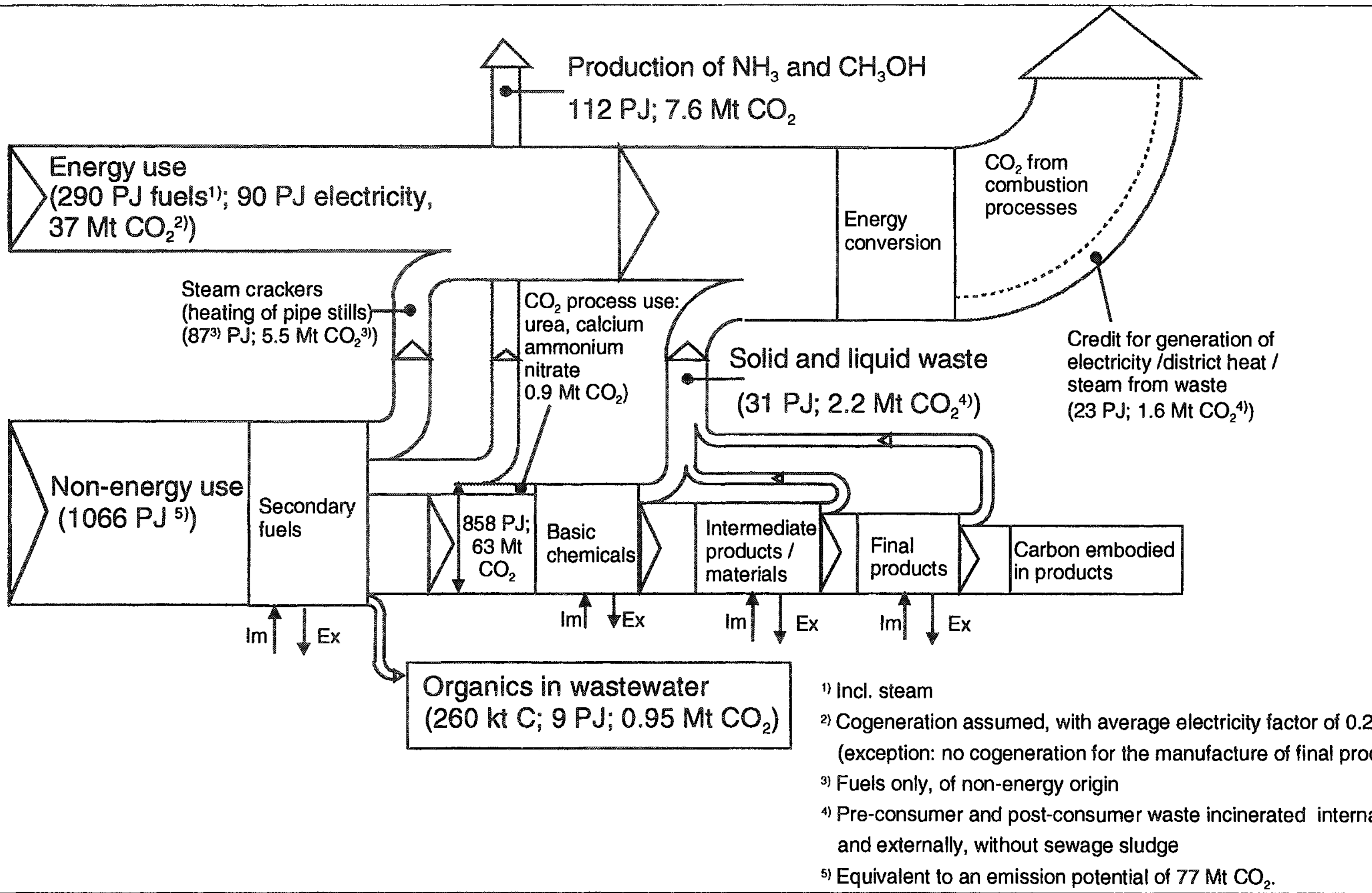

Figure 2. Interrelation of Energy, Material Flows and CO_2 for the Manufacture of Virgin Synthetic Carbon Products in Germany, 1995

