TECHNICAL PROGRESS IN THE ALUMINIUM INDUSTRY
–A SCENARIO APPROACH–

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Abstract

Analysis and modelling of material flows in complex production systems are appropriate instruments to show existing potentials for an efficient use of resources following the idea of sustainable development. Using scenario techniques significant future developments of aluminium production, manufacturing and recycling can be evaluated. This article focuses on technical progress along the material flow of aluminium from mining, smelting, to recycling and disposal. For this a technology-orientated process chain model has been developed. As an example the German packaging industry and its special recycling concept, including material and energy supply and transport has been chosen. The 1997 basis scenario is compared with a calculation considering newest technologies known today and a further one with regard to their possible application in the year 2010. The results help to identify technical potentials in different process steps of packaging life cycle and to analyse their impacts on the environment.

Introduction

Worldwide, the concept of sustainable development is being discussed. At the moment, the discussion is shifting to a group of resource and environmental sensitive industries. Aluminium production is regarded as one of the group [1]. Agreeing that sustainability requires to balance economic, ecological and social aspects, experts formulated strategic rules for the use of renewable and non renewable natural resources, the assimilative capacity of the environment, and the adequate consideration of time [2]. For more practical purposes there is a need to develop differentiated rules keeping in mind special aspects of products, production processes and industrial sectors.

Technical progress is regarded as a means of creating sustainable production systems by dematerialization or efficiency revolution besides other means as e.g. sustainable demand behaviour. Although technical progress can not be easily quantified, its impacts on resource use and emissions can be evaluated on condition that information is available on the level of different processes and locations. Furthermore, the concept of technical progress needs to integrate market processes. Therefore, reliable projections of technical progress differentiate between the technical potential of full capacity replacement by newest technology and the smaller potential of reduced replacement in 2010 which can be realistic implemented under consideration of financial and market aspects.

To reduce the complexity this study selects exemplary the use of aluminium in the German packaging system. It introduces the concept of technical progress for the production and recycling of aluminium packaging, giving detailed description of expected technical progress on the process level within the next decade. The approach follows the modelling concept of a process chain analysis [3]. Using a scenario approach and differentiating between the maximum and predicted technical potential the impacts of the implementation of modern technical concepts on resource use and emissions are quantified.

Production of aluminium and its use as basic material for packaging in Germany

Applications of aluminium as a packaging material are still increasing. The variety ranges from combined coffee-packaging with a low metal content to full aluminium containers. The following data and figures introduce the German packaging system.

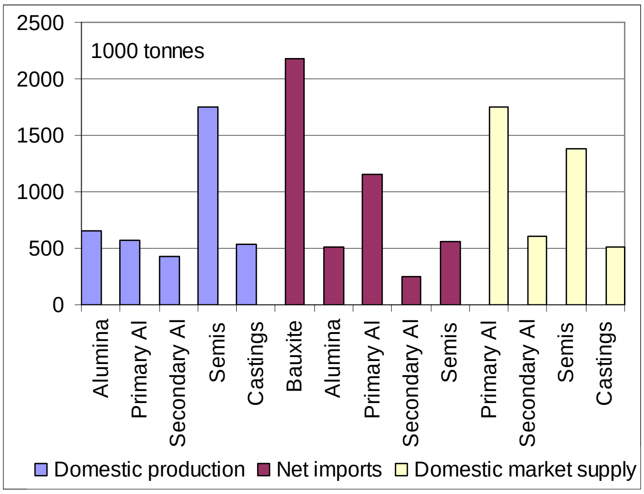
Production and use of aluminium packaging material in Germany

World aluminium demand in 1997 was 30 million tonnes. Germany’s share was 8.5% of total, but 30.7% of European metal demand which characterises Germany as one of the big aluminium markets.

German aluminium supply is highly dependent on imports (fig. 1). Whereas the proportion of imported bauxite is 100%, the proportion for alumina and aluminium is less but considerably high.

Roughly two thirds of primary aluminium supply is imported material. On the other hand the supply of secondary aluminium was mainly covered domestically. The overall use of primary and secondary aluminium was 2.5 million tonnes, 1.8 million tonnes were semi-finished wrought products and 0.6 million tonnes were castings.

The total German production of packaging material for domestic use and export was 540,000 tonnes which makes it the biggest in Europe with a share of 32% of total rolled products. In Germany itself, with 110,000 tonnes, the packaging sector is the third important end-use sector of semi-finished products behind building and transport.



