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Material Intensity of Advanced Composite Materials

Results of a study for the
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This Wuppertal Paper summarises the main results of a study of the Wuppertal Institute for the Verbundwerkstofflabor Bremen. Nowever, research on material intensity is never finished as industry is continuously changing. Thus, results and conclusions presented here are open to discussion and shall be treated as an invitation for further research in this area.

Abstract

In this paper the results of an analysis of the material intensity of advanced composite materials are presented. The analysis is based on the MIPS-concept of the Wuppertal Institute which allows the calculation of the overall material intensity of products and services. It can be shown that the production of one kg of E-Glass fibers is connected with the consumption of 6.2 kg materials, 95 kg water and 2.1 kg oxygen which is of similar size compared to the inputs required in steel production. Material inputs required to produce one kg of p-aramid are 37 kg of materials and 19.6 kg air. Values for carbon fibers are even higher yielding to 61.1 kg of abiotic materials and 33.1 kg of air. Similarly, the production of epoxy resins is connected with larger material flows than the production of polyester resins. Of core materials, inputs per kg for PVC-foam exceed those in PUR-foam production by a factor of 1.4 in water to 2.3 in abiotic material consumption.

However, ecologically decisive are not the inputs per kg but the material input per service unit. Therefore, the material input per service unit computed for the body of a passenger ship and a robot arm are compared with alternative steel and aluminium versions. Both examples show that in the case of significant inputs during the user phase of products, even a more material intensive investment in the production phase can yield significant ecological benefits over the whole life-cycle compared to metal versions. Improvements can easily reach a factor of two albeit significant potential for engine optimizations have still been neglected.

Results already include the actual recycling quota of metals whereas for composites only virgin material has been calculated as any form of real recycling does not actually exist but only certain types of downrecycling. Of those treatment options, first material recycling and second the use in blast furnaces would lead to better results in resource productivity than incineration and landfills.

The paper finally draws some conclusions about the potential advantages of material substitution in the automotive industry. Due to the rather short real operation time of cars during their user phase - around six months - an investment in advanced composite materials in car production only results in a significant improvement of the overall eco-efficiency of cars if it allows a substantial weight reduction of the overall vehicle.

Content

1. Introduction

Today eco-efficiency is broadly accepted as one of the most promising strategies towards sustainable development. Science, governments[1], international organisations[2] but also business[3] see eco-efficiency as being essential to answering the global ecological challenge. Whereas less unanimity exists when it comes to the detailed definition of eco-efficiency, all concepts call for a more efficient use of natural resources. This means that not only energy but all natural resources have to be taken into account. Among others, the Wuppertal Institute calls for a reduction in the use of material, energy and space[4].

Sustainable development calls for respecting the limited carrying capacity of our planet. Actually, however, the total volume of material flows (except water and air) moved by mankind exceeds even the total material flows by nature on a global scale. Obviously such human interference changes natural equilibria in an unknown direction. Thus, not limited supply but the inevitable impact on the environment which is related to the extraction and use of natural resources is the principle constraint we are facing today. Therefore, a 50% reduction in global material flows seems to be necessary as a first step to re-stabilize the ecosphere. Together with a further increase in wealth and a more equal use of those limited capacities, an increase in material productivity by a factor of 4 to 10 of our economy has to be achieved over the next decades[5].

One strategy to meet this ambitious goal is the development and use of new materials. Therefore, the Wuppertal Institute has been asked by the Verbundwerkstofflabor Bremen to analyse whether an extended use of advanced composite materials offers one option to meet this ecologicial challenge.

2. Measuring resource productivity - the MIPS-concept

If the extend of our consumption of natural resources is to be reduced, an appropriate measure has to be found. Otherwise eco-efficiency remains a catchword without any chance of it being implemented in business and politics. Eco-efficiency requires an indicator which does not require specific modifications but can be applied globally. Moreover, general considerations for

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[1] see: Deutscher Bundestag, Enquete-Kommission zum Schutz des Menschen und der Umwelt, Endbericht 1998.

[2] see: OECD: A strategy for further OECD work on sustainable development, C(98)46, Paris 1998.

[3] see: World Business Council for Sustainable Development (WBCSD), Annual Report 1997.

[4] see: Schmidt-Bleek, F.: Wieviel Umwelt braucht der Mensch ? mips - Das Maß für ökologisches Wirtschaften, Basel 1994.

[5] Carnoules Declaration, Factor 10 Club, 1997. Weizsäcker, E.U. von, Lovins, A.B., Lovins, A.H.: Faktor vier. Doppelter Wohlstand - halbierter Naturverbrauch, München 1995.

indicators like the ability to be communicated favour simple, easily calculable proxies instead of very sophisticated and complicated measures. Nevertheless, such simple measures have to be of high ecological relevance[6].

The MIPS indicator developed at the Wuppertal Institute meets all these criteria. MIPS stands for „**m**aterial **i**nput **p**er **s**ervice unit“. It serves as a proxy for the quantitative dimension of the ecological impact potential of human activities. MIPS is calculated over the whole life-cycle of goods and adds up the overall material input which humans move or extract for the production of products and the delivery of services. The dimension of MIPS is kg per service unit. The inverse of MIPS is resource productivity.

The material input is accounted in five categories[7]: abiotic raw materials, biotic raw materials, water, erosion and air. The category abiotic raw materials covers all minerals and ores extracted in mining operations, but also the total overburden and other earth movements. For the environment it does not matter whether gravel is shifted away only as overburden during lignite mining or if it is extracted for construction purposes. Moreover, and very important, all fossil fuels like coal, crude oil, etc., are included in this category. As it is not the energy itself but the related material flows which change ecological equilibria, those inputs are determined in mass units.

Biotic raw materials are not only all products of modern agriculture and forestry but also all biomass which is cut but not used during processing. Domestic animals are considered as being part of the technosphere. Here all feeding inputs are analysed. Additionally, directly harvested products like fish or mushrooms fall within this category.

Third, the quantitative dimension of the change of nature due to human agriculture and forestry has to be taken into account. Schmidt-Bleek stresses the impact potential of ploughing on large parts of this planet. However, for practical reasons, human induced erosion is taken as the material flow of highest ecological relevance in this category.

Beside these flows of solids mankind also intervenes in the flows of (sweet) water on Earth. In the MIPS concept all actively extracted or diverted water flows are accounted. This includes the extraction of ground and surface water, cooling water in power generation and industries, water for irrigation in agriculture, but also rivers diverted to other places and water running off from sealed areas. Thus, it is not water pollution but rather the influence on eco- systems due to changes in water flows which is indicated by this category.

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[6] see: Schmidt-Bleek, F., loc. cit.

[7] see: Schmidt-Bleek et al.: Handbuch der Materialintensitätsanalyse, Basel 1998.

Finally, all air chemically processed or converted into another physical state is measured in the category air. This figure is strongly correlated with the CO_2-emissions as principal gaseous output of processes. However, also oxygen reacting with other molecules, such as for example hydrogen, is included. Thus, this category reflects rather the potential mobilisation of atoms which are up to now bound in the litosphere when processing transforms the whole volume of the material handled. Fossil fuels are only one but, of course, the most important one among other materials in this respect.

Those material flows which are not forming part of the product itself but which are „hidden“ flows are called the „ecological rucksack“. If there are two or more products produced in one process, the ecological rucksack generally is distributed to these products according to the mass of each product. Besides this, as in the case of energetic outputs and services, other parameters like energy content or even prices might serve as the basis for the allocation. Waste or by-products are not assigned an ecological rucksack. They only bear the inputs for their further processing. This implies that - if an efficient recycling technology exists - secondary materials have a rather small ecological rucksack which makes them favorable as alternative inputs compared to virgin ones.

In principle, MIPS can be reduced - or equally the resource productivity increased - by two strategies: first, reducing the „MI“ (material input) - either by advanced production processes, closing of material cycles, substitution towards materials with a reduced ecological rucksack; second, enhancing „PS“ by a given material input. Here, options range from higher user frequency and longevity, to a better organisation increasing the services delivered by a product. To reach a factor 4 or even 10 both strategies will have to be combined. Therefore, besides analysing the improvement potential on the input side, in this study the service delivered during the user phase is included in the analysis.

3. Specific methodology in this study

An isolated national market for composite materials does not exist. Sourcing occurs globally or at least on a European scale. Consequently, this study tries to reflect the west European situation. In cases where only German data from older studies are available, rucksacks have been adjusted as far as electricity is concerned.

The treatment of electricity is a crucial point in each material intensity analysis - as in each life-cycle-analysis. Depending on the energy carrier and the technology, the ecological rucksack of one unit of electricity can vary by up to a factor of 10 and more. Thus, as electricity is used in nearly all production processes, results are hardly influenced by the choice of the methodology for their calculation. In this study for all electricity used the average material input in the European OECD-countries has been used. As long as not all or at least the majority of all production sites are analysed, the comparison of different kinds of materials should not depend on the place from where the specific data have been obtained.

This implies that materials produced in countries with a rather less material intensive electricity production, like Sweden which uses a huge amount of hydropower, or France with its - compared to lignite - less material intensive nuclear power, are treated equally to products coming from plants located in Germany.

Best would be to know every input for all processes. Of course, this is not the case. Instead, analysts are lucky to know the bulk inputs, notwithstanding all catalysator and trace materials. Fortunately, these substances are only of minor importance for the results of a material intensity analysis.

Determining an average can be done in two ways: either at each step of production or just at the final stage. The problem with the last is that it requires complete information on all production sites. This approach has been applied in the publications of the Association of the Plastic Manufacturers in Europe (APME) based on input data of nearly all large manufacturers. If data of the APME have been used - for chlorine and PVC - these averages have not be adjusted. For all other processes, such an approach was lacking the required information basis. Thus, average data on the ecological rucksack for the inputs in each production step has been used in the calculations, even when other specific information for one plant was available.

Advanced composite materials are rather new materials. Thus, recycling technology is still under development. Consequently, in the calculations of the applications using composite materials always virgin inputs have been considered as no real recycling of those materials actually exists. Future options are discussed separately in chapter 8.

4. Material intensity analysis of different fiber materials

As opposed to common metal materials, fibers have anisotropic properties. High modulus and strength in one direction is accompanied by only limited strength in the lateral dimension. But in a lot of applications, just one direction is in fact hardly strained. Moreover, combining different fibers and cores with an appropriate matrix allows the design of specific material properties. In the following, some of the most common basic materials for advanced composite materials will be analysed.

4.1. Glass Fibers

E-glass fibers are the most common basic material for reinforced plastics. They are also used in a lot of other applications, ranging from telecommunications to insulation materials. Of the various types of glass fibers, E-glass is by far the most important with a market share of about 99%. For special applications R-glass or S-glass are used which have a higher modulus and are also applicable in an alkaline environment.

The production chain of glass fibers starts with mining of the raw materials used for glass melting. The most important ones are glass sand, china clay, borate or colemanite, limestone, fluor and sulfates. Whereas the broad chemical composition of glass fibers is harmonized in certain ranges, specific batch composition is part of the know-how of the manufacturers and depends largely on the deposits of raw materials. The raw materials are milled, sometimes pelletized to reduce energy consumption and then molten in glass furnaces.