Table 1. Energy requirements and CO_2 emissions related to the manufacture and waste management of synthetic carbon products in Germany, 1995 (system analysed: national boundaries)

	Material flow [1] [kt]	Consumption of finite primary energy equivalents [PJ]	Fossil CO_2 emissions [kt CO_2]
Fuels Module (AB) [2]	26,510	899 [3]	4,542 [4]
Basic Chemicals Module (BC)	22,857	258 [5]	16,993 [6]
Intermediate Products/Materials Module (CD)	22,110	307 [7]	19,886 [8] [9]
Final Products Module (DE) [10]	22,973	175	10,661
Subtotal, Primary production	-	*1638*	*52,081*
Recycling back to Resources/Fuels (BTF)	520	1	75
Recycling back to Basic Chemicals (BTM)	15	0	5
Recycling back to Intermediate Prod./Mat. (BTP)	624	5	318
Recycling back to Final Products (RU)	14,815 [11]	99	3,262
Incineration (OXIDAT)	1,535	-35 [12]	1,629
Landfilling (DEP) [13]	2,047	0	0
Subtotal, Waste management [14]	-	*70*	*5,288*
Total, Entire System	-	*1708*	*57,369*

The table does not give any data for Module EF since the energy inputs and CO_2 emissions during the utilization phase are outside the scope of analysis.

The table does not give any data for Module FG since the energy inputs and CO_2 emissions due to transport & logistics have been allocated to the various waste management technologies (Modules BTF to DEP).

1) For the modules describing primary production (AB to DE) the output used for non-energy purposes is listed; for the modules describing waste management (BTF to DEP) the waste input is listed.

2) The data given in this line refer exclusively to outputs which are used for non-energy purposes and which are produced from fossil fuels.

3) Thereof 71 PJ as process energy; 828 PJ non-energy use (feedstock) in a narrow sense, i.e. without the fractions used to cover the process energy requirements in the following modules (including these fractions used for process energy: approx. 1070 PJ).

4) Only CO_2 emissions originating from process energy requirements, i.e. without the CO_2 equivalents of the carbon stored in the products.

5) Thereof 219 PJ originating from feedstocks.

6) Thereof 14600 kt CO_2 originating from feedstocks.

7) Thereof 20 PJ originating from feedstocks.

8) Credits for the chemical use of CO_2 have already been taken into account (360 kt CO_2 due to the manufacture of urea resins and melamine resins; 570 kt CO_2 due to the production of nitrogen fertilizers).

9) Thereof 650 kt CO_2 originating from feedstocks.

10) Consists of three parts, i.e. the Final Products Module for
i) plastics products, ii) rubber products/lubricants/bitumen products, iii) other final products.

11) Thereof 14700 kt of reclaimed asphalt pavement (RAP); this is equivalent to 600 kt of bitumen.

12) The value is negative because credits have been assigned to those amounts of steam and electricity which are co-produced in waste incineration plants. The credit is equivalent to steam/electricity production from primary resources.
Credits must be assigned to those flows which leave the system boundary marked in Figure 1 (please refer to footnote 2 for different procedure in Module AB).

13) Primary energy requirements and CO_2 emissions due to landfilling are negligible (mainly due to transportation).

14) Comprises only management of post-consumer waste; treatment of pre-consumer waste is included in the "Subtotal Primary Production".

Using this knowledge about energy and material flows it is possible to derive the definition of non-energy use as published in national energy balances. This has been done for three countries, i.e. for Germany and on a rougher scale for Italy and the Netherlands (Patel et al. 1998a). The examinations using primary data sources reveal that there are significant differences in the definitions of non-energy use among the analysed countries. This is of relevance for all those who use these data, e.g. in the context of the IPCC Reference Approach or for more detailed analyses on material flows, energy and CO_2, as conducted in this study.

