Carbon use for synthetic materials in Germany
- Current situation and saving potentials for energy and CO$_2$ *)

Abstract. This chapter 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 CO$_2$ in Germany. An overview of the material flows is given for Germany in 1995. Recycled and re-used products still accounted for less than 10% of the end products consumed domestically. The energy requirements and CO$_2$ emissions of the production and waste processes related to non-energy use have been calculated: it is estimated that approximately 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 represents 44% of the energy use and 20% of the fossil CO$_2$ emissions. Detailed analyses are performed in order to determine the saving potential for energy and CO$_2$. This is done by estimating the possible impacts of a) using waste as a resource, and b) using biomass as a feedstock. In the first group, recycling, re-use and enhanced energy recovery is investigated for plastics, discarded tyres, technical rubber products, asphalt, industrial bitumen and waste lubricants. The second group, i.e. the analysed bio-based materials, are bulk chemicals, oleochemical surfactants, lubricants from vegetable oils and starch polymers. The potential savings identified amount to 220 PJ of gross finite energy and 14 Mt of gross fossil CO$_2$. This is the equivalent of a 13% saving in energy and 24% for CO$_2$. Hence, the saving potential identified on the non-energy side is comparable to the saving potential discussed and negotiated for CO$_2$ mitigation through energy efficiency improvement.

8.1 Introduction

Much of the discussion related to climate change have focussed on the emissions of greenhouse gases (GHGs), the most important one being carbon dioxide (CO$_2$) (Houghton et al. 1996). Being the main source of CO$_2$, the combustion of fossil fuels has so far been at the centre of attention. However, a significant fraction of fossil fuels is also used for "non-energy" applications and this may also be relevant to climate change (see Chapter 2; Patel et al. 1999a). "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, paints, 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 relatively small, it is usually disregarded in energy balances. Therefore, non-energy use is usually defined as the consumption of fossil carbon feedstocks.

Non-energy use represents 11-12% of the total amount of fossil fuels for final consumption in Western Europe (EU-15, values for 1995/1996; Eurostat 1998). Within Europe, the share of non-energy use differs from country to country. For example, while the share in the Netherlands is in the range of 16-20%, it is about 10-11% in Germany (1995/1996; Eurostat 1998). German non-energy use in 1995, i.e. the amount of fossil carbon used as chemical feedstock, was equivalent

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to approximately 77 Mt\(^1\) of CO\(_2\) (Patel et al. 1999b). However, only part of this is released in the short term through industrial processes (steamcracking, 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 might be emitted in the longer term (see Chapter 2). While plastic products, for example, will virtually not result in CO\(_2\) emissions in the short term if they are landfilled, they are fully oxidised to CO\(_2\) if incinerated. On the other hand, plastics incinerated in municipal solid waste incineration plants (MSWI) may, to some extent, substitute the use of fossil fuels if the plant produces electricity and/or steam (waste-to-energy facilities). Moreover, technology for recycling and re-use might help to reduce the energy requirements of the entire system and curb CO\(_2\) emissions (Heyde, Kremer 1999). This may also be true for the increased use of biomass as a chemical feedstock (Gielen et al. 1998).

This chapter reports on a study that analysed non-energy use in Germany (Patel et al. 1999b). It includes

a) an inventory of the flows of all materials made from fossil carbon ("products of non-energy use"), including the manufacture and foreign trade at the various levels of production as well as the generation of waste and waste management in the year 1995;

b) the energy requirements of and the CO\(_2\) emissions from this entire system;

c) the evaluation of the most important measures that are applicable for improving resource efficiency and reducing CO\(_2\) emissions within this system; and

d) estimates of the potential savings of energy and CO\(_2\) for the system analysed, based on the technology developments in the short term.

This chapter presents the major results of the analyses. The study did not include an assessment of the energy efficiency potentials (e.g. Jochem, Bradke 1996; Patel 1998; Worrell 1994) nor of the possibility to use renewable energies to fuel the processes (bioenergy; e.g. Faaij et al., 1997).

An overview of the methodology that has been used is given first of all. This is followed by a description of the current situation, and includes an inventory of the material flows, the energy requirements and CO\(_2\) emissions of the system. The third section discusses the measures and potentials to improve resource efficiency and reduce carbon emissions. The chapter closes with a discussion of the results and some conclusions.

### 8.2 Methodology

The methodology of the material flow analysis is shown schematically in Figure 8.1. The products and processes included in the various modules are listed in Table 8.1. The material flows, energy requirements and CO\(_2\) emissions of synthetic organic products in the production chain and in the waste management section are simulated by a total of 13 coupled modules. Four production levels are distinguished in the production process chain: they are represented by the modules for the production of fuels (module AB), basic chemicals (module BC), intermediate products/materials (module CD) and end products (module DE). In the following service module (module EF), the use phase of the end products is modelled: products consumed at a certain point in time are returned as post-consumer waste at the end of their lifetime. The waste is then collected, possibly segregated and pre-treated (module FG). It is then moved on to the waste treatment facilities, i.e. landfilling (module DEP), simple incineration, waste-to-energy facilities or waste water treatment (module OXIDAT) and the various recycling options, i.e. Back-to-Feedstock recycling (BTF, two types), Back-to-Monomer recycling (BTM), mechanical recycling (Back-

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\(^1\) Mt stands for 10\(^6\) metric tonnes (Megatonnes).
to-Polymer, BTP) and end product recycling (Re-use). Examples of feedstock recycling are the hydrogenation of plastics waste (BTF-A) and the use of plastics waste in blast furnaces and for the production of paraffins (both BTF-B). Glycolysis of polyethylene terephthalate is an example for Back-to-Monomer Recycling. Mechanical recycling is mainly applied for thermoplastics and synthetic rubber. An example of end product recycling is the retreading of discarded tyres.

Recycling and re-use generally require processes tailored to the specific waste stream, and in some cases individual collection schemes are necessary (e.g. for waste bitumen). However, there are also substances which are not recoverable at all, e.g. surfactants; here, the carbon fixed in the product is used dissipatively (not shown in Figure 8.1).

For all conversion steps, input-output tables depicting the specific supply and demand relationships in physical terms, and the specific energy requirements by types of fuels were elaborated (Patel et al. 1999b). The data sets include import and export data and, if relevant, the volumes of feedback streams (reflux) and by-products. In the service module (EF) only the delay of material flows is simulated (see Chapter 3; Patel et al. 1998a), whereas the energy consumption and CO\textsubscript{2} emissions during the use phase are generally not covered. The main reasons are methodological difficulties\textsuperscript{2} plus the fact that the research objective would become vague due to the inclusion of all sectors of the economy (since products made of carbon are used practically everywhere).

The data used to simulate the current situation (reference year 1995) reflect the average of all units in operation in Germany (production & recycling processes, MSWI plants etc.). For projections for the future (chosen year: 2005) a performance equal to that of the best current commercial technology or of pilot plants in Germany has been assumed.

A submodel has been developed in order to describe electricity generation and steam production (see Chapter 4). The situation in the chemical industry is assumed to be representative: about two thirds of the electricity required by the manufacturing processes is provided through the public grid, the remainder is supplied from industrial cogeneration units (Stat. Bundesamt 4.1.1 1996).

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\textsuperscript{2} For products consisting of many different materials, the total environmental load (or benefit) must be divided into one part for synthetic carbon materials and another for other materials. Further allocation procedures may be required for the carbon materials. For example: only a part of the plastics used in cars saves weight, whereas the other part contributes to other functions, e.g. comfort and safety. To estimate the benefit of the weight-saving share, the materials substituted must be known (preferably by car component). Analyses of this type are very time consuming, especially if the dynamics over time are taken into account (Heyde, Nürenbach 1999).
Figure 8.1: Material flow model for the manufacture, use and waste management of synthetic carbon products
Table 8.1: Products and processes included in the model

<table>
<thead>
<tr>
<th>Secondary Fuels Module (AB)</th>
<th>Basic Chemicals Module (BC)</th>
<th>Intermediate Product/Materials Module (CD)</th>
<th>End Product Module (DE)</th>
<th>Recycling and Energy Recovery (BTF, BTM, BTP, RU, OXIDAT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Hard coal (coking plants excl.)</td>
<td>1. Methanol from brown coal</td>
<td>1. PVC</td>
<td>1. Synthetic fibres</td>
<td>Plastics</td>
</tr>
<tr>
<td>6. Natural gas</td>
<td>4b. - Production of carbon black</td>
<td>6. Polyvinylacetate (PVAc) etc.</td>
<td>6. Non-plastics</td>
<td>5. Alcoholsysis of PET</td>
</tr>
<tr>
<td></td>
<td>5. Processing of raw benzene for chemical use and production of chemicals in refineries</td>
<td>7. Polystyrene (PS) &amp; copolymers</td>
<td>7. Other plastics items</td>
<td>6. Decomposition of polyamides</td>
</tr>
<tr>
<td></td>
<td>7. Steamcracking of gas oil</td>
<td>8a. - Polyacrylic acid</td>
<td>9. EG as antifreeze agent</td>
<td>8. PARAK process*)</td>
</tr>
<tr>
<td></td>
<td>8. Methanol from fuel oil</td>
<td>8b. - Other polyacrylates</td>
<td>10. Surfactants from EO</td>
<td>9. Gasification (SVZ process)</td>
</tr>
<tr>
<td></td>
<td>18. Other plastics</td>
<td>20. Butenim products</td>
<td>Rubber waste</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20. Carbon black</td>
<td>22. Others</td>
<td>Rubber waste</td>
<td></td>
</tr>
<tr>
<td></td>
<td>21. Organochlorine compounds (from EDC)</td>
<td>22. Other organochlorine compounds (from EDC)</td>
<td>1. Retreading of waste tires</td>
<td>1. Waste oil refineries</td>
</tr>
<tr>
<td></td>
<td>22. Other organochlorine compounds (from EDC)</td>
<td>23. Ethylene glycol (EG), as antifreeze agent</td>
<td>2. Gasification (SVZ process)</td>
<td>2. Gasification of waste oils using EDC plants</td>
</tr>
<tr>
<td></td>
<td>28. Ethanol</td>
<td>29. n-Butanol (as solvent)</td>
<td>30. Derivatives of butylene for open systems</td>
<td>Bitumen waste</td>
</tr>
<tr>
<td></td>
<td>32. Xylene as solvent</td>
<td>32. Xylene as solvent</td>
<td>32. Xylene as solvent</td>
<td>2. In-situ asphalt recycling</td>
</tr>
<tr>
<td></td>
<td>34. Solid derivatives of paraffins</td>
<td>35. Solid derivatives of paraffins</td>
<td>35. Solid derivatives of paraffins</td>
<td>4. Removed asphalt as unbound base and fill</td>
</tr>
<tr>
<td></td>
<td>39. Other nitrogen compounds</td>
<td>40. Other intermediate products/materials</td>
<td>40. Other intermediate products/materials</td>
<td>*) No process data are available for this technology.</td>
</tr>
<tr>
<td></td>
<td>40. Other intermediate products/materials</td>
<td></td>
<td></td>
<td>**) Use of waste oil as supporting fuel.</td>
</tr>
</tbody>
</table>
This chapter discusses two systems with different boundaries, i.e. the "National Boundary System" and the "Total Process Chain System":

1. The "National Boundary System" is marked by the dotted box in Figure 8.1. Only the processes operated within Germany are included in the system. All the material and energy flows are modelled for these processes, whereas all the other sectors of the economy, e.g. households or industrial sectors with no relevance for the system analysed (e.g. non-metallic minerals) are not taken into account (see the broad vertical arrow in Figure 8.1). For this reason, the data for module AB only cover the energy input and CO₂ emissions that can be ascribed to non-energy use, i.e. to the input of module BC and to the process energy requirements of all modules of the system. Moreover, as shown in Figure 8.1, electricity and heat generated as by-products of waste-to-energy facilities (module OXIDAT) leave the system boundaries; the reason being that the electricity generated is usually supplied to the public grid and the heat is sold on to district heating systems or local industries. For the energy streams leaving the system boundaries a credit, representing the generation from primary resources, is introduced.