In general, those furnaces are heated with natural gas. However, heating with electricity can reduce final energy demand significantly but for the overall resource productivity material flows for electricity production also have to be accounted.

Data on energy consumption of glass fiber production could be obtained from 7 different sources, among them the large manufacturers PPG, OwensCorning and Vetrotex. They show a wide range. Lowest energy consumption is reported by OwensCorning with 10,500 MJ natural gas and 0.58 MWh electricity per ton of roving[8], highest by a German plant with 28,080 MJ and 1.2 MWh. However, even at one manufacturer values vary significantly. A Chalmers report[9] based on data by OwensCorning shows more than 23,000 MJ consumption of natural gas by a British plant of this company. Energy consumption at Vetrotex plants varies from 12,600 MJ to 29,900 MJ with an average of 19,180 MJ and 1.68 MWh[10].

According to OwensCorning the low energy consumption at their plants results from larger sizes, which allow energy savings of about 20%, pelletizing of the batch materials and also improvements in the design of the furnaces. Energy consumption is roughly independent of the filament diameter of the glass fibers produced. As even smallest impurities reduce the quality of the rovings, glass fiber waste or other glass scrap is generally not used to save energy. For this project, material intensity has been calculated with 1.27 MWh electricity and 380 kg natural gas.

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[8] Mirth, D., OwensCorning, 1997.

[9] Lundström, H., Livscykeanalys av ett framstycke, Jämförande studie av tva material till en bildetalj, Chalmers Tekniska Högskola, Göteborg, 1996.

[10] Guillermin, R., Vetrotex International, 1998; Wörtler, M., Vetrotex Deutschland 1997.

Producer	**natural gas MJ**	**electricity kWh**
Sisecam[11] (Turkey)	17,173	1.13
Vetrotex Germany (finer filaments)	23,040	2.5
Vetrotex Germany EC14-300 P185	28,080	1.2
Vetrotex International	19,180	1.68
PPG[12]	17,250	1.6
OwensCorning (USA)	10,500	0.58
OwensCorning ac. to Chalmers (GB)	23,159	0.55

Tab. 4.1.-1: Energy consumption in glass fiber production
Source: glass fiber producers 1997

Production waste in glass fiber production is generated for example by changing of bobbins or the interruption of the spinned fibers. Depending on the filament diameter, total waste volume is reported to be between 10 and 25%[13].

Bushings and nozzles are made out of platin and rhodium metal. Their lifetime is estimated to be between 250 and 350 days. Although being nearly fully recycled (more than 97%)[14] that material input for the plant is not to be ignored due to the huge ecological rucksack of platin metals.

data per ton E-glass-roving	**inputs [kg]**	**MI- factor [t/t]**	**MI- abiotic [t]**	**MI- factor [t/t]**	**MI- water [t]**	**MI-factor [t/t]**	**MI- air [t]**
glass sand	372	1.36	0.51	1.1	0.4	0.03	0.01
china clay	378	3.05	1.15	4.0	1.5	0.08	0.03
fluorspar	60	2.93	0.18	8.2	0.5	0.06	0.01
limestone	280	1.36	0.38	7.8	2.2	0.05	0.01
colemanite	196	6.17	1.21	7.8	1.5	0.05	0.01
sulfate	36	1	0.04				
solids	49	1.36	0.07	7.8	0.4	0.05	0.00
silane/epoxy resin	3,5	14.3	0.05	293	1.0	5.4	0.02
water	5.500	-	-	1	5.5	-	-
natural gas	380	1.20	0.46	0.4	0.2	3.82	1.45
electricity	1272	1.58	2.00	63.83	81.2	0.42	0.54
platinum losses	0,0004	403,000	0.16	407,000	0.4	7,371	0.00
Σ total process			**6.2**		**95**		**2.1**

Tab. 4.1.-2: Material intensity of E-glass
Source: own calculations

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[11] Kinayyigit, F., Erdemli, S., Sisecam, Türkei, 1997.
[12] PPG Research Center, Pittsburg, 1997.
[13] Loewenstein, K.L., The Manufacturing Technology of Continuous Glass Fibers, 3rd edition, Amsterdam 1993.
[14] Id., p.138.

To avoid sticking together, filaments are sized with a sizing agent made of epoxy and polyester resins, lubricants und silans. Consumption is about 0.38 l/kg glass fiber, but the silan content in the sizing agent is only 0.35%. Total water consumption in glass fiber production varies significantly depending on whether water is recycled in closed loops or not.

Tab. 4.1.-2 shows typical material input for the production of E-glass. Rucksack data for these inputs have already been analyzed by the Wuppertal Institute in various other studies[15]. Generally, there is no cogeneration in the glass fiber industry, thus electricity demand is covered by supply of the public grid. In this study average values for the OECD Europe have been used to make results comparable with other fiber materials.

For specific applications other types of glass fibers have been developed. R-Glass has a higher content of silicum oxid (58-60%), Alumina (23.5-25.5%) and magnesium (9%), but contains no boroxide. Thus, minerals used in the production are dolomite, limestone, china clay and glass sand. Data on the energy consumption for R-Glas production are not directly available as quantities are very small. Roger Guillermin of Vetrotex International[16] estimates that energy demand may be twice that for E-glass and that a total energy of 35 MJ/kg might be a good estimation. Mirth of OwensCorning[17] estimates the energy required to produce S-glass to be 16 MJ/kg electricity.

category	per t R-glass	unit
abiotic raw materials	10.8	t
water	307	t
air	2.0	t

Tab. 4.1.-3: material intensity of R-glass-rovings
Source: own calculations

Tab. 4.1.-3 shows the material intensity of R-glass calculated using the estimation by Mirth. Compared to E-glass, abiotic raw material input and water are significantly higher due to higher energy demand. The rather low air consumption is the result of the relatively lower oxygen consumption in electricity production compared to burning of natural gas. Due to the limited information, values have to be regarded rather as a minimum estimation.

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[15] Most batch materials have been analysed by Wurbs, J. et al: Materialintensität von Grund-, Werk- und Baustoffen (5). Der Werkstoff Glas. Materialintensität von Behälter- und Flachglas. Wuppertal Papers No. 64, Oct. 1996. Material intensity of electricity and energy carriers see: Manstein, C., Das Elektrizitätsmodul im MIPS-Konzept. Materialintensitätsanalyse der bundesdeutschen Stromversorgung . Wuppertal Papers No. 51, 1996.

[16] Guillermin, R., Vetrotex International, 1998.

[17] Mirth, D., loc. cit.

4.2. P-Aramid fibers

P-aramides or aromatic polyamides are organic compounds which can be spinned into fibers. Interest in these fibers exists due to their high E-modulus and tensile strength combined with a much lower density of 1.45 g/cm^3 than glass fibers and even carbon fibers.

Worldwide p-aramid fibers are produced mainly only by two companies. Dupont has a share of around 60% of the market with its Kevlar, the other 40% is supplied by Akzo Nobel with its Twaron. Total market volume is a bit less than 30,000 tons per year. Calculations for this study are based on confidential information by Akzo Nobel which gratefully supported this project. Thus, of course, only the final results of the material intensity analysis can be published here.

Poly-para-phenylene-terephthalamide (PPTA), a para-oriented aramid, is made by polycondensation out of a solution of of Phenylene-diamine (PPD) and terephalaloyl-dichloride (TDC)[18]. Basic chemicals for TDC are chlorine and p-xylene. The production of PPD requires aniline, sodiumnitride and HCL.

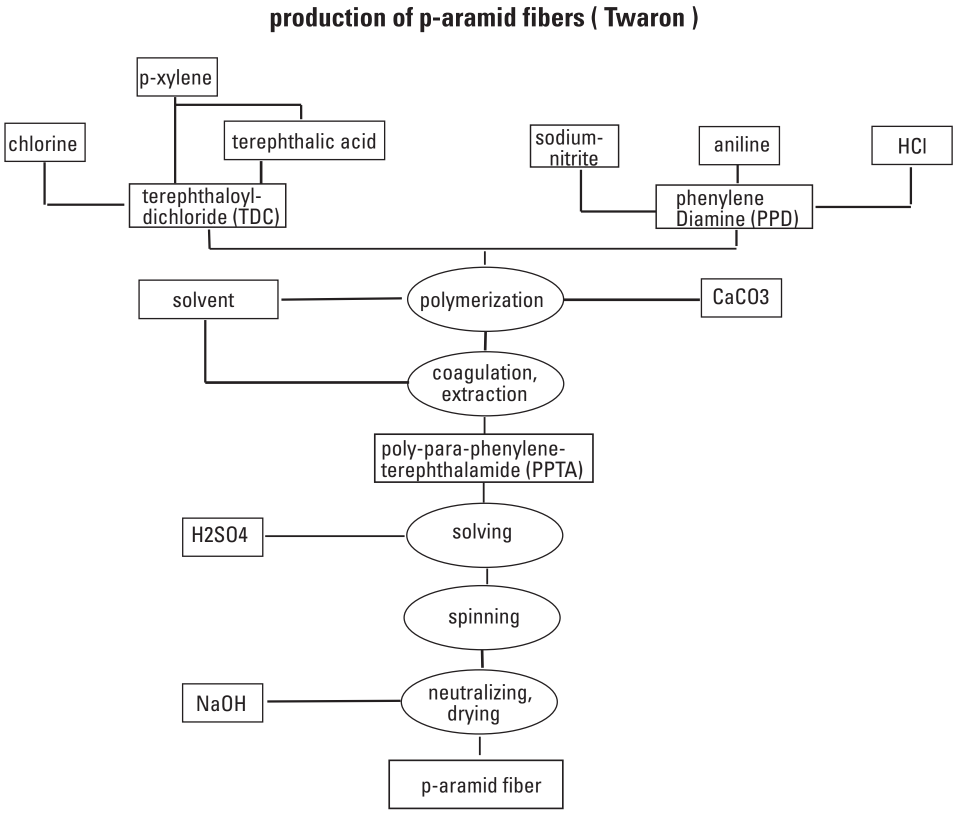

Fig. 4.1: process tree for p-aramid production (Twaron)

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[18] Caesar, H.M.: Twaron, its Technical Properties and Applications. Akzo Nobel, Arnheim, Vortragsmanuskript 1995.

To avoid material intensity of p-aramid being based only on the specific situation of one production plant, average data for chlorine which has been published by the Association of the European Plastic Manufactures (APME)[19] has been used for the calculation, albeit at Akzo Nobel´s plant chlorine is produced by a very efficient plant using the diaphragma process. However, sensitivity analysis shows only a minor impact on the final result by this methodological choice. More critical but dealed with equally is the treatment of the huge steam and electricity consumption in p-aramid fiber production. Again, at Akzo Nobel final energy is delivered by co-generation in a much more efficient way than the average electricity taken out of the public grid. However, to make results comparable, electricity has been weighted with the rucksack for average electricity produced in the OECD-Europe[20].

