Ecological rucksack
for materials used
in everyday products

Electricity
Zinc
Polypropylene
Renewable energy
Steel
Fibreboard
Hardwood
Polyethylene
Acrylic
Aluminium
Lead
SAN
Transport
PVC
Electronics
Gold
Acrylic fibres
ABS
Softwood
Iron
Plywood
Nylon
Stainless steel
Tin
Glass
Polystyrene
Leather
Nickel
Platinum
Ceramics
Silver
Chipboard
Pine wood
Copper
Synthetic rubber

Content

Introduction

This report contains estimates of the material input (MI) for a range of materials used in everyday products. The report provides background data for the production of Danish educational materials, which enable 15-18 year old students to calculate the ecological rucksack of everyday products. By writing the report in English, we hope that other organisations or individuals are encouraged to create similar educational materials in languages other than Danish.

It is assumed that the reader of this report has sufficient knowledge of the MI concept. If you are not familiar with the MI concept, we suggest that you read 'Calculating MIPS Resource productivity of products and services' by Michael Ritthoff, Holger Rohn and Christa Liedtke from the Wuppertal Institute (download from www.mips-online.info). MIPS is an abbreviation of Material Input Per Service unit.

In this report we use the term "MI", but for educational purposes it may be an advantage to use the term "Ecological Rucksack". In principle, the ecological rucksack is defined as the MI of a product, minus the weight of the product. It should be easy to calculate the "Ecological Rucksack" even when MI is divided into abiotic materials, biotic materials, water and air; it is in most cases easy to identify which of the components of specific products which consist of abiotic (metal, glass etc.) or biotic (wood, paper etc.) elements.

Attached to the report, you will find the Excel workbook, 'RucksackNOAH.xls', where calculations are made. The workbook contains 8 worksheets. The first worksheet explains how to read the tables and the last is an appendix. The remaining 6 worksheets are connected to the first 6 chapters of this report. References are mentioned in the workbook, and data is connected between the sheets whenever possible.

The data sources are divided into three categories:
- Data from the Wuppertal Institute. This includes data from their database and a list of MI-values which can be found on www.mips-online.info (hereafter MI-werte). This category is regarded as the most reliable data source.
- Much data has been collected from various studies carried out primarily in Germany. Quiet a few of these studies are carried out by students. This data is considered to be less reliable.
- Wherever possible data has been adjusted to electricity production in China (see chapter 1).

Although data has been adjusted to Chinese electricity production, MI's for many of the production processes are derived from Germany (and other western countries). For example, the MI for construction of power plants are German values. Assuming that German technology is more efficient when it comes to material use per produced unit than world average, it is likely that calculated MIs are smaller than actual world average production values.

We have made quite a few assumptions in the calculations. The assumptions occasionally have decisive influence on the final result. We have tried to present the assumptions in a transparent manner but we have chosen only to include a few short explanations where we have used assumptions. If the reader wishes to go more in depth with the values presented in the workbook, it will in most cases be necessary to procure the data source. Where it has been possible we have

compared calculated MIs to MI-werte in the excel worksheets. See chapter 9 for a short discussion of the reliability of the calculated MIs.

Acknowledgement

1. Electricity

Production

A large proportion of MI in connection with production of goods comes from the consumption of electricity. However, the MI for production of electricity changes a great deal from region to region.

Nowadays most production of primary material takes place in NIC (Newly Industrialized Countries). It would therefore serve our purpose to use MIs for production of electricity in NIC countries in the calculations of MI in the production processes. Because China has a fair share of the world's primary industrial production and because of practical reasons, we have chosen to use electricity production in China as a representative for electricity production in NIC countries.

In China there are three main categories of electricity production processes:
- Fossil fuels etc.
- Nuclear power
- Hydro power

It applies to all three categories that MI´s are used for construction and operation of the plants. For fossil and nuclear fuels MIs are used in the supply of combustibles.
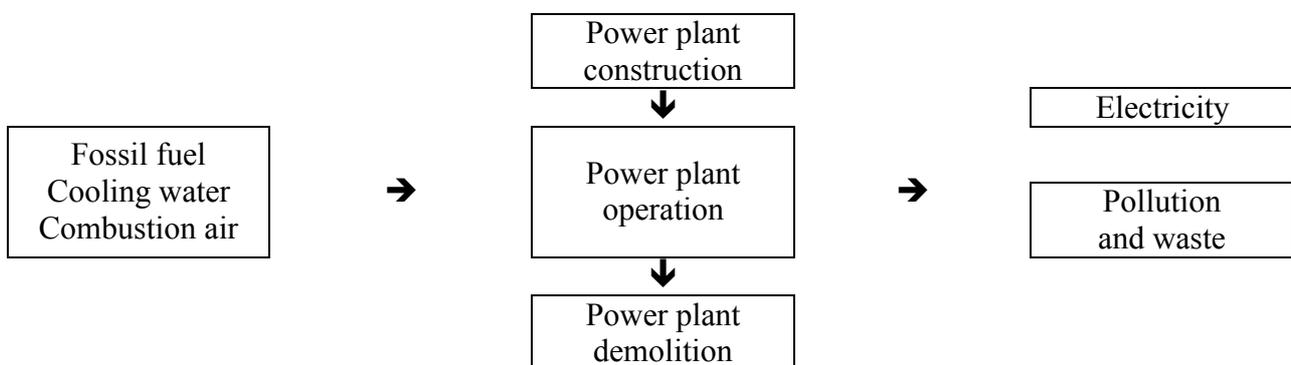
Figure 1.1. Process-chain for electricity production from fossil fuels.

Coal 384 g coal/kWh 6,7 kg abiotic/kg 0,97 kg water/kg 100 g air/kg	→	
Oil 8 g oil/kWh 1,2 kg abiotic/kg 6,6 kg water/kg 1,3 kg air/kg	→	**Electricity in China** 3,14 kg abiotic/kWh 54 kg water/kWh 620 g air/kWh
Natural gas 1 g natural gas/kWh 1,3 kg abiotic/kg 80 g water/kg 1,4 kg air/kg	→	
Nuclear fuel 2,1 g nuclear fuel/kWh 1,2 g abiotic/kWh 2,5 g water/kWh 16 g air/kWh	→	

Building of power plants
80 g abiotic/kWh
110 g water/kWh
40 g air/kWh
←

Operation of power plants
20 g abiotic/kWh
49 kg water/kWh
530 g air/kWh
←

Figure 1.2. MI for electricity production in China. The centre box illustrates average MI input for production of 1 kWh in China.

Renewable energy

The abiotic MI of electricity produced by wind mills in Denmark is approximately 71 g abiotic/kwh, 170 g water/kwh, 1 g luft/kwh (according to a master thesis by Johan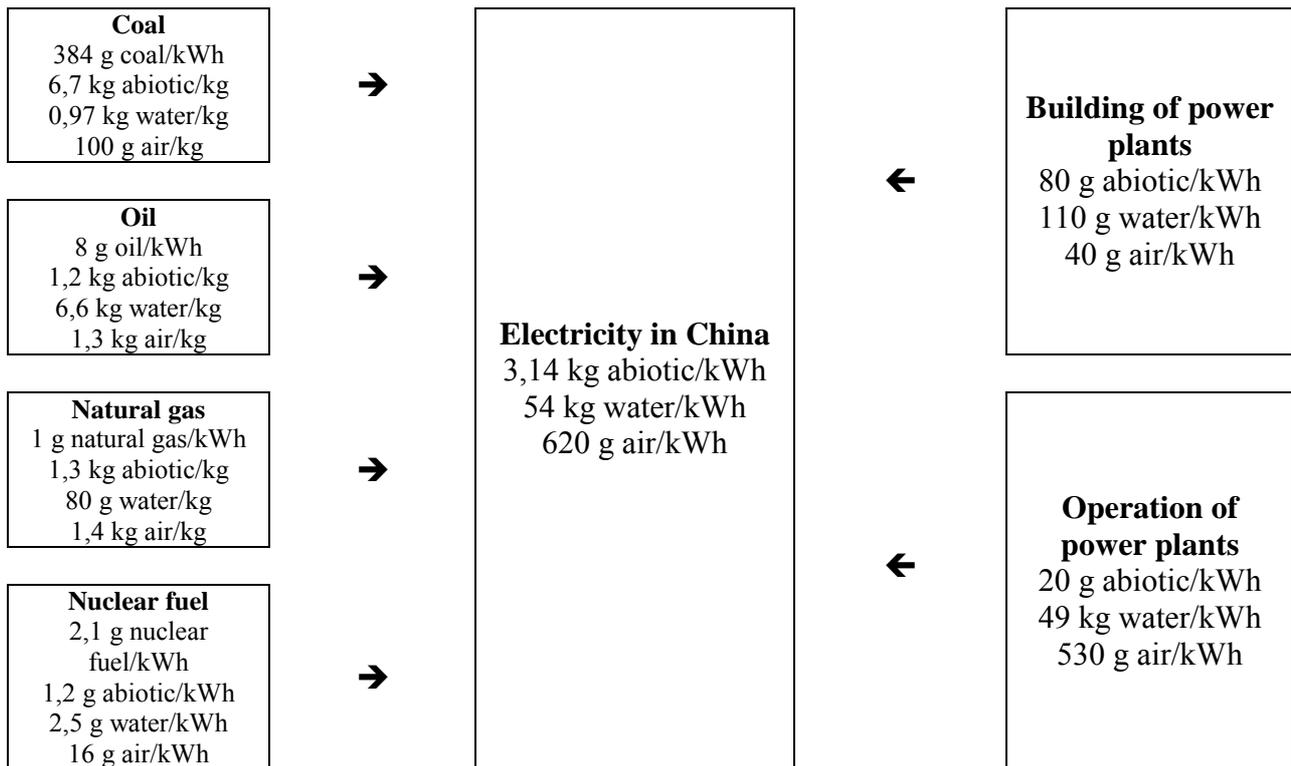nes Hacker, Bestimmung des lebenszyklusweiten Naturverbrauches für die Elektrizitätsproduktion in den Ländern der Europäischen Union). Respectively 44, 300 and 600 times lower than the MI for Chinese electricity.

2. Metals

2.1. Iron

Primary iron

The Iron Age was from 1300 – 1100 BC, when the Hittites were the first to forge iron (it was first heated, then hammered, then cooled quickly to produce iron that was harder than bronze, which people had been using before). By the time of the Roman Empire, iron was used for beds, gates, chariots, nails, saws, axes, spears, fishhooks and tools for sharpening. During the Middle Ages, with the introduction of the iron cannon and cannon ball, the consumption of iron increased to overtake copper and bronze as the most widely used metal. In the late 19th century the Age of Steel began, with wooden ships giving way to steel, machinery coming to the factories, and the invention of the railroad.

After the iron ore has been extracted from the earth the brown ore is cleaned and much of the clay and quartz is removed. The ore is broken in a breaker and the magnetic fraction is yielded in a magnetic machine (ore agglomeration). The magnetic portion is shipped to the furnace, and the waste to the dump heap. In the furnace, iron is separated by a reduction process at high temperature, i.e.: Ore (Fe_2O_3 and Fe_3O_4) and CO-gas from burning of coke are transformed into Fe and CO_2-gas.

From the excel-worksheet it is possible to find inputs to the production of most materials described in this report. For example 1 ton pig iron uses the following inputs (blast furnace route):

4600 kg iron ore incl. overburden	13 M^3 water	640 kg mineral coke
140 MJ Diesel	80 kg limestone	1700 MJ secondary fuel
700 g explosives	330 MJ natural gas	760 kg air
200 kWh electricity	3,2 Nm^3 compressed air	60 kg hardcoal
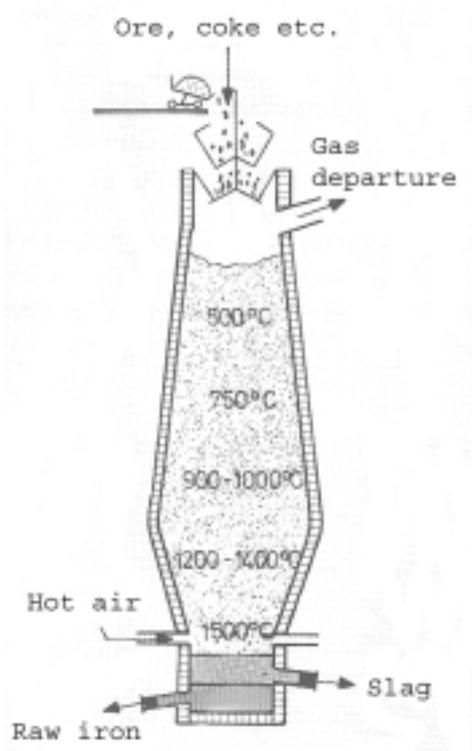
Figure 2.1. Schematic figure of a blast furnace for the production of iron. Blast furnaces are very high (<60 m).

Cleaning

Mineral surface ores often contains a high amount of clay and quartz. The removal of which is accomplished by a log washer. This is a disintegrator consisting of a long narrow cylinder revolving in a trough which is nearly horizontal. Upon the cylinder are knives or paddles set at an angle, which serve the double purpose of bruising and disintegrating the clay and of conveying the cleaned lump ore to be discharged at the upper end of the trough. The water meanwhile washes away the clay at the lower end.

The process chain for the production of pig iron (raw iron) is shown below (blast furnace route):

Diesel Explosives	➔	Iron ore extraction
		⬇
Electricity Water	➔	Cleaning
		⬇
Limestone Natural gas Compressed air Electricity Water	➔	Ore agglomeration
		⬇
Cooling water Coke	➔	Furnace
		⬇
		Pig iron
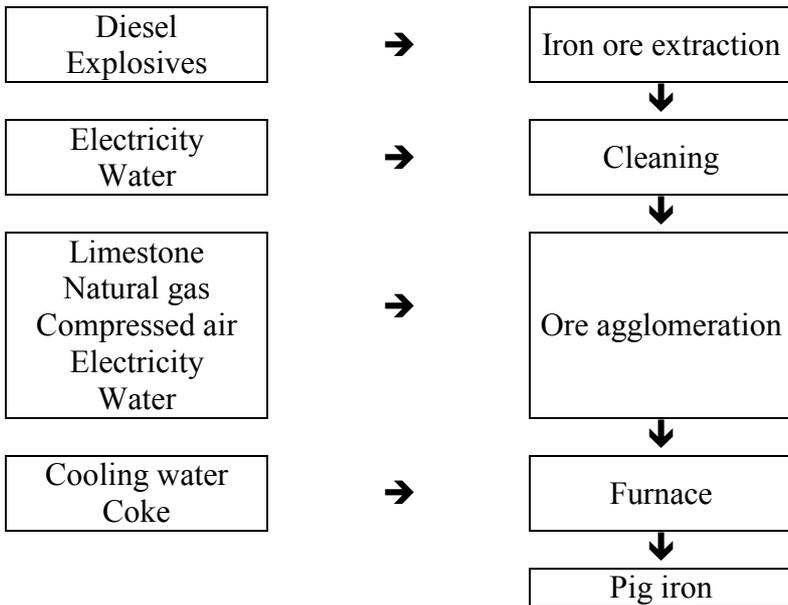
Figure 2.2. Process-chain for the production of raw iron.

It has been difficult to provide figures for the further processing of pig iron into wrought iron and cast iron. In reality some of the iron comes from scrap (especially cast iron has a high scrap content).

Iron ore 7,0 kg abiotic 330 g water 19 g air	**Cleaning** 131 g abiotic 5,6 kg water 26 g air	**Ore agglomeration** 280 g abiotic 6,6 kg water 111 g air	**Furnace** 740 g abiotic 27,6 kg water 1,2 kg air	**Casting** 3,9 kg abiotic 50,6 kg water 460 g air
⬇	⬇	⬇	⬇	⬇

Cast iron 12 kg abiotic 91 kg water 1,9 kg air
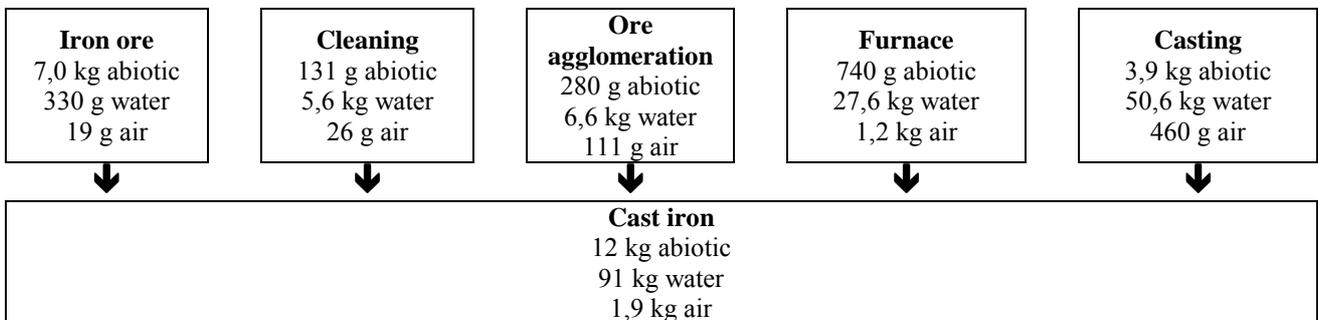
Figure 2.3. MI per kg cast iron (inputs are presented in the metal-worksheet).

2.2. Steel

Primary steel
Iron is alloyed with carbon to make steel (and a number of other metals). Pig iron contains about 4 % carbon. In this form the iron is extremely hard and brittle. To convert this material to a material which can be rolled it must be converted to steel, which contains less than 2 % carbon. This is done in a converter blowing air into the melted iron (figures for the conversion are unfortunately not available).