Energy & CO_2 Analysis for the Total System in 1995

We calculated the total energy requirements and fossil CO_2 emissions related to current non-energy use in Germany, i.e. for the entire system shown in Figure 1. The analysis includes both the use of fossil resources as feedstocks and as fuels to power the processes in production and waste management (compare Figure 1). As shown in Table 2, in total approx. 1700 PJ of finite primary energy were consumed by the system analysed and 57 Mt of fossil CO_2 emissions were released (figures for 1995). Finite energy is referred to as fossil and nuclear energy. Primary energy refers to the energy resources, e.g. coal, gas and crude oil; in contrast, electricity is, for example, a secondary energy since it has been produced by the conversion of primary energy. Compared to the total German industry (without non-energy use)[5] this is equivalent to nearly 44 % for energy (= 1700 PJ/3900 PJ) and 18 % for fossil CO_2 (= 57 Mt/312 Mt). If the *total* German economy is chosen as a yardstick the respective percentages are 12 % for energy (1700 PJ/14300 PJ) and 6 % for CO_2 (57 Mt/895 Mt).

Future Potentials for Energy & CO_2 Savings in the Total System

Considering the fairly low share of recycling and re-use in 1995 and the large amounts of post-consumer plastics which are landfilled (see Figure 1) the question arises to what extent resource efficiency could be improved, and fossil CO_2 emissions could be diminished by closing the loops. As a further strategy the use of biomass as a feedstock is studied.

The savings due to recycling, re-use, energy recovery and biomass use can be determined by drawing comparisons with primary or conventional production:

- The options of using waste as a resource are compared to primary production which is defined as the manufacture from virgin feedstocks and/or fuels. For example, recycled plastics are compared to an equivalent amount of virgin plastics.
- By analogy, the options of using biomass as a feedstock are compared to conventional production which is defined as the manufacture from fossil resources.

To make these comparisons, it is necessary to choose the system boundaries in such a way that the entire process chain, starting with resource extraction and ending with the prod-

5 This is the total primary energy use / the total fossil CO_2 emissions in German industry in 1995, including the entire productive sector, coking plants, blast furnaces, basic oxygen furnaces and the refinery sector: 3900 PJ, 312 Mt CO_2. The figures include the energy & CO_2 equivalents of electricity use. Non-energy use is excluded since it is usually not allocated to the industrial sector in inventories on energy & CO_2.

uct under consideration, is included. The corresponding energy demand in primary energy terms is called gross energy requirements (GER)[6]. Gross CO_2 emissions are defined by analogy. It is assumed that all the materials required are produced within the system boundaries. Therefore, imports and exports of intermediates are not modelled, since they would change the energy and CO_2 balances and hence, distort the comparison. As a consequence,

- not all of the savings determined may become effective in Germany (e.g. avoided energy consumption for the extraction of resources and for the manufacture of imported synthetic or agricultural products),
- but all of the savings originate from the more efficient use of fossil resources in Germany.

It is important to note that this view differs from the national boundary perspective taken in the previous section[7]. As a further difference, a reference case is introduced for the various options of using waste as a resource. The reference case serves as a baseline to determine the savings of energy and CO_2. Standard technologies have been chosen for this purpose. In the case of plastics recycling, for example, the average of all German MSWI plants was adopted as the reference case, because from the year 2005 onwards, it will become compulsory in Germany to incinerate all the waste containing organic carbon, i.e. direct landfilling will be prohibited (*TA Siedlungsabfall*). For all products made of biomass the manufacture from fossil resources was adopted as the reference case. To determine the net effect of the various technology options relative to the reference case, the so-called product basket-method is applied which is described in (Patel & von Thienen 1999). This is a method to compare processes which yield different types and quantities of outputs.

In **Table 2** the options analysed are listed and the results of the energy analysis are presented. For each option the chosen reference case is named. To put the savings into perspective the energy requirements of primary or conventional production are also given. The options of recycling, re-use and efficient energy recovery are given in the upper block and the use of biomass as a feedstock in the lower block. The column "Achieved savings" gives the savings in 1995 relative to the reference case. In the case of future savings there are two columns which both assume the state of technology as it will be available from the year 2005 onwards. The two columns differ with regard to the throughput of materials in the economy (year 1995 versus 2005): changes in the availability of waste[8] are directly linked to the potential savings due to recycling, re-use and efficient energy recovery, whereas changes in demand are directly linked to the manufacture of materials from biomass feedstocks.