Sources: Metal Statistics/Statistisches Bundesamt/GDA

Fig. 1: Aluminium balance for Germany, 1997

Another argument to investigate aluminium packaging is the actual discussion of the German system of recycling of light packaging materials [4].

The production of packaging material starts with primary aluminium production from bauxite (fig 2). In the cast houses of the smelters unalloyed aluminium is cast directly into rolling slabs for foils. Alloyed aluminium for strip, especially can body and can lid stock, is cast after addition of scrap and/or alloying elements to the molten metal. Latter is also done at remelting facilities of rolling mills which mainly use in-house fabrication and foreign scraps and primary ingots. The following strip production is done by conventional hot and cold rolling. There the foil reaches a size reduction down to 7 microns for unalloyed material and down to 100 microns for AlMgMn-Alloys. For the various aluminium bins, tubes and cans the investigation ends up with the production of alloyed strip for deep-drawing operation.

Recycling of aluminium packaging

In Germany, aluminium packaging is recycled together with other light packaging material (LPM) by the Duales System Deutschland AG (DSD). 1997 nearly 2 Million tonnes of LPM-material were collected separately from household waste and afterwards recycled. 56,470 tonnes of that were aluminium packaging with a metal content of 28,580 tonnes [5]. Beside that, 21,650 tonnes of bottle closures and 7,000 tonnes of menu plates were collected. It is to note that in Germany no separate collecting system for used beverage cans exist, because the share of aluminium cans is only about 15 %.

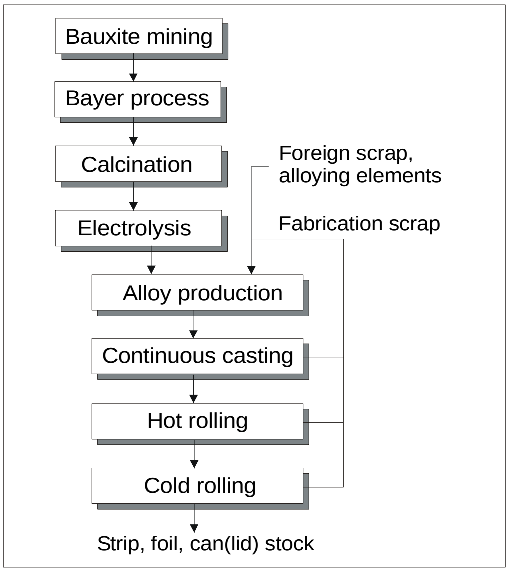


Fig. 2: Production scheme for aluminium packaging material

Figure 3 shows the process steps which form the system of LPM recycling in Germany. The system for the recycling of aluminium is divided into three levels. First, the collection of the secondary raw material takes place. Second, the material has to be processed in order to achieve an aluminium product which can be remelted. Therefore, the aluminium fraction is separated from other packaging material in sorting plants. As the aluminium fraction has an aluminium content of only about 40%, further processing is necessary prior to remelting. This processing takes place in three different types of plants and can be characterised as mechanical processing, processing of combined material with subsequent pyrolysis, and straight pyrolysis.

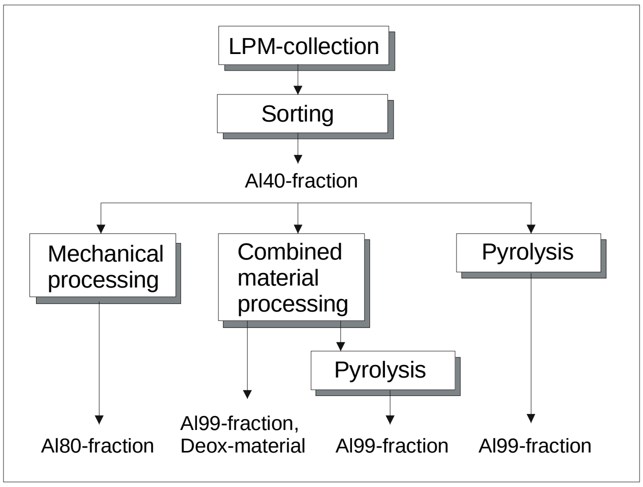


Fig. 3: German recycling system for LPM (level 1 and 2)

Finally, the remelting of the aluminium fractions on the third level of recycling takes place. Here, a certain amount of metal is lost due to oxidation in dross or salt cake.

The efficiency of the recycling system for aluminium packaging in Germany can be described for collection, processing and remelting. Each level of recycling causes losses of metal so that the overall recycling quota (collection, processing, remelting) is 60 % and the technical recycling quota (processing, remelting) is 67%.

