Energy and emission analysis in primary aluminium production – a technical contribution to an integrated resource management

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Abstract

This paper presents the balance of mass flows due to the primary aluminium production from bauxite to molten metal and the identification of optimisation potentials. To balance the mass flows and energy requirements of the worldwide aluminium production the developed process chain is divided into technique specific modules. There are nearly 70 alumina refineries with a total capacity of 56 Mt/a of alumina and nearly 200 smelters with a total capacity of 26 Mt/a of aluminium in operation. Different smelter technologies are classified in terms of the specific energy demand, anode consumption and emissions like CO_2 or C_xF_y. The specific electrical energy requirements for electrolysis range from 13.0 to 17.5 kWh/t of molten aluminium with a capacity weighted average of 14.9 kWh/t. Two case studies show that by an increase of the annual aluminium production of 6 Mt, the specific energy requirement will decrease to 14.1 kWh/kg Al due to the installation of new smelters and changes in the applied technology.

Introduction

Further developments of industrial sectors like aluminium production are often the subject of investigation. For a known market growth rate, future production can be extrapolated for years or decades. This is much more difficult to predict for technical progress, especially when considering technical and environmental aspects in the understanding of sustainable development. Furthermore, technical progress is different for different steps of a process chain and for different locations and its implementation is not predictable generally. Nevertheless realistic assumptions for future technology can be made, when the estimation of the maximum technical potential, which is known today in every process step is divided from the forecasting of its application in a certain time. Then the combination of them together with site-related analysis could give reliable results.

In order to analyse the complex system of metal production and recycling, different models have been developed. This paper will give an overview of energy and process-related emissions of processes during aluminium production. Furthermore, the impact of progress and change in aluminium electrolysis is analysed in two case studies in terms of energy demand, anode consumption and emissions of CO_2, CF_4/C_2F_6 and global warming potential. For this purpose the status quo of the year 1997 for anode consumption and demand for energy as well as the emissions of CO_2 and CF_4/C_2F_6 is determined. These figures belongs to a production of 22 Mio. t/a aluminum. The used technique is subdivided into categories which are orientated by the energy demand of the applied technique. The two case studies are taken as a basis, that the production increases to 28 Mio. t/a aluminium in 2010. We assume that on the one hand about 3 Mio t increased production through the restart and the enlargement of existing plants are produced. The other 3 Mio. t/a aluminium are produced by the new building of smelters with modern PFPB-technology which go to 2010 in operation. In the case study 1 the used technique is not changed, with which the initial ones 22 Mio. t/a aluminium to be produced. In case study 2 we assume, that the applied technology in the smelters, which are in operation since 1997, changes until 2010. These changes are limited to certain technical limitations, which do not approve the alternation of a technical category into the other one any. With that it possible to recognize which changes occur in the total and specific resource consumption if on the one hand the production is increased. On the other hand it is possible to recognize the changes that can be achieved with the technical possible changes of the today used technology

Alumina production by the Bayer process

Today the total capacity of alumina refineries approaches 56,326,000 t Al_2O_3, compared to a production of 46,379,000 t in 1997 and 41,745,000 t in 1994. The distribution of bauxite type used for alumina production, determined by the predominant alumina bearing mineral, in 1994 is shown in Table 1 [1, 2, 3].

Table 1: Bauxite types and their share of production

Bauxite type	Share of world alumina production (%)
Gibbsitic	54
Boehmitic	30
Diasporic	11
Nepheline (+ Alunite)	5

The type of bauxite determines the process technology from which the following results could be estimated:

Table 2: Alumina production in % according to process technology [1]

Bauxite type	Share of world alumina production (%)
Bayer LTD & AD	48
Bayer HTD & Sweetening	12
Bayer HTD (partly with lime)	18
Bayer & soda lime sintering	17
Nepheline (+ Alunite) sintering	5

LTD: Low Temperature Digestion, AD: Atmospheric Digestion, HTD: High Temperature Digestion

Energy requirements for the Bayer process

Detailed data are not available relating to the average energy consumption of the different types of alumina plants. Table 3 shows the energy consumption of five different alumina plants. It can be seen that it is possible to reduce the energy consumption to 5.1 MJ/kg Al_2O_3 by using a tube digester, which has been in operation for 25 years in Stade, Germany. Despite of its advantages this technology is applied very rarely. Natural gas (40 %) as well as fuel oil (38 %) are the typical energy sources for the Bayer Process.