The main technologies covered in the case of plastics recycling are various types of mechanical recycling and feedstock recycling, cement kilns and highly efficient MSWI plants (waste-to-energy facilities); further information on the use of plastics waste can be found in (Patel & von Thienen 1999). For waste tyres and technical rubber waste, the technical options studied are retreading, mechanical recycling, cement kilns and other types of incineration. For asphalt recycling the most important technologies are hot central-plant recycling, in-situ asphalt recycling, cold recycling and the use as unbound base and fill. Industrial bitumen,

[6] Other authors refer to "Gross Energy Requirements" (GER) as "Cumulative Energy Demand".

[7] In the national boundary system imports and exports are taken into account (see Figure 1).

[8] For plastics, see e.g. (Patel et al. 1998c).

which is mainly used to produce roofing felts, can be recycled into building materials (e.g. joint fillers) and asphalt or it can be fed to cement kilns. In the following, the strategy of increasing the production of oleochemical surfactants will be described in more detail; for all the other options reference is made to (Patel et al. forthcoming) and (Patel et al. 1998b).

Example: Oleochemical Surfactants

Surfactants (surface-active agents) can be derived from both petrochemical feedstocks and vegetable oils (oleochemical surfactants). In the mid and late 90s, about one third of the total surfactant production in Germany has been based on biomass-derived raw materials whereas two thirds originate from fossil resources. Shortly after use, surfactants are degraded and the fixed carbon is oxidised to CO_2. Depending on whether the CO_2 released is of fossil or non-fossil origin these emissions are relevant to climate change or not. In addition carbon dioxide related to process energy requirements has to be taken into account. If the total German production of fossil surfactants were replaced by their oleochemical counterparts made from coconut oil (CNO), fossil CO_2 emissions would decline by 0.52 Mt. This is equivalent to a 34 % reduction compared to 1996[9]. For finite energy (Table 2) the calculations yield a comparable percentage (32 %). These figures represent an overestimation of the available emission reduction potential according to the current state-of-the-art. However, it has been assumed in this paper that it can be achieved by the year 2005. As a further interesting result of these calculations, relatively high savings - both for finite energy and fossil CO_2 - were already achieved in 1996 (see Table 2 for energy) (Patel, Theiß & Worell 1999, Patel et al. 1998b).

[9] In contrast to the other options analysed the reference year chosen for surfactants is 1996, not 1995.

Table 2. Achieved and Potential Savings of Gross Finite Energy Requirements (GER) in Germany (Product Basket-Method)

	Reference case	Gross Finite Energy Requirements (PJ)			
		Primary / conventional production in 1995	Savings[1] achieved in 1995	Future potential savings[1] Technology 2005, Economy 1995	Technology 2005, Economy 2005
Waste as resource					
- Plastics (hydrocarbon-based)	Average MSWI plant	745	-29.5[2]	74.1	107.9
- Waste tyres[3]	Cement kiln	43	10.3	16.5	24.3
- Technical rubber waste[3]	Landfilling[4]	46[5]	0.0	16.0	21.2
- Asphalt	Landfilling	205[6]	29.1	30.0	30.0
- Industrial bitumen	Landfilling[4]	36	0.0	11.2	11.2
- Waste lubricants	Waste oil refineries[7]	45	2.3	5.4	4.7
Biomass Feedstocks					
- Bulk chemicals[8]	-	(375)[9]	(0)	(384)	(456)
- Oleochemical surfactants[10]	-	23.1	4.8	12.3	12.3
- Lubricants from vegetable oils	-	see above[11]	0.9	0.9	4.6
- Starch polymers	-	see above[12]	0.1	0.1	1.7
Total (without Bulk chemicals[13])	-	1144	18.1	166.6	218.0