In the metal-worksheet two calculation examples are given for the production of Wire Rod Engineering Steel. Wire Rod means round steel that is thicker than wire and can be considered to be all kinds of simple steel.
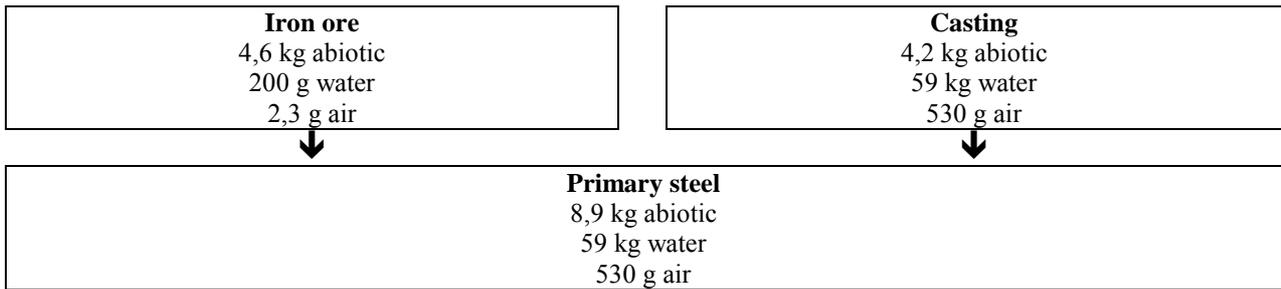
The first example is for the blast furnace route. The blast furnace process is dominated by inputs from iron ore, and the production can be considered as primary steel.

Logically the MI of steel should be bigger than MI for cast iron – this is not the case. The reason for this is that different data sources have been used. In the educational material we have chosen to use the figures for cast iron to represent both cast iron and steel. Please note that the Wuppertal Institute prefers to make use of MI-werte as primary data sources (i.e. close to MI for steel, figure 2.4).

USE	DESCRIPTION
Transportation	Steel railway carriages/engines, ships, car frames, engine cylinders.
Construction	Steel buildings, bridges (such as the Sydney Harbour Bridge), roofing, cladding, doors, fencing.
Machinery	Steel engines, pumps, cranes, workshop equipment (eg. cutting tools, drill bits).
Wire products	Steel wire fences, ships, cables, staples, door screens, nuts & bolts.
Storage	Steel food containers, storage tanks.
Oil and Gas	Steel drill rods, casing, pipelines.
Appliances, equipment	Steel refrigerators, washing machines, dishwashers, cutlery, hospital equipment.
Health	Pure iron is needed for proper plant growth. Animals need iron for making energy and carrying blood around the body (foods rich in iron include red meat and liver, egg yolks and leafy green vegetables.) Iron was the first element to be recognised as essential for people. A physician in 1681 successfully used iron to treat patients who were pale, lacking in energy and suffering from anaemia. Iron chloride is used in water treatment and purification.
Fun	Iron filings are used in 'sparklers'.
Electronics	Iron chloride is used to etch copper in the making of electrical printed circuits.
Cooking	Cast iron camp ovens and woks.
Decoration	Wrought iron outdoor furniture, porch railings and other decorative items.

Source: http://www.australianminesatlas.gov.au/info/rockfiles/iron.jsp

Iron ore	Casting
4,6 kg abiotic	4,2 kg abiotic
200 g water	59 kg water
2,3 g air	530 g air

↓ ↓

Primary steel
8,9 kg abiotic
59 kg water
530 g air

Figure 2.4. MI per kg primary steel (inputs are presented in the metal-worksheet).

Secondary steel

The second example of Wire Rod Engineering Steel production is for the electrical arc furnace route. This process is dominated by inputs of scrap and can be considered as secondary steel.

About 35 % of all steel consumption in EU(15) comes from scrap (Iron and Steel Industry in 2002, OECD, 2004 Edition).
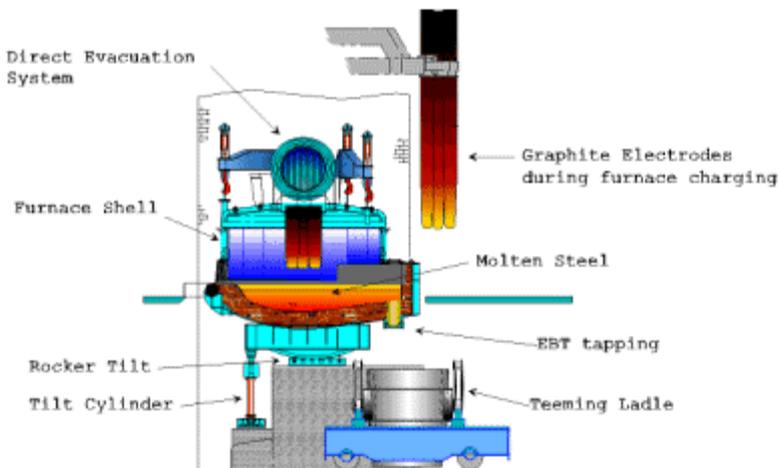
Figure 2.5. Schematic figure of an electrical arc furnace production of secondary steel.

The rucksack for abiotic materials is approximately 3 times heavier for primary steel than it is for secondary steel, whereas the rucksacks for water and air are about the same.

Primary steel
2,7 kg abiotic
51 kg water
660 g air
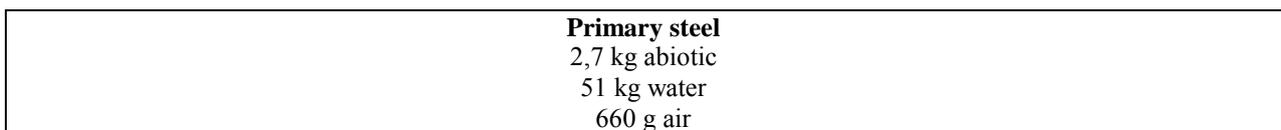
Figure 2.6. MI per kg primary steel (inputs are presented in the metal-worksheet).

2.3. Aluminium

Primary aluminium

Aluminium is the second-most used metal (after iron) as it can be alloyed with many other metals to create materials with a whole range of properties. Some of these alloys have special names; for example, Zincalume and Duralumin. Aluminium alloys are strong, lightweight and resistant to corrosion.

Aluminium is the most plentiful metal in Earth's crust. Whereas copper, gold, lead and zinc were used by humans thousands of years ago, aluminium has only been used for a little over 100 years because humans did not know until then how to extract it.

A major environmental problem with aluminium is the high energy demand in the production of aluminium; it is very energy demanding to remove oxygen from aluminia.

In the worksheet for metals, there are two examples of MI for the production of aluminium, one for primary aluminium and one for secondary aluminium.

There are four major steps in the production process of primary aluminium:
1. Mining. Extraction of bauxite, for instance in Northern Australia
2. Alumina plant. The cleaning removes iron oxides and silicates from the bauxite. The product aluminium oxide is called alumina. Alumina production could for instance take place in Corsica.
3. Electrolysis - reduction process. For instance in Northern Italia.
4. Casting of liquid aluminium and subsequently rolling into sheet aluminium.

USE	DESCRIPTION
Building and construction	As aluminium is strong, light, easily shaped and resistant to corrosion, it is used in cladding, doors, window frames, awnings and bridge rails.
Transport	For the above reasons, aluminium parts are found in cars, trucks, buses, aircraft, ships, rail and trams.
Appliances	Also for the above reasons: fridges, washing machines, lawn mowers etc.
Heating and ventilation	As aluminium is a good conductor of heat, it is used in heating and cooling systems.
Packaging	As aluminium can be rolled into very thin sheets and is non-toxic, it is used for kitchen foil, packaging foil, cans and containers.
Electrical and communications	Aluminium's ability to conduct electricity means it is used for power. transmission including towers, electrical conduit, machinery and equipment, telephone cables and capacitors.
Other	Utensils (cutlery, pans), industrial machinery, chemical industry, production of steel, anti-perspirants, furniture, reflectors in telescopes, making high octane petrol, road signs, antacids, and jewellery.

Source: http://www.australianminesatlas.gov.au/info/rockfiles/aluminium.jsp

Electrolysis of aluminium

Aluminium is obtained by the electrolytic reduction of its molten oxide, alumina (Al_2O_3). Because alumina has a very high melting point (2045 ºC), the mineral cryolite (Na_3AlF_6) is added to lower the melting point in order that the elctrolysis may be carried out at approximately 950 ºC. The electrolytic cell has carbon anodes and a carbon cathode (which forms the lining of the tank in which the electrolysis takes place). Carbon dioxide is formed at the anodes, and aluminium at the cathode. It is heavier than the molten alumina/cryolite mixture, and sinks to the bottom of the cell, where it is tapped off. The procedure is known as the **Hall-Heroult process**.
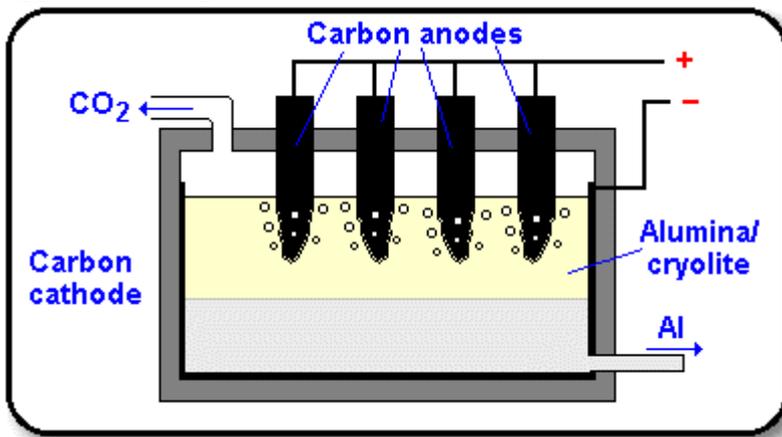
Aluminium extraction is very demanding on electrical current (typically, 800 V and 70 000 A), and is economical only where power is cheap.
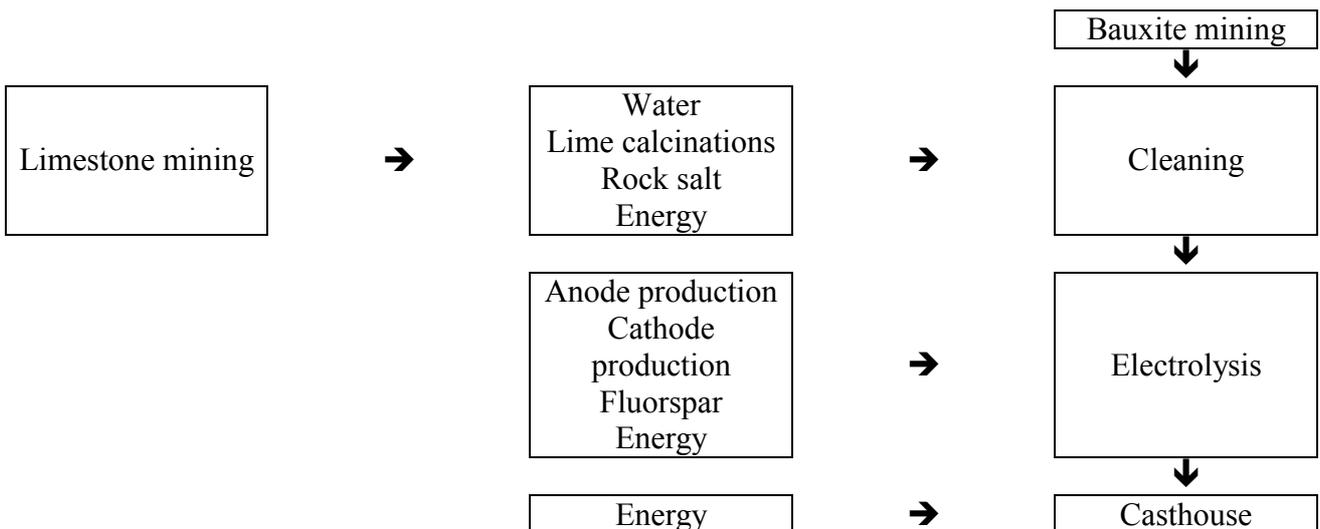
Figure 2.1. Process-chain for the production of aluminium.

Mining	Cleaning	Electrolysis	Casting	Rolling
8,6 kg abiotic	3,3 kg abiotic	50 kg abiotic	90 g abiotic	3,2 kg abiotic
2,4 kg water	36 kg water	848 kg water	910 g water	35 kg water
	2,5 kg air	11 kg air	100 g air	680 g air

Primary sheet aluminium
66 kg abiotic
920 kg water
15 kg air
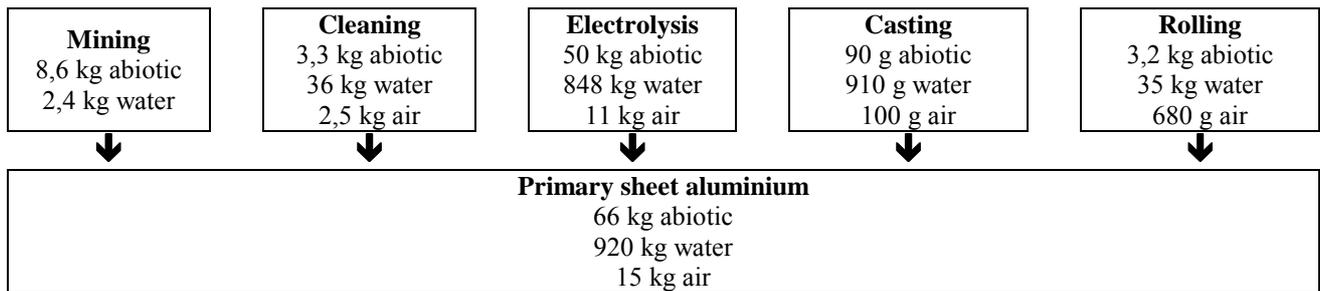
Figure 2.2. MI per kg primary sheet aluminium.

Secondary aluminium

In 2003 secondary aluminium made up only a little more than 20 % of total production of aluminium (World Statistics Yearbook 2004, World Bureau of Metal Statistics, May 7th 2004).

The rucksack for abiotic materials is around 40-50 times heavier for primary aluminium than for secondary aluminium.

Secondary aluminium
1,2 kg abiotic
24 kg water
900 g air
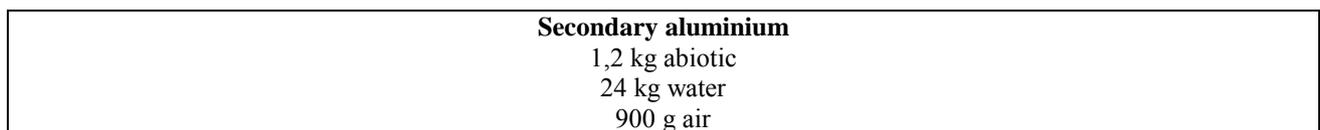
Figure 2.3. MI per kg secondary aluminium.

2.4. Copper

Primary copper

Copper's most important use is as an electrical conductor. It is also used in the manufacture of alloys, fertilisers and cooking utensils.

Copper was the first metal used by our ancestors, discovered by Neolithic Man about 9000 years ago and used in place of stone, as it was far easier to shape. Early coppersmiths in Iran found that heating copper softened it and hammering copper made it harder. In this way, they could shape copper into various useful items such as containers and utensils. Copper was also made into jewellery and ornaments. Around 4000 BC bronze, an even harder alloy, was discovered by mixing copper with a small amount of tin. It was used to make not only decorations but also weapons, armour and tools - thus began the Copper-Bronze Age.

The use of sulphuric ores (Cu_2S and $CuFeS_2$) is most common but non-sulphuric ores (e.g. Cu_2O) are also exploited.

In the worksheet for metals, you will find calculations for primary and secondary coppers as well as copper wires. It appears that the amount of primary copper used in production is the decisive factor for the input of abiotic material in copper goods.

Mining
Mining produces ores with less than 1 percent copper.

Crushing, grinding, and flotation purification
Concentration is accomplished at the mine sites by crushing, grinding, and flotation purification, resulting in ore with 15 to 35 percent copper. A continuous process called flotation, which uses water, various flotation chemicals, and compressed air, separates the ore into fractions. Depending upon the chemicals used, some minerals float to the surface and are removed in a foam of air bubbles, while others sink and are reprocessed.

Pine oils, cresylic acid, and long-chain alcohols are used for the flotation of copper ores. The flotation concentrates are then dewatered by clarification and filtration, resulting in 10 to 15 percent water, 25 percent sulfur, 25 percent iron, and varying quantities of arsenic, antimony, bismuth, cadmium, lead, selenium, magnesium, aluminum, cobalt, tin, nickel, tellurium, silver, gold, and palladium.

Roasting
Roasting is performed in copper smelters prior to charging reverberatory furnaces. In roasting, charge material of copper concentrate mixed with a siliceous flux (often a low-grade copper ore) is heated in air to about 650°C, eliminating 20 to 50 percent of the sulfur as sulfur dioxide (SO_2). Portions of impurities such as antimony, arsenic, and lead are driven off, and some iron is converted to iron oxide. Roasters are either multiple hearth or fluidized bed; multiple hearth roasters accept moist concentrate, whereas fluidized bed roasters are fed finely ground material. Both roaster types have self-generating energy by the exothermic oxidation of hydrogen sulfide, shown in the reaction below.
$H_2S + O_2 \rightarrow SO_2 + H_2O$ + Thermal energy

Smelting
In the smelting process, either hot calcine from the roaster or raw unroasted concentrate is melted with siliceous flux in a smelting furnace to produce copper matte. The required heat comes from partial oxidation of the sulfide charge and from burning external fuel. Most of the iron and some of the impurities in the charge oxidize with the fluxes to form a slag on top of the molten bath, which is periodically removed and discarded. Copper matte remains in the furnace until tapped. Matte ranges from 35 to 65 percent copper.

Converting
Converting produces blister copper by eliminating the remaining iron and sulfur present in the matte. Air, or oxygen-rich air, is blown through the molten matte. Iron sulfide is oxidized to form iron oxide (FeO) and SO_2. Blowing and slag skimming continue until an adequate amount of relatively pure Cu2S, called "white metal", accumulates in the bottom of the converter. A final air blast ("final blow") oxidizes the copper sulfide to SO_2, and blister copper forms, containing 98 to 99 percent coppers. The blister copper is removed from the converter for subsequent refining. The SO_2 produced throughout the operation is vented to pollution control devices.