2. The "Total Process Chain System" includes the entire process chain, starting with resource extraction and ending with the product under consideration. The corresponding energy demand in primary energy terms is called gross energy requirements (GER). Gross CO₂ emissions are defined by analogy. It is assumed that all the materials required are produced within the system boundaries. Hence, the system analysed may include processes which are located abroad. This type of system is also chosen in Life-Cycle Analyses (LCAs) to assess the environmental impacts of competing options for production or waste management. By contrast, accounting for the foreign trade of intermediates would distort the comparison since, e.g. in the case of large net imports, the environmental burden associated with the input manufactured abroad would not be taken into consideration.

The "Total Process Chain System" is chosen to determine the savings of energy and CO₂. Because of this choice

- not all of the savings established might become effective in Germany (since recycling might reduce the demand for imported resources or intermediates, i.e. the savings related to energy use and CO₂ emissions occur abroad to some extent),
- but all of the savings originate from the more efficient use of fossil resources in Germany.

The "National Boundary System" is applied to determine the current energy requirements and CO₂ emissions related to the production and waste management of synthetic organic materials in Germany (data for 1995) and to draw comparisons with other sectors of the German economy (see Sections 8.3 and 8.5).

The "Total Process Chain System" is applied first of all to estimate today’s energy use and CO₂ emissions and secondly, to assess the future potentials of reducing the energy input and the release of CO₂. To this end, two strategies are analysed: first, the use of waste as a resource (recycling, re-use, energy recovery) and second, the increased use of biomass feedstock (see section on "Future potentials"). When determining the potential for savings, a reference case is introduced for the technologies that use waste as a resource. This case describes a standard

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3 Primary energy refers to the energy resources, e.g. coal, gas and crude oil; by contrast, electricity, for example, is a secondary energy since it has been produced by conversion of primary energy.

4 Other authors refer to "Gross Energy Requirements" (GER) as "Cumulative Energy Demand".
technology for waste management and thus serves as a baseline to determine the savings. In the case of plastics recycling, for example, the average of all German MSWI plants was adopted as the reference case. This was because as of the year 2005 it will become compulsory in Germany to incinerate all waste with an organic carbon content and direct landfilling will be prohibited (TA Siedlungsabfall). The so-called product basket-method is used to quantify the net effect of the various technology options relative to the reference case. This is a method to compare processes which yield different types and quantities of outputs. The main idea behind this method is to ensure comparability by adding the missing outputs; it is assumed that these are produced in the conventional way, i.e. from fossil resources (see e.g. Chapter 7; Heyde, Kremer 1999).

The differences in system boundaries between the "National Boundary System" and the "Total Process Chain System" have to be kept in mind when it comes to comparisons (see below, "Discussion").

8.3 Current situation

shows the material flows by modules in the year 1995. All figures represent physical flows in 1,000 metric tonnes (kilotonnes, kt). The flows presented mainly contain carbon, with smaller amounts of hydrogen, nitrogen, oxygen and chlorine. Most of the fuels produced in module AB are consumed in the economy as energy carriers (energy use, 446 Mt) whereas 26.5 Mt is consumed for non-energy purposes. About 1% of this amount is supplied to module AB by BTF recycling of post-consumer lubricants (263 kt) and plastics (29 kt). These plastics are recycled by hydrogenation and in blast furnaces. The figure given for consumption and losses in module AB (10,519 kt) is mainly due to the petroleum refineries' energy requirements.

In module BC, a small amount of basic chemicals was provided by the BASF pyrolysis process (14 kt). In module CD, the recycled materials made from post-consumer plastics (557 kt) and rubber (67 kt) are shown. A considerable share of the recycled plastics was exported in 1995 (342 kt, see Figure 8.2).

Module DE is split into three parts in Figure 8.2: one for plastics (module DE-1), another for synthetic rubber, lubricants and bitumen (DE-2) and a third for all other products (DE-3). With regard to the latter, it is practically impossible to follow the imports, exports, domestic consumption and waste management because it contains a multitude of products, most of which cannot be traced in statistical sources.

About 715 kt of post-consumer materials were recycled back to module DE-2. The major part of this flow is bitumen (600 kt) which is recovered as reclaimed asphalt pavement (RAP) and fed back to road construction. Discarded 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 1,650 kt (plastics, synthetic rubber, lubricants, bitumen). This is equivalent to 7% of the total domestic consumption of end products made of synthetic organic materials (total output of the entire module DE in 1995: 22,973 kt).

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5 Waste is treated even if it is not used as a resource. Most of it is landfilled or burnt in simple incinerators. These are examples of standard technologies for waste management.

6 Including the whole range, from simple incinerators to advanced waste-to-energy facilities.
Examples for the various types of material flows shown in this picture are given in Figure 8.1, e.g. for Resources, Fuels, Basic Chemicals etc.

1) This amount of Secondary Resources was produced from 37 kt plastics waste, using the following processes:
   a) Production of syncrude by hydrogenation
   b) Substitution of heavy oil in blast furnaces.
2) Secondary Fuels (including e.g. gas oil, heavy fuel oil and lubricants), produced in waste oil refineries.
3) For all the following modules, no information was available on the changes of stocks.
4) Including the substitution of heavy oil in blast furnaces due to the use of plastics waste (non-energy use for non-chemicals).
5) Explanation for "Consumption&Losses":
   - Consumption of a part of the input, e.g. to cover the process energy requirements (esp. in Module AB and BC)
   - Losses due to leakages, due to decanting and chemical reactions; moreover, due to scrap which is not recovered as a material.
6) Produced from 15 kt plastics waste in the BASF pyrolysis plant (pilot plant).
7) Covers the following inputs which are dedicated to non-material final use: methanol for MTBE, butylene for knockproof polymer gasoline, acetylene for welding.
Figure 8.2: Mass flows (in kt) of materials made of fossil carbon in Germany, 1995

8) This figure was determined from the material balance for the Basic Chemicals Module. Since the inputs of nitrogen and oxygen have not been taken into account the calculated figure is lower than the real consumption.
9) Exclusively due to recycling of plastics.
10) Exclusively recycling of rubber.
11) Including 342 kt of secondary plastics; in contrast, the figure given for imports of intermediate products/materials comprises primary plastics only.
12) Except for the net increase of stocks, this figure may include smaller amounts of plastics which are incorporated in exported goods or which are not removed after the service period (e.g. pipes).
13) Without synthetic fibres and without non-plastics. For comparison: 4370 kt including synthetic fibres, but excluding non-plastics.
14) This amount is used to produce secondary resources, secondary basic chemicals and secondary intermediate products/materials; the amount does not include recycling of chemical fibres.
15) Including 47 kt of plastics waste which is gasified and subsequently used for power generation.
16) This figure only includes the exports of rubber products since the foreign trade of lubricants and bitumen has already been accounted for in Module AB.
17) Including Reclaimed Asphalt Pavement (RAP, equivalent to 600 kt bitumen), retreading of discarded tyres (100 kt) and other types of recycling/re-use (15 kt).
18) This figure includes the consumption & losses of lubricants due to: a) The use in dissipative applications (130 kt), e.g. anti-corrosives and vaseline  b) Co-combustion in engines (165 kt)  c) Other losses and leakages (270 kt).
19) The consumption of pigments, fillers and reinforcing agents has not been accounted for.
Figure 8.3: Interrelation of energy, material flows and CO₂ for the manufacture of virgin synthetic carbon products in Germany, 1995

Energy use (290 PJ fuels¹; 90 PJ electricity, 37 Mt CO₂²)

Non-energy use (1066 PJ ³)

Production of NH₃ and CH₃OH
112 PJ; 7.6 Mt CO₂

Solid and liquid waste
(31 PJ; 2.2 Mt CO₂⁴)

Credit for generation of electricity/district heat/steam from waste
(23 PJ; 1.6 Mt CO₂⁵)

Organics in wastewater
(260 kt C; 9 PJ; 0.95 Mt CO₂)

¹ Incl. steam
² Cogeneration assumed, with average electricity factor of 0.25 (exception: no cogeneration for the manufacture of final products)
³ Fuels only, of non-energy origin
⁴ Pre-consumer and post-consumer waste incinerated internally and externally, without sewage sludge
⁵ Equivalent to an emission potential of 77 Mt CO₂.
Table 8.2: Energy requirements and CO₂ emissions related to the manufacture and waste management of synthetic carbon products in Germany, 1995 (National Boundary System)

<table>
<thead>
<tr>
<th>Material flow 1) [kt]</th>
<th>Consumption of finite primary energy equivalents [PJ]</th>
<th>Fossil CO₂ emissions [kt CO₂]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuels Module (AB) 2)</td>
<td>26.510</td>
<td>899 3)</td>
</tr>
<tr>
<td>Basic Chemicals Module (BC)</td>
<td>22.857</td>
<td>258 5)</td>
</tr>
<tr>
<td>Intermediate Products/Materials Module (CD)</td>
<td>22.110</td>
<td>307 7)</td>
</tr>
<tr>
<td>End Products Module (DE) 10)</td>
<td>22.973</td>
<td>175</td>
</tr>
<tr>
<td><strong>Subtotal, Primary production</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recycling back to Resources/Fuels (BTF)</td>
<td>520</td>
<td>1</td>
</tr>
<tr>
<td>Recycling back to Basic Chemicals (BTM)</td>
<td>15</td>
<td>0</td>
</tr>
<tr>
<td>Recycling back to Intermediate Prod./Mat. (BTP)</td>
<td>624</td>
<td>5</td>
</tr>
<tr>
<td>Recycling back to End Products (RU)</td>
<td>14.815 11)</td>
<td>99</td>
</tr>
<tr>
<td>Incineration (OXIDAT)</td>
<td>1.535</td>
<td>-35 12)</td>
</tr>
<tr>
<td>Landfilling (DEP) 13)</td>
<td>2.047</td>
<td>0</td>
</tr>
<tr>
<td><strong>Subtotal, Waste management 14)</strong></td>
<td></td>
<td><strong>70</strong></td>
</tr>
<tr>
<td><strong>Total, Entire System</strong></td>
<td></td>
<td><strong>1708</strong></td>
</tr>
</tbody>
</table>

The table does not provide data for Module EF since the energy inputs and CO₂ emissions during the utilization phase are outside the scope of the analysis.