[1] Relative to the Reference case (see second column).
[2] The figure is negative because landfilling of plastics waste, which was still the dominating way of disposal in 1995, is a waste of resources relative to energy recovery in efficient MSWI plants.
[3] Products made of synthetic and natural rubber, including additives, carbon black etc.
[4] Currently there is no collection and recycling system, so the major part of post-consumer waste is landfilled.
[5] This figure is subject to considerable uncertainties since both the volume of primary production and the attendant energy requirements (and CO_2 emissions) had to be estimated.
[6] Energy requirements for the production of asphalt
[7] Status of the technology by the year 1993
[8] The analysis covers the bulk chemicals ethylene, propylene, butadiene, benzene, toluene and xylene.
The brackets indicate that this option will not be feasible for economic reasons in the foreseeable future. Moreover, the use of biomass to produce electricity and steam results in higher savings of fossil CO_2 and is therefore, more favourable from a climate protection aspect
[9] Steamcracking of naphtha has been assumed as conventional process for the production of bulk chemicals.
[10] These data refer to the year 1996 (data otherwise for 1995).
[11] The conventional production of lubricants has already been entered in this column in the line "Waste lubricants".
[12] The conventional production of plastics from fossil resources has already been entered in this column in the line "Plastics (hydrocarbon--based)".
[13] Without Bulk chemicals. The reason is given in footnote 8).

Conclusions

According to Table 2 the production of bulk chemicals from biomass feedstocks offers the highest potential for saving energy; the same result has been determined for CO_2 (not presented in this paper). However, the technology assumed in the model calculations – i.e. flash pyrolysis of wood for the production of olefins and aromatics - has only been demonstrated on the laboratory scale and the technology is not considered to be competitive in the foreseeable future. Moreover, according to our estimates, the gasification of woody biomass and subsequent electricity generation results in higher savings of CO_2, so this would be the preferred option within a carbon abatement strategy (Patel & Korell 1999). For these reasons, the possibility of producing bulk chemicals from biomass will not be followed up. Hence, this option is not included in the totals given in Table 2.

In total, the potential savings identified amount to **218 PJ** of finite energy and **13.6 Mt of fossil CO_2** (for CO_2, the calculations were not presented in this paper). As mentioned earlier not all of the savings identified occur in Germany, but all of the savings originate from measures taken in Germany. Keeping the underlying differences of system boundaries in mind it is possible to compare the total savings with the current energy consumption of the entire system analysed. According to our calculations, **a maximum of 12.8 % of energy and 23.8 % of CO_2 can be** saved by the options given in Table 2 (percentage relative to the system analysed[10]). Compared to the percentage for CO_2 (23.8 %), the figure for energy (12.8 %) is low, since for energy, the reference quantity ("Total System") includes the entire non-energy use. If compared to the total German industry[11], the savings amount to 5.6 % for energy and 4.4 % for CO_2 (here, the reference quantity excludes non-energy use).

These calculations lead to the important conclusion that the saving potential identified on the non-energy side is comparable to the one discussed and negotiated for energy efficiency improvement.[12]

It is important to note that this paper focusses only on energy and CO_2 emissions. To draw conclusions on the impacts on climate change a number of other greenhouse gases would have to be analysed. This is outside the scope of this paper. Moreover, this paper does not permit any conclusions concerning the environmental stand in general; such questions can only be answered by comprehensive Life Cycle Analyses (LCA).

It has been shown that **most of the saving potential** which is available in the short and medium term **can be mobilized by recycling and efficient energy recovery** and not by using biomass as a chemical feedstock (see Table 2). To extend the potential available by recycling and re-use, further R&D on processes and on the design for dissembly, recycling and re-use is required. For these strategies, reducing the costs will continue to be one of the major issues. High priority should be given to these goals considering the fact that the total amount of waste from carbon-based materials will continue to rise.

In the longer term the use of biomass feedstocks may become as important as or even more important than recycling & recovery strategies. This may be triggered by new developments in biotechnology, by allowing higher yields, product qualities and by providing products with new properties. It is expected that this will improve the chances of using plant-based sources as chemical feedstocks. Therefore, it should be assessed whether biomass feedstocks are given enough attention in current R&D agendas. Moreover, it seems appropriate to

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10 1700 PJ and 57 Mt CO_2 (see Section "Energy & CO_2 Analysis for the Total System in 1995")

11 3900 PJ (without non-energy use) and 312 Mt CO_2 (see Section "Energy & CO_2 Analysis for the Total System in 1995")

12 For example, German industry and trade have committed themselves to reduce their specific CO_2 to energy use by 20 % in the period 1990-2005. This voluntary agreement refers to CO_2 emissions related to energy use.

set quantity and cost targets and to conduct comparative assessments of the environmental effects.

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