Refining and reduction
Fire refining and electrolytic refining are used to purify blister copper even further. In fire refining, blister copper is usually mixed with flux and charged into the furnace, which is maintained at 1100°C. Air is blown through the molten mixture to oxidize the copper and any remaining

impurities. The impurities are removed as slag. The remaining copper oxide is then subjected to a reducing atmosphere to form purer copper. The fire-refined copper is then cast into anodes for even further purification by electrolytic refining. Electrolytic refining separates copper from impurities by electrolysis in a solution containing copper sulfate (Cu2SO4) and sulfuric acid (H2SO4). The copper anode is dissolved and deposited at the cathode. As the copper anode dissolves, metallic impurities precipitate and form a sludge. Cathode copper, 99.95 to 99.96 percent pure, is then cast into bars, ingots, or slabs.

		Mining		
		⬇		
Water				Water
Chemicals	➔	Crushing, grinding etc.	➔	Sulfur
Compressed air				Iron etc.

15-35 % Cu
⬇

				Iron oxide
Low-grade Cu ore	➔	Roasting	➔	SO2
Flames				Impurities
		⬇		

Fuel				
	➔	Smelting	➔	Slag
Siliceous flux				

35-65% Cu
⬇

				Iron oxide
Air	➔	Converting	➔	
				SO2

98-99 % Cu
⬇

Air, sulphuric acid	➔	Refining	➔	Slag / sludge

99,95 % Cu
⬇

		Casting		
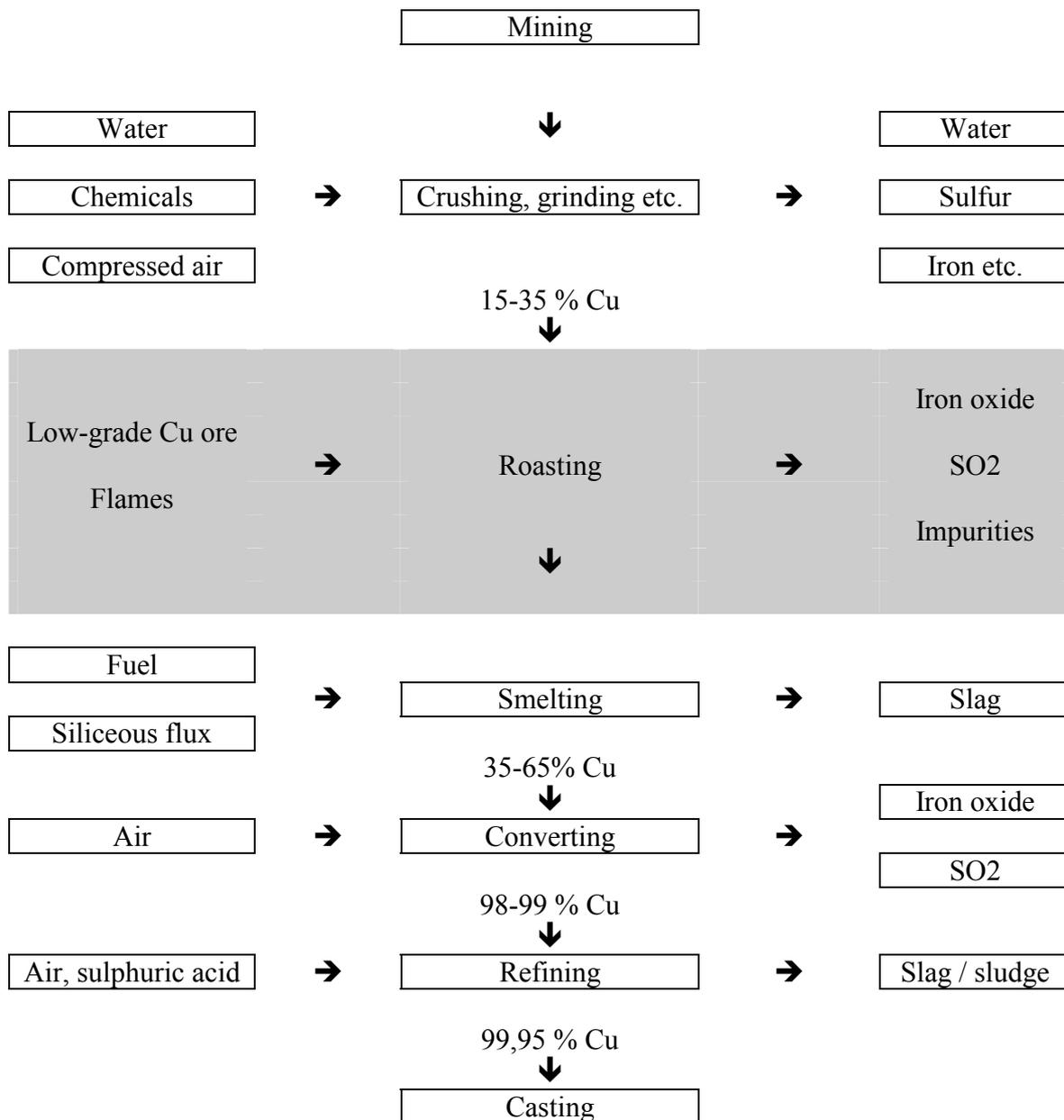
Figure 2.4. Process-chain for copper production. See text for details.

USE	DESCRIPTION
Electricity and communication	As copper is ductile and a great conductor, its main use is in electric generators, household/car electrical wiring, and the wires in appliances, computers, lights, motors, telephone cables, radios and TV sets.
Coins	The alloy 'cupronickel', a mixture of 75% copper and 25% nickel, is used for making 'silver' coins such as our 5, 10, 20 and 50 cent pieces. Our $1 and $2 coins are 92% copper, mixed with aluminium and nickel.
Pipes	As copper does not rust easily, and can be easily joined, it is useful for making water pipes (and hydraulic systems). The use of copper in water pipes dates back to the ancient Egyptians and of course the Romans!
Heat conducting	Copper's ability to conduct heat means it is used for car radiators, air conditioners, home heating systems, and boilers to produce steam. It is also ideal for the base of cooking pots.
Fungicides and insecticides	Copper sulphate is used to kill algal blooms in water reservoirs, to protect timber, to stop plant roots from blocking rains and sewerage systems, and to kill insects.
Fertilisers	Copper production was boosted in the 1950s and 1960s by the need for copper-based fertilisers to aid crop growth in previously unproductive land.
Bronze	Bronze (90% copper, 10% tin) is used for statues, and bearings in car engines and heavy machinery.
Brass	Brass (70% copper, 30% zinc) is particularly rust-resistant and so is used to make marine hardware. Many musical instruments are made from brass. Also decorative pieces, from light fittings to taps, and instruments for astronomy, surveying, navigation and other scientific purposes.

Source: http://www.australianminesatlas.gov.au/info/rockfiles/copper.jsp

Mining	Crushing, grinding etc.	Smelting	Converting	Refining and reduction
217 kg abiotic	132 kg abiotic	600 g abiotic	4,2 kg abiotic	1,2 kg abiotic
18 kg water	248 kg water	9,9 kg water	94 kg water	20 kg water
200 g air	1,4 kg air	190 kg air	1,7 kg air	420 g air

Primary copper
356 kg abiotic
391 kg water
3,9 kg air
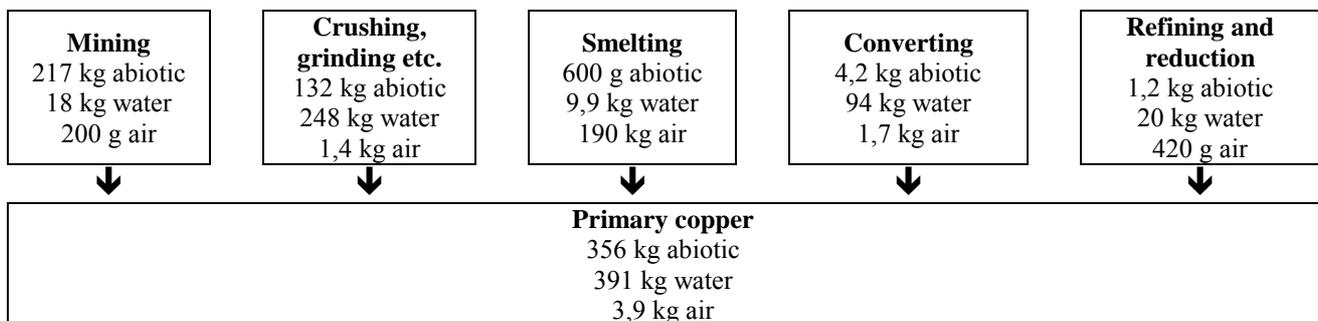
Figure 2.5. MI per kg primary copper.

Secondary copper
In 2003 secondary copper made up about 20 % of total production of copper (World Statistics Yearbook 2004, World Bureau of Metal Statistics, May 7th 2004).

The rucksack for abiotic materials is around 80 times heavier for primary cupper than for secondary copper, however the rucksacks for water and air are respectively 5 and 2,5 times larger for primary than for secondary cupper.

Secondary copper
4,5 kg abiotic
73 kg water
1,6 kg air

Figure 2.7. MI per kg secondary copper.

Copper wire

The rucksack of copper wire made from half primary and half secondary copper is about 50 % heavier than for primary copper when it comes to abiotic material, but the rucksacks for water and air are roughly the same as for primary aluminium.

50 % primary copper	50 % secondary copper
⬇	⬇

Copper wire 0,6 mm
184 kg abiotic
288 kg water
4,1 kg air
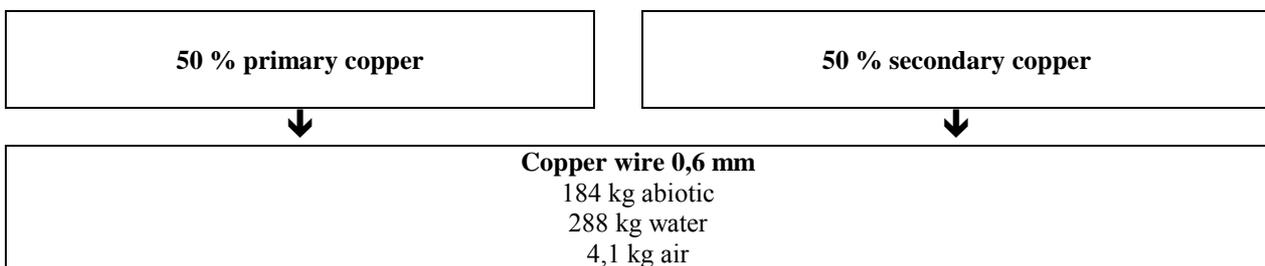
Figure 2.8. MI per kg copper wire 0,6 mm.

2.5. Zinc

Primary copper

Zinc (Zn) was used in Rome and China more than 2000 years ago as a component of brass (zinc-copper alloy). Zinc metal was first smelted from zinc ore in India in about 1200 AD and is known to have been used in China soon after. Commercial production of zinc did not start in Europe until the middle of the 18th century and in the United States until 1860. In deposits mined today, zinc ore (rock containing economic content of zinc and/or other materials) usually occurs mixed with ores of lead, silver and commonly copper, and is extracted as a co-product of these metals.

Zinc is mainly used for galvanising (coating) iron and steel to protect against rust.

In the worksheet for metal MI's for primary and secondary zinc are calculated.

Mining and processing

Zinc ore is extracted from both open pit zinc mining and underground mining. In underground mining ore is drilled and blasted in large volumes, transferred to underground rock crushers by large loaders and trucks, and then hoisted to the surface in skips or driven directly to the surface by truck via a spiral access tunnel (decline).

At the surface, the ore is subjected to additional crushing and fine grinding. The flotation process is then used to separate the zinc and other valuable sulphide minerals from the waste rock particles (tailings) to form a concentrate. Ground ore, water and special chemicals are mixed and constantly

agitated in banks of flotation cells. Air is blown through the mixture in each cell, and the fine zinc sulphide particles stick to the bubbles, which rise to form a froth on the surface of the flotation cell. The tailings sink and are removed from the bottom of the cell. T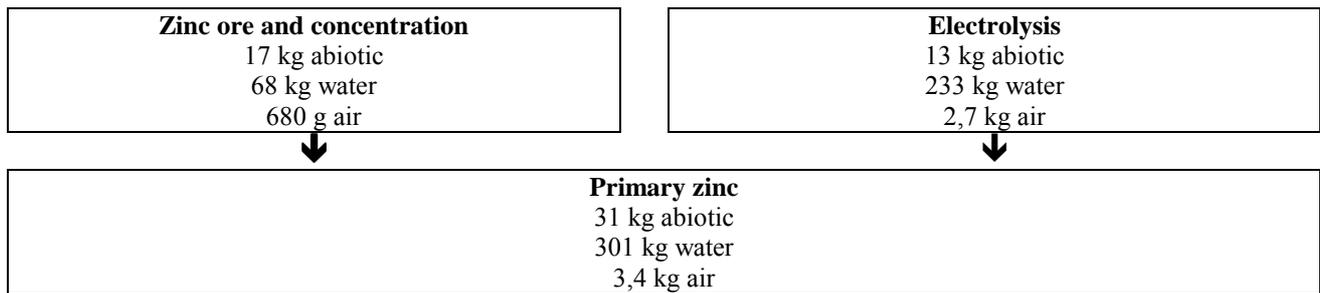he froth is skimmed off and the resulting zinc sulphide concentrate is dried. This process upgrades the ore, which may contain only 6% Zn, to a concentrate of more than 50% zinc. Up to 90% of the zinc in the ore can be recovered.

Electrolysis is one process used to produce zinc metal. A zinc refinery using the electrolytic process first roasts zinc concentrates to eliminate most of the sulphur, as sulphur dioxide, and makes impure zinc oxide. The roasted concentrate is then leached with sulphuric acid to form zinc sulphate solution. The zinc sulphate solution is purified by adding a small amount of zinc powder to precipitate and remove traces of copper, cadmium, cobalt and nickel. The solution is piped to electrolytic cells, where the zinc is electrochemically deposited on aluminium cathodes (electrodes). The zinc is removed from the cathodes, melted in a furnace and cast into slabs.

USE	DESCRIPTION
Galvanising	In Australia today, two-thirds of all the zinc used is to protect steel from rusting, by coating it using a process called galvanising (named after the Italian chemist, Luigi Galvani, who invented the process). The steel is dipped in molten zinc, often also with aluminium. Products include steel beams, roofs, poles, wires, nails, household appliances and car bodies, to name a few.
Diecast objects	Zinc mixed with small amounts of aluminium produces a very strong alloy. Its low melting point enables it to be diecast (cast into different shapes in steel moulds) to make all sorts of items (some requiring fine detail) from carburettors to doorhandles, staples to zips, even matchbox cars.
Brass	Brass (70% copper, 30% zinc) is particularly rust-resistant and so is used to make the hulls of sailing boats and other marine hardware. Many musical instruments are made from brass. Also decorative pieces, from light fittings to taps, and instruments for astronomy, surveying, navigation and other scientific purposes.
Batteries	When alloyed with other metals, zinc becomes a good electrical conductor. Zinc-bromide and zinc-nickel power cells are amongst the newest types of batteries.
Health	Humans and other animals need to ingest zinc for proper growth and healing of wounds to occur. Fruits, nuts, meat, oysters and other shellfish are good sources of zinc.
Zinc oxide	Zinc oxide is a unique and very useful material, used in the manufacture of rubber tyres, skin products (such as zinc cream, anti-dandruff shampoos, antiseptic ointments, and calamine lotion for healing skin disorders), paints, floor coverings, plastics (to help prevent them cracking) and ceramic glazes.
Zinc sulphide	In luminous dials on watches, TV screens, fluorescent lights and low-energy bulbs.
Other zinc compounds	As a dissolving agent, to help prevent plastics from cracking, in surgical dressings, glues, and to preserve and fire-proof timber.

Source: http://www.australianminesatlas.gov.au/info/rockfiles/zinc.jsp

Zinc ore and concentration	Electrolysis
17 kg abiotic	13 kg abiotic
68 kg water	233 kg water
680 g air	2,7 kg air

Primary zinc
31 kg abiotic
301 kg water
3,4 kg air

Figur 2.6. MI per kg primary zinc.

Secondary zinc

About 30% of zinc used in the Western World comes from recycled materials but we have not been able to procure data for secondary zinc. This is probably due to the fact that Zinc almost not is used in its pure form. We assume that the process and energy consumption is equal to secondary copper.

Secondary zinc
4,5 kg abiotic
73 kg water
1,6 kg air
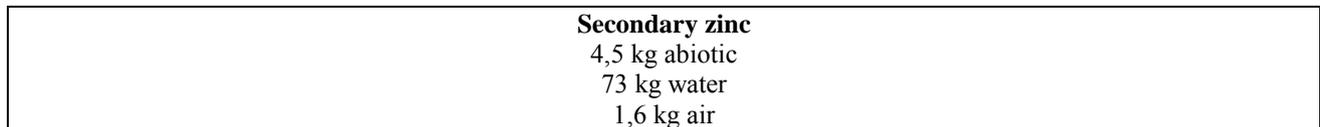
Figur 2.7. MI per kg secondary zinc.

2.6. Stainless steel

Primary stainless steel

Stainless steel is the generic name for a number of different steels used primarily for their resistance to corrosion. The one key element they all share is a certain minimum percentage (by mass) of chromium: 10.5%. Although other elements, particularly nickel and molybdenum, are added to improve corrosion resistance, chromium is always the deciding factor. The vast majority of steel produced in the world is carbon and alloy steel, with the more expensive stainless steels representing a small, but valuable, niche market.

In the metal-worksheet you will find a MI calculation for stainless steel containing 17% Cr and 12% Ni. Ferrochromium is an ore with high content of both Fe and Cr.