Process chain model

To analyse the material and energy flows of aluminium a process chain model has been developed [3]. Its main aspect is a technical link of production processes, showing the material and energy flow of the aluminium production using the concept of process description by input and output parameters. The process chain model describes the aluminium flow from bauxite mining to the production of aluminium including primary and secondary aluminium and the recycling of the used material.

Beside the production levels shown in figures 2 and 3 transportation and energy supplying processes are also taken into consideration as well as the production processes of intermediate products and waste treatment. Each production level represents a variation of technology-specific and location independent modules. The technical status of the processes is classified into different technology categories. They are old technologies (OT), present technologies (PT), and the newest available technologies (NT) which are already introduced. Furthermore, technical options for future use (FT) are existing.

The end product manufacturing process and also the use phase are important elements in the process chain, which will be included in near future [6].

The scenario “technical progress”

Technical progress is one subject in the discussion of sustainable development which can be evaluated using scenario technique [7]. For the chosen example the changes in material and energy flows due to technical progress and innovation and its impacts on the environment was investigated in a first analysis. To separate different effects the scenario approach is carried out in three steps:

1. The reference case shows the domestic market supply for Germany for **1997** (including import and export of primary aluminium, its pre-products and secondary aluminium).
2. As a second case the maximum technical potential is calculated considering the exclusive application of newest technology (**NT**) for each process of the 1997 structure.
3. In a third case financial and market aspects are taken into account. Looking at **2010** as the target year only a part of existing plants will be replaced by NT. Some plants will be upgraded and others will not be changed at all. This differentiation is not a model result but exogenously determined based on expert information.

The results of all three cases were compared resulting in possible and probable effects of technological progress and its impact on the environment in a medium term time frame.

Set of assumptions

The calculations are based on constant amounts of production and recycling. Also the import structure and the share of secondary raw materials for alloy production were not varied. To ensure comparability the different calculations need assumptions to close data gaps and differences between statistic and plant information.

1997 reference: For the production of semi-finished products for the packaging sector bauxite, alumina and primary aluminium were imported from several countries. Table I shows the share of these countries in 1997 distinguishing between direct sources and indirect sources. Latter are those countries which export pre-products to direct suppliers.

Table I: Direct and indirect sources of bauxite, alumina and primary aluminium for the German packaging system 1997

	Bauxite %	**Alumina** %	**Aluminium** %
Australia	14.8	8.5	
Brazil	9.1	7.5	7.5
Canada		2.4	9.0
France		0.4	0.9
Germany		19.9	46.9
Ghana	2.0		
Greece	0.1	0.1	
Guinea	19.0	0.1	
Guyana	8.6		
Iceland			4.4
Ireland		7.0	
Italy		2.9	
Jamaica	30.1	29.4	
Norway			12.0
Russia	11.8	11.8	12.8
Spain		1.4	
Suriname	4.0	3.6	
UK		1.9	6.4
USA		2.1	
Venezuela	1.2	1.2	
direct sources			
Total amount	2,459,000 t	1,158,000 t	573,000 t

For the bauxite mining the calculation bases on long-term supplying contracts, because of the lack of actual supplier structure information for the year 1997. Because no complete production numbers of single locations are available for the alumina production process data of different digestion techniques are capacity weighted and related to the missing plants in the various countries. With the supplying structure also unknown country related mixes are modelled. The same has been done for the primary smelters but with the distinction of pure and alloyed aluminium.

For the alloy production (incl. remelting and refining) a mass flow scheme for pure and alloyed aluminium has been created from several statistics, which was extended to single alloy groups. It is assumed that pure metal is made 100 % from primary materials and alloyed metal has a share of 43 % of secondary materials (which represents the 1997 average value, excluding in-house scrap from rolling). The same is assumed for the UK and France, imported alloys from the other countries are made of primary metal plus alloying elements.

For the LPM-recycling the existing mixture of mechanical processing, pyrolysis and processing of combined material with subsequent pyrolysis is used for the calculation as well as the mix of remelting furnaces.

The energy supply is based on the energy carrier mix in 1997. The power supply for electrolysis reflects a contract mix, which differs from the national grids due to ownership and base load supply [8].

NT (Full replacement): Under the viewpoint of technical progress, the selection of newest technologies in the different process steps followed the criteria in table II. It shows, that for nearly all process levels the technical potential is expressed through the saving of energy and reduction of emissions. Additionally, for alloy production, semis production and material processing the material yield becomes another major factor.