The table does not provide data for Module FG since the energy inputs and CO₂ emissions, since 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 product 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) Of which 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. 1,070 PJ).

4) Only CO₂ emissions originating from process energy requirements, i.e. without the CO₂ equivalents of the carbon stored in the products.

5) Of which 219 PJ originates from feedstocks.

6) Of which 14,600 kt CO₂ originates from feedstocks.

7) Of which 20 PJ originates from feedstocks.

8) Credits for the chemical use of CO₂ have already been taken into account (360 kt CO₂ due to the manufacture of urea resins and melamine resins; 570 kt CO₂ due to the production of nitrogen fertilizers).

9) Of which 650 kt CO₂ originates 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 end products.

11) Of which 14,700 kt 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 CO₂ 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”.
In the petrochemical industry there is a close relationship between energy and materials: part of the feedstock is used as a fuel in the production of the bulk chemicals methanol, ammonia and olefins. Moreover, production waste which is unsuitable for recycling is usually incinerated and some of the energy is recovered for steam and electricity generation. Finally, due to imperfect yields, a part of the carbon feed ends up in waste water and requires treatment. All of these processes lead to immediate CO₂ emissions. The energy and material flows and the CO₂ emissions for virgin material production are shown in Figure 8.3. On the left hand side, the upper stream represents the direct energy use in the modules AB to DE and the associated emissions of CO₂ (290 PJ fuels, 90 PJ electricity; 37 Mt CO₂), whereas the lower stream represents the non-energy use of fuels, i.e. the input of feedstocks (1,066 PJ); of the latter, a total of 239 PJ is oxidised, leading to immediate CO₂ emissions of 16.3 Mt. This demonstrates that the immediate emissions of non-energy origin are by no means negligible and should be included in emission inventories of the chemical industry.

Table 8.2 gives an overview of the energy inputs and the fossil CO₂ emissions by module. The analysis includes both the use of fossil resources as feedstocks and as fuels to power the processes in production and waste management. The energy data represent the consumption of finite primary energy. Finite energy is referred to as fossil and nuclear energy. All the data given in Table 8.2 and Figure 8.3 refer to the national boundary system as shown in Figure 8.1 (see dotted box). In total, approximately 1,700 PJ of finite primary energy was consumed by the system analysed and 57 Mt of fossil CO₂ was released (1995). The subtotals for waste management given in Table 8.2 are equivalent to 4% of the total primary energy requirements of the system analysed and 9% of the total fossil CO₂.

8.4 Future potentials

Considering the relatively low share of recycling and re-use in 1995 and the large amounts of landfilled post-consumer plastics (see Figure 8.2) the question arises as to the extent resource efficiency could be improved and fossil CO₂ emissions could be reduced either by using waste as a resource or by using biomass as a feedstock.

The net effect of recycling, re-use, energy recovery and the use of biomass 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 production 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, defined as the production from fossil resources.

Tables 8.3 and 8.4 present an overview of the results. The options of using waste as a resource (upper block) have been selected by taking into account current and future waste volumes, waste management technologies and legislative developments. The options of using biomass as a feedstock (lower block) fall into two categories: Bio-based bulk chemicals and intermediates could save substantial amounts of fossil resources and CO₂, but their production is not economically

7 This is the total of the following figures given in Figure 8.3: 87 PJ for steam crackers, 112 PJ for NH₃/CH₃OH, 31 PJ for solid and liquid waste and an equivalent of 9 PJ of organics in wastewater.
8 This is the total of the following figures given in Figure 8.3: 5.5 Mt CO₂ from steam crackers, 7.6 Mt CO₂ from NH₃/CH₃OH, 2.2 Mt CO₂ from solid and liquid waste and 0.95 Mt CO₂ from organics in wastewater. The captive use of CO₂ in urea and calcium ammonium nitrate (0.9 Mt CO₂) is not included in this total since these amounts of CO₂ are inherent in fertilizers and released as part of agricultural activity, not chemicals production.
viable under current conditions (figures are given in brackets for this reason). By contrast, the other products listed in Tables 8.3 and 8.4 are already on the market; oleochemical surfactants have been produced in substantial amounts for some time now, whereas lubricants from vegetable oils and starch polymers emerged more recently and currently represent niche markets.

As described in the methodology section (Section 8.2), the system chosen for all comparisons is the "Total Process Chain System". For the various options of using waste as a resource, different standard technologies have been chosen as the reference case. In view of German legislation from the year 2005 onwards (TA Siedlungsabfall), the average of all German MSWI plants was adopted as the reference case for plastics recycling. The reference case chosen for discarded tyres is incineration in cement kilns, the dominant process for this type of waste today. In other cases landfilling was selected as the reference, e.g. for reclaimed asphalt pavement (RAP) where incineration is not possible. For waste lubricants, the recycling technology used in the year 1993 was chosen as the reference.

The energy requirements of primary or conventional production are also given in Table 8.3 (by analogy: CO₂ emissions in Table 8.4). The column "Savings achieved in 1995" gives the savings relative to the reference case. In the case of future savings there are two columns, both of which assume the state of technology as 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): For example, the amount of plastics waste will rise between 1995 and 2005, and the saving potentials will increase accordingly (see Chapter 3). In other cases it has been assumed in this chapter that the waste volumes will stagnate (e.g. asphalt) and even a decrease is expected for waste lubricants (own estimates, e.g. based on Bitumen; Mineralölwirtschaftverband 1996 and 1998). All material flows in the future are based on the assumption that the GDP will increase by an average of 2.3% per year between 1995 and 2005. The developments of the individual waste volumes and the markets of biomass-derived products are described in more detail below.

The following describes the options given in Tables 8.3 and 8.4 in more detail.

The use of biomass very often offers the possibility to curtail the use of fossil resources. The use of biomass derivatives as a chemical feedstock is particularly suited to reduce CO₂ emissions if the product is oxidised after use. To make this aspect visible, all CO₂ data referring to biomass use as a feedstock (see lower block in Table 8.4) include the CO₂ equivalents of the fossil carbon which is fixed in the products; by contrast, the figures for the recycling and energy recovery options do not include the fossil CO₂ equivalents of captive carbon use, but only represent the actual emissions released in 1995.

---

9 Hence, the CO₂ equivalents of the fossil carbon fixed in the product (captive use) are included in the entire line, i.e. also in the figures given for conventional production (third column from the left, block "Biomass as feedstock"). Consequently, the data on CO₂ emissions for conventional production, as well as for the savings, are consistent for all the options of using biomass as a feedstock. However, this choice makes the data of conventional production inconsistent with those of primary production for the recycling and energy recovery options (see upper block in Table 8.3 and 8.4) where the fossil CO₂ equivalents of captive use are not included.
Table 8.3: Achieved and potential savings of gross finite energy requirements (GER) in Germany (product basket-method)

<table>
<thead>
<tr>
<th>Waste as resource</th>
<th>Reference case</th>
<th>Gross Finite Energy Requirements [PJ]</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Primary / conventional production in 1995</td>
<td>Savings (^1) achieved in 1995</td>
<td>Future potential savings relative to 1995 (^2) Technology 2005, Economy 1995 (^3)</td>
<td>Technology 2005, Economy 2005 (^4)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Waste as resource</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Plastics (hydrocarbon-based)</td>
<td>Average MSWI plant</td>
<td>745</td>
<td>-29.5 (^5)</td>
<td>74.1</td>
<td>107.9</td>
</tr>
<tr>
<td>- Discarded tyres (^4)</td>
<td>Cement kiln</td>
<td>43</td>
<td>10.3</td>
<td>16.5</td>
<td>24.3</td>
</tr>
<tr>
<td>- Technical rubber waste (^4)</td>
<td>Landfilling (^5)</td>
<td>46 (^6)</td>
<td>0.0</td>
<td>16.0</td>
<td>21.2</td>
</tr>
<tr>
<td>- Asphalt</td>
<td>Landfilling (^5)</td>
<td>205 (^7)</td>
<td>29.1</td>
<td>30.0</td>
<td>30.0</td>
</tr>
<tr>
<td>- Industrial bitumen</td>
<td>Landfilling (^5)</td>
<td>36</td>
<td>0.0</td>
<td>11.2</td>
<td>11.2</td>
</tr>
<tr>
<td>- Waste lubricants</td>
<td>Waste oil refineries (^8)</td>
<td>45</td>
<td>2.3</td>
<td>5.4</td>
<td>4.7</td>
</tr>
<tr>
<td>Biomass Feedstocks</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Bulk chemicals (^9)</td>
<td>-</td>
<td>(375) (^10)</td>
<td>(0)</td>
<td>(384)</td>
<td>(456)</td>
</tr>
<tr>
<td>- Oleochemical surfactants (^11)</td>
<td>-</td>
<td>23.1</td>
<td>4.8</td>
<td>12.3</td>
<td>12.3</td>
</tr>
<tr>
<td>- Lubricants from vegetable oils</td>
<td>-</td>
<td>see above (^12)</td>
<td>0.9</td>
<td>0.9</td>
<td>4.6</td>
</tr>
<tr>
<td>- Starch polymers</td>
<td>-</td>
<td>see above (^13)</td>
<td>0.1</td>
<td>0.1</td>
<td>1.7</td>
</tr>
<tr>
<td>Total (without Bulk chemicals (^14))</td>
<td>-</td>
<td>1144</td>
<td>18.1</td>
<td>166.6</td>
<td>218.0</td>
</tr>
</tbody>
</table>

\(^1\) Relative to the Reference case (see second column from the left; only for the category “Waste as resource”). In those cases where the technology named as reference case is the only type of process in operation in 1995, the figure in this column is zero.

\(^2\) The term “Economy” refers to the activities of material production and waste use in the year 1995 (second column from the right) and 2005 (first column from the right). Assumed average growth of GDP between 1995 and 2005: 2.3% per year.