Ferrochromium	Hard coal	Ferrous nickel	Limestone
1,9 kg abiotic	4,8 kg abiotic	57 kg abiotic	100 g abiotic
27 kg water	2,4 kg water	404 kg water	16 g water
570 g air	22 g air	8,8 kg air	0,3 g air

⬇ ⬇ ⬇ ⬇

Mixing/casting

⬇

Primary stainless steel
23 kg abiotic
208 kg water
4,0 kg air
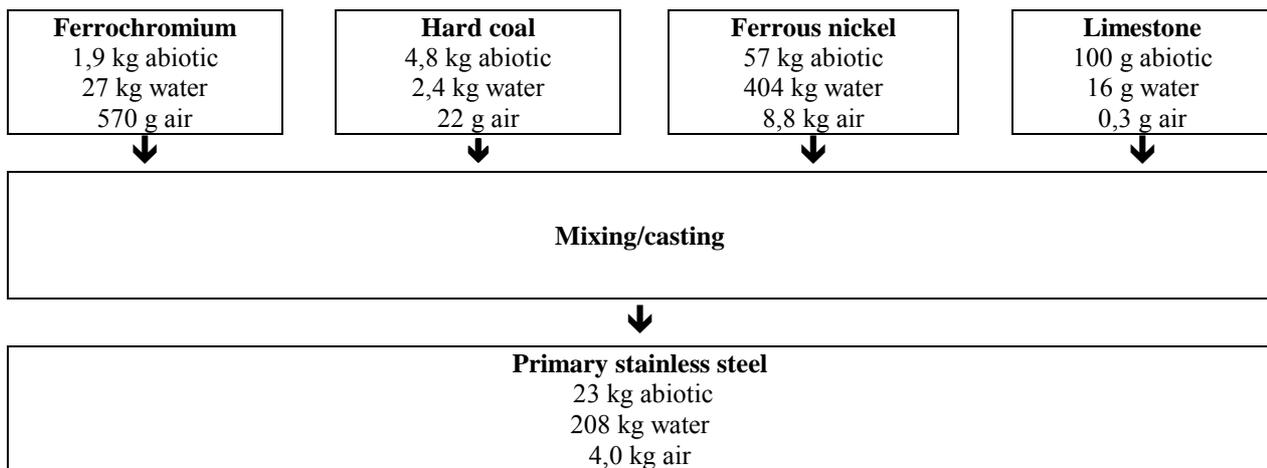
Figure 2.9. MI per kg primary stainless steel.

Secondary stainless steel

According to International Stainless Steel Forum 60 % of world stainless steel production is secondary. We have no data for recycled stainless steel, but we assume that the process can be compared to secondary steel produced in an arc furnace. In that case the rucksack for primary stainless steel is 9, 4 and 6 times heavier for, respectively, abiotic material, water and air than for primary stainless steel.

Secondary stainless steel
2,7 kg abiotic
51 kg water
660 g air
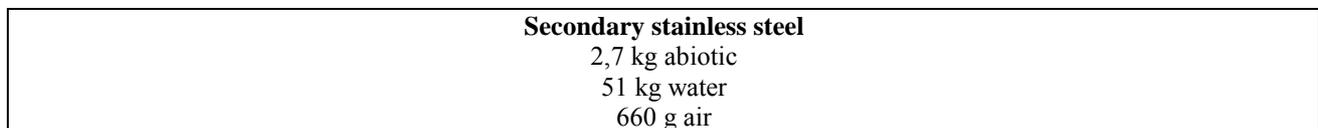
Figure 2.10. MI per kg secondary stainless steel.

2.7. Other metals

Table 2.1. MI-values (kg/kg) for other metals
Source: MI-werte

	Abiotic material	*Water*	*Air*
Lead	15,6		
Gold	540.000		
Nickel	141	233	40,8
Platinum	320.300	193.000	13.800
Silver	7.500		
Tin	8.486	10.958	149

3. Wood

In the worksheet for wood we present MI data for softwood (conifer) and hardwood (deciduous) produced in Germany. Data for tropical tree was unavailable. Data for chipboard is also presented, but we have not been in a position to translate the words from German to English. MI for the production of trunks comes, among others, from machinery and conveyance.

3.1. Softwood

Trunk	Energy	Energy
6,6 kg biotic	0 g biotic	0 g biotic
470 g abiotic	225 g abiotic	150 g abiotic
1,1 kg water	3,8 kg water	2,5 kg water
210 g air	50 g air	30 g air

Wood-cut	Drying
6,6 kg biotic	0 g biotic
690 g abiotic	150 g abiotic
5,0 kg water	2,5 kg water
270 g air	70 g air

Dried softwood
6,6 kg biotic
850 g abiotic
7,4 kg water
340 g air
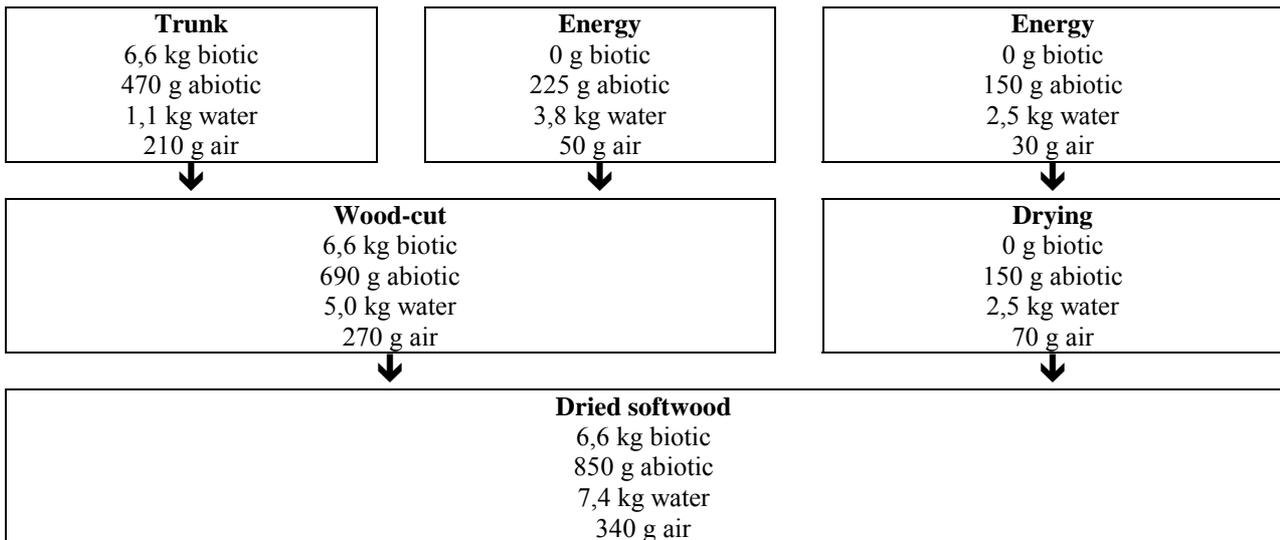
Figure 3.1. MI per kg dried softwood.

3.2. Hardwood

Trunk	Energy	Energy
5,7 kg biotic	0 g biotic	0 g biotic
190 g abiotic	170 g abiotic	150 g abiotic
470 g water	3,0 kg water	2,5 kg water
110 g air	40 g air	70 g air

Wood-cut	Drying
5,7 kg biotic	0 g biotic
370 g abiotic	150 g abiotic
3,5 kg water	2,5 kg water
150 g air	70 g air

Dried hardwood
5,7 kg biotic
520 g abiotic
5,9 kg water
220 g air
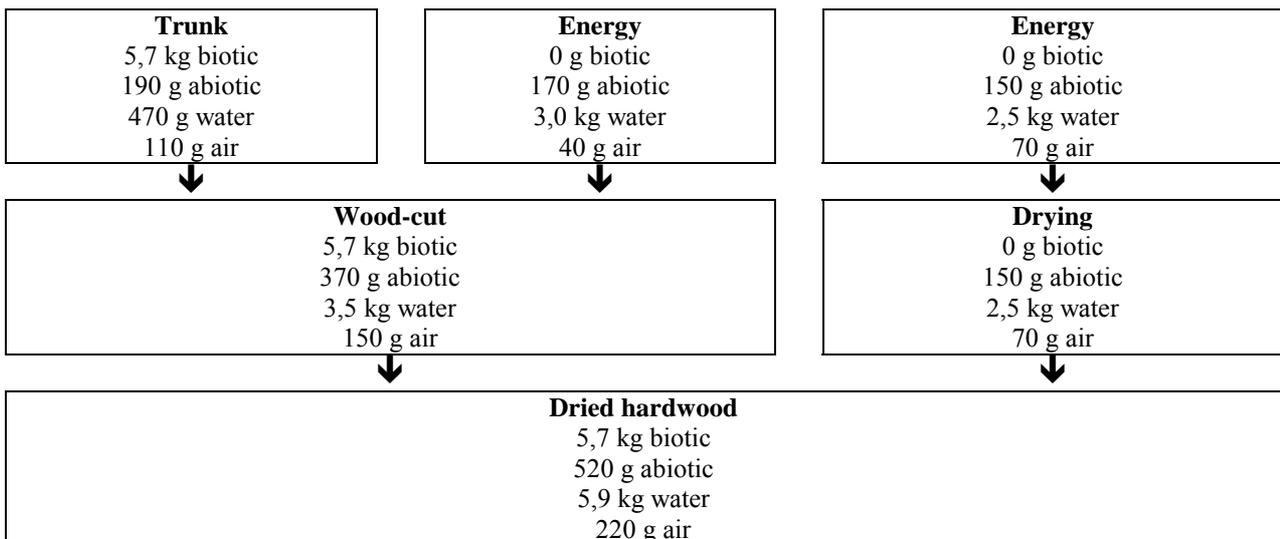
Figure 3.2. MI per kg dried hardwood.

3.3. Chipboard

For chipboard there is a huge difference between the figures presented in the excel-file and the MI-werte. We recommend the use of MI-werte.

Chipboard
650 g biotic
680 g abiotic
18,4 kg water
290 g air

Figure 3.3. MI per kg chipboard (MI-werte values)

Table 3.1. MI-values (kg/kg) for other wood products
Source: MI-werte

	Abiotic material	Biotic material	Water	Air
Plywood	2,00	9,13	23,6	0,541
Douglas fir wood (baked; cut timber)	0,63	4,37	9,2	0,166
Spruce wood (baked; cut timber)	0,68	4,72	9,4	0,156
Hardboard / moulded fibre board	2,91		49,1	0,980
Pine wood (baked; cut timber)	0,86	5,51	10,0	0,129
Fibreboard (average density)	1,96		32,9	0,481

4. Plastics and synthetic rubber

Background data for calculating MI for plastic are LCAs (Life Cycle Assessments) carried out by the Association of Plastics Manufacturers in Europe. The LCA reports can be found on the association's homepage if you order a free login password (www.apme.org). The data includes input to the production, however not very detailed data. For instance, it is not possible to distinguish between the amount of oil used as feedstock or energy production. Apparently there is a great deal of MI which is not included in the data provided by the European plastic industry, such as for example plan construction and demolition.
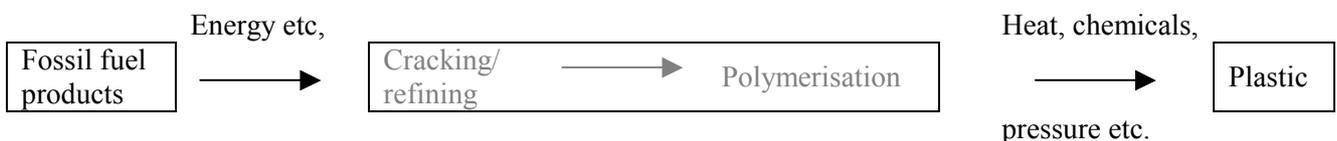
Figure 4.1. Schematic process-chain for plastic production. Fossil fuel products are transformed to plastic by means of heat, chemicals and pressure.

Natural gas → Synthesis gas generation → Methanol → Poly-ethylene

Crude oil → Refinery → Steam cracker → Ethylene → Ethylene oxide → Ethylene glycol

Ethylene → Propylene → Poly-propylene

Propane

Butanes

Butadiene → Poly-butadiene → Acrylic

Acryl-onitrile

Styrene → Poly-styrene

Benzene → Cyclo-hexane etc. → Nylpn 6

p-Xylene → Terephthalic acid → Polyester

m-Xylene → Isophthalic acid

Aromatics separation

Xylenes → o-Xylene → Phthalic anhydride

Coal → Coke plant

Sodium chloride → Electrolysis → Chlorine → Ethylene dichloride → Vinyl chloride → PVC

Caustic soda

Hydrogen

Figure 4.2. Overview of process-chains for production of a number of plastics.

4.1. Nylon

There are many types of nylon available, e.g. Nylon 6, nylon 66, nylon 6/6-6, nylon 6/9, nylon 6/10, nylon 6/12, nylon 11, nylon 12. As the Association of Plastics Manufacturers in Europe has made a Eco-profile report for nylon 6, we have chosen to use nylon 6 as a representative for all nylon types. We have also chosen to leave out of account nylon materials filled with for instance glass fibre.

The polyamides (i.e. nylons) are a group of polymers characterised by a carbon chain with – CO-NH-groups interspersed at regular intervals along it. They are commonly referred to by the generic name nylon. Different nylons are usually identified by a numbering system that refers to number of carbon atoms between successive nitrogen atoms in the main chain. Polymers derived from amino-acids are referred to by a single number, for example, nylon-6: $-NH^-(CH_2)_5-C(=O)-$.

About two thirds of the nylon produced in Europe is used for fibres (textiles, carpets etc.) while most of the remainder is used in injection moulded components (automotive parts, consumer goods etc.). Other smaller users are films and filaments.

There are a number of different routes to the production of nylon 6. The starting chemical is benzene, which is used to produce cylohexanone. This conversion can be achieved by two distinct routes. One route hydrogenates the benzene to produce cyclohexane, which is then oxygenated to give cyclohexanone. The alternative route is to react the benzene with propylene. This gives cumene that can then be oxygenated to phenol giving acetone as by-product. The phenol can then be hydrogenated to cyclohexanone.

The cyclohexanone is then converted into the oxime by reacting with hydroxylamine (NH_2OH). Finally the oxime is converted into caprolactam, the immediate precursor for nylon 6, by an acid catalysed reaction called Beckmann rearrangement. The most common route employs sulphuric acid but an alternative uses phosphoric acid.

730 g oil 0 g biotic 891 g abiotic 3,2 kg water 6 g air	**1,4 kg gas** 0 g biotic 1,7 kg abiotic 700 g water 3 g air	**470 g coal** 0 g biotic 990 g abiotic 4,3 kg water 230 g air	**210 g lignite and peat** 0 g biotic 2,0 kg abiotic 1,9 kg water 5 g air
⬇	⬇	⬇	⬇

1 kg nylon 6 100 g biotic 8,0 kg abiotic 310 kg water 1,6 kg air

⬆	⬆	⬆	⬆
20 g wood 10 g biotic 11 g abiotic 77g water 4 g air	**4 g biomass** 0 g biotic 0 g abiotic 0 g water 0 g air	**234 kg water** 0 g biotic 2,3 kg abiotic 304 kg water 230 g air	**1,1 kg air** 0 g biotic 0 g abiotic 0 g water 1,1 kg air

Figure 4.3. MI per kg nylon 6.

Secondary nylon
Nylon is recycled but we have not been able to procure data on MI.

4.2. Polyethylene and Polypropylene

Polyethylene is chemically the simplest of all polymer structures. The starting material, ethylene, is called the *monomer* and the final compound consisting of many thousands of ethylene units is called the *polymer*.
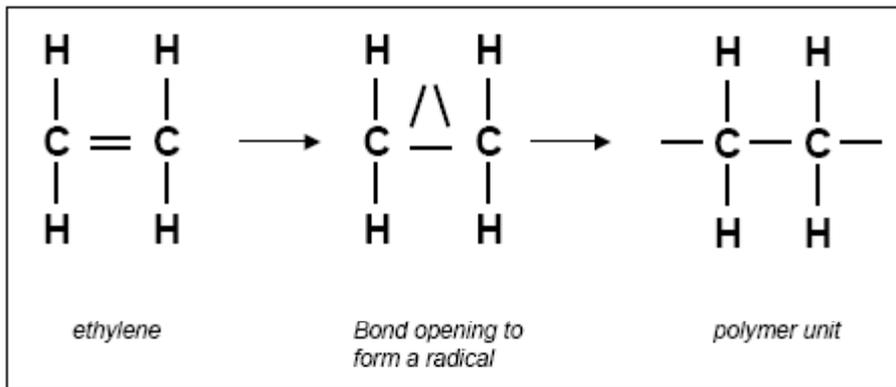
Figure 4.4. Schematic diagram of the formation of polyethylene

Low density polyethylene (LDPE) has traditionally been defined as polyethylene with a density less than 940 kg/m3. It is produced by a high pressure process and so is often referred to as high pressure polyethylene.

High density polyethylene (HDPE) has the same repeat unit as LDPE and is usually regarded as polyethylene with a density greater than 940 kg/m3. It is produced in low pressure reactors and so is often referred to as low pressure polyethylene. Densities range from 940 to 960 kg/m3.