The modelled levels from bauxite mining to electrolysis consider only one technique. The bauxite quality remains the same. For the alumina production only the tube-digestion and fluid bed calcining takes place. The Russian alumina production from nepheline was not replaced. A fully automated pre-baked cell technology with point feeding is used for modelling the electrolysis [9]. The alloy production (incl. remelting and refining) changes completely to modern technology of the various furnace types by implementing oxygen burners or heat recovery systems.

Table II: Selection criteria for "newest technology"

Process step	Selection criteria for NT
Bauxite mining	Energy, emissions
Alumina production	Energy, yield
Red mud disposal	Land use, emissions
Primary smelting	Energy
Anode production	Emissions
Alloy production, remelting, and refining	Energy, metal yield
Semis production	Metal yield
Material processing	Energy, metal yield, material quality
Transport	Energy, emissions
Energy supply	Efficiency, emissions

For continuous casting slab weights of 30 t are assumed. So the amount of fabrication scrap during the strip and foil production can be minimised. Due to the high throughput of rolling mills for strip and foil stock production, the conventional route via hot rolling has not been replaced by continuous strip casting.

LPM-recycling is only done by fully automated separation, pyrolysis and twin chamber furnace to reach best metal recovery.

For the transport system all modules have been replaced by newest technology.

For electric power supply also newest conversion technology is used, but the mix of energy carriers remains equal to 1997.

2010 (Reduced replacement): Technological improvements are limited realised considering beside possible physical improvements also financial and markets aspects. Some plants will be expanded or upgraded and others will not change at all.

For bauxite mining the closure of some mines until 2010 has to be considered. Again the bauxite quality do not change.

For the alumina production a reduction of energy consumption of 10 % can be expected by lowering the liquor volume. Also an improvement of the metal yield of 1 % seems achievable. The land filling of red mud will only take place in orderly deposits.

For the aluminium smelters a modernisation by computer control of the cells and the feeding system and a capacity expansion only by modern point-feeder technology can be assumed.

For the alloy production (incl. remelting and refining) the share of furnaces with modern technology like oxygen burners or heat recovery systems increases.

Continuous casting will change to bigger slab weights causing decreasing amounts of fabrication scrap during the whole strip and foil production. Beside decreasing metal demand hot and cold rolling itself changes to lower energy and material demand.

For packaging recycling the fully automated separation for LPM reaches a share of 10 % and the mechanical processing will be replaced by pyrolysis and combined material processing.

In addition to the technical improvement a variation in the German energy carrier mix is expected until 2010, which has a big influence to the electricity depending results.

Results

As mentioned before the energy demand is one major parameter to represent technical progress. Therefore, focus is laid on the investigation of the amount, share and influence of the reduction for the different process steps, in the evaluation of the scenario results. First of all table III gives an overview on the absolute final energy demand for the three scenario calculations and the achieved improvements. The data are given for the production of one tonne primary aluminium for the German packaging system for the main consuming process steps. For the electrolysis, which demands 92 % of the electric energy, there seems a maximum improvement of 10 % possible and a predicted one for 2010 of 4 % for the aluminium suppliers of the German market (table I).

Table III: Scenario results for the final energy demand of the production of one tonne primary aluminium

final energy	unit	1997	NT		2010	
per tonne prim. Al				Δ		Δ
el. power	kWh	16,405	14,927	-9.0%	15,858	-3.3%
electrolysis	kWh	15,191	13,617	-10.4%	14,503	-4.5%
alumina production	kWh	1,006	956	-5.0%	1,010	0.4%
heavy oil	MJ	17,380	4,331	-75.1%	15,926	-8.4%
steam production	MJ	12,866	0	-100.0%	11,402	-11.4%
lime-sinter/nephelin	MJ	2,940	2,940	0.0%	2,940	0.0%
transport	MJ	1,009	774	-23.3%	991	-1.8%
fuel oil	MJ	5,518	4,430	-19.7%	5,555	0.7%
calzination	MJ	4,776	3,874	-18.9%	4,782	0.1%
natural gas	MJ	7,052	13,590	92.7%	6,975	-1.1%
alumina production	MJ	4,196	10,898	159.7%	4,103	-2.2%
electrode production	MJ	2,050	1,959	-4.4%	2,066	0.8%

Especially for the NT case a shift of the energy carrier can be recognised, due to the change of technology for bauxite digestion. Here steam heated autoclaves are replaced by gas fired tube reactors. Only the part of oil fired alumina production from lime-sinter and nepheline process in Russia remains the same.