\(^3\) The figure is negative because landfilling of plastics waste, which was still the dominating method of disposal in 1995, is a waste of resources relative to energy recovery in an average MSWI plant.

\(^4\) Products made of synthetic and natural rubber, including additives, carbon black etc.

\(^5\) Currently there is no collection and recycling system, so the major part of post-consumer waste is landfilled.

\(^6\) 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.

\(^7\) Energy requirements for the production of asphalt.

\(^8\) Status of the technology by the year 1993.

\(^9\) The analysis covers the bulk chemicals ethylene, propylene, butadiene, benzene, toluene and xylene. It is assumed that naphtha steamcrackers are replaced by flash pyrolysis of wood.

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.

\(^10\) Steamcracking of naphtha has been assumed as conventional process for the production of bulk chemicals.

\(^11\) These data refer to the year 1996 (data otherwise for 1995).

\(^12\) The conventional production of lubricants has already been entered in this column in the line “Waste lubricants”.

\(^13\) The conventional production of plastics from fossil resources has already been entered in this column in the line “Plastics (hydrocarbon-based)”.

\(^14\) Without Bulk chemicals. See note 9).
### Table 8.4: Achieved and potential savings of gross fossil CO₂ emissions in Germany (product basket-method)

<table>
<thead>
<tr>
<th>Waste as resource</th>
<th>Reference case</th>
<th>Gross fossil CO₂ emissions [Mt]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Primary / conventional production in 1995</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Technology 2005, Economy 1995²</td>
</tr>
<tr>
<td>Waste as resource</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Plastics (hydrocarbon-based)</td>
<td>Average MSWI plant</td>
<td>25.12</td>
</tr>
<tr>
<td>- Discarded tyres ³</td>
<td>Cement kiln</td>
<td>2.47</td>
</tr>
<tr>
<td>- Technical rubber products ³</td>
<td>Landfilling ⁴</td>
<td>2.69 ⁵</td>
</tr>
<tr>
<td>- Asphalt</td>
<td>Landfilling ⁴</td>
<td>5.69 ⁶</td>
</tr>
<tr>
<td>- Industrial bitumen</td>
<td>Landfilling ⁴</td>
<td>0.15</td>
</tr>
<tr>
<td>- Waste lubricants</td>
<td>Waste oil recycling ⁷</td>
<td>0.17</td>
</tr>
<tr>
<td>Biomass Feedstocks ⁸</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Bulk chemicals ⁹</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>- Oleochemical surfactants ¹¹</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>- Lubricants from vegetable oils</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>- Starch polymers</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Total (without Bulk chemicals ¹⁴)</td>
<td></td>
<td>37.8</td>
</tr>
</tbody>
</table>

¹ Relative to the Reference case (see second column from the left; only for the category "Waste as resource"). In those cases where the technology named as reference case is the only type of process in operation in 1995, the figure in this column is zero.
² The term "Economy" refers to the activities of material production and waste use in the year 1995 (second column from the right) and 2005 (first column from the right). Assumed average growth of GDP between 1995 and 2005: 2.3% per year.
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 CO₂ emissions) had to be estimated.
⁶ CO₂ emissions due to the production of asphalt.
⁷ Status of the technology by the year 1993.
⁸ All figures listed in this section of the table include the CO₂ equivalents of the fossil carbon stored in the products.
⁹ The analysis covers the bulk chemicals ethylene, propylene, butadiene, benzene, toluene and xylene. It is assumed that naphtha steamcrackers are replaced by flash pyrolysis of wood. 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 CO₂ and is therefore, more favourable from a climate protection aspect.
¹⁰ Steamcracking of naphtha has been assumed as conventional process for the production of bulk chemicals.
¹¹ These data refer to the year 1996 (data otherwise for 1995).
¹² The conventional production of lubricants has already been entered in this column in the line "Waste lubricants".
¹³ The conventional production of plastics from fossil resources has already been entered in this column in the line "Plastics (hydrocarbon-based)".
¹⁴ Without Bulk chemicals. See note 9).

### Post-consumer plastics

The total amount of post-consumer plastics waste is estimated at 3.65 Mt in the year 1995 (without chemical fibres) and 5.3 Mt in 2005 (see Chapter 3). In 1995, 15% of the entire amount of post-consumer plastics waste was recycled mechanically, 3% was used in feedstock recycling...
facilities, 27% was incinerated and 55% was landfilled. The figures for the year 2005 are based on a scenario (see Chapter 3) which assumes that 36% of the waste is recycled mechanically, 32% processed in feedstock recycling plants, and the remaining 32% fed to advanced waste-to-energy facilities. In the case of mechanical recycling, energy and CO₂ savings vary, depending on whether virgin polymers are substituted (22% of the waste in 2005) or other materials - mainly wood, concrete and iron - are replaced (14% of the waste in 2005). According to Table 8.3 the savings in gross energy achieved in 1995 are negative (relative to the reference case, i.e. MSWI plants). This is due to the fact that landfilling, which accounts for a substantial share of waste (55% in 1995), does not recover the energy contained in plastics waste (heating value). By contrast, landfilling of plastics waste causes practically no CO₂ emissions in the short term, and thus the CO₂ savings achieved in 1995 are positive.

Discarded tyres

This study estimates the total amount of discarded tyres at 600 kt in 1995 (own estimate based on Hirsch 1997; Institut für Umweltforschung 1997; personal communication with P. Krieg, Tyre Recycling & Produkt GmbH, 27.8.1998) and at 885 kt in 2005 (own estimate based on personal communication with H. Hirsch, Gesellschaft für Altgummi-Verwertungssysteme, 31.8.1998). The breakdown of the waste management processes is given in Table 8.5. Similar to what is planned for plastics waste, landfilling of discarded tyres will also be prohibited from the year 2005 onwards. The further development of retreading processes depends to a large extent on the acceptance level of private consumers (Hirsch 1997). Recycling of discarded tyres - and waste rubber in general - might grow considerably in the future, especially if the recently promising developments of devulcanising rubber waste ultimately proves to be a success (Shaw 1996; Kohler, O’Neill 1998; Klingensmith, Baranwal 1998). Most of the savings given in Tables 8.3 and 8.4 originate from retreading (energy saved: ca. 80 GJ/t waste; CO₂ saved: ca. 6.0 t CO₂/t waste) and from mechanical recycling (energy saved: ca. 55 GJ/t waste; CO₂ saved: ca. 3.5 t CO₂/t waste; all figures are relative to incineration in a cement kiln which is the reference case) (Patel et al. 1999b).

Technical rubber waste

Compared with the figures for discarded tyres, the estimates given in Tables 8.3 and 8.4 for technical rubber waste are less certain. The reason for this is the lack of a comprehensive inventory of production and waste management for technical rubber products. It is estimated that total post-consumer waste will increase from 400-450 kt in 1995 (own estimate based on personal communication with Mr. Willing, German Federal Environmental Agency, UBA, 7.9.1998; pers. comm. with Mr. Krieg, Tyre Recycling & Produkt GmbH, 27.8.1998; Institut für Umweltforschung 1997) to 500-650 kt by the year 2005 (own estimate based on personal communication with Mr. Willing, German Federal Environmental Agency, UBA, 7.9.1998). It is expected that only about 5% will be recycled mechanically while the rest will be incinerated, mainly in MSWI plants and cement kilns. This enables indisputable energy savings (see Table 8.3), which mostly originate from mechanical recycling (energy saved: ca. 85 GJ/t waste) and from energy recovery in advanced waste-to-energy facilities (in the range of 40 GJ/t waste; all figures relative to landfilling which is the reference case; Patel et al., 1999b). In total, the CO₂ emissions remain practically unchanged (see Table 8.4) although advanced waste-to-energy facilities have been assumed for the year 2005;

10 The amount fed to feedstock recycling facilities has more than tripled between 1995 and 1997.

11 However, these CO₂ emissions could be released in the long term; in this case the environmental burden is simply shifted to the future.
the reason being that, even in these highly efficient plants, the production of steam and electricity leads to more fossil CO₂ than modern power plants or cogeneration units; this compensates for the savings made by mechanical recycling (Patel et al. 1999b).

Table 8.5: Recycling and incineration of discarded tyres in Germany in the years 1995 and 2005 (own estimates based on Baumann, Ismeiser 1998 and various other sources; compare Patel et al., 1999b)

<table>
<thead>
<tr>
<th>Re-use, recycling and incineration, in kt and %</th>
<th>1995</th>
<th>2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>Retreading</td>
<td>100</td>
<td>170</td>
</tr>
<tr>
<td>Other types of product recycling</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Mechanical recycling</td>
<td>67</td>
<td>160</td>
</tr>
<tr>
<td>Cement kilns</td>
<td>217</td>
<td>350</td>
</tr>
<tr>
<td>Other types of incineration *)</td>
<td>65</td>
<td>190</td>
</tr>
<tr>
<td>Landfilling</td>
<td>35</td>
<td>0</td>
</tr>
<tr>
<td>Exports</td>
<td>60</td>
<td>0</td>
</tr>
<tr>
<td>Unknown</td>
<td>40</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>599</td>
<td>885</td>
</tr>
</tbody>
</table>

*) Incineration in municipal waste incineration plants and CHP plants fuelled with discarded tyres.

Recycling of asphalt

Asphalt recycling processes can be divided into two major methods, hot recycling and cold recycling (OECD 1997). Reclaimed asphalt pavement (RAP) can also be used as unbound base and fill (OECD 1997). Generally, the final engineering properties of hot-mix asphalt (HMA) are higher than those achievable by cold-mix technologies (Beligni 1997). This results in the following list of processes (which has been ordered according to the declining quality of recycling) (OECD 1997):

- Hot, central-plant recycling: The old pavement material which has been removed, is transported to a plant where it is mixed with new bitumen and virgin aggregates. The share of RAP is usually around 30%; at most, recycling percentages of 50-70% are achieved, depending on the quality requirements of the mix and the properties of the old asphalt (OECD 1997; Hugener 1995; Forschungsgesellschaft für Straßen- und Verkehrswesen 1993).

- In-situ asphalt recycling: This is a new technology for heating and removing 5-10 cm of the top road layer, mixing it with virgin materials and then applying it directly as the final asphalt layer ("asphalt recycling travelplant"; OECD 1997; Hugener 1995; Forschungsgesellschaft für Straßen- und Verkehrswesen 1993).

- Cold recycling, either in-situ or in central plants: Two types of binders, foamed bitumen and bitumen emulsion, are used without the application of heat (OECD 1997; Caddet; Hugener 1995; Forschungsgesellschaft für Straßen- und Verkehrswesen 1993).

- Finally, removed asphalt can be used as unbound base and fill, mainly for road construction (OECD 1997; Forschungsgesellschaft für Straßen- und Verkehrswesen 1993).