Table 3: Energy requirements (MJ/kg Al_2O_3) for some alumina refineries [1]

Plant	Digestion	Evaporation	Others	Total	%
Stade	3.5	0.5	1.1	5.1	100
Wagerup	2.5	2.5	3.2	8.2	160
Gove	2.5	2.5	3.2	8.2	160
Damanjodi	1.4	3.6	4.7	9.7	190
HTD Autoclave	4.0	3.0	3.0	10.0	196

Calcination of alumina

The aluminium hydroxide produced in the Bayer process has to be calcined to aluminium oxide. This is done in stationary fluid bed calciners and rotary furnaces. An average of 4.8 MJ/kg Al_2O_3 is required for calcination in the rotary furnaces and only 3.3-3.1 MJ/kg in the stationary furnaces. Natural gas as well as heavy fuel oil can be used for the calcination. The share of rotary and stationary furnaces according to the total worldwide installed capacity is not well known, but we assume that one third of the alumina is calcined in rotary furnaces and two thirds in the stationary type. According to the data above, the world average energy consumption from both stationary as well as rotary furnaces is 4.3 MJ/kg Al_2O_3, amounting to 130 % of today's applied technical minimum.

Aluminium electrolysis

In 1997 there were worldwide nearly 200 smelters in operation with a total capacity of 26 Mio. t/a, of which the greatest is the Bratsk smelter in Siberia (800,000 t/a) and the smallest one (in the western world) the smelter at Kinlochleven, Scotland (11,000 t/a). The latter was shut down in the summer of 2000. Furthermore some 5,000 t/a or even smaller smelters exist in the PR China.

Different smelter technologies were examined with respect to the specific energy consumption and anode consumption as well as to emissions of CO_2 and CF_4/C_2F_6.

Aluminium smelting technology can be roughly divided into five different technologies:

- HSS: Horizontal Stud Söderberg
- VSS: Vertical Stud Söderberg
- SWPB: Side Worked Prebake
- CWPB: Centre Worked Prebake (with centre brake bar system for alumina feeding)
- PFPB: Point Feeder Prebake (with point feeder technology for alumina feeding)

Even at the same smelter location different technologies have been applied in different pot lines, e.g. at the smelters at Kurri Kurri in Australia and Sorocaba in Brazil.

For an analysis of current and future energy requirements and mass flows, considerable data on smelters around the world have been collected and analysed. Further, each smelting technology mentioned above has been divided into three categories of technical standard: Old Technology (OT), Present Technology (PT) and Newest Technology (NT). Criterion for the classification was only the electric energy requirement, following Table 4. Smelters for which the energy requirements were not available, were appointed to these technical categories using other criteria, such as start-up. Smelters, for which the technology was not available, were not examined and excluded from the following analysis. These are predominantly small smelters in PR China. With regard to the old technologies used in PR China smelters up to the present, the results on this analysis seem to be moderate.

Table 4: Energy requirements of different technical smelter categories

	Old Technology (OT) kWh/kg Al	Present Technology (PT) kWh/kg Al	Newest Technology (NT) kWh/kg Al
HSS	> 16.5	16.5 - > 14.5	≤ 14.5
VSS	> 16.5	16.5 - > 14.0	≤ 14.0
SWPB	> 15.5	15.5 - > 13.5	≤ 13.5
CWPB	> 15.5	15.5- > 13.5	≤ 13.5
PFPB	> 14.5	14.5 - > 13.5	≤ 13.5

By following these criteria, in 1997 a smelting capacity of nearly 22 Mt was analysed.

Table 5: Installed capacities for each technical category and share of world production

Technology	Technical category	Capacity (t/a)	Share of total production (%)
HSS	OT	1,204,000	5.5
	PT	779,000	3.5
	NT	--	--
VSS	OT	1,916,000	8.7
	PT	2,698,000	12.3
	NT	--	--
SWPB	OT	--	--
	PT	1,455,000	6.6
	NT	572,000	2.6
CWPB	OT	1,060,000	4.8
	PT	2,165,000	9.7
	NT	--	--
PFPB	OT	2,106,000	9.6
	PT	4,502,000	20.5
	NT	3,485,000	15.9
Total		21,944,000	100.0

The electrical energy requirements and demand of anodes for each technical category and the total averages, weighted by the production, are listed in Table 6. The figure from table 5 and 6 are used to describe and analyse the situation for energy demand, anode consumption and emissions in 1997 and the case studies. Figure 1 shows the comparison of production share and energy requirements for each technical category in 1997. It can be seen that the share of total electrical energy demand is smaller compared to their share of production only for PFPB-NT and PFPB-PT smelters. The other technical categories require more electrical energy compared to their production share.