Total material input of abiotic raw materials is calculated to be 37 ton per ton p-aramid fibers and thus 6 times higher than for the same quantity of E-glass. Around 60% of the material consumption in all three categories results from polymerisation and spinning, especially due to the high electricity consumption of these processes. High water demand results mainly from cooling water for electricity production. Direct water input at Akzo Nobel is significantly below 10% of the total water input.

category	**per t p-aramid fiber**	**unit**
abiotic raw materials	37.0	t
water	940	t
air	19.6	t

Tab. 4.2: material intensity of p-aramid fibers
source: own calculations

4.3. Carbon fibers[21]

Whereas p-aramid fibers can have a slightly higher tensile strength per tex, carbon fibers have the largest E-modulus of all fibers regarded here. Several types of carbon fibers are produced. HM-fibers und UMS-fibers have a higher modulus, but the bulk of the production (around 90%) are HT-fibers which have a specific high tenacity. Analysis here will only deal with these type of fibers. Actually, most carbon filament yarns have between 6K and 12K filaments, but the tendency is towards an increasing number of filaments[22].

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[19] APME (ed.): Eco-profiles No. 5,6 Allocation in Chlorine Plants; Polyvinyl Chloride. Bruxelles 1994.
SRI International: The Global Chlor-Alkali-Industry - Strategic Implications and Impacts. Final report Vol. II. SRI Process Industries Division, Zürich 1993.

[20] A similar approach has been used in an internal energy balance for p-aramid fibers at Akzo Nobel.

[21] We are grateful to Mr. H. Blumberg of Tenax Fibers for supporting this part of the study with confidential data by Toho Rayon and Tenax Fibers.

[22] Karl, Toray Deutschland, 1998.

World production capacity of carbon fibers is only a tiny fraction compared to glass fibers. It is estimated to be 18,050 tons in 1998[23]. Demand has been growing steadily in recent years due to the increasing use of carbon fibers by industry. Other major markets are sports equipment producers and the civil aircraft industry.

The process chain of carbon fibers starts with acrylnitrile production which is produced mainly by oxidation of ammonium and propylen in the so called SOHIO-process. By-products such as cyancali acid and CO can be sold. In the next step the acrylnitrile is polymerized mostly by dissolving it in dimethylformamide. However, other solvents such as $ZnCl_2$ are also used which are said to yield fibers with better material properties but require huge inputs of steam in the production of the precursor. As the polymerization has an impact on the performance of the final fibers, each (independent) manufacturer has its own specific polymerization process.

Afterwards the polyacrilnitrile is dissolved again for the spinning of PAN-yarn. The PAN-precursor then undergoes a high temperature treatment for stabilisation, carbonisation and - for specific applications - also further graphitisation. Finally, the fibers are sized with sizing agent to improve the later reactions with the matrices.

Production of carbon fibers is a resource intensive process. Of each kg polyacrylnitrile only about 450 to 500 gs are transferred into the final product[24]. The rest is lost due to changing chemical composition in the stabilisation and the carbonisation process. Thus, increasing yields would reduce cost and improve resource productivity. However, up to now yields significantly higher than 50% have not been reported. Pitch as basic material would allow a much higher transformation rate of up to 85%, but shows other disadvantages and is therefore used today only in negligible quantities.

Publicly available information on energy and material inputs of carbon fiber production are scarce. In Zogg[25] an energy equivalent of 286 MJ/kg is reported, more than 10 times the energy required for the production of one kg of steel. A Toray specialist has estimated total energy consumption roughly to be 280 - 340 MJ/kg[26]. Of this input, around 160 MJ are required just for the production of the two kg of acrylnitrile. In this study the calculation of the material intensity is based on data submitted confidentially by Tenax Fibers and Toho Rayon[27]. Thanks to detailed information even equipment like the furnaces could be included in the analysis. The total energy requirement in this study cannot be reported here, but is influenced by the fact that

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[23] Karl, loc. cit.

[24] Blumberg, H.: Fibers for composites - status quo and trends. In: Chemical Fibers International, Vol. 47, Feb. 1997, p. 36-41.

[25] Zogg, M., Neue Wege zum Recycling von faserverstärkten Kunststoffen, IKB-Zürich 1996.

[26] According to Karl, Toray Deutschland, 1997.

[27] Blumberg, H., Tenax Fibers, Wuppertal 1997.

the precursor used is produced by using $ZnCl_2$ whereas the above mentioned figures are based on precursors made by using dimethylformamide as a solvent.

Results show that the material intensity of carbon fibers is by far the largest of all fibers analysed in this study. Consumption of abiotic raw materials adds up to 61.1 tons per ton carbon fiber, air consumption is 33.4 tons, water is calculatetd to be 2411 tons. These figures are already adjusted by calculating with the average European data for the electricity consumption instead of using the less material intensive Japanese electricity supply in presursor production and the more material intensive average German one in fiber production.

category	per t carbon fiber	unit
abiotic raw materials	61.1	t
water	2411	t
air	33.4	t

Tab. 4.3: material intensity of carbon fibers
Source: own calculations

4.4. Textile production

In general, not a roving directly but fabrics and multi-axial fabrics (UD) are used in composite production. Their manufacture is similar to the conventional production of textiles. Depending on the type of yarn crossing different types of weaving are obtained. Weight per square meter depends greatly on the amount of filaments in the roving and the type of weaving. As average values electricity consumption is about 0.11 kWh per m^2 glass fibers and 0.214 kWh/m^2 for carbon fibers have been reported. Additional inputs might be required for the acclimatization of the manufacturing halls.

inputs	glass fiber	unit
electricity	0.1093	kWh/m^2
steam	0.8	kg/m^2
gas	0.0188	m^3/m^3
electricity(furnishing)	0.09	kWh/m^2

Tab. 4.5.-1: Inputs for the production of glass fiber tissue
Source: CS-Interglas, 1997.

Energy consumption for multi-axial fabrics (UD) depends on the speed of the machinery. As p-aramid fibers allow up to 1,000 rotations per minute, specific electricity consumption per m^2 is lower than for glass fibers and only half of fragile carbon fibers. Nevertheless, data show that UD production requires less energy compared to textile weaving.

fiber	**electricity consumption**	**unit**
carbon fibers	0,052	kWh/m^2
aramid fibers	0,029	kWh/m^2
glass fibers	0,038	kWh/m^2

Tab. 4.5.-1: typical electricity consumption for UD-production
Source: own calculation based on data by Mr. Wummer, LIBA 1997.

5. Matrices

5.1. Epoxy resins

Epoxy resins are the most common matrix resin if composite materials are used for structural applications requiring optimal mechanical properties. As opposed to thermoplastic resins, epoxy resins connect molecules by fixed bonds forming large macro-molecules. Bonding starts by using specific curing agents, e.g. amines or anhydrids.

Theoretically, a large number of different types of epoxy resins exists. However, around 75% of all epoxy resins are produced using Epichlorinehydrin and bisphenol A. Material intensity analysis concentrated just on this class.

Fig. 5.1. shows the process tree with the main material inputs required to produce a typical epoxy resin. On the one side cumene is produced by the alkylation of propylene and benzene, afterwards being split into acetone and phenol which are then synthesized in another stochiometrical relation to bisphenol A. Epichlorhydrin, as the other basic material for the production of epoxy resins, is obtained by chlorohydrination of chlorine and allyl chloride[28]. This is produced at high temperatures out of chlorine and propylene.

There are different types of epoxy resins. Viscosity of the resin depends on the amount of soda and the relation of epichlohydrin and bisphenol A. Data shown here in Tab. 5.2. are from Witco and Shell[29] and are suitable for the balance of liquid resins. The epoxy resins obtained by this process is not the final product. Depending on the application and the required properties, various curing agents like amines and carbon acid anhydrides, additives and other trace substances are added[30]. Fillers for example reduce the shinking of the resin during curing. The portfolio of SP-Systems, for example comprises 273 different chemicals[31]. However, as the quantities

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[28] data: Prognos AG, Basel, 1997.

[29] Witco, Shell, 1997.

[30] Brandan, E.: Duroplastwerkstoffe, VCH Weinheim, 1993.

[31] Behmer, H., SP Systems Advanced Composite Materials, Great Britan, Bremen 1997.

added in general are very small, neglecting these substances still yields a good approximation of the overall material intensity of epoxy resins.

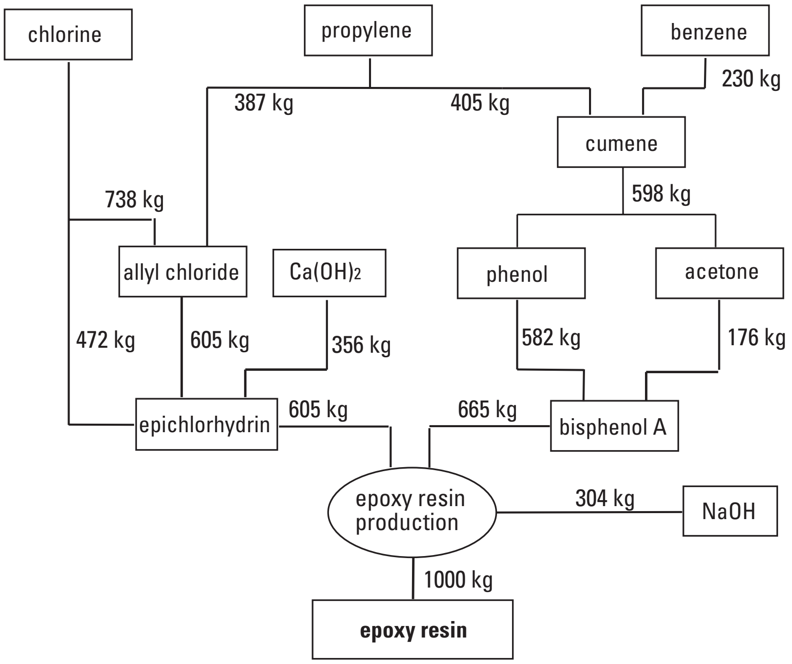

Fig. 5.1.1: epoxy resin production - principal material inputs in the process tree

Overall, tab. 5.2 shows that the production of one ton of liquid epoxy resin requires material inputs of 14.3 ton of abiotic raw materials, nearly 300 tons of water and 5.4 tons of air. Of these inputs chlorine production alone consumes 7.8 tons of abiotic raw materials, around 60% of the water and more than 40% of the air inputs. If - what is technically feasible but economically only the second best option - epichlorhydrin would be synthesized using hydrogen and propin acid, two-thirds of the chlorine input could be avoided which would reduce the material intensity of epoxy resins significantly[32].

data per t epoxy resin	inputs [kg]	MI- factor [t/t]	MI- abiotic [t]	MI- factor [t/t]	MI- water [t]	MI-factor [t/t]	MI- air [t]
bisphenol A	665	5.0	3.32	88.5	58.8	2.45	1.63
epichlorhydrin	605	16.4	9.93	325.2	196.8	5.53	3.34
NaOH	304	2.8	0.84	90.3	27.4	1.06	0.32
water	750	-	-	1.0	0.8	-	-
electricity (kWh)	150	1.58	0.24	63.8	9.6	0.41	0.06
Σ total process			**14.3**		**293**		**5.4**

Tab.5.1.2.: Material intensity of one ton epoxy resin
Source: Own calculations

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[32] Umweltbundesamt, Handbuch Chlorchemie I, Berlin 1992, p.345.