In 1995, 12 Mt of RAP were processed by hot, central-plant recycling (personal communication with Mr. Els, Deutscher Asphaltverband, DAV, 14.9.1998). This is equivalent to savings of 500–700 kt of virgin bitumen12. An additional 3 Mt of RAP were used as unbound base and fill (fourth

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12 Asphalt is produced by mixing 4-8% bitumen with 92-96% mineral materials.
option; pers. comm. with Mr. Els, see above). A share of 2% of used asphalt was landfilled (pers. comm. with Mr. Els, see above). Almost all the energy and CO₂ savings given in Tables 8.3 and 8.4 resulted from the hot-mix process. For the short-term future it is expected that the total amount of RAP will remain about the same since the intensity of road repairs will remain at a level similar to 1995 (own estimate based on personal communication with Mr. Höltken, Arbeitsgemeinschaft der Bitumen-Industrie, ARBIT, 11.9.1998; moreover, it has been assumed in the calculations that use as unbound base and fill will practically disappear in favour of hot processes and cold recycling.

Recycling of industrial bitumen

Industrial bitumen is mainly used for the manufacture of roofing felts. It is estimated that about 300 kt of bitumen waste is generated from this source every year (own estimate based on various sources; compare Patel et al. 1999b). It is expected that the volume of waste will remain more or less constant up to the year 2005 (own estimate based on personal communication with Mr. Höltken, Arbeitsgemeinschaft der Bitumen-Industrie, ARBIT, 11.9.1998). At present, most of the industrial bitumen waste is landfilled (due to the low costs); smaller fractions are incinerated in cement kilns (energy recovery) or recycled as building materials (e.g. for joint fillers, building protective matting and silencing matting) and asphalt (used for deeper pavement layers; compare Krieger et al.). Since organic material landfilling will be prohibited from the year 2005 onwards it has been assumed in this chapter that 50% of all industrial bitumen waste will be fed to cement kilns and the remainder will be recovered for building materials in 2005. The energy savings given in Table 8.3 are based on specific savings of about 42 GJ/t waste for incineration in cement kilns and 33 GJ/t waste for recycling (all figures are relative to landfilling which is the reference case; Patel et al. 1999b). No CO₂ savings are achieved by this combination of processes (see Table 8.4).

Waste lubricants

The total amount of waste lubricants in 1995 is estimated at about 1,260 kt, but only 690 kt are recovered after use (personal communication with K. Fricke, German Federal Environmental Agency, UBA, 2.12.1998), whereas the rest is lost due to co-combustion in engines (165 kt; Trischler&Partner 1997), product use in mostly dissipative applications (130 kt, e.g. vaseline and anti-corrosives; Trischler&Partner 1997) or other losses & leakage (270 kt; Trischler&Partner 1997). Of the amount recovered, about 480 kt \(^{13}\) were fed to waste oil refineries, 170 kt incinerated in cement kilns and 40 kt gasified in the SVZ plant \(^{14}\) (personal communication with K. Fricke, German Federal Environmental Agency, UBA, 2.12.1998). It is expected that the domestic consumption of lubricants will decline in the future \(^{15}\); accordingly, it has been estimated in this chapter that the amount of waste lubricants available for recovery will decrease from 690 kt to about 600 kt by the year 2005 (own estimate based on various sources, e.g. Mineralölwirtschaftsverband 1996 and 1998). The figures given in Tables 8.3 and 8.4 are based on the assumption that 50% of all waste lubricants will be recovered in waste oil refineries, 40% in cement kilns and most of

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\(^{13}\) Water content included.

\(^{14}\) SVZ (Sekundärstoffverwertungszentrum) is a company operating a solid bed gasification process in Schwarze Pumpe, Germany.

In 1995, the entire production of synthesis gas in the SVZ plant was fed to a cogeneration unit. Since 1997, 60% of the synthesis generated is converted to methanol and the rest is fed to the cogeneration unit (compare section “Current situation”).

\(^{15}\) Due to improved engine technology, the monitored demand for oil change and new technologies for saving or avoiding the use of lubricants in metal cutting.
the remaining 10% will be gasified. The energy savings are achieved mainly from cement kilns (10.9 GJ/t waste) and advanced waste oil refineries (6.6 GJ/t waste), whereas virtually all the CO₂ savings are achieved from cement kilns (0.8 t CO₂ /t waste; all figures are relative to an average waste oil refinery in Germany in 1993 which has been chosen as the reference case; Patel et al., 1999b).

Bulk chemicals from biomass

Many organic chemicals can be produced from biomass feedstocks instead of from fossil resources (see e.g. Technical Insights 1983). To obtain an impression of the potentials and the difficulties involved, a group of bulk chemicals, consisting of olefins (ethylene, propylene and butadiene) and aromatics (benzene, toluene and xylene) has been studied (Patel et al. 1999b; Patel, Korell 1999). A comparison was made between three processes used to manufacture these bulk chemicals from biomass: These are high temperature flash-pyrolysis of wood, dehydration and the Methanol-to-Olefins (MTO) process. The technologies differ in terms of development status, prospects and yields. The highest yields of organic chemicals are achieved from flash pyrolysis of wood, but so far the viability of this process has not been proven on a larger scale. Nevertheless, to determine the maximum saving potential, flash pyrolysis has been chosen for further analysis. It is assumed that the total German production of olefins and aromatics in naphtha steamcrackers (6.2 Mt in 1995; Stat. Bundesamt 3.1. 1996) is produced by this technology. As Table 8.3 shows, the savings of finite energy and fossil CO₂ achieved by flash pyrolysis of wood are comparable with the respective inputs to naphtha steamcrackers (primary production). The reason is that the steam and electricity requirements of the flash pyrolysis process are covered by a fraction of the pyrolysis gas which is generated from the biomass feedstock. As mentioned earlier, the CO₂ data in Table 8.4 include the fossil carbon inherent in the products. It is assumed that the demand for the bulk chemicals analysed will increase by 2.3% p.a. between 1995 and 2005

According to Tables 8.3 and 8.4, production of the bulk chemicals in the year 1995 would involve a land use of 20,000 km², representing about 12% of the total arable land in Germany. If the production of bulk chemicals from all steamcrackers (including those operated on gas oil and light hydrocarbons) was added, then the land use requirements would increase by about 40%.

Oleochemical surfactants

Surfactants (surface-active agents) can be derived from both petrochemical feedstocks and vegetable oils (oleochemical surfactants). In the mid and late 1990s, about one third of the total surfactant production in Germany was based on biomass-derived raw materials and two thirds originate from fossil resources (see Chapter 5; Patel et al. 1998b). Shortly after they are used, surfactants are degraded and the fixed carbon is oxidised to CO₂. Whether these emissions are relevant to climate change depends on whether the CO₂ released is of fossil or non-fossil origin. Carbon dioxide related to process energy requirements must also be taken into account. Table 8.4 shows the results of these calculations: if the most important fossil surfactants produced in Germany (215 kt in 1996) were replaced by their oleochemical counterparts made from coconut oil (CNO), then fossil CO₂ emissions would decline by 0.52 Mt (see Chapter 5). This

16 This assumption is plausible since most of the bulk chemicals analysed (ethylene, propylene, butadiene, benzene, toluene, xylene) are used to a large extent for plastics production; the ratio of plastics production over GDP (measured in tonnes over Deutsch Mark) increased considerably in the past, but now seems to be stabilizing.

17 The following surfactants are included in this total: LAS, SAS, AS-Pc, AE₃S-Pc, AE₃-Pc and AE₇-Pc (Pc stands for "petrochemical").
is equivalent to a 34% reduction compared to 1996\textsuperscript{18}. For finite energy (Table 8.3) the calculations yield a comparable percentage (32%). These figures are an overestimation of the available emission reduction potential according to the current state of the art. However, it is assumed in this chapter that this can be achieved by the year 2005. Relatively high savings - both for finite energy and fossil CO\textsubscript{2} - were already achieved in 1996 (see Tables 8.3 and 8.4 and Chapter 5; Patel, Theiß 1998). It has been assumed in this study that the production of surfactants will remain constant between 1995 and 2005.\textsuperscript{19}

**Lubricants from vegetable oils**

In 1995, lubricants made from vegetable oils (mainly rape-seed oil) accounted for about 30 kt, which is the equivalent of less than 3% of the total lubricants market in Germany (1.14 Mt). Projections for the future range from about 100 kt (Bundesministerium für Ernährung 1996) up to 700 kt (Kanswohl 1995). In this chapter, it is assumed that 150 kt of lubricants, i.e. 15% of the total lubricants market, will be produced from vegetable oils by the year 2005 (compare Bundesumweltministerium 1996; Mang 1994).

In principle, there are two types of bio-based lubricants, i.e. natural esters (triglycerides) and synthetic esters derived from vegetable oils. Natural esters are comparatively simple to produce. However, the material properties of natural esters are inferior to those of synthetic esters (especially due to ageing). Therefore, to be on the safe side, an important lubricant belonging to the group of synthetic esters has been chosen for the calculations presented in Tables 8.3 and 8.4: this is a polyol ester synthesized from trimethylolpropane (TMP) and rape-seed fatty acid. Compared to a petrochemical lubricant, the savings related to the TMP ester are 31 GJ non-renewable energy per tonne of lubricant and about 2.4 t CO\textsubscript{2}/t. (Patel et al. 1999b)

**Starch polymers**

Over the past few years an increasing number of plastics made from biomass feedstocks have entered the market, e.g. starch polymers, polylactides, polyurethanes\textsuperscript{20}, polyhydroxyalkanoates\textsuperscript{21} (PHA) and plastics reinforced with natural fibres. On the other hand, some of the classic biomass-derived plastics are losing their share in the market, e.g. regenerated cellulose. It is impossible to make a general statement about whether plastics from biomass are favourable in terms of energy use and CO\textsubscript{2} emissions compared to petrochemical polymers. For example, the gross energy requirements for PHA are currently higher than for polyolefins; this is due to the complicated production process of PHA (Kopf 1999; Patel et al. 1999b). R&D is under way to optimize the process and this should reduce the energy input. On the other hand, starch polymers, which are available both with and without petrochemical co-polymers\textsuperscript{22}, already offer a potential to save energy and curtail fossil CO\textsubscript{2} emissions (Kopf 1999; Patel et al. 1999b). Depending on the share

\textsuperscript{18} In contrast to the other options analysed the reference year chosen for surfactants is 1996, not 1995.

\textsuperscript{19} This is a conservative assumption compared to other projections which assume an increase in the range of 2% p.a. (e.g. Ward (1996) for Western Europe). Considering the maturity of the sector and the market in Germany, it was considered appropriate to make this cautious assumption.