Table 6: Installed production of each technical category and share of world production

Technical category	Elec. energy demand (kWh/kg Al)	Net anode consumption (kg/t Al)
HSS-OT	17.1	536
HSS-PT	14.9	557
VSS-OT	17.1	572
VSS-PT	15.8	529
SWPB-PT	14.5	427
SWPB-NT	13.2	409
CWPB-OT	16.4	474
CWPB-PT	14.7	431
PFPB-OT	15.1	436
PFPB-PT	14.0	426
PFPB-NT	13.3	410

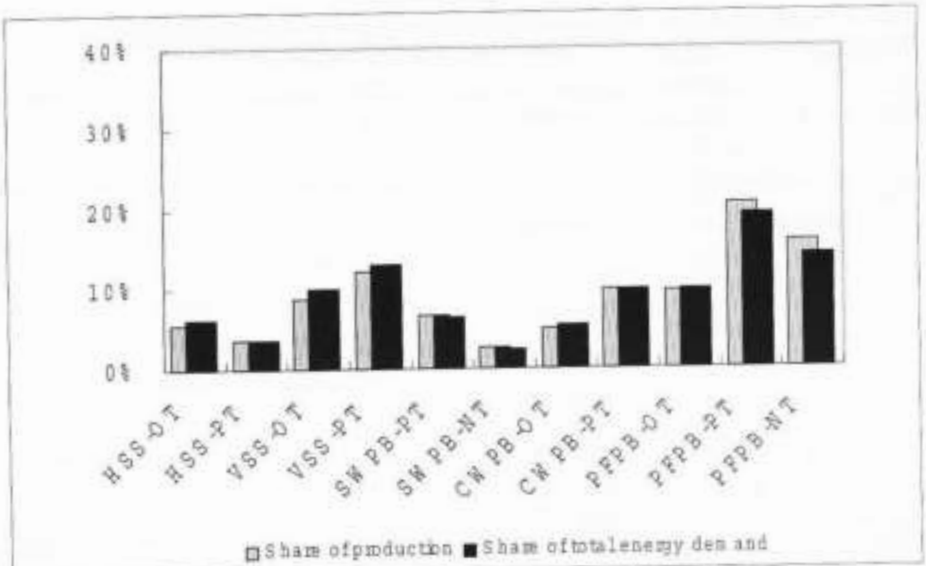

Figure 1: Share of production and total energy requirement for different technical categories of Al electrolyses cells in 1997.

Electrical energy case study 1 for the year 2010

To answer the question, how much energy will be required for each kg of aluminium in the future, some boundary conditions have to be defined.

Between 1997 and 2003 some smelters already have or will restart their shut-down capacities, also some new smelters have come online, or will go online until 2003 (e.g. the Alma project of Alcan, the Ikot Abasi smelter in Nigeria or the Maputo smelter in Mozambique). Some other smelters will shut down their capacity (e.g. Isle Maligne in Canada). This will result in an increase of worldwide primary aluminium production of 3 Mt/a. Beside these changes we assume an increase of primary aluminium production worldwide of another 3 Mt/a before 2010, so that the total aluminium production will increase from 22 Mt in 1997 to 28 Mt in 2010, resulting in a yearly increase of nearly 2 %. This seems to be a moderate and conservative value in comparison to other studies. It is assumed that in new projects exclusively install PFPB-NT technology. Furthermore, we assume that the other smelters will not change technology and energy requirements.

Under these conditions, the average electrical energy requirements will decrease from 14.9 kWh/kg in 1997 to 14.6 kWh/kg in 2010 (amounting to 98.2 % of the 1997 value), caused only by the installation of new smelters and shut- down of some smaller less efficient capacities.

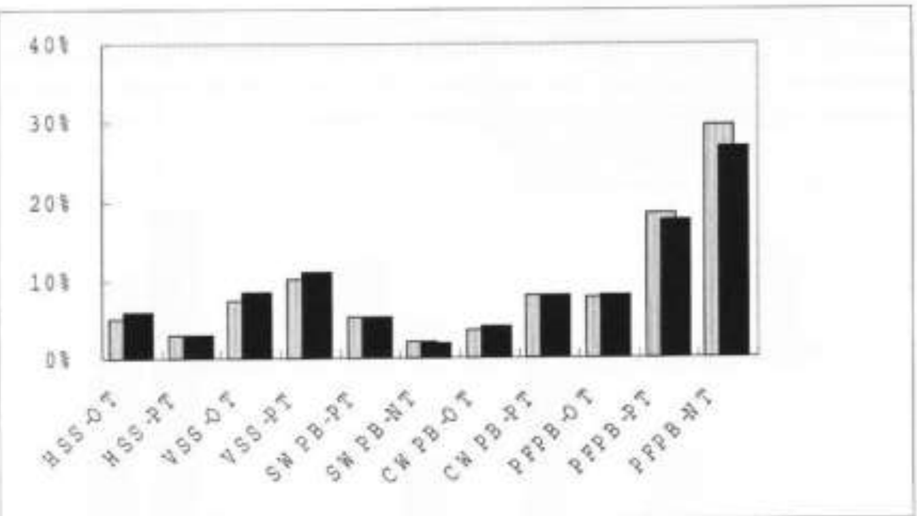

Figure 2: Share of production and total energy requirement for different technical categories of Al electrolysis cells in 2010 according to case study 1.