The repeat unit for polypropylene is:

800 g oil	490 kg gas	130 g coal	2 g lignite and peat
0 g biotic	0 g biotic	0 g biotic	0 g biotic
980 g abiotic	6,0 kg abiotic	280 g abiotic	22 g abiotic
3,4 kg water	240 g water	1,2 kg water	21 kg water
6 g air	1 g air	70 g air	0 g air

↓ ↓ ↓ ↓

1 kg Polyethylene (Low Density)
0 g biotic
2,4 kg abiotic
68 kg water
320 g air

↑ ↑

480 kg water	200 g air
0 g biotic	0 g biotic
480g abiotic	0 g abiotic
630 kg water	0 g water
48 g air	200 g air

Figure 4.5. MI per kg Polyethylene (Low Density)

840 g oil	520 g gas	110 g coal	2 g lignite and peat
0 g biotic	0 g biotic	0 g biotic	0 g biotic
1,0 kg abiotic	640 g abiotic	240 g abiotic	15 g abiotic
3,6 kg water	260 g water	1,0 kg water	14 kg water
7 g air	1 g air	50 g air	0 g air

↓ ↓ ↓ ↓

1 kg Polyethylene (High Density)
0 g biotic
2,3 kg abiotic
50 kg water
390 g air

↑ ↑

480 kg water	290 g air
0 g biotic	0 g biotic
340 g abiotic	0 g abiotic
45 kg water	0 g water
34 g air	290 g air

Figure 4.6. MI per kg Polyethylene (High Density).

950 g oil	390 g gas	90 g coal	1 g lignite and peat
0 g biotic	0 g biotic	0 g biotic	0 g biotic
1,2 kg abiotic	480 g abiotic	180 g abiotic	9 g abiotic
4,1 kg water	200 g water	790 g water	8 kg water
8 g air	1 g air	40 g air	0 g air

1 kg polypropylene
0 g biotic
2,3 kg abiotic
63 kg water
430 g air

450 kg water	340 g air
0 g biotic	0 g biotic
450 g abiotic	0 g abiotic
58 kg water	0 g water
45 g air	340 g air
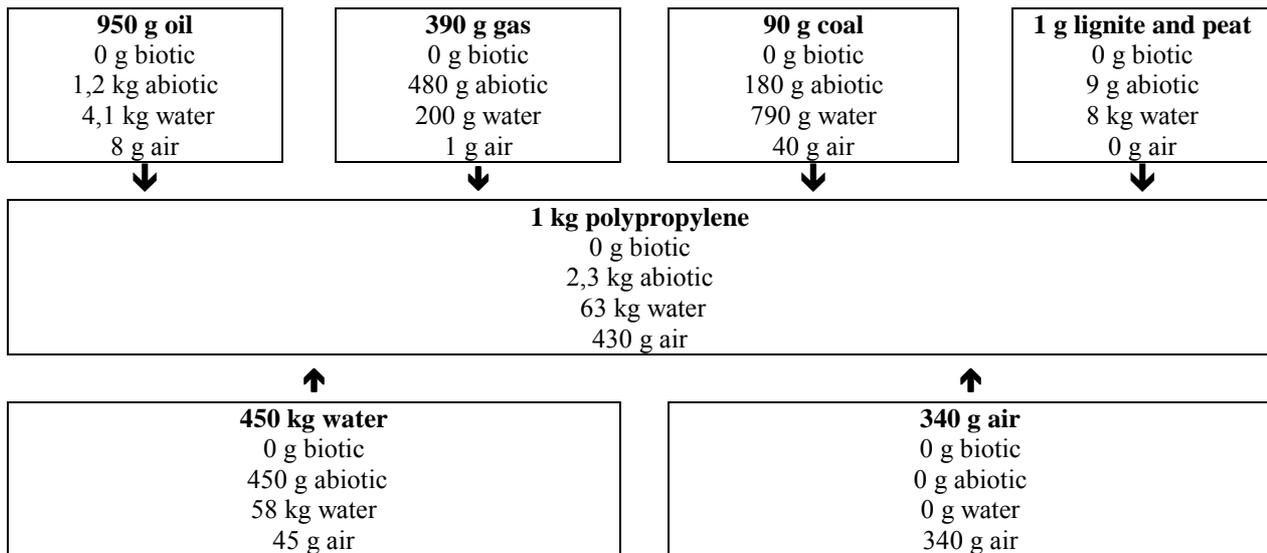
Figure 4.7. MI per kg polypropylene.

4.3. Polystyrene

Chemical structure:
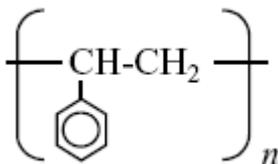
Typical uses:
- Packaging
- Electronics

Polystyrene is a versatile polymer resin used in a wide range of applications - especially in the packaging industry. It is sold in three main forms: crystal or general purpose polystyrene (GPPS), high impact polystyrene (HIPS) and expandable polystyrene (EPS).

The production of styrene monomer can be thought of as replacing one of the hydrogen atoms in ethylene by a benzene ring (C_6H_6). The monomer is then polymerised in a manner similar to polyethylene; the double bonds in the monomer molecules are opened and neighbouring molecules link together to form a chain.

In practice, the production route from crude oil and natural gas is as shown below. Crude oil refining produces a fraction known as naphtha which contains a mixture of low molecular weight, saturated hydrocarbons of various composition. Naphtha is converted into a smaller group of unsaturated hydrocarbons by cracking - a process in which the naphtha is heated to a high temperature in the absence of air, maintained for a short time at this high temperature and then very rapidly cooled back to a low temperature when all of the reactions stop and the mix of products is essentially fixed. The resulting mixture is then separated into its constituent components by

distillation producing principally ethylene (C_2H_4), propylene (C_3H_6), mixed butenes of general formula C_4H_8 and a number of other compounds which find uses elsewhere in the petrochemical plant either as feedstocks or fuels. The precise mix of products from cracking are determined by a number of factors such as cracker temperature, residence time and the nature of the feedstock and the operation of a cracker can often be adjusted to produce the required mix of products. Natural gas is also converted into ethylene, propylene, butenes and other products by cracking.
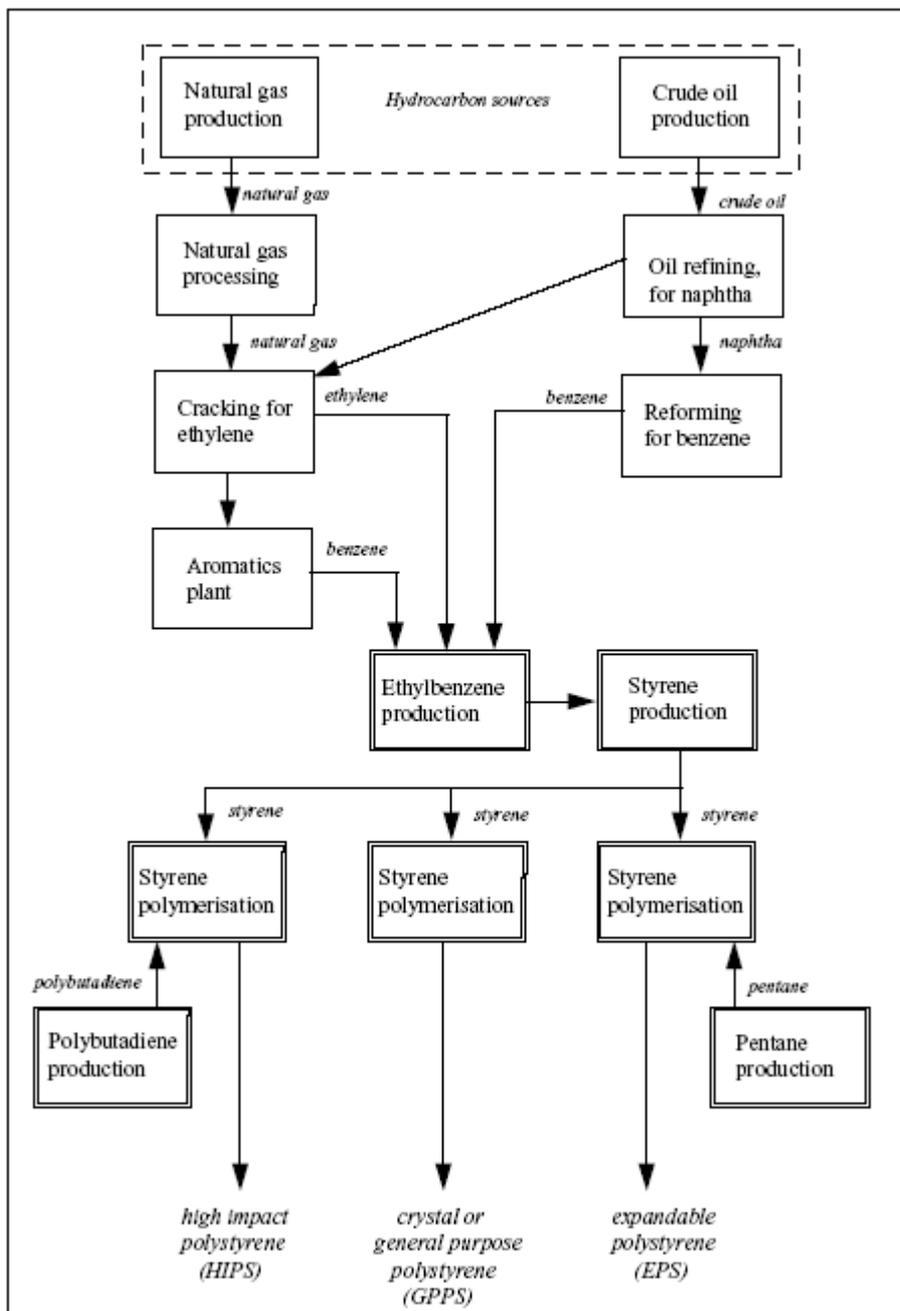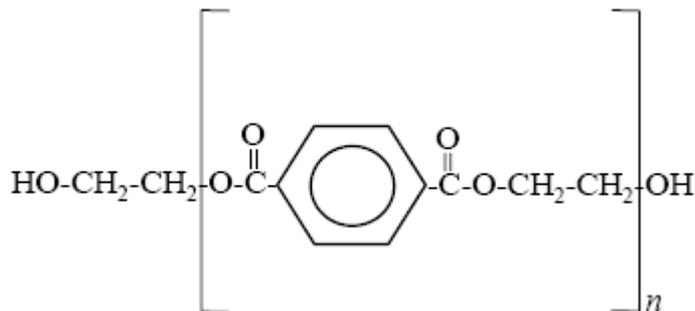

Figure 4.8. Sequence of operations used in the production of the different forms of polystyrene from crude oil and natural gas. All operations include storage and delivery.

740 g oil	1,1 kg gas	60 g coal	8 g lignite and peat
0 g biotic	0 g biotic	0 g biotic	0 g biotic
900 g abiotic	1,3 kg abiotic	120 g abiotic	80 g abiotic
3,2 kg water	550 g water	530 g water	80g water
6 g air	2 g air	30 g air	0 g air

$\downarrow$ $\downarrow$ $\downarrow$ $\downarrow$

1 kg polystyrene
1 g biotic
4,3 kg abiotic
240 kg water
330 g air

$\uparrow$ $\uparrow$ $\uparrow$

1 g biomass	180 kg water	110 g air
1 g biotic	0 g biotic	0 g biotic
0 g abiotic	1,8 kg abiotic	0 g abiotic
0 g water	240 kg water	0 g water
0 g air	180 g air	110 g air

Figure 4.9. MI per kg polystyrene.

4.4. Polyethylene terephthalate (PET)

Chemical structure:

Polyethylene terephthalate (PET) was first developed in 1941. The patent rights were subsequently sold to DuPont and ICI who, in turn, sold regional rights to many other companies. Although originally produced for fibres, the use of PET films in packaging began in the mid-1960's. Then, in the early 1970's the technique for blowing bi-axially oriented bottles was commercially developed so that PET bottles now represent the most significant use of PET moulding resins.

PET is a thermoplastic polymer. The starting compounds for the commercial production of PET are ethylene ($CH_2=CH_2$) for the production of ethylene glycol and para-xylene for the production of terephthalic acid.

Ethylene is usually produced by cracking either natural gas or the naphtha fraction of crude oil. Cracker feeds may be naphtha from oil refining or natural gas or a mixture of both. Other refinery hydrocarbons are also used. When natural gas feeds are used, the primary function of the cracker is to introduce unsaturation into the molecules.

The raw hydrocarbon feed from the refinery is fed to the furnace section where it is raised to a high temperature. The reaction products that are formed depend upon the composition of the feed, the temperature of the furnace and the time that the hydrocarbons are held within the furnace (residence time). The cracker operator chooses temperature and residence time to optimise product mix from a given feed.

Upon leaving the furnace, the hydrocarbon gas is quench cooled to inhibit further reactions. It is then passed to the separation stage where the individual hydrocarbons are separated from one another by fractional distillation. The principal products from the cracker are ethylene (ethene), propylene (propene) and a mixture of butene isomers. Usually there will be some hydrogen and a number of other hydrocarbons, some of which will be separated, others will be fed back to the furnace and yet others will be used as fuels. Cracking also produces small quantities of xylenes but most xylenes are produced directly from naphtha by a process known as catalytic reforming.

The basic feedstock is converted into a mixture of products of which the principal components are benzene, toluene and xylenes (the process is often referred to as the BTX process). Benzene and other aromatics are isolated in the pure state from the output of the reformer by solvent extraction and fractional distillation. The output from xylene production is a mixture of the three forms (isomers) of xylene:

In practice there are two routes used in the production of PET and these are shown schematically in the figure. In the first, shown on the right hand side, p-xylene is oxidised to terephthalic acid which is then purified. This purified terephthalic acid (PTA) is then reacted with ethylene glycol to produce bishydroxyethyl terepthalate (BHET) with water. The alternative route, shown on the left hand side of the figure, oxidises pxylene to terephthalic acid but then immediately reacts the acid with methanol to produce dimethyl terephthalate (DMT):
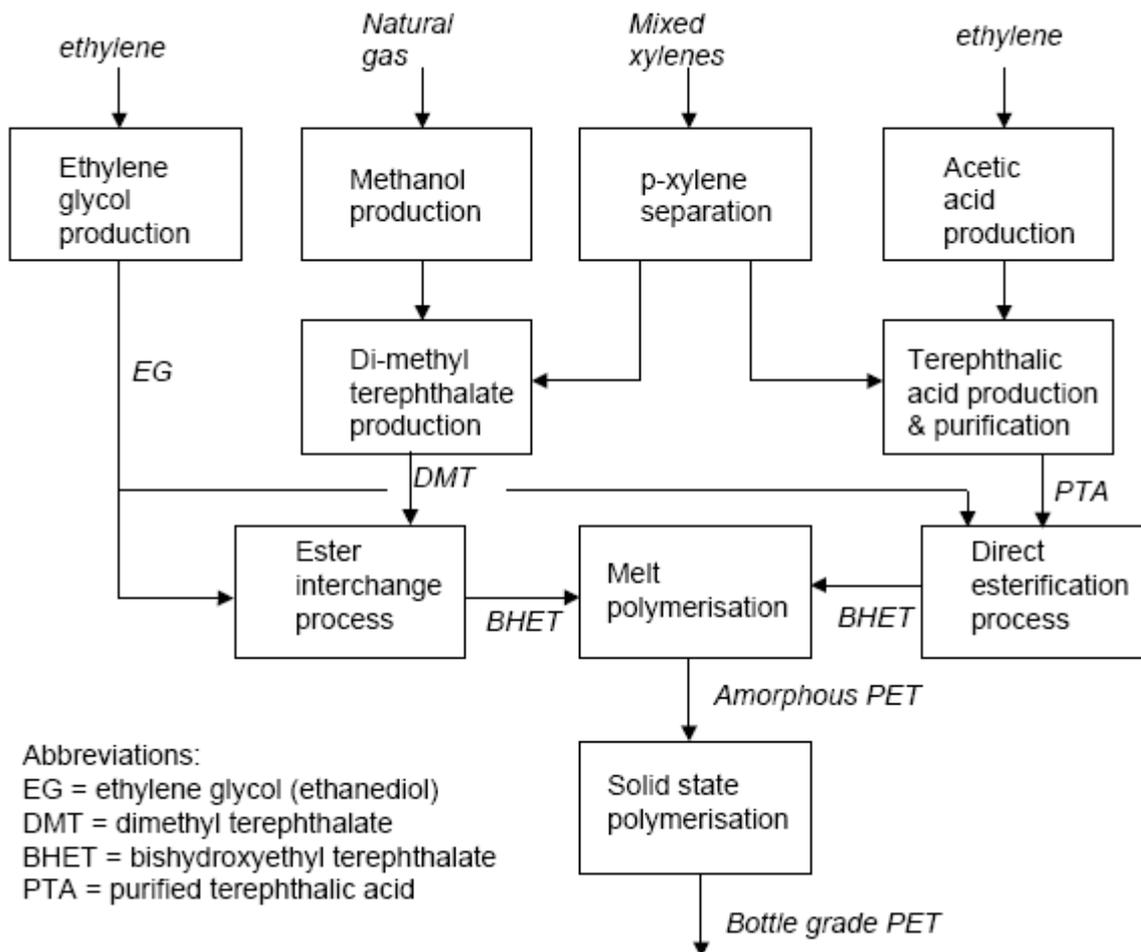
Figure 4.10. Schematic flow diagram showing the two routes to polyethylene terephthalate.

When DMT is reacted with ethylene glycol, the result is again BHET, as in the alternative route, but the by-product is now methanol rather than water. The methanol is recovered and re-used. The monomer from either route can now be polymerised in the liquid phase to produce amorphous PET. This form of the polymer is suitable for the production of fibres and film.

A second polymerisation in the solid state increases the molecular weight of the polymer and produces a partially crystalline resin that can be used to produce bottles via injection moulding and stretch blow moulding.

970 g oil	**410 g gas**	**300 g coal**	**17 g lignite and peat**
0 g biotic	0 g biotic	0 g biotic	0 g biotic
1,2 kg abiotic	500 g abiotic	630 g abiotic	160 g abiotic
4,2 kg water	200 g water	2,7 kg water	160g water
8 g air	1 g air	150 g air	0 g air

↓ ↓ ↓ ↓

1 kg bottle grade PET
2 g biotic
2,9 kg abiotic
63 kg water
4,3 kg air

↑ ↑ ↑

2 g biomass	**43 kg water**	**4,1 kg air**
2 g biotic	0 g biotic	0 g biotic
0 g abiotic	430 g abiotic	0 g abiotic
0 g water	56 kg water	0 g water
0 g air	40 g air	4,1 kg air

Figure 4.11. MI per kg bottle grade PET.