\textsuperscript{20} Only the polyol components are synthesized from biomass feedstocks. Research is under way to produce the isocyanate component from non-fossil resources too (Müller 1998).

\textsuperscript{21} The main representatives are polyhydroxybutyrate (PHB) and polyhydroxyvalerate (PHV).

\textsuperscript{22} The most prominent representatives are combinations of thermoplastic starch with polyvinylalcohol and polycaprolactone. Pure thermoplastic starch is also marketed. Blends of thermoplastic starch with polyolefins have not been taken into account in Tables 8.3 and 8.4 since they are not fully biodegradable (this is considered to be an important marketing aspect).
of petrochemical co-polymers, starch polymers offer saving potentials relative to polyethylene in the range of 12-40 GJ/t plastic and 0.8-3.2 t CO₂/t plastic. However, the inferior material properties of starch polymers, especially their sensitivity to moisture, limit their market potential. For most of the other, new biomass-derived plastics, no process or LCI data have been published so far. It is for this reason that only starch polymers are included in Tables 8.3 and 8.4. In 1995, starch polymers accounted for about 5 kt and 80% of the entire production of bio-based polymers. It is assumed that the share of starch polymers will increase up to 70 kt by the year 2005²³. This is considered to be a moderate, yet positive development. In the event of unfavourable conditions, a market volume of only 20-30 kt is expected, whereas a booming demand would result in a market growth up to 100-150 kt (personal communication with Dr. S. Facco, Novamont GmbH, Eschborn). The savings of energy and CO₂ in absolute terms are exceeded by all the other options studied (compare Tables 8.3 and 8.4) since the assumed production volume of starch polymers by 2005 is very small (for comparison: total plastics manufactured was 10.4 Mt in 1995).

8.5 Discussion

The analysis showed that the finite primary energy input related to non-energy use within Germany’s national boundaries totalled approximately 1,700 PJ in 1995 (see Table 8.2). This figure includes the feedstock, the entire chain of production and waste management. Total fossil CO₂ emissions released from this system amount to 57 Mt. If compared to the entire industrial sector in Germany (without non-energy use²⁴) the share is 44% for energy and 20% for CO₂. The respective percentages relative to the total German economy²⁵ are 12% for energy and 6% for CO₂. The higher percentage for energy results from the use of fossil fuels as a feedstock: fuels equivalent to about 830 PJ were fixed in synthetic organic products, part of them for many years or even decades. Another 239 PJ, also of non-energy origin, were oxidised immediately during the production process, resulting in 16.3 Mt of fossil CO₂. These emissions are often overlooked in national emission inventories.

The above products, for which the potential for recycling, recovery and bio-based feedstocks has been assessed, represent about two thirds of the total production of materials of non-energy use in Germany.

According to Tables 8.3 and 8.4 the production of bulk chemicals from biomass feedstocks offers the highest potential for energy saving and CO₂ mitigation. However, flash pyrolysis of wood for the production of olefins and aromatics has only been demonstrated on the laboratory scale and this technology is not expected to be economically competitive in the foreseeable future. Moreover, the gasification of woody biomass and subsequent generation of electricity results in higher savings of CO₂ (Patel, Korell 1999), and so this would be the preferred option within a carbon abatement strategy. For these reasons, the possibility of producing bulk chemicals by way of flash pyrolysis will not be followed up in this assessment. Hence, this option is not included in the totals given in Tables 8.3 and 8.4.

²³ The shares of the various types are:
- in 1995: 20% Pure thermoplastic starch (TPS), 10% Starch/Polyvinylalcohol (85%/15%), 70% Starch/Poly-caprolactone (47.5%/52.5%).
- in 2005: 20% Pure thermoplastic starch (TPS), 15% Starch/Polyvinylalcohol (85%/15%), 65% Starch/Poly-caprolactone (47.5%/52.5%).

²⁴ For the energy requirements and CO₂ emissions of the entire industrial sector in Germany, see footnote 4 in Table 8.6.

²⁵ Primary energy requirements of the total German economy equalled 14,300 PJ in 1995; in total, 895 Mt of fossil CO₂ were emitted (Bundesministerium für Wirtschaft 1998).
It should be noted that only one single technology has been chosen as the reference case (e.g. incineration in an average MSWI plant). If, in reality, further practices are in use for one type of waste, the calculation usually yields savings even for 1995 (see Tables 8.3 and 8.4, third column from the right; the figures for 1995 are relative to the reference case).

As mentioned earlier, while not all of the savings identified occur in Germany they all originate from measures taken in Germany. Keeping the different system boundaries in mind, it is possible to compare the totals according to Tables 8.3 and 8.4 with the 1995 figures given in Table 8.2. The result is shown in Table 8.6 in the lines “Total Savings / Total System” (separate lines for energy and CO2): a maximum of 12.8% of energy and 23.8% of CO2 can be saved. It may seem quite remarkable that the saving potential for energy (12.8%) is much smaller than that for CO2 (23.8%); the reason is that for energy, the reference quantity (“Total System”) includes the entire non-energy use. Table 8.6 also shows the ratios relative to the chemical industry, to the entire German industry and to the entire German economy.

The reason for the low percentage of recycled and re-used synthetic organic materials is that considerable amounts of waste are landfilled and incinerated and, more importantly, that there is a large increase in stocks. For example, in the case of plastics, the increase of stocks represents 58% of the consumption of end products (see Figure 8.2). 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 more than 11 years (see Chapter 3; Patel et al. 1998a). The large increase of stocks (accumulation) is the main reason why the ratio of savings to the values of primary/conventional production is particularly low for some of the types of materials listed in Tables 8.3 and 8.4. Since direct landfilling of organic carbon content waste 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 increase in the future. The potential is very high in the longer term. Two reasons can be given for this: first, the amount of post-consumer plastics waste, being the largest stream of the materials studied, would increase by a factor of 2.4 (Chapter 3) if there was no net increase in stocks (based on data for 1995 according to Figure 8.2). And second, the use of some materials - again especially plastics -, will continue to rise in the future, and this too will result in larger amounts of waste.

When calculating the potential of future savings, a plausible mix of technologies was assumed; for example, in the case of discarded tyres, the saving potential was determined on the basis of a combination of retreading, mechanical recycling and incineration (see Table 8.5). In nearly all cases, the technologies assumed are already commercially available; in the remaining cases the assumed technology could be available by the year 2005. Hence, the future data given in Tables 8.3 and 8.4 represent the technical potential by the year 2005.

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26 There is no straightforward way for harmonising the two approaches. Both
   - the calculation of the saving potential following the "National Boundary System" and
   - the calculation of the total system's energy requirements and CO2 emissions in 1995 according to the "Total Process Chain System"
would require several assumptions resulting in uncertainties.

27 In contrast to the "Total System" (see footnote 2 in Table 8.6), chemical industry includes the production of inorganics but it excludes all the downstream processes of manufacturing (e.g. plastics processors) and waste management.

28 The domestic consumption of virgin petrochemical plastics equalled 8.7 Mt in 1995, whereas the total waste available for recycling/recovery amounted to 3.65 Mt in the same year (excluding chemical fibres); this gives a factor of 2.4.
### Table 8.6: Gross Energy and Gross CO\textsubscript{2} savings presented in perspective

<table>
<thead>
<tr>
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<tbody>
<tr>
<td><strong>Energy</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total savings\textsuperscript{(1)} [PJ]</td>
<td>18.1</td>
<td>166.6</td>
<td>218.0</td>
</tr>
<tr>
<td>Ratio (Total Savings / Total System 1995\textsuperscript{(5)})</td>
<td>1.1%</td>
<td>9.8%</td>
<td>12.8%</td>
</tr>
<tr>
<td>Ratio (Total Savings / Chemical Industry w/o Non-Energy 1995\textsuperscript{(5)})</td>
<td>2.4%</td>
<td>22.0%</td>
<td>28.8%</td>
</tr>
<tr>
<td>Ratio (Total Savings / Total German Industry 1995\textsuperscript{(5)})</td>
<td>0.5%</td>
<td>4.3%</td>
<td>5.6%</td>
</tr>
<tr>
<td>Ratio (Total Savings / Total German Economy 1995\textsuperscript{(5)})</td>
<td>0.1%</td>
<td>1.2%</td>
<td>1.5%</td>
</tr>
<tr>
<td><strong>CO\textsubscript{2}</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total savings\textsuperscript{(1)} [Mt CO\textsubscript{2}]</td>
<td>6.2</td>
<td>9.6</td>
<td>13.6</td>
</tr>
<tr>
<td>Ratio (Total Savings / Total System 1995\textsuperscript{(5)})</td>
<td>10.9%</td>
<td>16.7%</td>
<td>23.8%</td>
</tr>
<tr>
<td>Ratio (Total Savings / Chemical Industry w/o Non-Energy 1995\textsuperscript{(5)})</td>
<td>12.7%</td>
<td>19.6%</td>
<td>27.8%</td>
</tr>
<tr>
<td>Ratio (Total Savings / Total German Industry 1995\textsuperscript{(5)})</td>
<td>2.2%</td>
<td>3.3%</td>
<td>4.7%</td>
</tr>
<tr>
<td>Ratio (Total Savings / Total German Economy 1995\textsuperscript{(5)})</td>
<td>0.7%</td>
<td>1.1%</td>
<td>1.5%</td>
</tr>
</tbody>
</table>

\textsuperscript{(1)} See Table 8.3 and 8.4, bottom line (Total without bulk chemicals).

\textsuperscript{(2)} "Total System" gives the primary energy equivalents / fossil CO\textsubscript{2} emissions of the entire system analysed in this paper, i.e. the total covering all the modules AB to DEP. The figures are given in the bottom line of Table 8.2.

\textsuperscript{(3)} "Chemical Industry without Non-Energy": This is the total chemical sector's energy use and CO\textsubscript{2} emissions, without feedstocks: 756 PJ, 49.0 Mt CO\textsubscript{2} (the equivalents of electricity use are included) (VCI 1997).

The lower percentage for energy (compared to CO\textsubscript{2}) results from the high value in the denominator reflecting the use of fossil fuels as a feedstock. Fuels equivalent to about 830 PJ were fixed in synthetic organic products in 1995, a part of them for many years or even decades; after the use of these products, the largest part of the waste is landfilled whereas only a small fraction of plastics waste is oxidised to CO\textsubscript{2} soon afterwards. Hence, the difference between the percentages for energy and CO\textsubscript{2} originates from the fact that only a part of the fuels consumed as a feedstock is oxidised fairly quickly. It should be noted that the percentages also include the process energy requirements (and the CO\textsubscript{2} emissions from this source); however, this part has only a minor influence on the difference in percentages for energy and CO\textsubscript{2}.