Electrical energy case study 2 for 2010

What is the impact if the technology in the existing smelters changes? It seems most likely that smelters will optimise their operation and decrease their energy consumption by installation of automatic pot control or optimisation of the manual work at the pots, in order to further minimise operational costs.

We assume that all changes from 1997 to 2010 will take place as described in the case study 1. Additionally, some smelters will change their technical categories shown in Table 7. These changes consider that it is not possible to change the pot type from HSS or VSS to PB technology without accepting and paying for substantial changes in the superstructure of the pot. It is also difficult to change from SWPB to PFPB, but easier to change from CWPB to PFPB technology. Moreover, it is difficult, or impossible, to decrease the energy demand of PFPB-OT/PT to the demand of a large, magneto-hydrodynamic compensated cell typical of the PFPB-NT technology.

Table 7: Change of technical categories of Al electrolysis cells in case study 2

1997	HSS-OT	VSS-OT	SWPB-OT	CWPB-OT	CWPB-PT	PFPB-OT
2010	HSS-PT	VSS-PT	SWPB-NT	PFPB-PT	PFPB-PT	PFPB-PT

These changes result in a decrease of the average energy demand to 14.1 kWh/kg Al (or 94.9 % of the 1997 value).

Figure 3 shows the share of production and energy requirements for each technical category in 2010 according to case study 2. It can be seen that some technical categories are missing due to the boundaries for the case study one described above. Only for the PFPB-NT smelters the share of production is grater compared to the share of total energy demand.

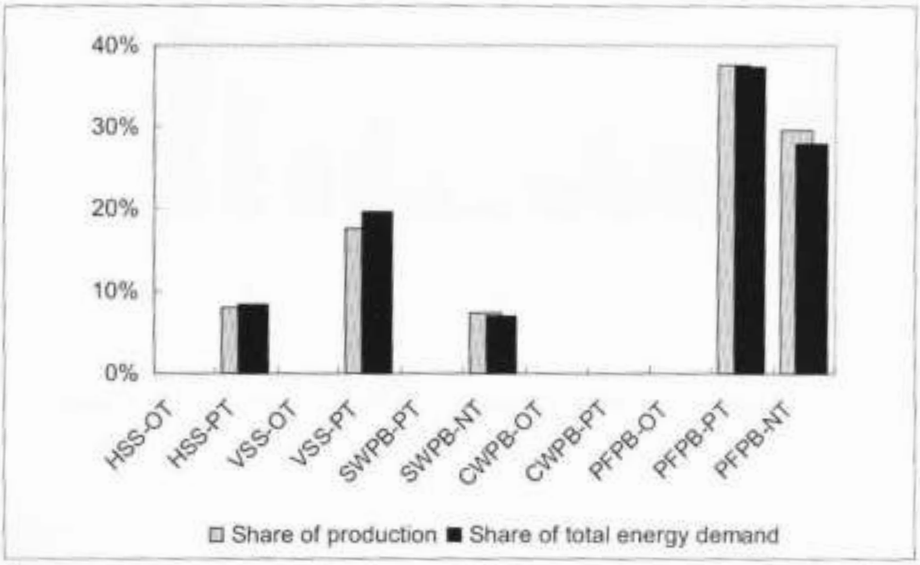

Figure 3: Share of production and total energy requirements of different technical categories of electrolysis cells in 2010 according to case study 2.

Anode consumption (status and case studies)

The average anode consumption in 1997 is 463 kg/t Al (Söderberg and Prebake). Generally, the share of anode consumption is higher for Söderberg technology and less for Prebake technology compared to their share of production (excluded for CWPB-OT, but there are few data available). This situation does not change in case studies 1 and 2. The average anode consumption will decrease in case studies 1 and 2 to 424.1 and 415.6 kg/t Al, respectively, amounting to 98.1 % and 96.9 % of the 1997 value.

The figures 4 to 6 compare the share of production and the share of total anode consumption for the different smelter categories. In all cases the PB-technologies consume less anodes compared to their share of production.