5.2. Polyester resins

Polyester resins have been used for a long time used for reinforced plastics. They are much cheaper than their epoxy competitors. Unfortunately, polyester resins do not reach the same performance as epoxy resins. Thus, they are used in applications where less critical properties are required.

Of the huge family of polyester resins, two specific types of resins have been analysed here: a resin based on Iso-neopentylglycol (NPG) which shows good water resistance and is used in ship building, and a cheaper resin based on orthophthalic acid.

Fig 5.2.1 shows the main inputs for an orthophthalic polyester resin. Styrene input is here estimated to be 400 kg; however, resins with a smaller input also exist on the market.

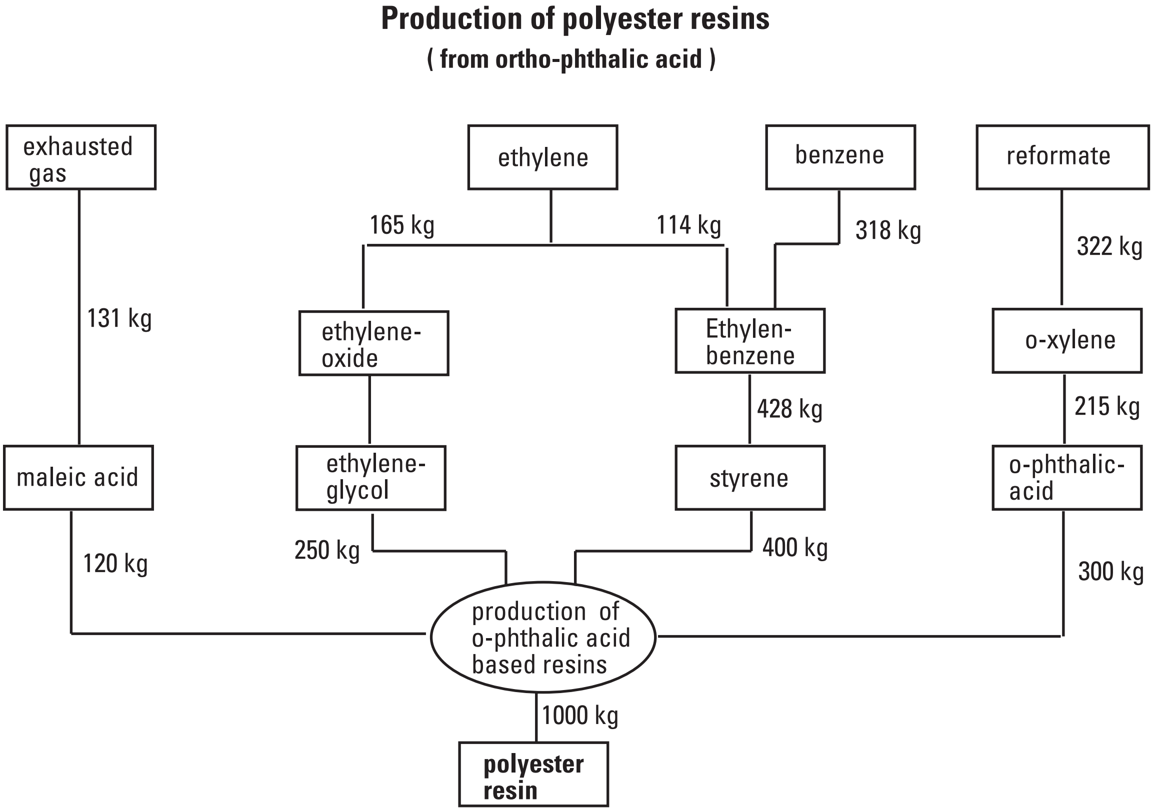

Fig. 5.2.1: process tree of polyester resin production

As tab. 5.2.2. indicates material intensity of polyester resins is significantly lower than the material intensity of epoxy resins[33]. Especially the abiotic raw material input with 5.6 tons is only 39% of the input required for epoxy resins.

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[33] input data polyester production: Klass, Hüls AG, Marl 1997.

The production chain for Iso-NPG is a little bit more complicated as neopentyl-glycol is produced by formaldehyde and isobutylaldeyde. Instead of o-xylene, m-xylene is used to produce iso-phathalic acid. Malein acid is replaced by fumaric acid. Material intensity analysis yields inputs of 5.4 tons of abiotic raw materials, 209 tons of water and 3.2 tons of air. However, it has to be mentioned that for some process steps - the production of neopentylglycol, isobutylaldehyde and m-xylene no specific process data could be obtained. If those processes were fully balanced, material intensity of Iso-NPG would probably be higher than the value calculated for orthophthalic based resins.

Polyester resins are also basic materials for gelcoats and topcoats which are put on top of the surface of composites. Depending on whether the surface comes in to contact with water or not, different polyester resins are used in coat production. Gelcoats are not composed to 100 percent of resins. Filler materials, either cheaper limestone or china clay and some curing agents such as MEKP (methylethylcetoneperoxide) are added[34]. Values for the coats in tab. 5.2. are calculated with 30% filler for the gelcoat and 8% for the topcoat based on Iso-NPG but the amounts vary depending on the quality of the gelcoat.

category	**polyester resin (o-acid)**	**Iso-NGP resin**	**Gelcoat (inside)**	**Gelcoat (outside)**	**unit**
abiotic raw materials	5.6	5.4	4.3	5.1	t/t
water	235	209	167	188	t/t
air	3.5	3.2	2.4	2.9	t/t

Tab. 5.2.2: Material intensity of polyester resins and gelcoats
Source: own calculations

6. Core materials

Composite sandwiches can include core materials to add specific additional features like acustic or thermal insulation. Moreover, those materials can enhance the stiffness of the sandwich. Common core materials are rigid foams either made of PVC or of PUR whose material intensity will has been analysed in the following.

6.1. Semi-rigid PVC-foam

PVC foam is produced in Europe only by the Swiss company AIREX and the Swedish Divinycell International company. Whereas AIREX didn´t give access to any kind of

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[34] typical compositions: Punke, Büsing&Fasch, 1997.

information on their production process, we are grateful that Divinycell International supported this study by submitting the required process relevant information for the calculation of the material intensity[35]. Thus calculations for PVC-foam are based on these data, but as for fiber materials, rucksacks of inputs and especially electricity consumption have been balanced with the inputs required for the production of one kWh in OECD-Europe. As production takes place partly in Sweden, the ecological rucksack of products sold from this plant might be overestimated as the average Swedish electricity supply is less resource consuming due to a high percentage of hydropower. Nevertheless, PVC-foam is also produced in plants in Italy and the U.S. As mentioned above, comparison of core materials should not depend on specific locations of production plants but more on the average material input to be calculated.

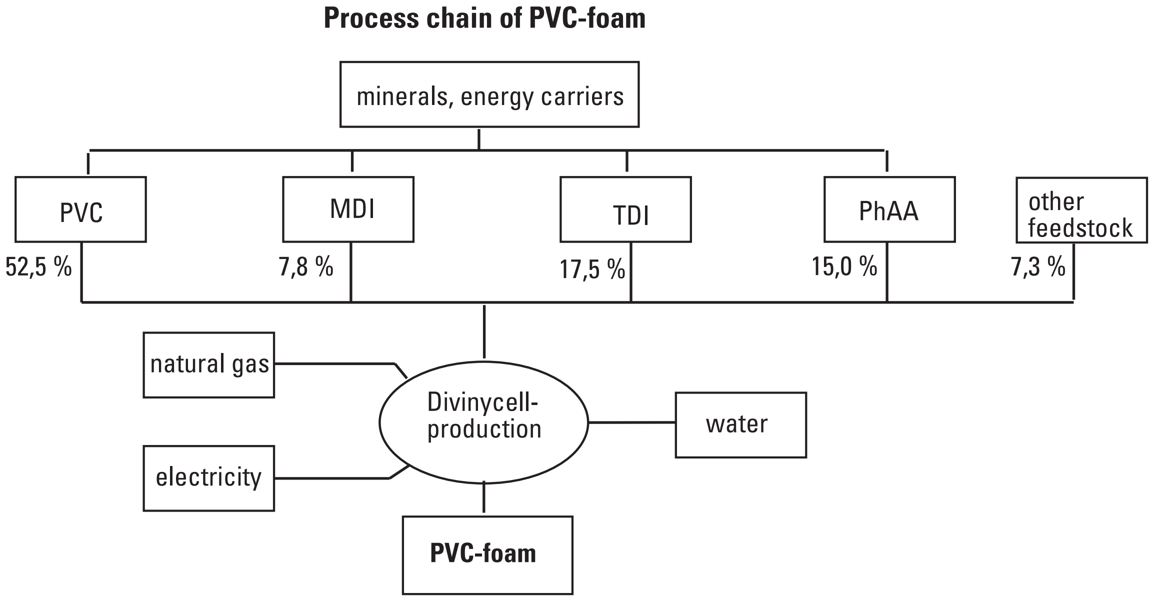

Fig. 6.1.1: Process chain of PVC-foam production

Feedstock used for PVC-foam production includes PVC, MDI, TDI and PhAA which represent about 92.7% of the total feedstock. Other components have not been reported in the underlying LCA of Divinycell.

Isocyanates are required for the foaming process. The process chain for both TDI and MDI starts with toulene and benzene. The next step is a nitration. TDI and MDI are finally obtained by further reaction with phosgene, which is made from chlorine and carbon monoxide. Data for both process chains have recently been published by the Association of the European Isocyanate Producers (ISOPA)[36]. Adjusted for the specific MIPS-methodology by including the ecological

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[35] Baczynska, M., Divinycell International AB: LCA as a tool for environmental impact description, Laholm, 1996. Moreover: Kellner, Divinycell International, Hannover 1997.

[36] ISOPA/APME (ed.): Eco-profiles, polyurethane precorsurs, Report No. 9, Bruxelles, 1997.

rucksack of mining activities which is neglected in the data-base of the APME studies, those data have been used also for calculation of the material intensity of Isocyanate.

PhAA (Phthalic acid anhydide) is produced by mixing hot air with o-xylene. One of the outputs of the exotherme reaction is PhAA which is separated. Direct data for PhAA production have been not available. However, the LCA of Divinycell allowed a reconstruction of the principal inputs. Total energy consumption has been reported to be 72.04 GJ/t including a feedstock of 58.2 GJ.

Largest feedstock material for Divinycell production is PVC. Due to the controversial discussion about the ecological impact of this material, several extensive studies exist which also investigate the material flows in PVC-production. Comparing the data from different sources does not result in large differences in the overall resource consumption for PVC production. In this study data of the APME have been used, equally adjusted as those for TDI and MDI. Of the three different production processes of PVC, material consumption for average PVC has been calculated.

Other inputs for PVC-foam production are reported to be other anhydrides, filler, softener, pigments, stabilizer, expanding agents. These inputs are part of the specific production know-how and are neglected in the calculations.