4.5. Liquid epoxy resin

Epoxy resins find many applications ranging from adhesives and electrical castings to metal (e.g. can) coatings. Table 1 summarises some of the principal applications.

Epoxy resins are a group of thermosetting plastics. The most commonly used epoxy resins are produced from bisphenol-A. The reaction proceeds by a series of steps but yields a structure of the form:
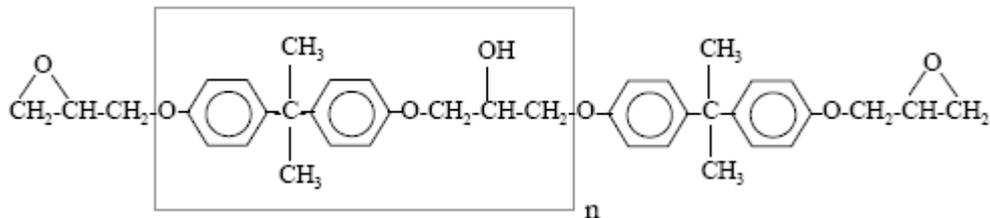
The segment surrounded by the box is repeated a number of times. If the value of n is low (<10) then the resin is a liquid but as n increases the resin gradually becomes a viscous liquid and eventually a solid; at n=25 it is a tough, hard solid.

the figure shows a typical sequence of operations that might be used in the resin production facility.
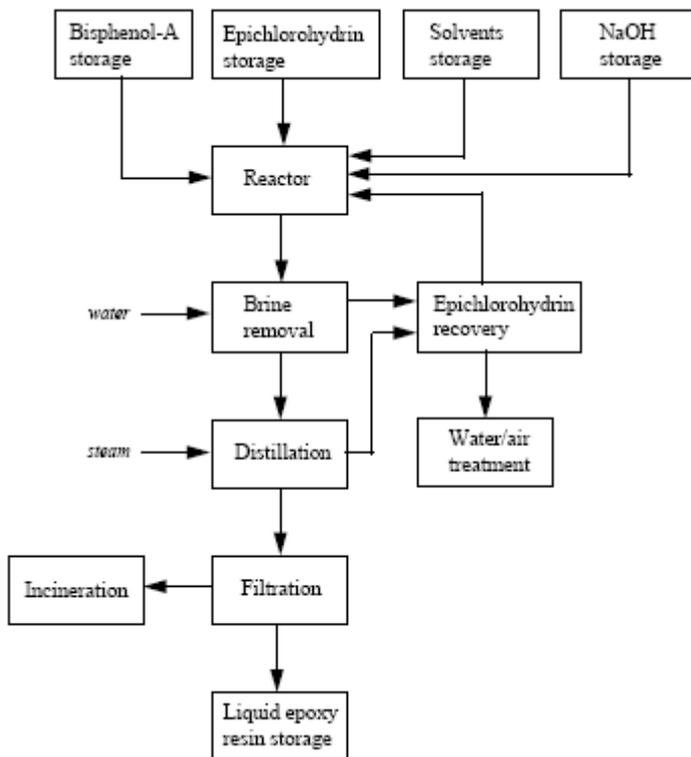
Figure 4.12. Typical sequence of operations used in the production of liquid epoxy resins.

Epoxy resins should really be regarded as intermediates in the production of finished components because they are further reacted (cured) so that the chains are increased in length (advancement) and cross-linked to produce a three dimensional network (reticulation). The cross linking is achieved by opening the epoxide group and most curing agents or hardeners which accomplish this are amines, acid anhydrides and mercaptans, most of which have active hydrogen atoms available to initiate the curing reaction. One major advantage of the epoxy resins is that they can be cured over a wide range of temperatures and during the curing process exhibit very low shrinkage.

Depending on molecular weight and choice of hardener, epoxy resins find its many applications.

It is noted that the MI for liquid epoxy resins is higher than all other plastics presented here. We have no obvious explanation to this.

670 g oil	1,7 kg gas	360 g coal	210 g lignite and peat
0 g biotic	0 g biotic	0 g biotic	0 g biotic
820 g abiotic	2,1 kg abiotic	760 g abiotic	2,0 kg abiotic
2,9 kg water	850 g water	3,6 kg water	1,9 g water
5 g air	3 g air	180 g air	5 g air

1 kg liquid epoxy resins
19 g biotic
9,7 kg abiotic
530 kg water
1,5 kg air

9 g biomass	400 kg water	940 g air
9 g biotic	0 g biotic	0 g biotic
0 g abiotic	4,0 kg abiotic	0 g abiotic
0 g water	530 kg water	0 g water
0 g air	400 g air	940 g air

Figure 4.13. MI per kg liquid epoxy resins.

4.6. Polycarbonate

Polycarbonate is a transparent, thermoplastic polymer. It possesses unusually high impact strength and toughness even at low temperatures, has low moisture absorption, good heat and electrical resistance and good oxidative and thermal stability. It is biologically inert and possesses good chemical resistance.

Typical uses are:
- Housings for domestic appliances
- Office equipment
- Electrical systems, switches and housings
- Compact discs and optical storage
- Medical devices
- Food containers and packaging
- Glazing and lighting applications
- Safety glasses

Polycarbonate is commonly produced by the reaction of phosgene,

$$Cl-\underset{\underset{\|}{O}}{C}-Cl$$

with bisphenol-A,

CH₃ structure...

$$HO-\bigcirc-\underset{\underset{CH_3}{|}}{\overset{\overset{CH_3}{|}}{C}}-\bigcirc-OH$$
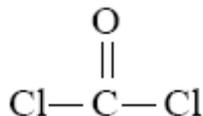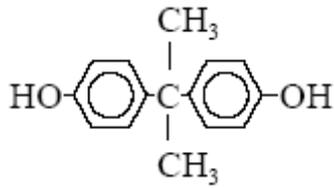
Phosgene is produced by reacting chlorine from the electrolysis of sodium chloride with carbon monoxide produced by the partial oxidation of coal, oil or gas. Phosgene is usually manufactured as needed on-site to avoid transport and storage for reasons of occupational safety and health and is directly used for further reaction.

The production route for bisphenol-A is however more complex. Naphtha or natural gas are subjected to cracking to produce propylene and hydrogen as well as other products, including some benzene. Some of the benzene and all of the toluene are produced by hydrogenating the naphthenic compounds in naphtha. Benzene and propylene are reacted to produce cumene which in turn is reacted to acetone with by-product phenol. Some phenol is also produced directly from toluene. Finally the phenol and acetone are reacted to produce bisphenol-A. The overall process leading to polycarbonate is shown schematically in the figure.
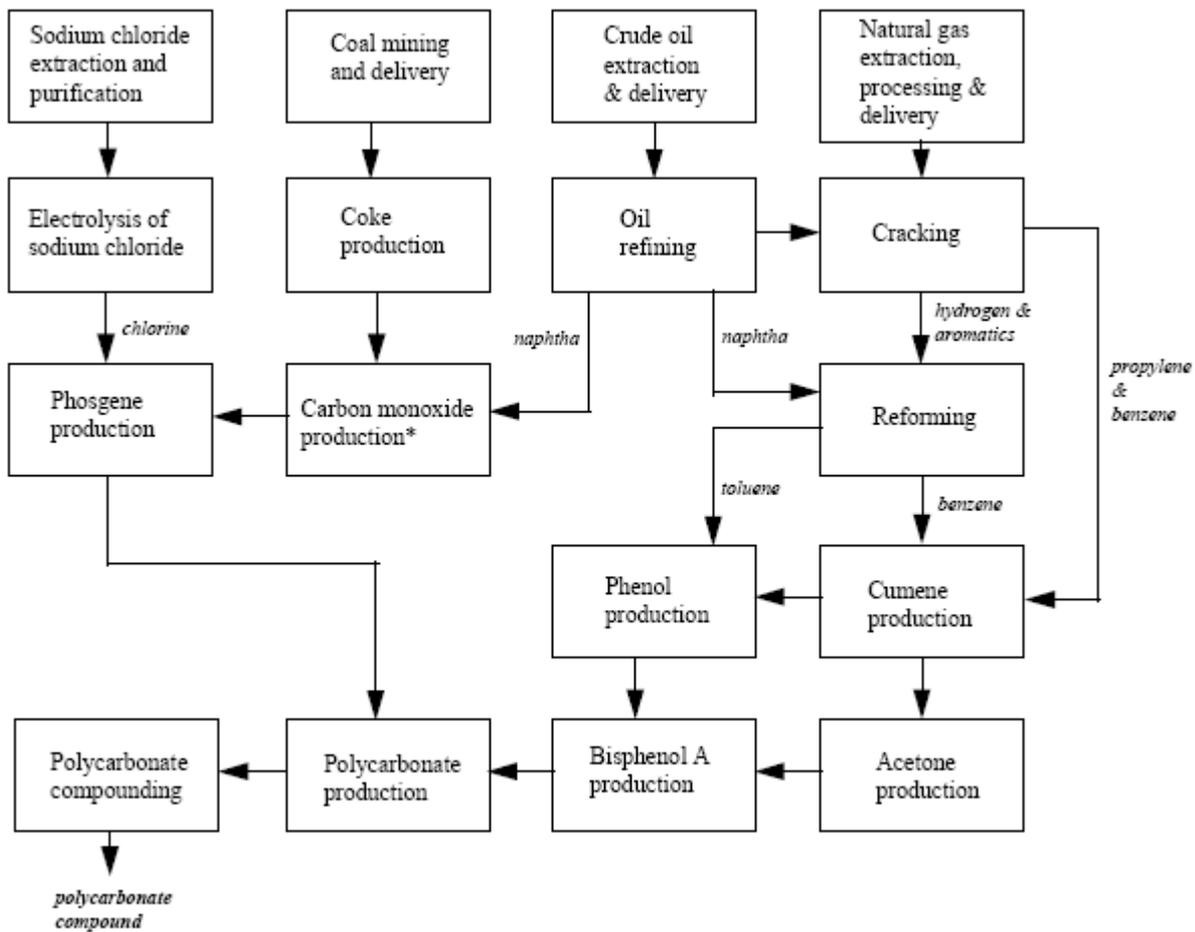
Figure 4.14. Schematic diagram of the principal operations used to produce polycarbonate.

470 g oil	**1,4 kg gas**	**410 g coal**	**250 g lignite and peat**
0 g biotic	0 g biotic	0 g biotic	0 g biotic
570 g abiotic	1,7 kg abiotic	870 g abiotic	2,4 kg abiotic
2,0 kg water	700 g water	3,7 kg water	2,3 g water
4 g air	3 g air	210 g air	6 g air

1 kg polycarbonate
1 g biotic
6,8 kg abiotic
180 kg water
1,2 kg air

1 g biomass	**128 kg water**	**810 g air**
1 g biotic	0 g biotic	0 g biotic
0 g abiotic	1,3 kg abiotic	0 g abiotic
0 g water	170 kg water	0 g water
0 g air	128 g air	810 g air

Figure 4.15. MI per kg polycarbonate.

4.7. Polyurethane

Polyurethanes (PUR) were first produced in 1937 by Otto Bayer and his coworkers in Germany and represent a family of polymers rather than a single polymer. Urethane polymers can be produced with a wide variety of properties, ranging from soft flexible foams through to hard solids and so can be used in a diverse range of applications.

There are five main areas of use for polyurethanes:
(1) the furniture and mattress sector, which uses almost exclusively flexible foams,
(2) the automotive industry which provides a market for flexible foams, filling foams, rigid and flexible integral skin foams as well as elastomers for engineering components,
(3) the consumer sector, which is diversified in a manner similar to the automotive industry,
(4) the building industry, which is by far the largest consumer of rigid foams as insulation materials,
(5) refrigeration engineering, which represents the second largest area for use of rigid polyurethane foams as insulation materials.

Other applications of polyurethanes include coatings, adhesives, sealants, elastomers ("CASE") as well as fibres.

Despite their differing properties, urethane polymers have one common characteristic in that they all incorporate the urethane group (-NH-CO-O-) into their structure. However, they differ from simple thermoplastic polymers, such as the polyolefins, in that they are not sold as ready-made polymers but as precursors which are mixed at the conversion stage. These precursors are commonly polyols (compounds containing multiple -OH groups) and diisocyanates (compounds containing -NCO groups).

MDI (Diphenylmethane-diisocyanate), TDI (Toluene-diisocyanate) and polyether-polyols are among the precursors used in the production of polyurethanes. Here we have chosen to describe polyether-polyols. Data for the other two mentioned precursors of polyurethanes can easily be found at www.apme.org.

A variety of different polyols are used in the production of different specifications of polyurethane and the principal operations are shown schematically in the figure. Note that propylene oxide may be produced by three different routes. These are from (1) ethylbenzene and propylene, (2) iso-butane and propylene or (3) via the chlorohydrin process.
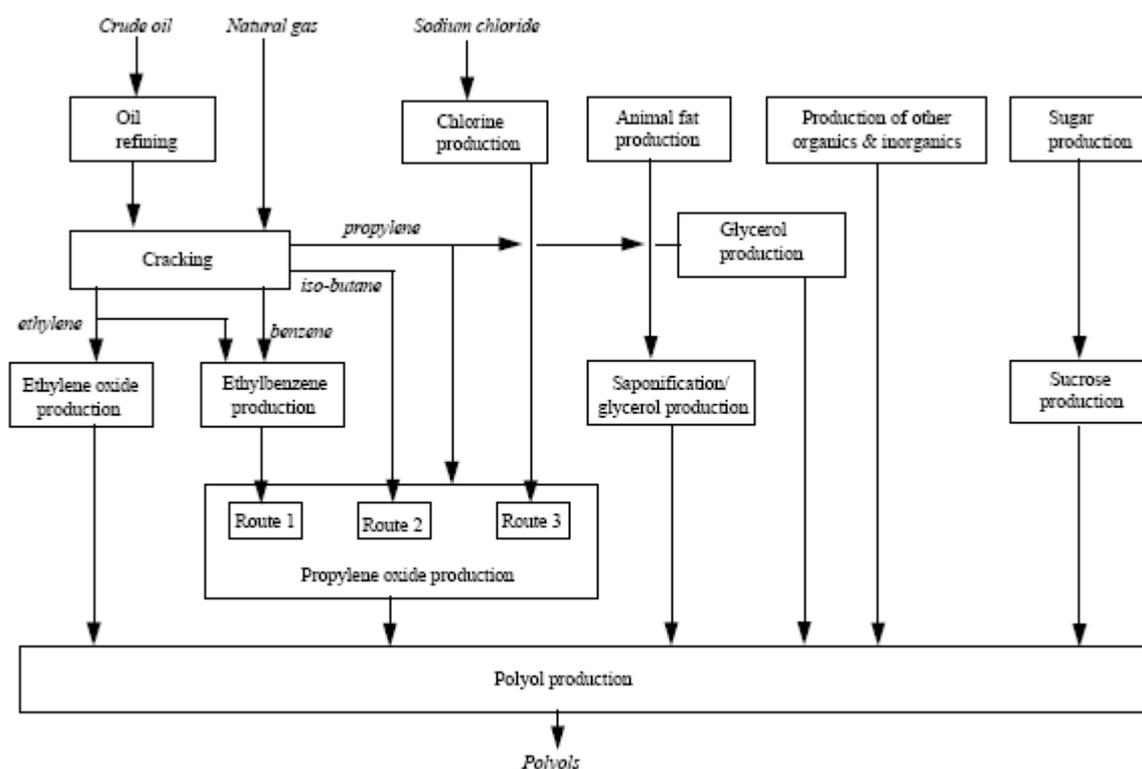
Figure 4.16. Inputs to polyol production.

780 g oil	**720 g gas**	**230 g coal**	**180 g lignite and peat**
0 g biotic	0 g biotic	0 g biotic	0 g biotic
950 g abiotic	8,8 kg abiotic	490 g abiotic	1,7 kg abiotic
3,4 kg water	360 g water	2,1 kg water	1,7 kg water
6 g air	1 g air	120 g air	4 g air

1 kg polyurethane
135 g biotic
7,7 kg abiotic
480 kg water
720 g air

135 g biomass	**360 kg water**	**230 g air**
135 g biotic	0 g biotic	0 g biotic
1 g abiotic	3,6 kg abiotic	0 g abiotic
4 g water	470 kg water	0 g water
0 g air	360 g air	230 g air

Figure 4.17. MI per kg polyurethane (precursor)

4.8. Acrylic

Acrylonitrile is a chemical intermediate used in acrylic fibres, ABS (acrylonitrile-butadiene-styrene), SAN (styrene-acrylonitrile) and NBR (nitrile-butadiene-rubber). Approximately 52% of the total EU production of acrylonitrile is used in production of fibres, 15% in production of ABS and SAN resins, 15% in the production of acrylamide and adipronitrile and 18% for other uses (source PCI World Acrylonitrile Report 1996).