In Table IV the input and outcome of important materials is presented, showing the changes in amount depending on the scenario. The selected materials give a small insight in the complex aluminium flow system. Bauxite and foreign scrap are inputs to the overall system. The values of primary aluminium and fabrication scrap represent mass flows within the system which induce further changes in preceding or following processes. On the output side a small portion of unalloyed fabrication scrap leaves the packaging system and feeds other systems. The aluminium content in the processed scrap represents the achievement in the recycling system. Red mud and carbon dioxide, CF_4 and C_2F_6 are selected emissions caused by production and recycling of aluminium which can strongly be reduced by improved technology.

Table IV: Scenario results for the material flow due to the production of one tonne packaging material

	1997	NT		2010	
Input per tonne packaging material [kg]			Δ		Δ
Bauxite	4,554	3,957	-13.1%	4,322	-5.1%
Primary aluminium	1,062	985	-7.3%	1,023	-3.7%
Foreign scrap	239	237	-0.8%	238	-0.4%
Fabrication scrap (circuit)	325	211	-35.1%	268	-17.5%
Output per tonne packaging material [kg]					
Fabrication scrap	297	225	-24.5%	261	-12.2%
Al-content of recycled LPM	38	48	26.6%	40	4.7%
CO2	4,668	3,423	-26.7%	4,315	-7.6%
CF4	0.531	0.049	-90.7%	0.358	-32.6%
C2F6	0.053	0.005	-90.7%	0.036	-32.6%
red mud	2,368	1,871	-21.0%	2,165	-8.6%

To compare the energy consumption of the various process steps, each using different forms of energy, the final energy consumption was converted into a primary energy demand. Figure 4 shows a ranking of the absolute values of primary energy demand of the different scenario calculations.

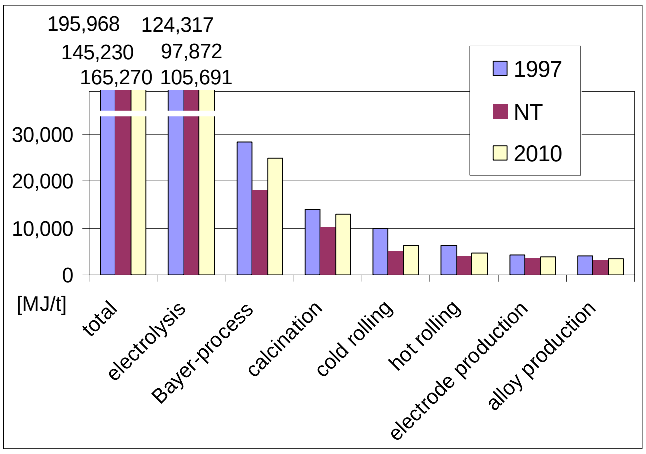


Fig. 4: Primary energy consumption of the scenario calculations per tonne of packaging material

Here the big total and electrolysis values are cut and given by numbers. The energy demand per tonne of packaging material was 196,0 GJ in 1997 and is 145,2 and 165,3 GJ for newest and 2010 realised technique respectively. Beside the dominating primary smelting the Bayer-digestion and the alumina calcination show remarkable energy demands followed by the cold and hot rolling operation, the electrode production (including coke and pitch production for pre-baked and Söderberg cells) and the alloy production from primary and secondary raw materials.

On the further places not shown in the diagram follow caustic soda production, transport, lime production, bauxite mining, aluminium fluoride production, continuous casting and red mud treatment.

The NT and 2010 scenario calculations of primary energy consumption are influenced mainly by three different effects, the technical improvement of the different processes itself, the increase of material efficiency per tonne of produced packaging material and the improvement of the energy supply. The particular share of these three effects varies for each process level. Figure 5 shows the share of the overall primary energy savings. It can be seen, that the entire improvement in the case of newest technology (NT) is 26% and that in the year 2010 16% can be realised.