Production of PVC foam starts by gelatinization of PVC in an aqueous environment and the forming of the cell structure by thermal decomposition of the blowing agent. In the second phase, the foam is expanded, mainly through the reaction between the isocyanates and water forming CO_2. Finally, the PVC-foam is cured by completion of all chemical reactions. Output of this direct production process is a plate which has to be cleaned by removing the moulded skin and which is further processed into customer-oriented sizes by cutting and sawing. These operations together result in a high waste volume of more than 700 kg per ton of final product.

Production also requires a surprisingly high amount of electricity and natural gas. They account for 52% of the total input of abiotic raw materials and even 58% of the air inputs. Direct water consumption contributes to less than one percent to the total water inputs. The bulk of the water is consumed by feedstock and electricity production[37]. Overall, total input of abiotic raw materials for the production of one ton of final semi-rigid PVC-foam is calculated to be 17.3 tons. Additionally, some 679 tons of water are used and 11.6 tons of air are required for the production.

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[37] Divinycell has requested not to report the exact figure on direct inputs for competition reasons.

category	**per t PVC-foam**	**unit**
abiotic raw materials	17.3	t
water	679	t
air	11.6	t

Tab. 6.1.2: material intensity of PVC-foam
source: own calculations

This material input is nearly double the inputs required per ton of rigid-PUR-foam. However, this difference does not result from using PVC instead of polyols. Whereas production waste during PUR-production is a few kg per ton, PVC-foam production requires more than 1.7 times the input per ton of output. Moreover, energy consumption in PUR-foam processing is much lower compared to PVC-foam production. Thus, it is not surprising that PVC-foam is used only for specialised applications whereas PUR-foam is sold in the mass market. Finally, it has to be remembered that services of both foams differ slightly as PVC-foam has advanced material properties for application in the composite sandwich structures regarded here. If the durability of the PVC-foam in an application is much larger compared to the PUR-foam, the PVC-foam even might be the less material intensitive solution.

6.2. Rigid PUR-foam

Polyurethane (PUR) is a multi-purpose product. Additives allow PUR to be designed with a broad range of features. Generally PUR-foam can be classified into three main types: soft-PUR-foam which is used for example in car seats, mattresses, etc, semi-rigid-PUR-foam and rigid-PUR-foam which are used as insulation material in the construction sector, and among other uses, also as core material in sandwich constructions. Total volume of PUR production worldwide was around 5 million tons in 1990, of which about one quarter was rigid-foams.

PUR has a cell-like structure which can be expanded by using blowing agents. Until recently CFCs had been used as the blowing agent; nowadays pentane or even CO_2 is used. The advantage of PUR-foam is the extreme low heat transition coefficient (0.019 W/m K), whereas tenacity and stiffness are a little bit lower than those of PVC-foam[38].[39]

Production of rigid PUR-foam requires Isocyanate (MDI), polyols and pentane. The foam is produced by exotherm reaction of the isocyanate with the alcohol forming the urethane group.

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[38] see for example: Ullmann´s Encyclopedia of Industrial Chemistry, Vol. A21, 1988-1993, S. 698

[39] previous studies are: beicip-franlab Petroleum Consultants, Eco-Bilans, production of expanded Polytyrene, extruded Polytyrene, rigid Polyurethane Foam. Document prepared for Pittsburgh Corning Europe, Finland 1993. Ceuterick, D.: Life cycle inventory for wall insulation products. Document prepared by „Vlaamse Instelling voor Technologisch Onderzoek“ (VITO for the Danish Envrionment Protection Agency, Mol, Belgium 1993.

-NCO + HO- --> -NH-CO-O-
Isocyanate + alcohol --> urethane group

Types of polyols and the amount of isocyanate vary considerably depending on the type of foam produced. Data on the accumulated inputs for these free chemicals which have been published recently by the APME have been used also for the analysis of material intensity of PUR-foam after the adjustments mentioned above[40].

Inputs per t rigid PUR-foam	**inputs [kg]**	**MI- factor [t/t]**	**MI- abiotic [t]**	**MI- factor [t/t]**	**MI- water [t]**	**MI-factor [t/t]**	**MI- air [t]**
polyoles	385	6.50	2.50	465.0	179.0	3.51	1.35
MDI	616	5.20	3.12	440.1	271.6	3.89	4.06
pentane	54	1.98	0.11	109.7	5.9	2.18	0.12
precursor-delivery	1001	0.84	0.84	5.1	5.1	0.42	0.42
electricity(kWh)	417	1.58	0.66	63.8	26.6	0.42	0.18
Σ total process			**7.3**		**488**		**6.1**

Tab. 6.2.1.: material intensity of rigid-PUR-foam
Source: inputs: APME-Report No. 9, Bruxelles 1997; rucksacks: Wuppertal Institute

Results show that delivery of one kg of rigid-PUR-foam is connected with the consumption of 7.3 kg abiotic raw materials, the use of 488 kg water and the burning of 6.1 kg of air. These values are far below the inputs required for one ton of PVC-foam. However, differences in life-time and the amount of material required in a specific application have to be taken into account to decide which core material is leading to a lower material input to provide a specific service.

7. Material intensity of competing materials

7.1. Material intensity of steel

Today steel continues to be the dominant construction material. World production of about 750 million tons exceeds the amount of glass fibers nearly by a factor of 100. Thus, material intensity of steel has been analysed in previous studies of the Wuppertal Institute by Merten[41]. and Haberling[42] In these studies material flows of the whole process tree of steel production

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[40] APME (ed.), loc.cit.

[41] Merten, T., Liedtke, C., Schmidt-Bleek, F.: Materialintensitätsanalysen von Grund-, Werk- und Baustoffen (1). Die Werkstoffe Stahl und Beton. Materialintensität von Freileitungsmasten, Wuppertal Papers No. 27, Januar 1995.

[42] Haberling, C.: Der Schrottkreislauf. Unpublished report to the Division on Material Flows and Structural Change, Wuppertal 1996.

starting from mining operations, carbon and coke production, iron meting until steel refining in blast furnaces and electric steel plants has been inventigated

category	**primary steel MI in t/t**		**secondary steel MI in t/t**		**steel(83:17) MI in t/t**	
abiotic raw materials	6.00	6.87	0.16	1.24	5.00	**5.91**
water	10.5	45.7	0.9	44.4	8.9	**45.5**
air (oxygen)	2.18	2.41	0.15	0.44	1.83	**2.08**
electricity (kWh)	551	-	681	-	573	-
energy (GJ)	21.8	26.8	2.0	8.2	18.5	23.6

Tab. 7.1: Material intensity of primay-, secondary- und average steel according to German production excluding and including the rucksack of electricity production calculated after the average for the OECD-Europe. **Source:** Wuppertal Institute

Whereas in blast furnaces only tiny amounts of secondary materials are used, in the electro furnace steel is produced mainly by using secondary materials. Nevertheless, in Germany electric steel plants only contribute 17% to the overall steel production in the early nineties. Although worldwide the share of electric steel is higher, here the German relation of blast furnace steel and electro steel has been used.

In analogy to the composite materials, material intensity is calculated using OECD-average data for electricity production. Thus, MI for steel is slightly lower here than for German production.

7.2. Material intensity of aluminum

Material intensity of aluminum production has been already published by the Wuppertal Institute[43]. Starting at bauxite mining, alumina production by the bayer process, anode production by petrol coke and pitch and finally the elctrolytical refining has been analysed.

Due to the huge electricity demand of the refining process methodology of electricity accounting is of crucial importance for the final results. The European aluminum industry claims that about 50% of the electricity used in the melting is produced by hydropower. However, it would be methodologicaly not correct just to use there data as a basis for aluminum production but calculateing carbon fiber production with world average data. Therefore, here electricity consumption in aluminum prodcution is accounted with the OECD-Europe average data. It should be mentioned that there are also about 20% hydropower included within this figure.

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[43] Rohn, H., Manstein, C., Liedtke, C.: Materialintensitätsanalysen von Grund-, Werk- und Baustoffen (2).Der Werkstoff Aluminium. Materialintensität von Getränkedosen. Wuppertal Papers No. 38, Juni 1995.

Second important parameter is the amount of recycling scrap as this reduces electriticy consumption down to less than 10%. Wolrd average is about 30% which also has been using in this study.

category	**primary aluminum MI in t/t**		**secondary aluminum MI in t/t**		**aluminum (70:30) MI in t/t**	
abiotic raw materials	7.50	33.3	0.59	1,55	5.42	**23.8**
water	21.3	1,062	10.2	49,2	18.0	**758**
air(oxygen)	3.72	10.65	0.26	0,52	2.69	**7.61**
electricity (kWh)	16,301	-	609	-	11,594	-
energy (GJ)	40.9	188.2	3.2	8.8	29.6	134.3

Tab. 7.2: Material intensity of primay-, secondary- und average aluminum according to German production excluding and including the rucksack of electricity production calculated after the average for the OECD-Europe.
Source: Wuppertal Institute

8. Applications

The composite material does not exist. Instead it is designed for each specific application according to the required features. Eco-efficiency calls for the analysis of the whole life-cycle including the services delivered during the user-phase. Therefore, in this study two applications have been further analysed: the body of a passenger ship on the Weser river, and secondly, the mobile arm of a robot in an application in mechanical engineering.

8.1. Catamaran

In the following it will be examined whether either a steel, aluminum or composite version of a passenger ship providing the service of passenger transportation on the Weser has the highest resource productivity. Therefore, first the material inputs required for the production of the three ship-bodies will be calculated and compared. In the second and deciding step, the material input over the whole life-cycle, in this case especially during the user-phase, will be calculated. Further equipment and superstructure of the ships will not be considered as well as maintenance and repair.

Tab. 8.1.1 shows the underlying data for the comparision of the three versions. Due to the lower weight the composite version requires a smaller motorization compared to the aluminum und steel ships. Motorization of the aluminum-version could be reduced; however, performance of different engines does not vary continuously. Production waste is assumed to be 20% in the case of composites and 15% for the metal bodies. The structure of the outside hull is shown in Tab. 8.1.2. The laminate is designed out of 4 layers of E-glass, 6 layers of R-glass, 2 layers of aramid tissue and PVC-foam contributing to around 22% of the total weight. Epoxy is used as matrix resin. Framework only requires biaxial e-glass, surface finishing consumes about 120 kg of gelcoat and topcoat.

	composite-version	**steel-version**	**aluminum-version**	
type of material	laminate	St 42	AlMg 4,5 Mn	
surface hull	72	72	72	m^2
weight of outside hull	565	2060	897	kg
frame	37,5	975	440	kg
production waste	20%	15%	15%	
gelcoat, topcoat	120	120	120	kg
operating data:				
daily operation	10	10	10	hours
yearly operation time	300	300	300	days
lifetime	25	25	25	years
performance	2*405	2*850	2*850	KW
speed	28-30	25-30	33	nudes

Tab. 8.1.1: Input data of the catamaran and operation features
Source: Verbundwerkstofflabor, 1997.

laminate	**angle degree**	**layer-thickness in mm**	**weight of fibers g/ m^2**	**weight of resin g/ m^2**	**weight of laminate g/ m^2**
E-glass tissue	0	0,13	105	105	210
R-glass tissue	0	0,45	500	300	800
R-glass UD	45	0,23	250	151	401
R-glass UD	0	0,23	250	151	401
R-glass UD	- 45	0,23	250	151	401
p-aramid tissue	0	0,27	182	168	350
E-glass tissue	0	0,13	105	105	210
PVC-foam H80	0	20			1600
E-glass tissue	0	0,13	105	105	210
p-aramid tissue	0	0,27	182	168	350
R-glass UD	- 45	0,23	250	151	401
R-glass UD	0	0,23	250	151	401
R-glass UD	45	0,23	250	151	401
R-glass tissue	0	0,45	500	300	800
E-glass tissue	0	0,13	105	105	210
total		23,34			7146

Tab. 8.1.2: Composition of the laminate of the body for the catamaran
Quelle: Verbundwerkstofflabor, 1997.