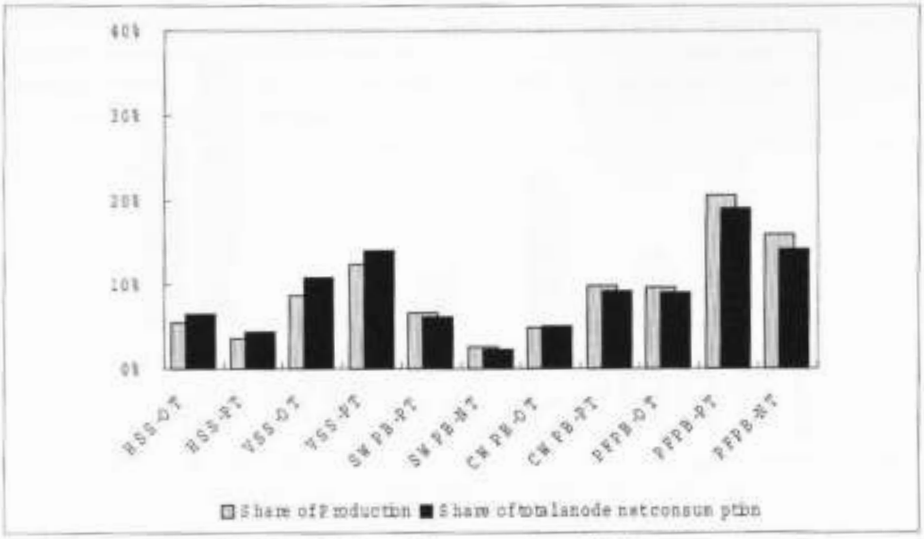

Figure 4: Share of production and total anode consumption of different technical categories of Al electrolysis cells in 1997.

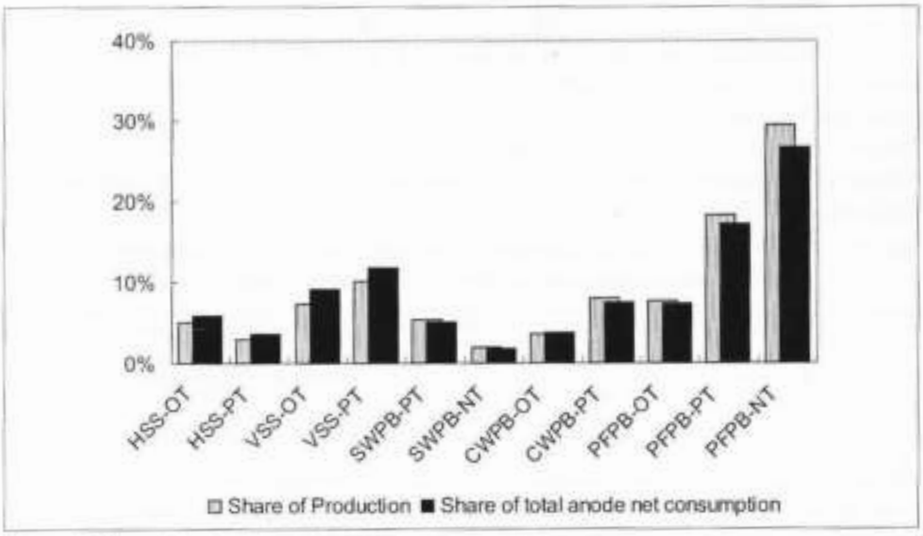

Figure 5: Share of production and total anode consumption of different technical categories of Al electrolysis cells in 2010 according to case study 1.

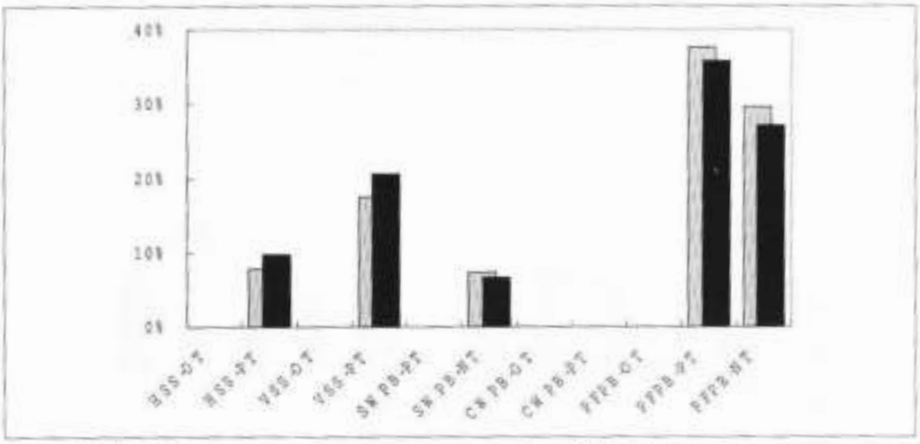

Figure 6: Share of production and total anode consumption of different technical categories of Al electrolysis cells in 2010 according to case study 2.