\textsuperscript{(4)} "Total German Industry": This is the total primary energy use / the total fossil CO\textsubscript{2} emissions in Germany in 1995, including the entire productive sector, coking plants and the refinery sector: 3,900 PJ, 290 Mt CO\textsubscript{2}. The figures include the energy and CO\textsubscript{2} equivalents of electricity use. Non-energy use is excluded since it is usually not allocated to the industrial sector in inventories on energy and CO\textsubscript{2}. The energy figure has been estimated on the basis of (Arbeitsgem. Energiebilanzen 1998); the CO\textsubscript{2} figure has been estimated on the basis of (Arbeitsgem. Energiebilanzen 1998) and (Bundesmin. fuer Wirtschaft 1998), including 27 Mt CO\textsubscript{2} from industrial processes (Bundesmin. fuer Wirtschaft 1998).

This is the only comparison where the percentage for energy is larger than that for CO\textsubscript{2}. The exclusion of non-energy use and the inclusion of CO\textsubscript{2} from "industrial processes" are the reasons.

\textsuperscript{(5)} "Total German Economy": This is the primary energy use / the fossil CO\textsubscript{2} emissions of the total German economy in 1995: 14,300 PJ, 895 Mt CO\textsubscript{2} (Bundesmin. fuer Wirtschaft 1998).

The figures for the total German economy include the contribution from non-energy use, which is however, relatively small. Therefore, the figures for the total German economy are dominated by the energy system and its immediate conversion of energy to CO\textsubscript{2}. The total saving potential on the non-energy side (218 PJ energy and 13.6 Mt CO\textsubscript{2}) well reflects the energy to CO\textsubscript{2} ratio in the country's energy system.

\textsuperscript{(6)} The term "Economy" refers to the activities of material production and waste use in the year 1995 (second column from the right) and 2005 (first column from the right). Assumed average growth of GDP between 1995 and 2005: 2.3% per year.
However, the complete diffusion of these technologies, i.e. introduction at all relevant sites, will require additional time (possibly another 10 to 20 years under current conditions). In addition, a commercially available technology will probably not be implemented, despite the fact that it can save energy, if the net economic effect is not a positive one. These aspects are taken into account in the so-called economic potential for saving energy resources or mitigating CO₂ emissions (Worrell 1994). We may expect only a part of the economic potential to be realised in practice. This part is given by the so-called market potential which is determined by investment decision criteria applied by investors under prevailing market conditions (Worrell 1994). Neither the economic potential nor the market potential has been studied in this chapter.

There are other opportunities available for reducing the consumption of finite energy and curbing fossil CO₂ emissions which have not been discussed in this chapter. Examples are the application of traditional measures to improve energy efficiency (e.g. by improved heat exchange or optimized separation processes) and the introduction of advanced designs, new processes or catalysts enabling higher yields in conventional production. The options of using renewable energies to cover (parts of) the process energy requirements were also excluded from this analysis.

In the following, the various assumptions are assigned to three categories: the first category comprises assumptions which are not expected to cause a bias of the results, or on which there is too little information available to be able to draw qualitative conclusions about the uncertainties; the second category lists those assumptions that could lead to an overestimation of the saving potentials; and finally, the third category contains the assumptions that could lead to underestimation.

(1) The following assumptions and methods are considered to be neutral in terms of the results, or their impact cannot be assessed because of the lack of more detailed information:

- In many cases the calculations rely on grey or unpublished literature and personal communication with experts. This refers in part to the production volumes (both of products made from biomass feedstocks and from recycling) and partly to the data on process energy requirements. In general, somewhat conservative estimates were made wherever the uncertainties were obvious, e.g. for the future production volumes of starch polymers and lubricants from vegetable oils.

- The saving potentials identified in the areas of recycling and biomass use (see Tables 8.3 and 8.4) are generally not additive, i.e. they each exclude the other to some extent: most importantly, not all of the recycling technologies for petrochemical plastics are easy to apply for bio-based plastics (e.g. hydrogenation). However, the assumed production volumes of bio-based plastics are still comparatively small (less than 0.3% of the total non-energy use), so the effect of double counting is negligible.

- It is a well-known fact that important changes have taken place in plastics recycling since 1995 (reference year of this analysis). When this chapter was prepared, the latest set of reliable data originated from the year 1997. In 1997, the amount of secondary resources produced by BTF recycling had increased to about 130 kt (29 kt in 1995); this was due to the increased amounts of plastics waste fed to the hydrogenation and the blast furnace process, and the start-up of a demonstration plant to produce paraffins from plastics (PARAK process). While in the case of BTM recycling the BASF pilot plant for pyrolysis had been closed down (-14 kt), about 90 kt of plastics waste and 40 kt of waste lubri-

29 In the German project report (Patel et al. 1999b) the saving potential of 12 innovative processes for the manufacture of synthetic organic intermediated from petrochemical feedstocks has been estimated (e.g. vinyl chloride, propylene oxide, ethylene oxide). The inclusion of these processes increases the saving potential for CO₂ by 3%, i.e. from 24% to 27% (ratio: Total Savings / Total System 1995, see Table 8.6).
cants was gasified in the SVZ\textsuperscript{30} plant, and 60% of the synthesis gas generated was converted to methanol (the rest being fed to a cogeneration unit). Whereas mechanical recycling for domestic use remained more or less constant between 1995 and 1997, the total amount of agglomerates and waste exported for recycling decreased in that period (Patel et al. 1999b). To summarize: Although plastics recycling continued to increase between 1995 and 1997, recycled and re-used synthetic organic materials still accounted for less than 10% of the total amount of the end products consumed domestically in 1997\textsuperscript{31}.

(2) The following assumptions contribute to the overestimation of the saving potentials:

- There is some uncertainty as to the total amount of post-consumer plastics waste since this has not been surveyed. The value will be higher or lower depending on whether the total amount has been determined by using a top-down or a bottom-up approach (see Chapter 3; Patel et al. 1998a). The amounts assumed for this analysis are somewhat on the high side. Further analysis is needed to refine the two methods.
- For oleochemical surfactants it was assumed that the most important petrochemical surfactants produced at present in Germany will be replaced by their oleochemical counterparts. While this is an overestimation of today's technical potential, it could be achieved in the near future if the necessary efforts are made in R&D.
- It has been assumed for all processes using bio-based feedstocks that the biomass is produced in a sustainable fashion; this implies that the energy produced from biomass sources is infinite and that CO\textsubscript{2} originating from bio-based sources is recaptured in plant growth (i.e. there are no net CO\textsubscript{2} emissions apart from the fossil fuels used in the process chain, e.g. for tractors). However, there are also examples of unsustainable agriculture which have not been taken into account in the calculations presented in this paper. If they were taken into consideration, the savings of energy and CO\textsubscript{2} might decline to some extent.

(3) The following assumptions contribute to the underestimation of the saving potentials:

- The list of options studied in order to identify the total savings potential is bound to be incomplete. For example: neither the recycling and re-use of chemical fibres, nor the manufacture of biomass-derived plastics other than starch polymers and PHA has been studied. In addition, the material flows were only studied in detail for plastics, synthetic rubber, lubricants and bitumen. There is, however, a multitude of other synthetic organic materials that cannot be traced in statistical sources as pure substances since they are combined with other materials to form end products ("Other end products"; see above, Section 8.3 and Figure 8.2). This remaining group comprises certain products which can be recycled and re-used, and in some cases processes are even in operation, e.g. for solvents and degreasing agents. These processes were excluded from the further analysis since there was no reliable data available; this could lead to a relatively small underestimation of the total potential presented in this chapter since the quantities recycled and re-used are generally small. Innovations on which there is no reliable data available at the moment, but which are likely to undergo substantial progress up to the year 2005.

\textsuperscript{30} SVZ (Sekundärrohstoffverwertungszentrum) is a company which operates a solid bed gasification process in Schwarze Pumpe, Germany.

\textsuperscript{31} It might be thought inappropriate to choose the total amount of the end products consumed domestically as the reference quantity. The reason for doing this is that recycling/re-use is not possible for many of the products covered in the "Other End Products Module" in Figure 8.2 since the materials are used in a dissipative way in these applications (e.g. surfactants). If the "Other End Products" are excluded (i.e. if the reference quantity only consists of plastics & rubber products, lubricants and bitumen) the percentage increases by about 50%. Hence the percentage recycled and re-used is still close to 10%. 
(e.g. devulcanisation of post-consumer rubber), have also not been taken into account. Further saving potentials that might be achievable through material substitution, both within the system investigated and by replacement of other materials, have not been analysed\(^{32}\) and are therefore not included in the estimates of the saving potentials. All in all, the aspect of incompleteness could add up to a considerable level of under-estimation.

- Only the savings achieved from recycling in the first cycle have been identified. The real savings potential is higher if materials are not only recycled once, but twice or even three times, i.e. if a strategy of quality cascading is pursued. Feasibility depends mainly on the quality of waste, the efforts in separation and purification and the actual application of the recycled material.

- It is has been assumed that surfactant production will stagnate until 2005; this is a conservative assumption, if compared with the expectations found in the literature (e.g. Ward 1996; see also footnote in the section on "Oleochemical surfactants").

- The amount of waste lubricants estimated for the future may be on the small side; on the basis of available information it would also be justified to assume a standstill as opposed to a decline in the amounts of waste.

- A high quality product (TMP ester) has been assumed for lubricants from vegetable oils; it is more energy intensive to produce this lubricant compared to natural esters (these represent other potential substitutes for petrochemical lubricants).

An attempt was made to quantify the uncertainty ranges by module. These range from -50% to +25% for the material flows, and from -20% to +30% for the energy data and CO\(_2\) emissions (Patel et al. 1999b). On this basis it was estimated that for the majority of all cases (85%) the uncertainty of the energy data and CO\(_2\) emissions is (Patel et al. 1999b):

- +/-15% for the reference year 1995
- +/-30% for the year 2005.

If the latter uncertainty range is applied to the ratio "Total Savings / Total System 1995" in the case "Technology 2005, Economy 2005" (see Table 8.6) the range of saving potentials (in 85% of all cases) is:

- 9% - 17% for energy and
- 17% - 31% for CO\(_2\).

As a general limitation, this chapter focuses only on energy and CO\(_2\) emissions. To draw conclusions related to the issue of global warming, other greenhouse gases would also have to be analysed. This would go beyond the scope of this chapter. Moreover, this chapter does not permit any conclusions to be drawn on the environmental impacts in general; this can only be done on the basis of comprehensive Life-Cycle Analyses (LCA).

According to Tables 8.3 and 8.4, most of the saving potential available in the short term can be mobilized by using synthetic organic waste as a resource (199 PJ and 12.3 Mt CO\(_2\) in total), and not by using biomass as a chemical feedstock.