In all cases energy consumption for the production has been ignored, the same for auxiliary materials and mechanical tools. Nevertheless, generally composite manufacturing should require less resources compared to metal manufacturing as the basic materials are more flexible and forming does not require such high pressures or temperatures.

Overall, production of the light composite version requires only about half of the abiotic resources required for a steel version and air consumption is down from 14.1 t to 9.9 tons per ship-body. Responsible for the high water consumption of the composite version is the R-glass in the laminate with its high rucksack of 307 t/t water.

The rucksack of the aluminum version is even larger, being 2.3 to 3 times the material input of the composite version, although a share of 30% secondary aluminum has been assumed. If, like for moulded alloys, only primary aluminum could be applied, material intensity would be even higher.

body production of	**composite-version**	**steel-version**	**aluminum-version**	
abiotic raw materials	22.6	39.4	68.6	t/body
water	641	337	2,194	t/body
air	9.9	14.1	22.2	t/body

Tab. 8.1.3: Material intensity of the production of the two bodies of the catamaran

Nevertheless, decisive from the ecological point of view is the overall resource productivity over the whole life-cycle. If it is assumed that the ships will operate on 300 days per year, 10 hours per day, for a period of 35 years, calculation yields the results shown in tab. 8.1.4. Obviously, accumulated material input during operation is far larger than during production[44]. Overall, the smaller engine under operation in the composite version results in a 52% decrease in fuel consumption compared to the steel and aluminum versions. The contribution of the body production is far less than 1 %. Even if not only body production but total ship construction would be analysed, the principal result would not be very different. Similarly, inclusion of disposal would not change these results as in the worst case of complete disposal to landfill only material flows of the same weight as the ship would have to be added.

Thus, this example shows that light structure engineering in ship building reduces material intensity of the service delivered and increases resource productivity by a factor of 2.

user phase	**composite-version**	**steel-version**	**aluminium-version**	
abiotic raw materials	9,997	20,981	20,981	t/25 years
water	58,082	121,900	121,900	t/25 years
air	27,851	58,453	58,453	t/25 years

Tab. 8.1.4: Cumulated material inputs of the different ships during operation

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[44] Fuel consumption for a medium speed engine is assumed to be 170 g/KWh. Hansa 1993, No. 4, p.51-55.

8.2. Robot arm

The second example deals with the replacement of a conventional steel robot arm in a spraying-machine by a carbon fiber slab. As the mobility of the arms is decisive for the performance of the machinery, performance could be doubled by substituting the steel arm allowing accelerations up to 13 m/s^2 by a much lighter carbon fiber version reaching up to 32 m/ s^2.

However, analysing just the isolated slab shows that weight reduction in itself does not necessarily reduce the material input. Even though with 4.8 kg the carbon fiber epoxy slab is much lighter than the steel version weighting 12.8 kg, tab. 7.2.1 shows that the production of the composite version requires more than twice the material as the steel slab. In both cases, material input for manufacturing has been left out but including them would not change the message.

category	**composite-version**	**steel-version**	
weight slab	4.8	12.8	kg/arm
abiotic raw materials	163	76	kg/arm
water	5.684	582	kg/arm
air	82	27	kg/arm

Tab. 8.2.1: Material intensity of the production of the robot arms compared
Source: own calculations

However, the slab alone does not provide a service. Taking into account the whole machinery, the picture is less dramatic. Besides the slab, two other parts have been replaced in this example, but the bulk of the machinery including the electrical equipment and engine have not been changed or optimized. In total, the weight of the machinery with the composite slab is about 601 kg, whereas the steel version comes to 628.8 kg. Overall, again there is a slight advantage to the steel version. However, if the increase in performance can save having a second machine, an investment of 600 kg abiotic raw material can avoid 9.5 tons which would othwise be needed to provide the capacity.

category	**composite-version**	**steel-version**	
weight of machinery	601	628,8	kg
abiotic raw materials	9,5	10,1	t/machinery
water	168	201	t/machinery
air	2,2	2,6	t/machinery

Tab. 8.2.2: Material input in the production of the two spraying machines
Source: own calculations

Nevertheless, again decisive for resource productivity is the whole life-cycle. Therefore, the increased performance of the machinery has to be taken into account. Fig. 8.2.3 shows how the specific material input decreases if the output of the machinery is growing. The assumptions for these calculations are the continuous use of the machine 16 hours a day, 250 days per year and an electricity consumption of 3 kWh per hour. Within 5 years this leads to 72 MWh electricity demand causing on the average a material consumption of 114 t abiotic raw materials, 4600 tons of water and 31 tons of air. Obviously, even a slight increase in the performance of the machiner could save the 0.6 tons of abiotic raw materials or 0.4 tons of air invested in the production phase. Savings can be obtained either by reducing the daily time of operation or by increasing output of the same machine thus saving the construction and operation of an additional one. Thus the example shows that in the case of a rather high material input during operation, material intensity per service unit can be substantially reduced by using carbon fiber epoxy composites instead of conventional materials.

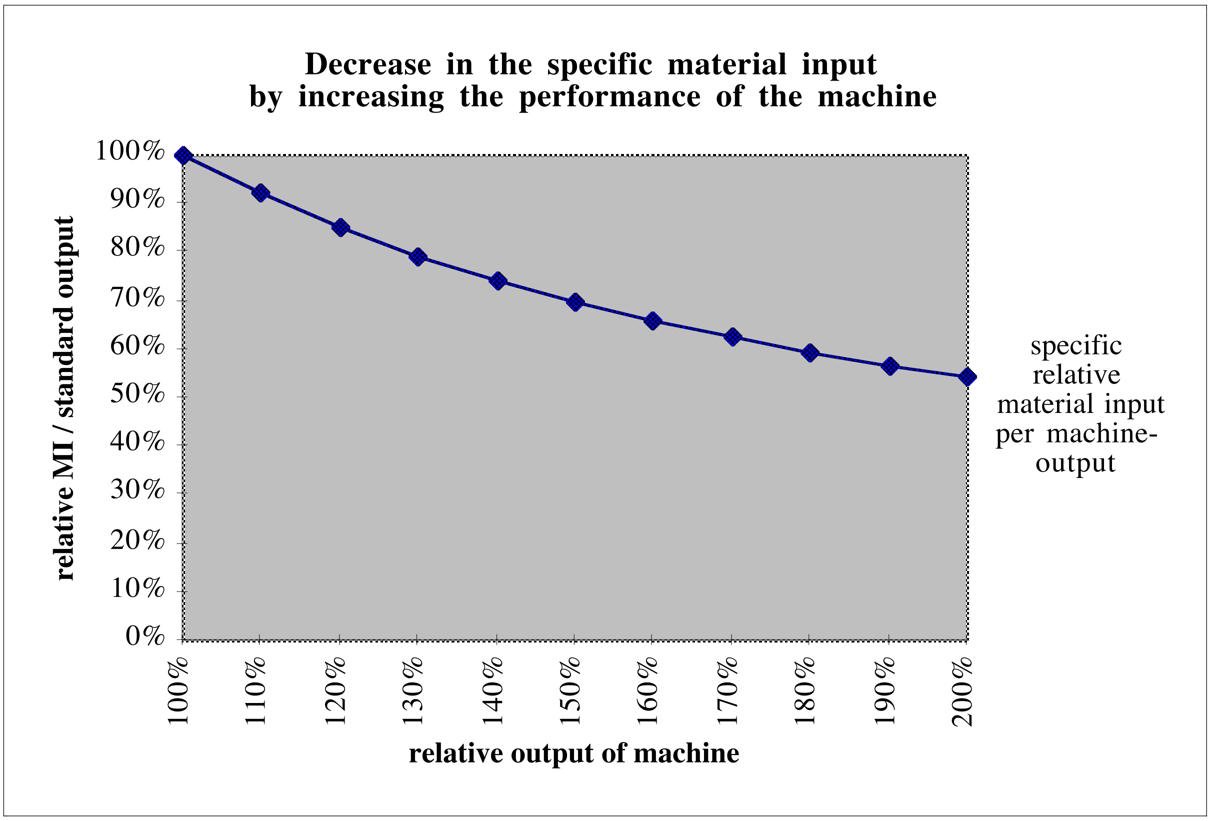

Fig. 8.2.3: Decrease in the relative specific material inputs if the performance is increased by the use of light composite materials; output may be depend on the specific conditions of operation.

9. Disposal and recycling of composite materials

Disposal and recycling of composite materials is a tricky matter. Obviously, an analysis of the whole life-cycle of products and materials has to include also the phase after using a product. In a lot of cases, but not always, use of recycled materials results in a decrease in the material intenisity thus being one strategy to increase resource productivity[45]. However, in a lot of cases recycling does not in fact result in a material of the same quality. Instead it has to be seen as a down-cycling leading to a new kind of material which is able to substitute other virgin material but which in general is of reduced economic value compared to the original product.

The MIPS concept calculates the real inputs in the production process of the materials. Thus, using waste materials as inputs is of advantage to the product made out of these secondary materials. On the other hand there are no credits granted for the original products being recycled at the end of their life-cycle, other than the material consumption for disposal in landfills being saved. Such an approach is of special advantage in the case of long-life-materials and products because otherwise knowledge about future waste treatment facilities would be required which would be highly speculative. In the MIPS concept the only assumption made relates to the percentage of waste which is created after the use of the product. Therefore, potential uncertainties due to the future method of disposal are rather small.

Regarding composite materials, today a real recycling technology does not exist which allows the re-use of the fiber-tissues[46]. Thus, all conclusions of the other chapters concerning the actual resource productivity of those materials remain unaffected. However, in the following the various options for further treatment of the disposal will be examined and some possible future solutions discussed.

The principal aspect limiting the recycling of composites analysed in this study is the use of a thermoplast resin as matrix. Once cured, such materials can not be transferred back to the original materials. Thus each real recycling technology has to deal with the question how to separate fibers and matrix which allows the re-use of the structural fibers and tissues and not only of short fiber pieces. Thermoset resins could be an alternative in the future but up to now such recoverable resins do not have the same quality material features as thermoplastic resins.

9.1. Re-use of material

Public discussion on waste volume has put pressure on composite manufacturers and users to develop recycling strategies. As a result of this concern the ERCOM company, which is part of the BASF group, has developed a technology to recycle SMC/BMC (sheet mould compound/ bulk mould compound) which are used, among other areas, in the automotive industry.