Acrylic fibres
Acrylic fibres are used, for instance, in jumpers, waistcoats, cardigans, jackets, socks, knee-high stockings, training, jogging suits and carpets, either pure or in blends for example with wool. The modacrylic fibre, a modified form of acrylic, is found in flame-retardant garments, children's and baby wear, and in dolls clothes and soft toys. It is mostly used in a crimped staple fibre. Both dry and wet spinning processes are used to make acrylic fibres. In the dry-spinning process the spinning mass emerges from the spinneret into a spinning chamber, into which warm air is blown. In wet spinning the spin mass is pressed into a so-called coagulating bath. The largest proportion of the production is made and used as crimped staple fibre. On care labels the acrylic fibre is often designated as "PAN" and the modacrylic as "MAC".
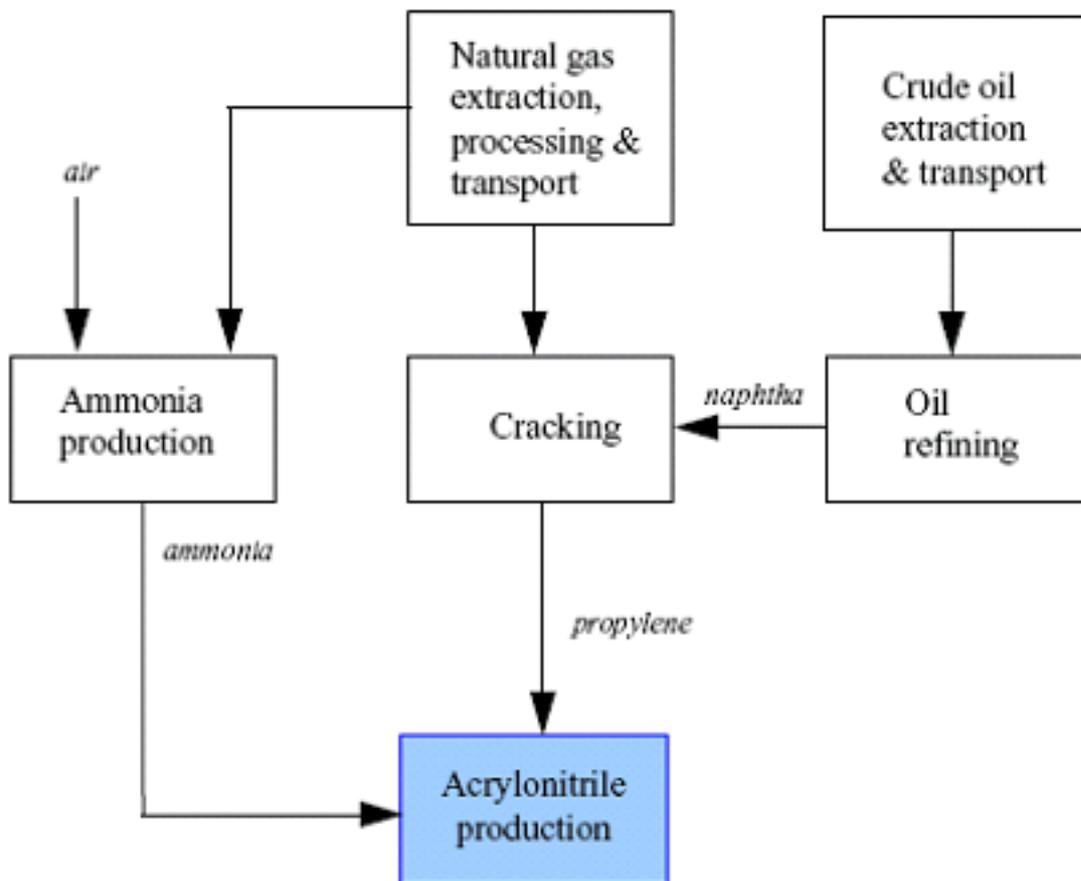
Figure 4.18. Schematic flow chart for the production of acrylonitrile.

840 g oil	**940 g gas**	**70 g coal**	**15 g lignite and peat**
0 g biotic	0 g biotic	0 g biotic	0 g biotic
1,0 kg abiotic	1,1 kg abiotic	140 g abiotic	150 g abiotic
3,6 kg water	470 g water	610 g water	140g water
7 g air	2 g air	30 g air	0 g air

1 kg Acrylonitrile
0,1 g biotic
4,4 kg abiotic
250 kg water
530 g air

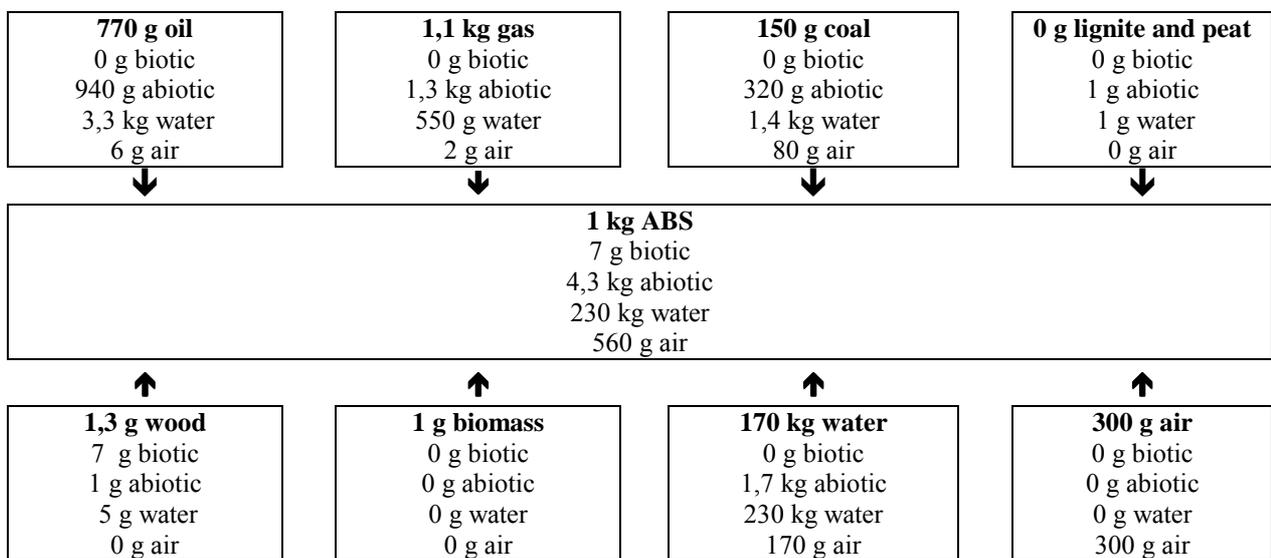| **1 g biomass**	**190 kg water**	**300 g air**
0 g biotic	0 g biotic	0 g biotic
0 g abiotic	1,9 kg abiotic	0 g abiotic
0 g water	250 kg water	0 g water
0 g air	190 g air	300 g air

Figure 4.19. MI per kg acrylonitrile.

4.9. ABS
(Acrylonitrile-butadienestyrene copolymer)

Typical uses:
- Interior & exterior automotive parts
- Housings for domestic appliances such as hair driers and vacuum cleaners
- Kitchen appliances such as refrigerator linings and mixing machines
- Furniture parts
- Telephones
- Toys
- Pipes and profiles

770 g oil	**1,1 kg gas**	**150 g coal**	**0 g lignite and peat**
0 g biotic	0 g biotic	0 g biotic	0 g biotic
940 g abiotic	1,3 kg abiotic	320 g abiotic	1 g abiotic
3,3 kg water	550 g water	1,4 kg water	1 g water
6 g air	2 g air	80 g air	0 g air

1 kg ABS
7 g biotic
4,3 kg abiotic
230 kg water
560 g air

1,3 g wood	**1 g biomass**	**170 kg water**	**300 g air**
7 g biotic	0 g biotic	0 g biotic	0 g biotic
1 g abiotic	0 g abiotic	1,7 kg abiotic	0 g abiotic
5 g water	0 g water	230 kg water	0 g water
0 g air	0 g air	170 g air	300 g air

Figure 4.20. MI per kg ABS.

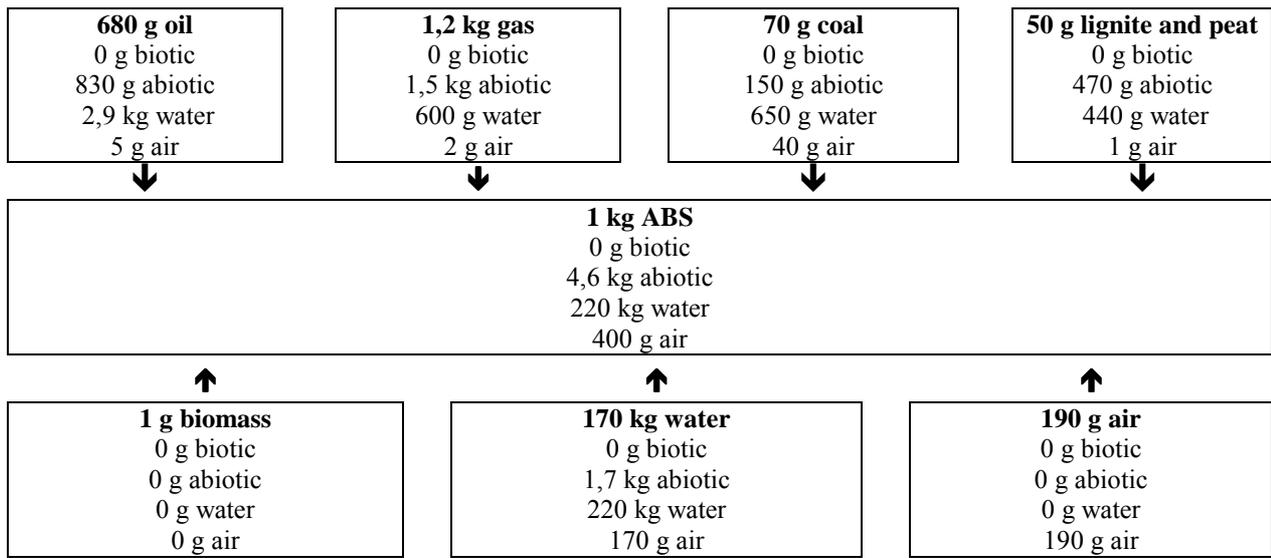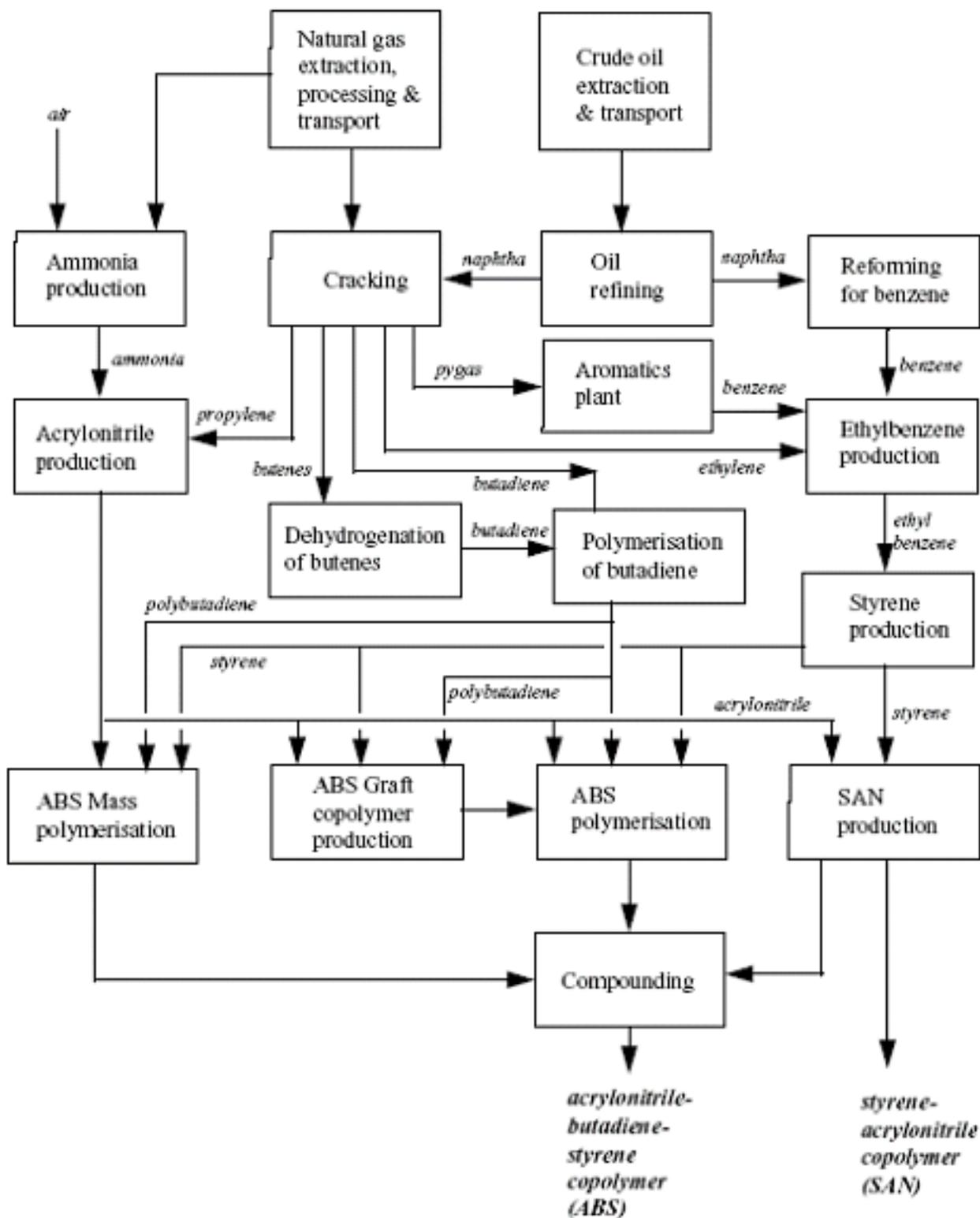## 4.10. SAN
(Styrene-acrylonitrile copolymer)

Typical uses:
- kitchen appliances
- refrigerator inner parts
- food containers
- lighting & glazing parts
- blend polymer with polybutadiene in ABS

The principal operations leading to the production of ABS are shown in the figure below. As can be seen in the schematic flowchart, styrene-acrylonitrile (SAN) is also produced within this sequence.

680 g oil	1,2 kg gas	70 g coal	50 g lignite and peat
0 g biotic	0 g biotic	0 g biotic	0 g biotic
830 g abiotic	1,5 kg abiotic	150 g abiotic	470 g abiotic
2,9 kg water	600 g water	650 g water	440 g water
5 g air	2 g air	40 g air	1 g air

1 kg ABS
0 g biotic
4,6 kg abiotic
220 kg water
400 g air

| 1 g biomass	170 kg water	190 g air
0 g biotic	0 g biotic	0 g biotic
0 g abiotic	1,7 kg abiotic	0 g abiotic
0 g water	220 kg water	0 g water
0 g air	170 g air	190 g air

Figure 4.21. MI per kg ABS.

Figure 4.22. Schematic flow diagram of the principal operations leading to the production of SAN and ABS.

4.11. PVC

Globally, over 50% of PVC manufactured is used in construction, in products such as pipelines, wiring, siding, flooring and wallpaper. As a building material PVC is cheap, easy to install and easy to replace. PVC is replacing 'traditional' building materials such as wood, concrete and clay in many areas. Although it appears to be the ideal building material, PVC has high environmental and human health costs that its manufacturers fail to tell consumers.

From its manufacture to its disposal, PVC emits toxic compounds. During the manufacture of the building block ingredients of PVC (such as vinyl chloride monomer) dioxin and other persistent pollutants are emitted into the air, water and land, which present both acute and chronic health hazards. During use, PVC products can leach toxic additives, for example phthalates. When PVC reaches the end of its useful life, it can be either landfilled, where it leaches toxic additives or incinerated, again emitting dioxin and heavy metals. When PVC burns in accidental fires, hydrogen chloride gas and dioxin are formed.
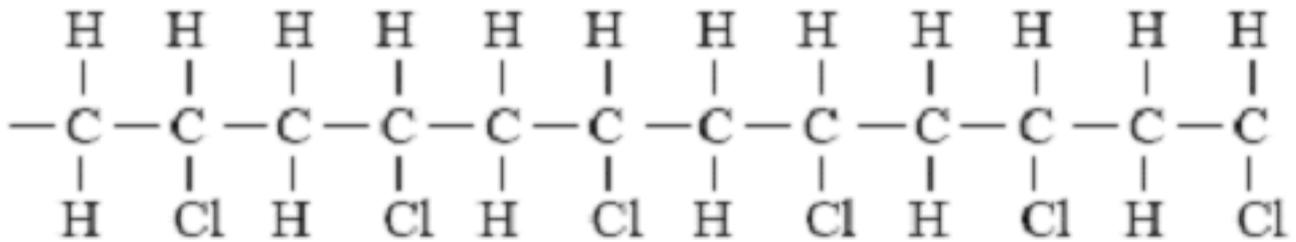
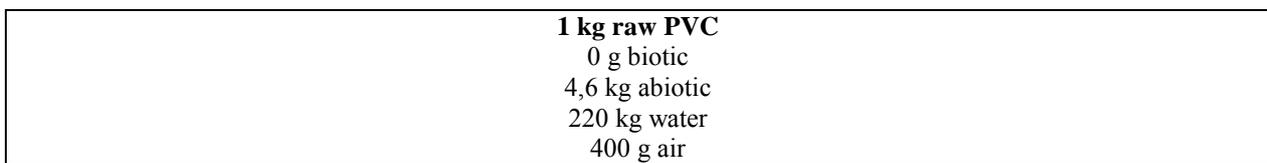**Figure 4.23.** Structure of polyvinyl chloride.
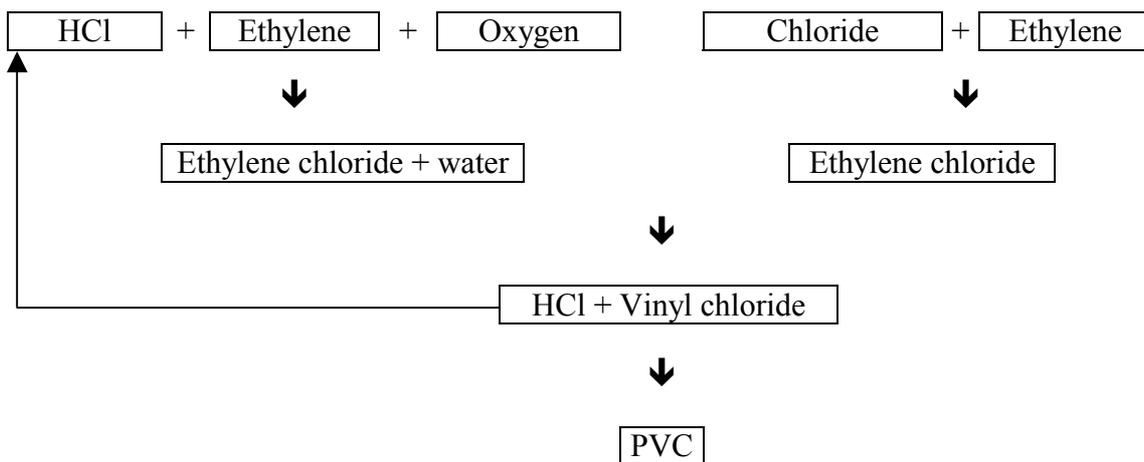
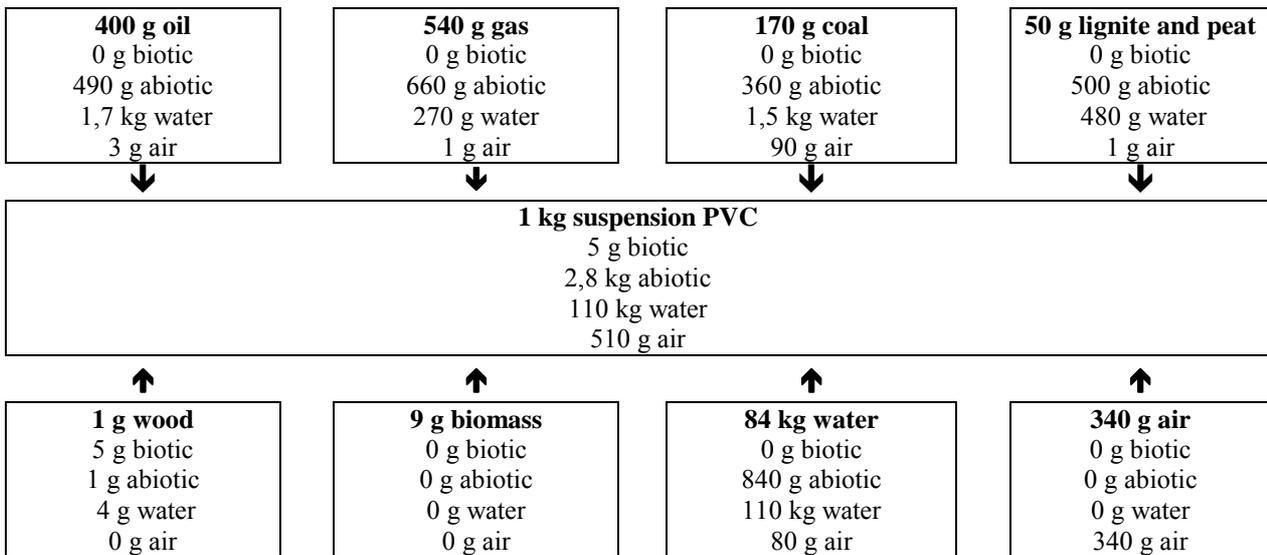**Figure 4.24.** Process-chain for the production of PVC.