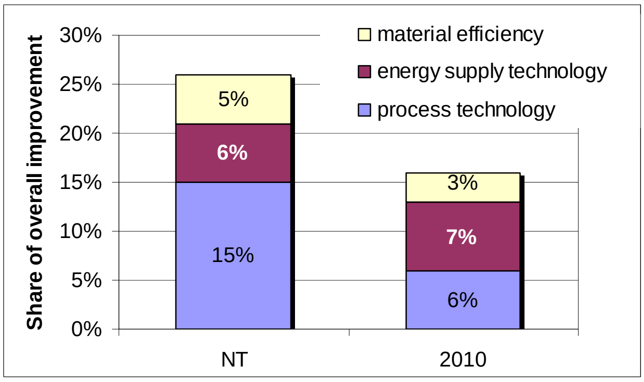


Fig 5: Share of overall primary energy saving for full (NT) and reduced capacity replacement (2010)

Beside the dominating part of technical improvement for the exclusive use of newest technology it is shown that in 2010 the part of energy supply improvement increases significantly. In addition to technical improvements of the energy conversion the expected changes of the energy carrier mix for electrical power supply in Germany generate a big influence of the energy system. The average conversion efficiency of the national grid increases from 31,5 to 43,1 %. Again it is to note that all results are based on the production of one tonne of packaging material (foil, strip, can stock and can lid stock).

Analysing the primary energy savings at the process level further questions for both, newest technology and 2010 realised technology arise: How big is the share of technique, material and energy influenced changes, what are the improvements of each single process step, and what impact do they have on the overall improvements of the entire process chain?

To identify each part of the energy saving fig. 6 compares the pure technique specific potential of selected NT process steps with the product specific potential (per tonne packaging material) excluding improved energy supply. So the effect of decreasing mass flows and respective increasing metal and material yield can be isolated. A third calculation gives the values for the product specific potential including the energy supply to isolate the effect of more efficient fuel and electricity production as well as changes in the energy carrier mix.

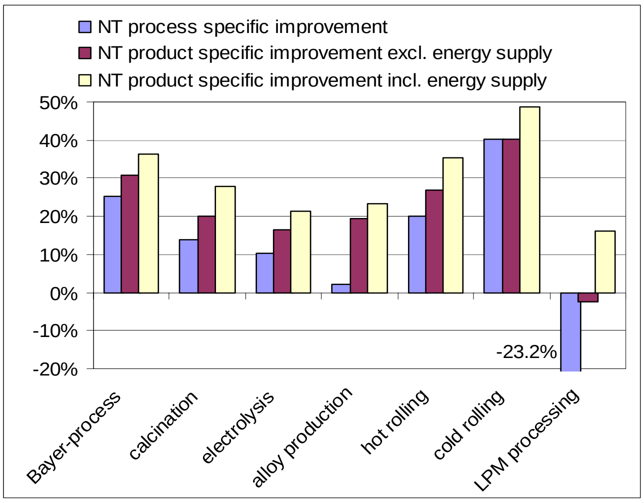


Fig. 6: Comparison of selected process and product specific improvements for the use of newest technology

As it can be expected from fig. 5 the three parts of the process improvements are generally in the same order of magnitude. For cold rolling there is no mass depending part, because it is the last step of the process chain. So the process specific improvement is equal to the product specific one. The alloy production, which also includes all remelting activities for secondary raw materials shows the largest influence of mass reduction per tonne of packaging material due to the decreasing amount of fabrication scraps. On the other hand there is only a small energy related improvement for these mainly fuel fired operations. Another exception of the values shows the LPM-processing where technology development causes a higher energy demand. But concerning the better metal recovery the decline decreases and even turns to an improvement also concerning better energy conversion.

In spite of the higher energy demand it has to be considered, that the NT and 2010 recycling concepts for LPM recover 3880 re-

spective 740 tonnes of aluminium more than 1997. The overall recycling quota increases to 72 % for NT and 62 % for 2010 and the technical recycling quota reaches 81 and 70 % respectively. That results in an energy saving of 860 respective 180 MJ/t aluminium packaging taking the corresponding primary metal substitution into account. That aspect wins importance due to the small part of closed loop recycling for packaging material of only 2% and that the other part feeds other recycling systems.
Fig. 7 shows the corresponding results for the 2010 case. There is no change in technology expected for the calcination and alloy production facilities related to the German packaging system. The 2010 realised improvement is about 13 percent points below that one for newest technology. The share of energy related improvement, especially for the electric powered processes like electrolysis, rolling and LPM-processing, again has increased against NT due to the assumed change in electric energy supply until 2010.