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[45] see: Bringezu, S., Stiller, H., Schmidt-Bleek, F.: Material Intensity Analysis - A screening step for LCA. In: Proceedings of the Second International Conference on EcoBalance, Tsukuba 1996, p.147.152.

[46] Allred, R. E.: Recycling Process for Scrap Composites and Prepregs. SAMPE Journal, Vol. 32, No. 5,1996, p. 46.

The ERCOM technology allows the mechanical separation of the short-fibers and matrix resins[47]. After a preliminary cutting the material is transported to the ERCOM recycling plant where metalic parts are separated by magnetic separators. There follows a further breakup of the material, drying and separation into different material fractions. This mechanical technology allows a separation of short-fibers and matrix particles which can be reused either as filler added to the compound or partly even as substitute for virgin short-fibers. In effect, the ERCOM products show slightly different features compared to conventional fillers and fibers as the material has a lower density. Re-use in SMC by 30% volume leads to an increase in resin consumption by around 2%, a reduction of fiber glass requirement by 5% and a substitution of 75% of the filler used in this example[48].

However, when it comes to carbon fibers, no experience with such a material exists. According to ERCOM there is no evident obstacle why a similar treatment with CF-epoxies should not be possible. In the case of the laminate, there is a politically motivated resistance to products containing PVC but no technical obstacle.

Overall, the principle disadvantage of the ERCOM process is the fact that there is no real recycling of the long-fibers and not even potential for technical improvement in this direction. Thus, if it comes to high value carbon and p-aramid fibers the ERCOM process can save only a tiny amount of the invested resources.

9.2. Low temperature catalytic pyrolysis

Low temperature catalytic pyrolysis is a technology developed by the Adherent Technologies Company at Albuquerque, New Mexico designed for the recycling of carbon fibers[49]. The principal idea of the process is to decompose the matrix at rather low temperatures below 200 °C into short chain hydrocarbons which can be re-used in the chemical industry or serve as fuel, thus allowing the re-use of the remaining fiber materials. According to the company the quality of the recycled carbon fibers is nearly the same as of virgin fibers due to the low temperature during the pyrolysis. Actually, the incoming material is cut mechanically but the company claims that in principle the process technology also allows principally the recycling of long-fibers. As the technology is still under development there is not sufficient information available whether this technology really can serve as recycling technology to recycle carbon fibers for

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[47] Schaefer, P.: ERCOM Composite Recycling GmbH, 1997.

[48] Schaefer, P.: Eigenschaften und Anwendungen von Rezyklaten aus faserverstärkten, gehärteten Kunststoffen (GFK), in: Brandrup, J. et al: Die Wiederverwertung von Kunststoffen, München, Wien, 1995, p 766-681.

[49] see: Unser, F. J., Stadely, T., Larsen, D.: Advanced Composites Recycling. „Society of Plastics Industry Composite Institute“, 1996, p.52.

structural applications. Also, at the current stage an estimate of the resource intensity is not possible.

Compared to these rather promising results, experiences with the conventional pyrolysis of glass-fiber reinforced pureurethane-foam at Hamburg University have been less positive. Problems with the clogging of cooling equipment by tar could only be avoided by using larger portions of xylene. Moreover, fibers were found to form clusters. PVC from laminates could additionally increase corrosion and form toxic substances. Therefore, at the current stage of investigation conventional pyrolysis can not be regarded as an option for the recycling of structural composite materials.

9.3. Inverse gasification

Inverse gasification is a process which decomposes the matrix into short-chain hydrocarbons and synthesis gas. Thus there is some similarity to pyrolysis. However, whereas a pyrolysis requires additional energy inputs, inverse gasification is an exothermic process. Final products are fibers and filler materials which remain in the reactor. The technology is still under development by Environmental Technical Services (ETS) in Missouri. Whereas the recycled short-fibers show good mechanical properties, inverse gasification does not allow the recycling of long-fibers[50]. Data about the efficiency of the process are not available.

9.4. Methanolysis

Methanolysis is a well established process for the recycling of PET to regain the basic materials of PET production, dimetyltherephthalate and ethylen glycol. At temperatures higher than 200° C and pressures above 20 bar, PET decomposes if catalysts are used[51]. Although the process was up to now only used for thermoplastics, according to Cornell[52] it should also be applicable to advanced composite materials. However, the principal problem to solve is again the question of how to regain the long-fibers and fiber-tissues. One idea is the use of specific „fixing“-resins which would not be dissolved during methanolysis. As methanolysis is actually not applied for composite recycling, no data on the resource productivity are available.

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[50] see: Unser et al., cit loc.

[51] see: Klein, P.: Solvolytische Verfahren für spezielle Kunststoffe in: Brandrup, J. (Ed.): Wiederverwertung von Kunststoffen, Wien 1995, p.509.

[52] Cornell, D.: Estaman Chemical Company, pers. com. to A.Lovins, 1995.

9.5. Incineration

Strictly defined incineration of composites is not a recycling option but a method of disposal. In fact, a specific plant for the incineration of composite material does not exist. Volumes are far too small, also such a method of disposal is not enforced by state regulation. Thus, composites as one fraction in conventional waste incineration have to be discussed. Here, the principal objective is rather the treatment and volume reduction of waste. Cogeneration of energy and electricity is only a secondary aim. Consequently, efficiency of electricity generation at most incineration plants is only at 20-25%[53], compared to more than 50% in modern gas-fired power plants, partly due to extensive cleaning of the exhaust gases. Heating value of epoxy resins is about 30 MJ/kg. Fillers and fibers reduce the heating value of composite materials as SMC down to 12 MJ/kg. Whereas glass fibers end in slags heating value of carbon fiber composites is slightly higher as the fibers can be incinerated, too.

9.6. Steel-making processes

In steel-making carbon atoms are used to supply the energy required for the process and serve as reduction agent. Conventionally carbon is supplied by coke coal. However, advanced steel making technology has substituted and thereby reduced coke input by pulverised coal and heavy fuel oil. Therefore, in principle, composite waste should also be able to serve as carbon source and fuel.

Experimental use of plastic packaging waste of the German DSD at Klöckner Steel Company, Bremen in the early nineties showed that although inputs supplied didn´t meet the official criteria, steel making hadn´t been negatively affected[54]. Control of exhausted gases didn´t show any enhanced concentration of dioxine due to the high temperature in the oven and the highly reductive environment. Nevertheless, mainly for political reasons the amount of chlorine in the input materials was not alowed to exceed 0.5%. Niemöller[55] points out that only political arguments can justify such a figure. But he also mentioned that high chlorine concentration might speed up corrosion processes in the blast furnace and exhaust gas treatment equipment. An important positive side-effect of the use of plastics in steel-making is the rather low capital investment required[56]. Thus, such structures are more flexible if the waste volume decreases. Krupp Hoesch is more sceptical about composite waste as carbon supplier not because of

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[53] Umweltbundesamt: Energieaspekte bei der rohstofflichen Verwertung von Altkunststoffen aus DSD-Sammlungen, Berlin, 1994, nach: Lahl, U.: cit loc.

[54] Janz, J.: Recycling von Mischkuststoffen im Reduktionsprozeß - Das ökologische und ökonomische Potential des Hochofens, in: Breuer, H., Dolfen, E. (Ed.), Kunststoff-Recycling Kolloquium 1996, p.17-34.

[55] Niemöller, B.: Reduktion im Hochofen, in: Brnadrup, J. et al. , a.a.O.

technological reasons but rather because they fear that a fixed amount of composites could not be supplied[57].

As no experiences exist on using composite waste in blast furnaces, conclusions on resource efficiency can only be obtained by crude estimates using analogies. Experience with heavy fuel oil and plastics shows that there is a substituion rate of 1:1 because of a similar heating value. Thus blowing in 1 kg of GF/EP with a heating value of 12 MJ/kg would save some 280 g heavy fuel oil. As the glass fiber is composed of minerals which might reduce furnace efficiency to some extent, energy demand could slightly increase. On the other hand, some minerals like limestone are added anyway to improve slag composition. For carbon fiber composites such problems do not occur as the fiber is burnt in the furnace, too. In general, slag is not put onto a landfill but used as construction material, for example in road or waterway construction. Therefore, use of composites in blast furnaces would avoid material inputs for landfills. Overall, calculations show saving to be 1,4 t/t abiotic raw material input and 0,4 t/t water input compared to putting reinforced plastics on landfills, whereas air consumption increases by 0,3 t/t.

9.7. Comparision of the various options for disposal

In the previous paragraphs serveral options for a future recycling of disposed composite materials has been presented. However, none of them up to now allows a full recycling. How far a real recycling can be achieved at all remains an open question as the high quality of the fibers made out of very sophisticated production processes and surface treatment requires very tricky solutions. Thus, the material intensity of advanced composite materials, which is calculated according to the real inputs in the production process, is nearly not affected by this open question because for high performance composites production will continue to be based on primary materials in the near future.

Smaller changes only might occur due to the avoidance of landfill disposal which would add the use of about 1 ton abiotic raw materials per ton disposed material, 0.4 tons of water and an insignificant amount of oxygen (0.015 tons)[58].

Nevertheless, recovery of fibers at reduced quality seems to be possible. Best results can be expected if, on the one hand, the fibers are re-used thus increasing the resource productivity of another product and, on the other hand, if the energy content or the basic chemical components

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[56] Lahl, U.: Der Einsatz von Kunststoffen im Hochofen - Ein Rückblick, in: Müll und Abfall, Heft 5, Vol. 27, May 1996, p.309-313.

[57] Erdmann, Krupp-Hoesch AG 1997.

[58] calculated using data of: Schaefer, H., Mauch, W.: Energiebilanz und Entsorgungspolitik im Widerspruch ?: in: VDI-Berichte No. 100, 1994, p.101-116.

of the matrix are used. But as there is no information available in detail at the current stage of technological development about the performance of the recycled fibers, quantitative judgements about the various processes such as low temperature pyrolysis, methanolysis, gasification, etc., would be highly speculative. However, as material intensity of some composite materials is rather high, obviously the quality of the recycled fibers is a decisive factor in the assessment of these different options. Nevertheless, output fibers are rather a new product with specific features which allow the substitution of various materials depending on their use. Approximation of these materials by data for virgin fibers could lead to ecologically conterproductive conclusions.