There are different types of PVC:

- Suspension polymerised. Suspension PVC is the general purpose grade and is used for most rigid PVC applications such as pipes, profiles and other building materials. It is also used for most flexible applications such as cable insulation, foils and various products made by injection moulding
- Emulsion polymerised. Emulsion PVC is primarily used for coating applications such as PVC coated fabrics
- Bulk polymerised. Bulk PVC is used for specific types of hard sheets and bottles.

We use suspension PVC as an representative for all PVC's .

1 kg raw PVC
0 g biotic
4,6 kg abiotic
220 kg water
400 g air

Figure 4.25. MI per kg raw PVC.

400 g oil	540 g gas	170 g coal	50 g lignite and peat
0 g biotic	0 g biotic	0 g biotic	0 g biotic
490 g abiotic	660 g abiotic	360 g abiotic	500 g abiotic
1,7 kg water	270 g water	1,5 kg water	480 g water
3 g air	1 g air	90 g air	1 g air

1 kg suspension PVC
5 g biotic
2,8 kg abiotic
110 kg water
510 g air

1 g wood	9 g biomass	84 kg water	340 g air
5 g biotic	0 g biotic	0 g biotic	0 g biotic
1 g abiotic	0 g abiotic	840 g abiotic	0 g abiotic
4 g water	0 g water	110 kg water	0 g water
0 g air	0 g air	80 g air	340 g air

Figure 4.26. MI per kg suspension PVC.

400 g oil
0 g biotic
490 g abiotic
1,7 kg water
3 g air

550 g gas
0 g biotic
670 g abiotic
280 g water
1 g air

350 g coal
0 g biotic
740 g abiotic
3,2 kg water
180 g air

140 g lignite and peat
0 g biotic
1,4 kg abiotic
1,3 kg water
3 g air

↓ ↓ ↓ ↓

1 kg emulsion PVC
1 g biotic
4,1 kg abiotic
110 kg water
3,2 kg air

↑ ↑ ↑ ↑

0,2 g wood
1 g biotic
0 g abiotic
1 g water
0 g air

8 g biomass
0 g biotic
0 g abiotic
0 g water
0 g air

83 kg water
0 g biotic
830 g abiotic
110 kg water
80 g air

2,9 kg air
0 g biotic
0 g abiotic
0 g water
2,9 kg air

Figure 4.27. MI per kg emulsion PVC.

360 g oil
0 g biotic
440 g abiotic
1,5 kg water
3 g air

430 g gas
0 g biotic
530 g abiotic
220 g water
1 g air

100 g coal
0 g biotic
200 g abiotic
880 g water
50 g air

40 g lignite and peat
0 g biotic
350 g abiotic
330 g water
3 g air

↓ ↓ ↓ ↓

1 kg bulk PVC
0 g biotic
2,0 kg abiotic
610 kg water
1,3 kg air

↑ ↑ ↑ ↑

0 g wood
0 g biotic
0 g abiotic
0 g water
0 g air

16 g biomass
0 g biotic
0 g abiotic
0 g water
0 g air

45 kg water
0 g biotic
450 g abiotic
59 kg water
50 g air

1,2 kg air
0 g biotic
0 g abiotic
0 g water
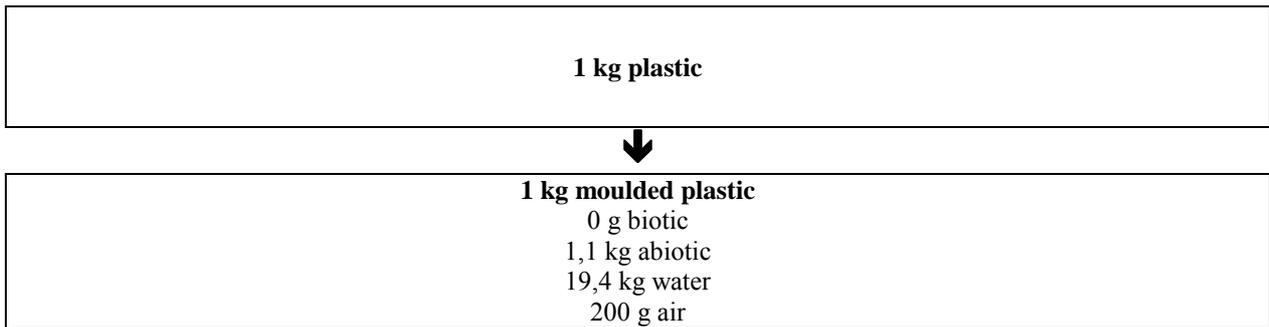1,2 kg air

Figure 4.28. MI per kg bulk PVC.

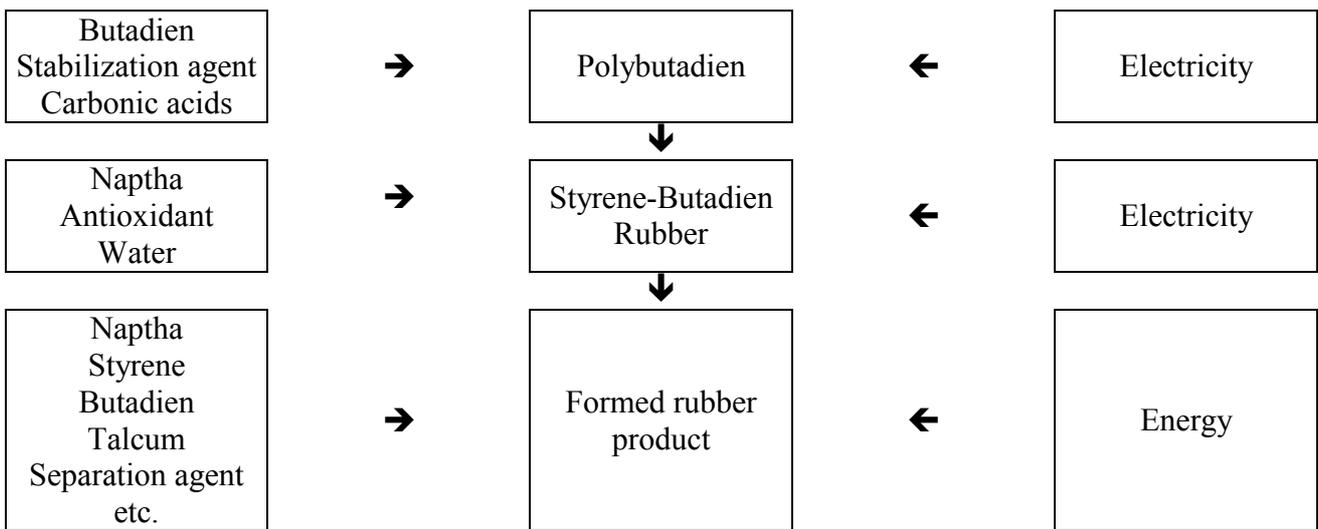## 4.12. Moulding of plastic

In Wuppertal paper nr. 63 the MI for production of PVC tubes is described. Taking the difference from raw PVC and PVC tubes we have an estimate for the MI used in a casting process for plastic.
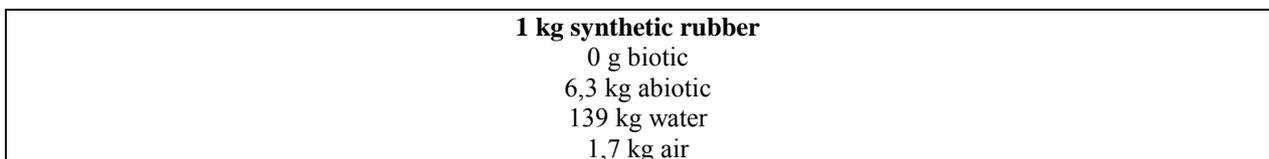
1 kg plastic

⬇

1 kg moulded plastic 0 g biotic 1,1 kg abiotic 19,4 kg water 200 g air

Figure 4.29. MI for 1 kg of moulded plastic.

4.13. Synthetic rubber

There are quite a number of different syntetic rubbers. Styrene-butadiene rubber is the most common and we use this type of rubber as a representative for all rubbers.

Butadien Stabilization agent Carbonic acids	➔	Polybutadien	⬅	Electricity
		⬇		
Naptha Antioxidant Water	➔	Styrene-Butadien Rubber	⬅	Electricity
		⬇		
Naptha Styrene Butadien Talcum Separation agent etc.	➔	Formed rubber product	⬅	Energy

Figure 4.30. Schematic process-chain for synthetic rubber production.

1 kg synthetic rubber 0 g biotic 6,3 kg abiotic 139 kg water 1,7 kg air

Figure 4.31. MI for 1 kg of synthetic rubber

5. Glass and ceramics

5.1. Glass

The raw materials (e.g. silica sand, calcium, soda and magnesium) are properly weighted and mixed and then introduced into a furnace where they are melted at 1500° C.

MI for bottle glass, float glass and recycled glass is presented in the attached excel-file.

Bottle glass

1 kg bottle glass
0 g biotic
2,6 kg abiotic
13 kg water
800 g air

Figure 5.1. MI for 1 kg bottle glass.

Float glass

1 kg float glass
0 g biotic
2,5 kg abiotic
11 kg water
350 g air

Figure 5.2. MI for 1 kg float glass.

Recycled glass

1 kg recycled glass
0 g biotic
550 g abiotic
7 kg water
400 g air

Figure 5.3. MI for 1 kg recycled glass.

5.2. Ceramics

Ceramics are typically made from clays that are hardened by firing at high temperatures. Ceramics are a class of non-metallic materials that are strong, brittle and resistant to heat and attack by chemicals.

Like glass, ceramics are based on silicates, but there the resemblance ends. Glass can be melted and remelted as often as desired; but once ceramics has been hardened, it is resistant to extremely high temperatures.

There has been made no calculations of MI in connection with ceramics. We have therefore assessed the MI for the production of refractory bricks in order to find an estimate of MI for ceramics.

Process: Al_2O_3 + heat ➜ Al_2O_3

Our calculations of MIs can be seen in the attached excel-fil.

1 kg ceramics
0 g biotic
6,5 kg abiotic
20 kg water
1,6 kg air

Figure 5.4. MI for 1 kg ceramics.

6. Leather

There are a number of processes whereby the flesh of a dead animal can be formed into a supple, strong material commonly called leather. In the attached excel-fil MI for chrome tanned leather as well as vegetable tanned leather is presented, which also are the most common used leathers. Also alum-tanned leather and rawhide are in use to a lesser extent.

6.1. Vegetable-tanned leather

Vegetable-tanned leather is tanned using tannin and other ingredients found in vegetable matter - tree bark, and other such sources. It is supple and brown in color, with the exact shade depending on the mix of chemicals and the color of the flesh. Vegetable-tanned leather is not stable in water; it tends to discolor, and if left to soak and then dry it will shrink and become less supple and harder. In hot water, it will shrink drastically and plasticize, becoming a rigid, brittle material of little use.

1 kg vegetable tanned leather
740 g biotic
15 kg abiotic
350 kg water
2,9 kg air

Figure 0.1. MI for 1 kg vegetable tanned leather.

6.2. Chrome-tanned leather

Chrome-tanned leather is tanned using chromium sulfate and other salts of chromium. It is more supple and stretchier than vegetable-tanned leather, and does not discolor or lose shape as drastically in water as vegetable-tanned. More esoteric colors are possible using chrome tanning. There are both environmental and health problems by using chrome-tanned leather. During

manufacturing and when the leather becomes waste chrome escapes into the environment and during use users can be exposed to chromium compounds.

1 kg chrome tanned leather
0 g biotic
17 kg abiotic
410 kg water
2,9 kg air

Figure 0.2. MI for 1 kg chrome tanned leather.

Until the 1990s Denmark had quiet a few tanneries using chrome compounds. Now there are only a few tanneries left and none of them make use of chrome. The tanneries have moved to other European countries and Asia.

6. Other

6.1. Electronics

The ecological rucksack of electronic components is notorious difficult to estimate. However most of the common ingredients in electronic components are described in this report, e.g. lead, iron, cupper, zinc, ceramic. The problem can be solved by estimating the percentage by weight of each ingredient of different electronic components, i.e. circuit boards condenser, resistances etc. Percentage by weight can for instance be found in "Ökobilanzierung komplexer Elektronikprodukte. S. Behrendt, R. Kreibich, S. Lundie, R. Pfitzner and M. Scharp. Institut für Zukunftsstudien und Technologiebewertung. Springer-Verlag Berlin Heidelberg 1998".

6.2. Fibre

It has been difficult to find realistic rucksack figures for fibres and textiles. We have chosen not to publish collected data. In the beginning of the project we believed that specially girls would prefer to work with textiles, but a test of the educational material has demonstrated that girls might as well choose other goods.

6.3. Transport

Please see table below.

Table 6.1. MI-values (kg/kg) for transport
Source: MI-werte

	Abiotic material	*Water*	*Air*
	g/tkm	*g/tkm*	*g/tkm*
Sea going vessels	6,0	52	10
Cargo trains	77	3600	34
Truck transport of cargo	220	1900	210

7. Reliability of the results

The data source for most MI-data presented in this report originates from the Wuppertal Institute. For an assessment of the reliability of this data, please refer to their publications. However, for some materials, especially plastic and fibres, we have obtained data elsewhere. In order to form an idea of the reliability of this data we have in the following compared the calculated MI values with values presented by the Wuppetal Institute (MI-werte). After each box we present our assessment of the reliability of the results. The comparison gives fairly good accordance with abiotic material and water whereas the MI for air differs by significant amounts.

MI-values are not available form the Wuppertal Institute for SAN and ABS.

Table 7.1. Factor between Wuppertals MI-verte and calculated MI values for nylon:

	Biotic Material	Abiotic Material	Water	Air
Factor	n.a.	1,4	1/2,9	1/2,9

A factor 3 is within a reasonable order of magnitude.

Table 7.2. Comparison with Wuppertals MI-values (LDPE)

	Biotic Material	Abiotic Material	Water	Air
Factor	n.a.	1/1,1	1/1,8	1/5,0

The factors for abiotic material and water are within the limits of uncertainty, whereas 5 is reasonable.

Table 7.3. Comparison with Wuppertals MI-values (LDPE)

	Biotic Material	Abiotic Material	Water	Air
Factor	n.a.	1/1,1	1/2,1	1/4,9

The factors for abiotic material and water are within the limits of uncertainty, whereas 4,9 is reasonable.

Table 7.4. Comparison with Wuppertals MI-values (PP)

	Biotic Material	Abiotic Material	Water	Air
Factor	n.a.	1,1	1,8	1/4,4

The factors for abiotic material and water are within the limits of uncertainty, whereas 4,4 is reasonable.

Table 7.5. Comparison with Wuppertals MI-values (Polystyrene)

	Biotic Material	Abiotic Material	Water	Air
Factor	n.a.	1,7	1,5	1/8,5

The factors for abiotic material and water are within the limits of uncertainty, whereas 8,5 is reasonable.