Chemical Energy Consumption

Chemical energy in this paper is defined as 1. the energy for anode baking, 2. the chemical energy content of the anodes which are consumed during electrolysis and 3. the chemical energy from packing coke, which is consumed during the anode baking process. For the calculations it is assumed that the fuel for anode baking is always oil, also due to lacking information about the use of natural gas. The energy contents of the materials and the energy demand for anode production are listed in Table 8. For the case studies it is assumed also that no changes are made in anode baking technology, e.g. decrease of fuel or packing coke consumption. The changes are only originated by the changes of the applied smelter categories.

Table 8: Energy content of fuel oil, packing coke and baked anodes, mass requirements for anode production and specific energy consumption for anode production

	Energy content	Mass required during anode baking [6]	Energy consumed during anode baking
Oil	40.5 MJ/kg	50 kg/t anode	2,025 MJ/t anode
Packing coke	30.0 MJ/kg	45 kg/t anode	1,350 MJ/t anode
Baked anodes	30.0 MJ/kg	--	

It can be seen from figure 7 that the differences between the proportions of chemical energy consumption and total aluminium production are marginal. The chemical energy demand from anode consumption is smaller for PB technologies, but they need chemical energy for anode production, too. But generally more chemical energy is required for the Söderberg technologies.

In 1997 nearly 15,800 MJ chemical energy are required for the production of one ton of aluminium. This will decrease to 15,500 MJ in case study 1 and 15,300 MJ/t Al in case study 2 respectively, amounting to 98.2 % and 96.8 % of the value from 1997. The changes are only small due to the similar consumption of chemical energy.

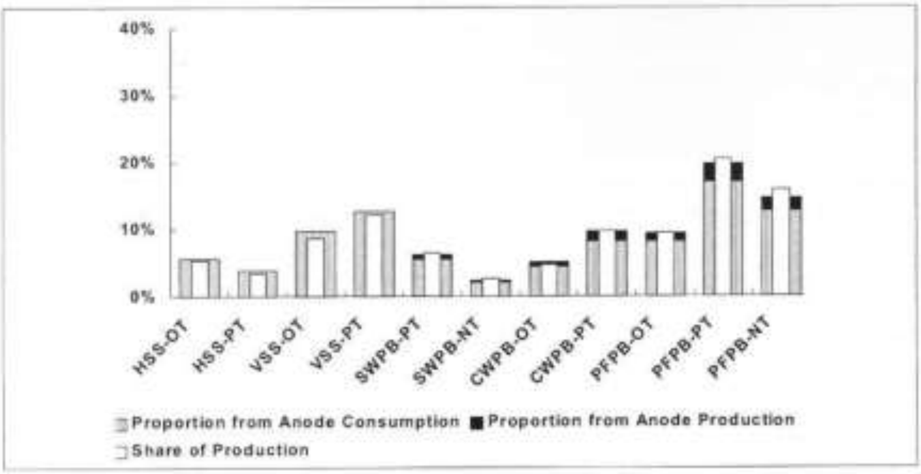

Figure 7: Share of production and total chemical energy consumption of different technical categories of Al electrolysis cells in 1997. For better clarity the chemical energy consumption for anode production due to fuel consumption and packing coke are combined

Emissions of CO_2 from electrolysis and anode production

CO_2 is emitted during the aluminium production due to anode production (combustion of fuel for baking and packing coke) and consumption of anodes during the electolysis. In 1997 1.825 t/t Al of CO_2 are emitted from these sources. In case study 1 these emissions decrease slightly to 1.799 t/t Al and in case study 2 to 1.792 t/t Al. The changes are only small due to the similar consumption of anodes, fuel for anode baking and packing coke of the different smelter categories.

CF_4 emission in 1997

What amount of CF_4/C_2F_6 is emitted today from primary aluminium smelters?

CF_4 and C_2F_6 are emitted from electrolysis cells only during the so-called anode effect. The specific amount of the emissions depends of the anode effect frequency, duration of the anode effect, cell amperage and current efficiency. We assume that the different technical smelter categories lead to the following specific amounts of CF_4/C_2F_6 emitted to the atmosphere. The data were taken from [4, 5] and modified.

Table 9: Specific emissions of CF_4/C_2F_6 caused by different technical categories of Al electrolysis cells

Technical category of Al electrolysis cells	CF_4 (kg/t Al)	C_2F_6 (= 10 % of CF_4) (kg/t Al)
PFPB-NT	0.05	0.005
PFPB-PT	0.30	0.030
PFPB-OT	0.50	0.050
CWPB-PT	0.30	0.030
CWPB-OT	0.50	0.050
SWPB-NT	0.70	0.070
SWPB-PT	1.20	0.120
VSS-PT	0.55	0.055
VSS-OT	1.10	0.110
HSS-PT	0.07	0.007
HSS-OT	0.40	0.040

In 1997 primary aluminium smelters emitted 10,032 t of CF_4 and 1,003 t of C_2F_6, corresponding to an average specific emission rate of 0.46 kg/t Al. The comparison of CF_4 emissions and total Al production shows that some technical categories emit much more CF_4 compared to their share of production, especially VSS-OT, -VSS-PT and SWPB-PT.