To give at least some quantitative assessment of the resource productivity of the different ways of disposal, mechanical re-use of glass fiber compostites (SMC) by the ERCOM technology, incineration, their use as input in blast furnaces and disposal to landfill have been compared. Results show that the largest amount of material inputs is saved by the re-use of fibers. Second best option seems to be incineration regarding the abiotic raw materials and the blast furnace if it comes to air input. It has to be mentioned that the advantage of incineration in this calculation is based on the rather high material intensity of electricity compared to heavy fuel oil which is the substituted product in the steel-making process. If electricity was only produced by heavy fuel oil or gas, the use of composite waste in blast furnaces would show higher savings due to the more efficient use of the energy content of the matrix. Worst resource productivity shows the disposal to landfill. Here the rather good value for air is the consequence of the specific system boundary. Whereas in the case of use for incineration and in blast furnaces the air for oxidation is taken into account, air inputs in chemical reactions after the deposition is not included in the data for landfills. Therefore, the air figure in this case is only of limited value.

	landfill	incineration	blast furnace	re-use (ERCOM), SMC/BMC	
abiotic raw materials	1	-0.72	-0.39	-1.9	t/t $_{\text{waste}}$
water	0.2	-53.07	-0.20	-12.4	t/t $_{\text{waste}}$
air (oxygen)	0.015	0.58	0.33	-0.15	t/t $_{\text{waste}}$

Tab.9.7.1: Saved material inputs by different options of waste disposal of sheet/bulk mould compound
Source: own calculations

10. Conclusions

This study systematically provides the necessary information to compare composite materials with conventional construction materials. It has been shown that depending on the specific boundary conditions composite materials can enhance resource productity and thus reduce ecological impact potentials.

Whereas the example of the catamaran showed that light composite materials can already reduce the material input during construction, the use of carbon fibers epoxy composite does not result in a direct dematerialisation in the second example. This leads to the conclusion that in the case of products which require no or only a small material input during their use, the use of composite materials might but not necessarily increases the resource productivity.

Nevertheless, the larger the material inputs during operation, the higher the chances will be for an overall improvement in resoure productivity by weight reduction. Similarly, an increase in resource productivity is more likely if the use of composite materials increases the number of services delivered of the product during its life-time.

Both examples in this study show the tremendous importance of the user-phase. In the case of the catamaran, more than 99% of the life-cycle wide material intensity is contributed by the user phase ignoring the inputs for equipment and maintenance. In the case of the robot arm higher inputs during the construction are by far outweighed by the reduced material input per service unit as the performance of the machinery has been increased. Of course, in a more detailed analysis inputs for material processing and parameters like breakdown records have to be included. Thus, potential ecological benefits of the use of composite materials depend on the user-characteristics.

These results, for example, allow a first estimate whether weight reduction by using composite materials in the automotive industry will improve the resource productivity as Amory Lovins

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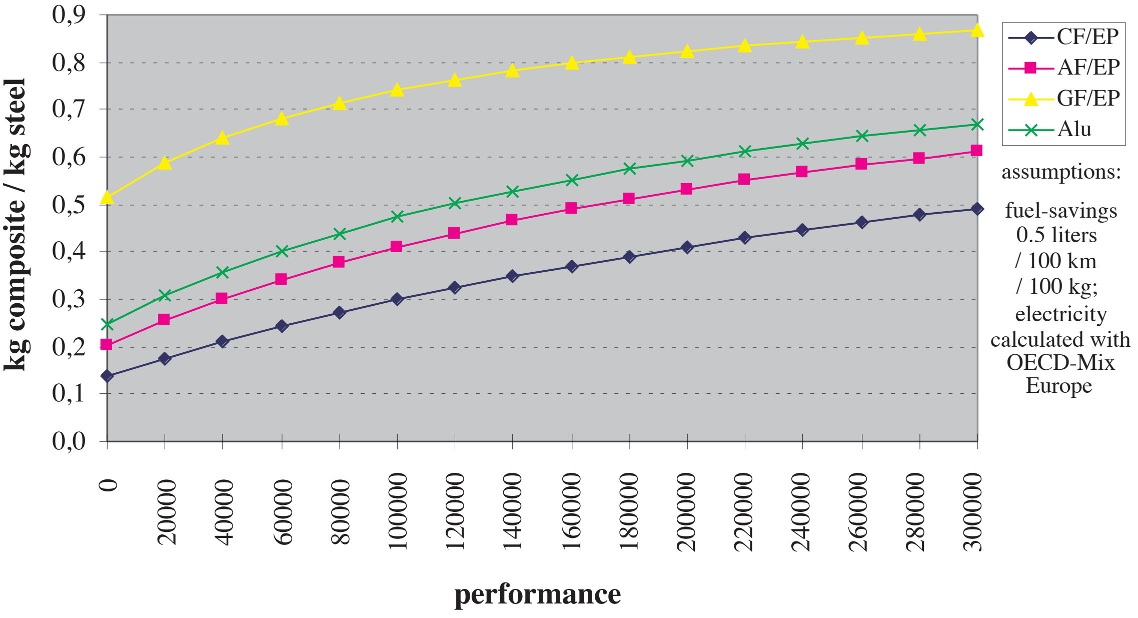
proposes for a reduction in fuel consumption of nearly 10-timers the amount[59]. If all other parameters like engine, size, performance, security, etc., are faded out, figures 10.1 and 10.2 show how much composite material can be used to substitute one kg of conventional steel so that the overall resource productivity is still increasing. The underlying assumption is a reduction in fuel consumption by 0.5 l per 100 km and per 100 kg. Inputs for processing are neither included in the figures for steel nor for the alternatives. The two figures show that investment in composite materials or aluminum is amortized much slower when taking the raw material input compared to the air indicator. Obviously, at a typical performance of 200,000 km using carbon-fiber epoxy composites, there has to be a 60% weight reduction compared to the steel version before the overall resource productivity improves. Thus, to enhance the overall resource productivity per car km for each kg of steel less than 0,4 kg of carbon fiber composites can be used. Even if a more detailed analysis is made of the rather energy intensive processing of a steel body in white, an easy reduction of the abiotic material inputs is not likely to happen. Compared to this indicator, figures for air, which strongly correlate with the CO_2-emissions, show a much lower break-even point at a 40% weight reduction compared to a steel version. And more convenient composite materials like glass fibers do not reduce the weight so far but lead to an improvement at a much earlier stage. Thus it is not surprising that advanced composite materials like carbon fibers up to now have been used mainly in shipbuilding and the airplane industry where performance is typically not 200,000 km but several million km. Their use in the automotive industry has to be accompanied by an increase in resource productivity of their production.

material substitution for automobiles:
Weight reduction required for the reduction of
abiotic raw materials (MI abiotic) during their whole life-cycle



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[59] Lovins, A.B. et al: Hypercars: Material and Policy Implications: Rocky Mountains Institute, 1995.

Fig.10.1: Material substitution for automobiles: Weight reduction required for the reduction of inputs of abiotic raw materials during their whole life-cycle; without inputs for material manufacturing
Source: own calculations

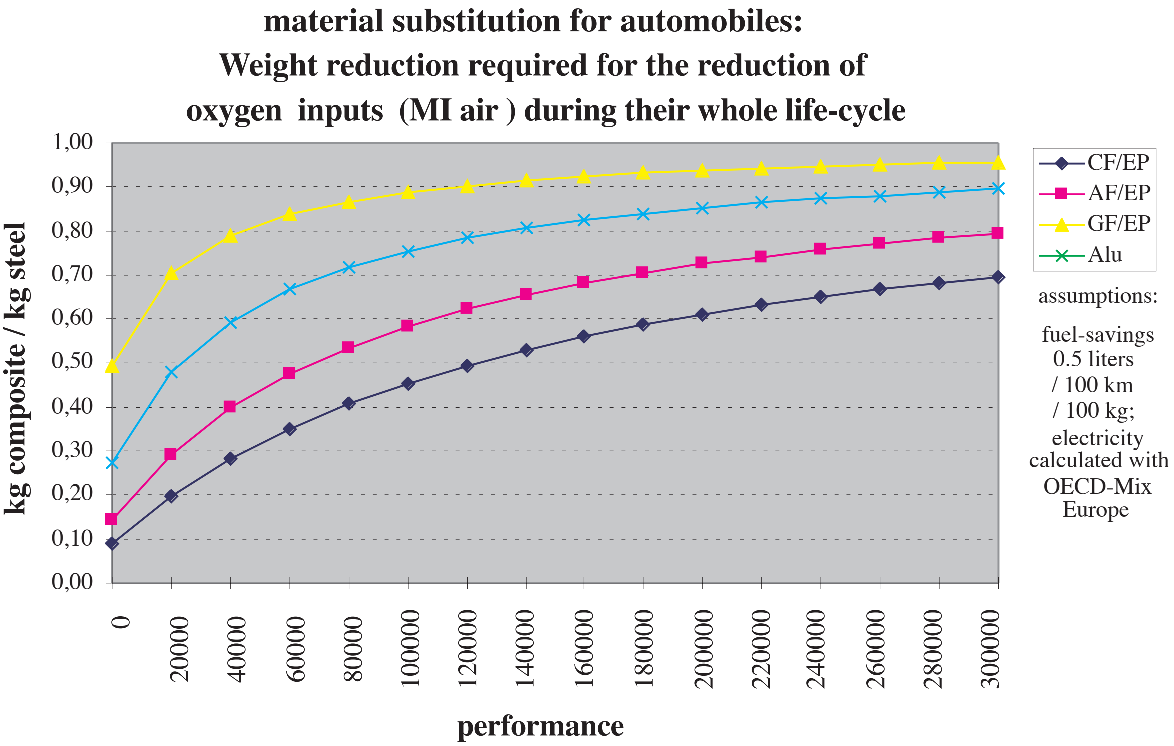

Fig.10.2: Material substitution for automobiles: Weight reduction required for the reduction of air (oxygen) inputs during their whole life-cycle; without inputs for material manufacturing
Source: own calculations

However, even though the MIPS-concept tries to measure the ecological impact potential in a rather simple way, not all aspects of the process chains from the cradle to grave could be analysed, although in a lot of cases results of previous studies of the Wuppertal Institute and other sources could be used. Sometimes material input for a specific substance has been approximated by data for similar substances. As an example, in this study terephthalic, orthophalic and isophthalic acid have been considered as having the same ecological rucksack even though there are specific differences in the production processes of these isomeres. Moreover, as the data for glass fiber production have shown, production inputs even for the same product might vary considerably. And in several cases only a few or even one source have been analysed although several manufacturers and plants exist. Enlargement of the data basis would stabilize some of the calculated ecological rucksacks und would sometimes even lead to small changes in the values reported here.

Moreover the manufactureing of the laminates has been left aside Hand lay up, prepreg production, RTM, pultrusion, etc., have not been analysed. This is partly because analog steel processing has not been included because the analysis of the basic materials required much more effort than expected. In a more detailed analysis the differences in the material input due to the various processing options should be analysed. But even more important would be a more detailed approach towards the various products of the fiber and resin producers. In reality one type of e-glass, carbon fiber, epoxy resin, etc., does not exist. Data presented here represent average values over a whole product class. Even those reported by a single manufacturer in general have been average values for total production facilities. So far it has not been analysed whether and how much the quality or specification of materials influences the total material input. However, this kind of information cannot be generated by roughly calculated values but would require detailed input data at the company level provided by an environmental management system.

Finally, for an overall ecological impact assessment not only the resource productivity but also if well-known toxics like styrene emissions are released during final processing can be of importance.

Nevertheless, if there are no serious impacts by toxic releases the examples show that there is a significant potential for an improvement is the resource productivity by the use of composite materials especially if it comes to mobile applications. It is the task of designers and constructors to use the results presented here in their development of more ecological products and services. The decision which material can be used for a specific purpose of course depends on a lot of factors. Material flows in their production and induced flows during opertion should be one of them.