Nowadays recycling and the re-use of carbon materials is faced with two main problems:

\(^{32}\) There is one exception which is the use of recycled plastics as substitutes for wood, concrete and steel; this has indeed been taken into account (see also Chapter 7). However, there are many other possibilities for substitution which have not been analysed, e.g. the use of (virgin) plastics to replace glass and aluminium in the packaging and automotive sector.
• First, for many materials the generation of waste is still small when compared with consumption (no steady state and net exports). There is a very large net increase of stocks in the economy (see Figure 8.2, modules EF) and there is a long retention time of the materials in society (e.g. asphalt, piping and window frames in buildings; compare Chapter 3).

• Second, recycling is still not economical for many types of waste; the main reasons being the abundance of low-priced virgin products and the large amount of different materials and lightweight items in the waste stream (high entropy; Hornbogen 1995). This generally results in high costs for recycling logistics, sorting and recycling processes since these usually have to be tailored specifically to the type of waste.

However, the fact that the amount of waste will continue to rise for most synthetic organic materials will motivate the development of waste management strategies and effective technologies (which should also give due consideration to recycling and re-use). For the near future, policy pursued in Germany is to prohibit landfilling of materials containing organic carbon (TA Siedlungssabfall). As a consequence, the major part of this waste will be incinerated from the year 2005 onwards. Compared to landfilling this will save fossil fuel resources. However, if the average efficiency of all MSWI plants fails to increase compared to today, then CO₂ emissions are very likely to rise. High priority should therefore be given to the construction of advanced waste-to-energy facilities which will have to be combined with district heating systems in order to ensure that the heat generated is used in an efficient way. The main problems are firstly, the time required for these changes in the infrastructure and secondly, the high investments involved. For these reasons, the potentials available in the areas of recycling and re-use must be tapped in parallel with the improvement of energy recovery systems. The measures taken should be oriented towards the optimisation of the total system. It must also be kept in mind that increased efforts in recycling will result in larger and larger amounts of materials in the waste stream which have already been recycled once or twice. Therefore, it will become necessary to develop appropriate strategies for the second and third cycle. Here, open-loop recycling may become more important, e.g. by using plastics waste and rubber waste in road construction (OECD 1997; Bullin et al., 1996). In general, the preferred situation is to establish a cascade of mechanical recycling and, finally, to apply feedstock recycling or to extract as much as possible of the energy embodied in the material by incineration. Further R&D on processes and on design for disassembly, recycling and re-use is required (Hornbogen 1995), in order to both increase the environmental benefits and to reduce the costs and thus reach the ultimate goal of cascading. Apart from the technical improvement measures mentioned, organisational measures and the adaptation of standards will continue to be needed to improve the competitiveness of recycling and re-use (European Commission 1998).

The use of biomass as a feedstock is currently hampered by the low prices of conventional products made from fossil resources. Moreover, the technologies used to manufacture bio-based materials lag behind those of conventional, fossil-based processes because of the large differ-

33 The use of PVC in construction (e.g. window frames) is a good example of the volume of waste returned for recycling being much lower than expected.

34 For example, there is fierce competition among manufacturers of virgin plastics. Domestic manufacturers are currently faced with particularly heavy import competition due to the Asia crisis and moreover, oil prices are very low. As a consequence, e.g. the prices of standard quality PVC and PP (homopolymers) dropped below 1 Deutsch Mark at the end of 1998 (1 Deutsch Mark = 0.51 EURO = 0.57 U.S.$; data for Jan.-Nov. 1998; Kunststoff-Information 1999). In terms of heating value this means that PP is about half as expensive as gasoline under the German tax system!

35 Logistics are particularly expensive in high-income countries. This is less true for developing countries where there is also pressure to recycle due to the general scarcity of materials. These are the main reasons why, for example, recycling rates for plastics waste are about four times as high in India compared to Germany (~90% versus 22%; value for India incl. 2nd and 3rd loop recycling; India-Report 1997; Chapter 7; additional calculations).
ence in amount of experience. As an additional problem, the properties of bio-based material are often inferior to those of competing materials derived from fossil feedstocks (e.g. starch polymers compared to polyolefins). For these reasons, stakeholders suggest concentrating on those biomass-derived products that show specific advantages compared to their conventional counterparts, instead of duplicating compounds which are already being manufactured from fossil resources (personal communication with J. Bozell, National Renewable Energy Laboratory, Golden, USA and D. Wittmeyer, German Association of Chemical Industry).

The potential of energy saving and CO$_2$ emission reduction by biomass feedstocks will only be small in the short term (see Tables 8.3 and 8.4). However, biomass feedstocks could enable large saving potentials in the longer term as own calculations for bulk chemicals (see Tables 8.3 and 8.4) and analyses by Gielen (1999; p.158, pp.188) indicate. This will probably be triggered by new developments in biotechnology, allowing higher yields (e.g. ethanol) and product qualities (e.g. detergents with tailored enzymes) and by new products (Ast, Sell 1998; OECD 1998; Chemical engineering 1999; Lynd et al., 1996; Chemical engineering 1999). It is expected that these developments will improve the chances of using bio-based sources as chemical feedstocks (Menrad 1998). Therefore, it may be worth assessing whether biomass feedstocks are being given sufficient attention in current R&D agendas, including assessments of the potentials and risks.

LCAs should be conducted to compare competing options of producing bio-based materials, and also to compare the most promising of these with the use of biomass for the supply of energy (electricity, heat). Analyses conducted for two case studies show that, depending on the specific application, either the use of biomass for energy or for materials is more favourable: e.g. on the one hand it was shown that the use of biomass for the production of bulk chemicals cannot compete with biomass gasification and electricity generation in terms of fossil CO$_2$ abatement (Patel, Korell 1999). On the other hand, there is strong indication that – in terms of the savings in finite energy and GHG emissions – it is more effective to use vegetable oils to produce surfactants as opposed to liquid biofuels (Patel et al. 1999c). Based on further comparisons which should also include other environmental indicators, e.g. waterborne emissions and waste, it will be possible to set quantity targets (not quota) and cost targets for the use of biomass as a feedstock. Non-binding quantity targets already exist for the U.S. where the Department of Energy (DOE) stated that at least 10% of the bulk chemicals should be produced from biomass feedstocks by the year 2020, and that the share should be increased up to 50% by 2050 (U.S. Department of Energy 1998). By contrast, the goals in Europe have only been set for bioenergy, which is supposed to increase from the current 3% of the total domestic energy consumption to 6% in 2010 (Figures for EU-15; Kommission der Europäischen Gemeinschaften 1997).

### 8.6 Conclusions and policy implications

The manufacture and waste management of synthetic organic materials accounts for a considerable consumption of fossil resources and entails substantial CO$_2$ emissions: If compared to the entire industrial sector in Germany (without non-energy use$^{36}$) the share is 44% for energy and 20% for CO$_2$.

It has been shown that the share of synthetic organic materials produced by recycling or re-use is still very low in Germany; the total amount of end products consumed domestically having a share of less than 10%. This already indicates that, in general, recycling and re-use still offer a high untapped potential for energy saving and CO$_2$ abatement.

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$^{36}$ See footnote 4 in Table 8.6 for the energy requirements and CO$_2$ emissions of the entire industrial sector in Germany.
In total, the potential savings relative to the various reference cases amount to 220 PJ of finite energy and 14 Mt of fossil CO₂ by the year 2005 (see Table 8.6). These are substantial saving potentials, even when compared to the current figures for the total German industry, with percentages of 6% for energy and 4½% for CO₂. Relative to the system analysed in this chapter (see the dotted box in Figure 8.1) an equivalent of 13% of energy and 24% of CO₂ can be saved (uncertainty ranges: 9% - 17% for energy; 17% - 31% for CO₂). This leads to the significant conclusion that the saving potential identified on the non-energy side is comparable to that discussed and negotiated for energy efficiency improvement. Compared to the total German economy, the savings identified amount to 1.5% for both energy and CO₂ (see Table 8.6). Hence, given that some countries may have difficulty in meeting the Kyoto target, the potentials on the non-energy side deserve to be given more attention.

As of 2005 Germany will prohibit organic carbon content landfilling. This is very likely to cause a rise in fossil CO₂ emissions unless the average efficiency of MSWI plants (including waste-to-energy facilities) increases in comparison with today's figures or larger amounts of waste are recycled and re-used. It is therefore imperative that only highly efficient MSWI plants are built in the future. Moreover, future policies will have to take into account the saving potentials related to recycling and re-use. Optimised strategies combining re-use, mechanical recycling, feedstock recycling and energy recovery will have to be developed for the various types of waste.

To extend the scope for recycling and re-use it is essential to conduct further R&D on processes and design for disassembly, recycling and re-use, and to support the competitiveness of the recycling industries by introducing further measures.

Own analyses show that it is impossible to make a general statement about whether products made of biomass sources are to be preferred in terms of finite energy use and fossil CO₂ emissions as opposed to their petrochemical counterparts. Especially those bio-based products that require complicated processing may be less favourable in terms of energy use and CO₂ emissions than their counterparts derived from fossil resources (see polyhydroxyalkanoates).

On the other hand, it must be kept in mind that technological progress is rapid (e.g. due to the progress made in biotechnology), i.e. new processes with an improved ecological and cost performance are under development. In terms of finite energy and fossil CO₂, oleochemical surfactants, lubricants from vegetable oils and starch polymers, offer advantages compared to their petrochemical counterparts even today.

According to the potentials that have been established, recycling, re-use and energy recovery of synthetic organic materials can contribute the most towards saving energy and to reducing CO₂ emissions in the short term. For the longer term, the use of biomass feedstocks may contribute as much, or even more than recycling and energy recovery strategies (as the calculations for bulk chemicals indicate). This will probably be triggered off by new developments in biotechnology. Therefore it may be worth looking into whether biomass feedstocks are being given enough attention in current R&D agendas, including assessments of the potentials and the risks involved.

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37 For example, German trade and industry undertook the commitment to reduce their specific energy-related CO₂ emissions by 20% in the period 1990-2005 (RWI 1997). This voluntary agreement refers to CO₂ mitigation by improving energy efficiency. These savings of energy-related CO₂ emissions (20%) refer to the current CO₂ emissions from the energy system (fuels and electricity to power the processes), whereas the saving potential related to non-energy use (24%, see Table 8.6) refers to the CO₂ emissions both from the energy system and the materials system. This means that the denominators differ in the two cases. Nevertheless, the comparison is valid because the differences between the two denominators is in the range of 10% only (compare Table 8.2).

38 On the other hand, the increased incineration of municipal solid waste will probably result in a substantial decrease of methane emissions originating from landfilling. For the time period covered in this study, these methane emissions practically exclusively originate from natural organic waste, e.g. food waste, and are therefore outside the scope of this analysis which is focusing on synthetic organic materials.
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