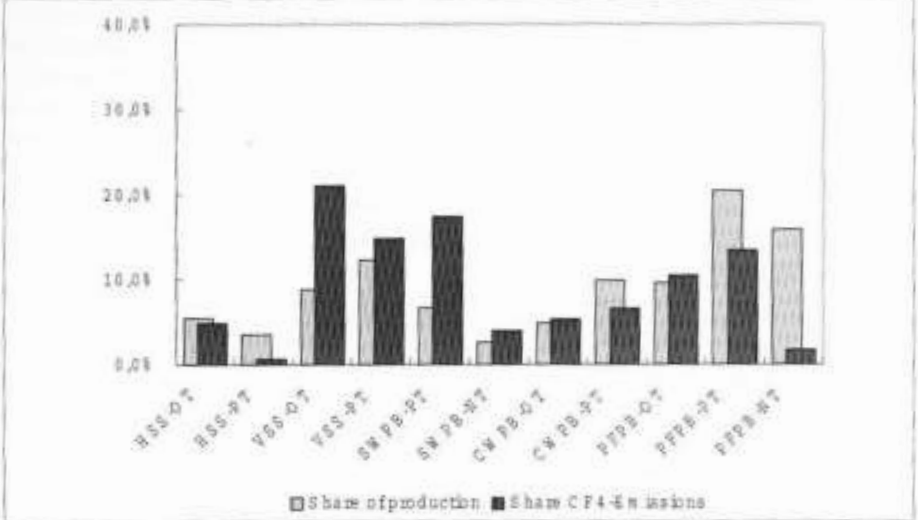

Figure 8: Share of production and total CF_4 emissions from different smelter categories in 1997

CF_4/C_2F_6 emission case study 1 for 2010

How much will the emissions of CF_4/C_2F_6 change by 2010?

Under the conditions outlined in the **electrical energy case study 1** described above, the total emitted amount of CF_4/C_2F_6 will increase to 10,907 t/a CF_4 by 2010, representing an increase of 8.7 % of the total amount in 1997. The specific emitted amount will decrease to 84.8 % of the 1997 value, or 0.39 kg/t Al of CF_4. The comparison of production and emission share with respect to technology is only slightly different to 1997.

But it can bee seen that the differences in share of production and share of emissions are much larger compared to the situations for energy demand and anode consumptions. The PFPB-NT smelters are the best, their share of production is much larger than the share of production. VSS-OT, VSS-PT and SWPB-PT smelters are the largest sources of CF_4. These three categories emit nearly 50 % of the total CF_4, but their share of production is only 23 %.

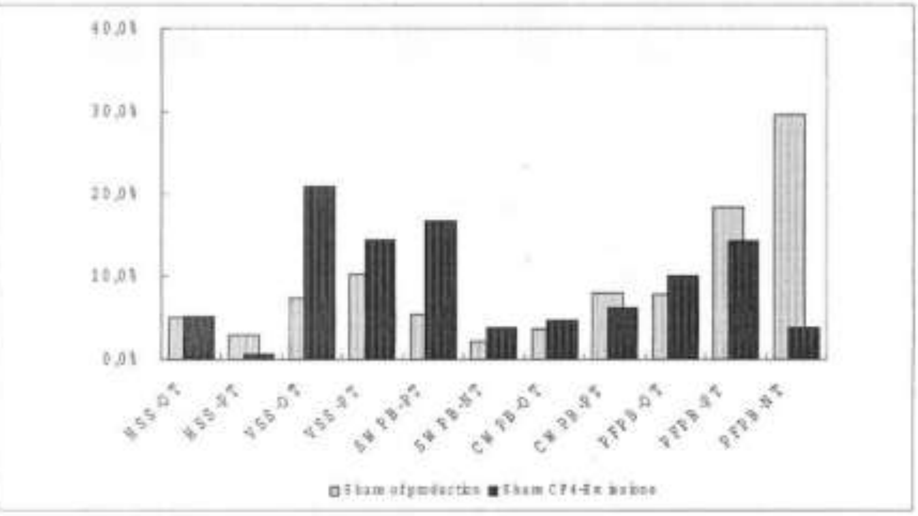

Figure 9: Share of production and total CF_4 emissions of different smelter categories in 2010 according to case study 1.