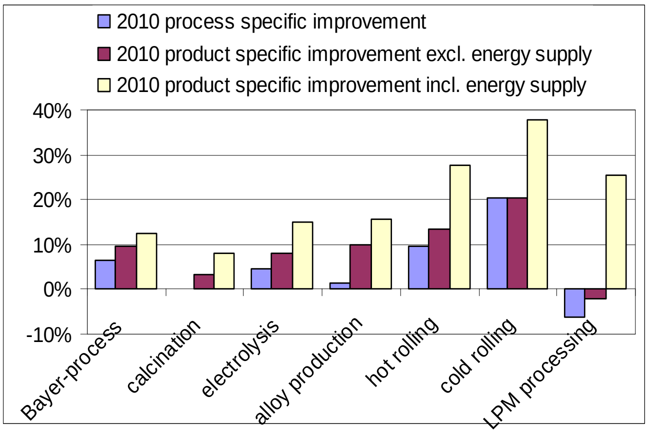


Fig. 7: Comparison of selected process and product specific improvements for the 2010 realised technology

Evaluating the calculated reduction potentials of primary energy demands for the different process steps there is a big variation of total and realised potentials. The specific improvement of each process level related to one tonne packaging material shows fig. 8.

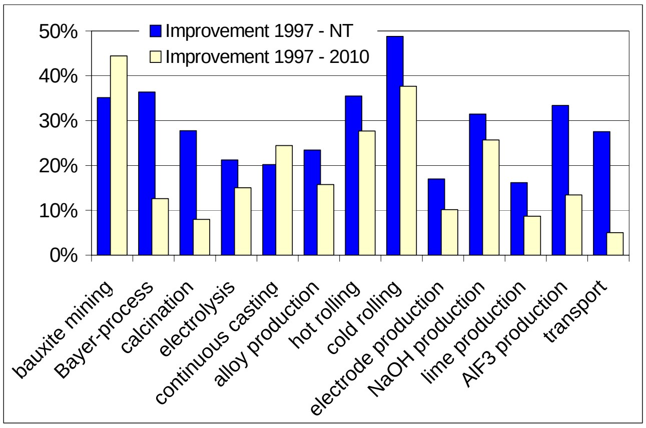


Fig. 8: Product specific improvements of the various process steps per tonne produced packaging

It can be seen that the difference for the NT and 2010 scenario is process specific. As expected the realised 2010 improvements are smaller than the possible technical ones except mining and casting. For mining there are bigger technical improvements expected in 2010 due to the short lifetime and fast development of mining equipment. For continuous casting the effect of electrical power supply overlay the technical improvements.
Changing the entire process chain towards newest technology it is also of interest which processes have the biggest share of the overall improvement. In direct comparison to the maximum product specific values discussed before the results for the NT calculation in fig. 9 confirm the dominance of the electrolysis with 52% of entire technical potential.

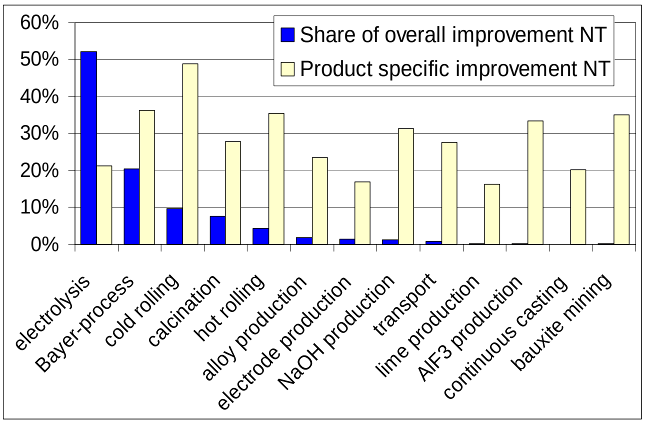


Fig. 9: Comparison of overall and product specific improvement for the NT case study

In spite of strongly increasing specific values it is followed by 20% for the Bayer-digestion, 10% for cold rolling, 8% for calcination and 4% for hot rolling. The corresponding diagram for the 2010 case study in fig. 10 shows slightly different values.

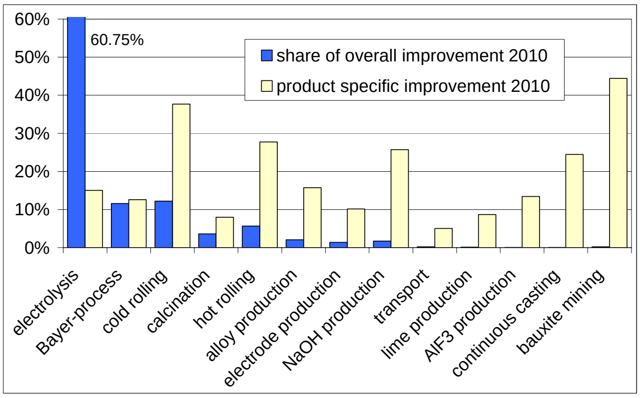


Fig 10: Comparison of overall and product specific improvement for the 2010 case study

Fig. 11 compares the share of the entire process chain improvement of NT and 2010. It can be seen that the Bayer-process steps digestion and calcination, the two mainly fuel fired processes, will achieve significant bigger parts of the overall improvement for newest technology. For 2010 the improvement of the big electric energy consumers dominates the picture due to different mix of energy carriers together with more efficient power conversion.

Beside the energy consumption the influence of technical progress on resource use and emissions are also of interest. As mentioned before a change in material efficiency has an impact on the energy demand and on the same time on the use of resources itself. Analysing the emissions along the entire process chain the share of the various process levels can be investigated.

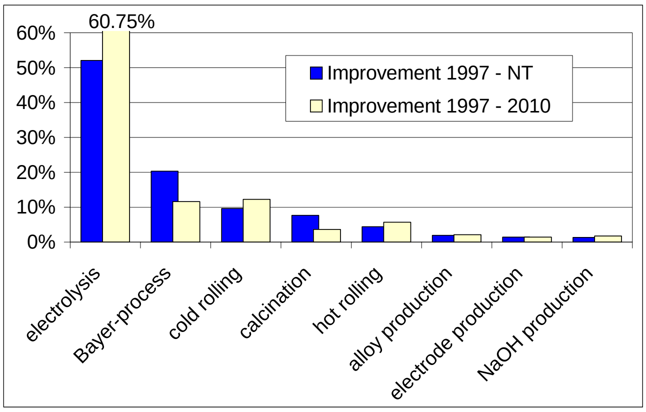


Fig 11: Share of process steps of the overall improvement

In fig. 12 various greenhouse gases are represented, showing impact of the different process levels of primary aluminium production on the global warming potential (GWP). It is to note, that the biggest share of CO_2 emissions is related to the supply of electricity for electrolysis (energy el.) and alumina production (energy a.p.). The CH_4 emissions are only related to energy supply. The CF_4 and C_2F_6 emissions are only process related to electrolysis and show the biggest reduction potential. The overall reduction potential is 43 % for the NT case and 14 % for 2010.

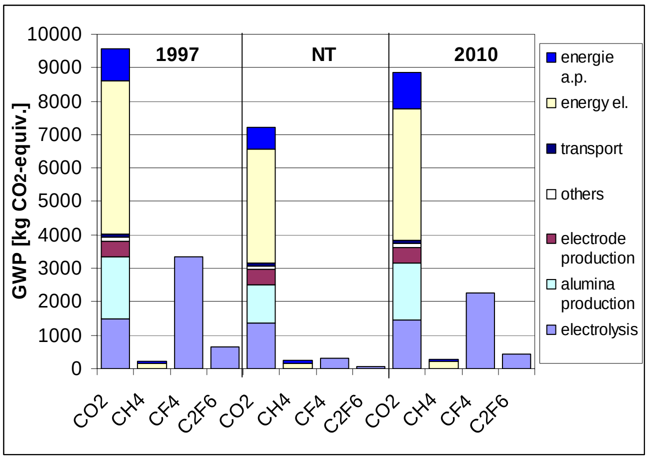


Fig 12: Share of process steps on the GWP in CO_2-equivalences

These results are representative for a variety of possible calculations in the field of environmental impact assessment which can be determined from the existing data base.

Conclusion

To model technical progress in the aluminium industry a scenario has been developed for the German packaging industry. Here the 1997 reference case is compared with a full capacity replacement by newest technology and a realistic case of reduced replacement due to economic and market considerations. Reduced replacement means partial replacement as well as upgrading and capacity expansion. The most important assumptions were that no structural changes of the packaging system itself take place until 2010 except the energy carrier mix of the power plants. It is to note that the results are strongly depending on the assumptions to forecast realistic conditions. The results show a big difference between the maximum technical potential and its predicted application in 2010. The entire primary energy savings in the case of newest technology (NT) is 26% (50 GJ/t packaging material) and in 10 years 16% (30 GJ/t) can be realised. For the isolated technology aspects improvements of 15 respective 6% can be expected. The material related effect will be 5 and 3% and the energy related one 6 and 7%, taking the dominating effect of a changed energy carrier mix in 2010 into account. Under realistic market conditions the technology related improvement potential in 2010 is relatively low due to the long lifetime and high investment costs of metallurgical plants. Compared with world-wide average values the German aluminium system has already undertaken big efforts to reach a high technical and environmental standard. Nevertheless further process optimisation like automation and circuit material reduction are promising possibilities for domestic as well as foreign producers.

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