CF_4/C_2F_6 emission case study 2 for 2010

Under the conditions outlined in **electrical energy case study 2** described above, the total emitted amount of CF_4/C_2F_6 will decrease to 7,914 t/a CF_4 by 2010, corresponding to a decrease of 21.1% of the total amount in 1997. The specific emitted amount will decrease to 60.9 % of the 1997 value or 0.28 kg/t Al of CF_4.

Figure 10 shows that nearly 35 % of the total amount is emitted from the VSS-PT pots, which produce only 17 % of the aluminium. On the other hand, the PFPB-NT pots produce nearly 30 % of the world aluminium production and emit only 5 % of the total CF_4 amount. This is mainly due to an ongoing reduction of the number of anode effects extending almost to 2010.

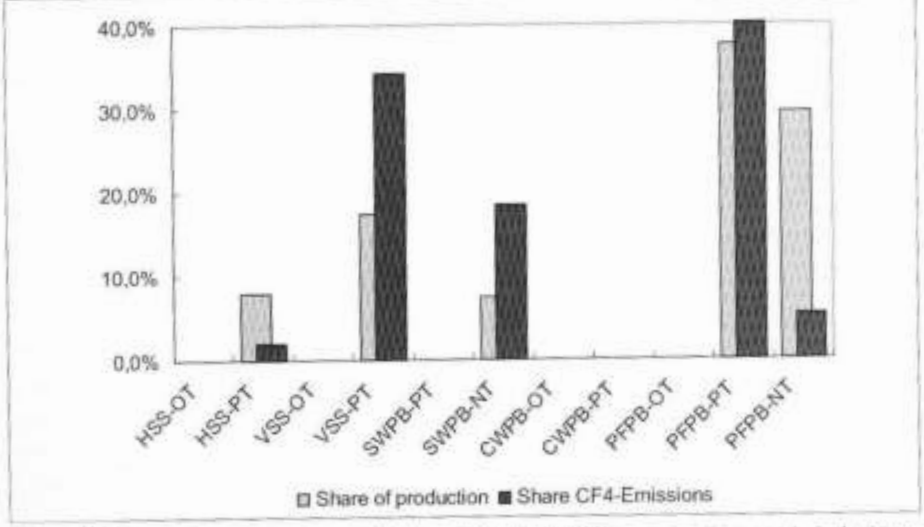

Figure 10: Share of production and total CF_4 emissions from smelters of different technical categories in 2010 according to case study 2 .

Total emissions of Green House Gases (CO_2 and C_xF_y)

The GWP of CF_4/C_2F_6 is very high, at 6,500 and 9,200 times that of CO_2, respectively, on a 100 year basis. It can be seen from figure 11 that the share of greenhouse gases emitted from the smelters depends on technical category and differs from their share of production. The most critical seems to be the smelters of VSS-OT and SWPB-PT technical categories. Their share of greenhouse gas emissions is twice as large as their share of production, most of it coming from CF_4. An average of 5.2 t/t Al of Green House Gas is emitted from aluminium smelters, including 1.8 t directly as CO_2 from production and consumption of the anodes.

What will happen by 2010?

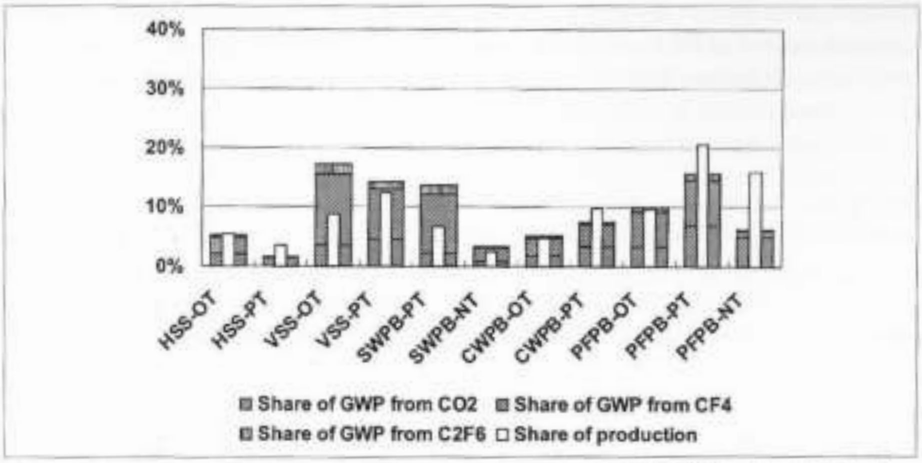

Figure 11: Share of production and emissions of CO_2 and CF_4 caused by different technical smelter categories in 1997

Emission of Green House Gases case study 1 for 2010

Under the conditions of case study 1, with no change of smelter technology and an additional production of 5 Mt/a Al the production share of PFPB-NT smelters will increase to nearly 30 %. There is little difference in the share of production and GWP emissions, compared with the situation in 1997.

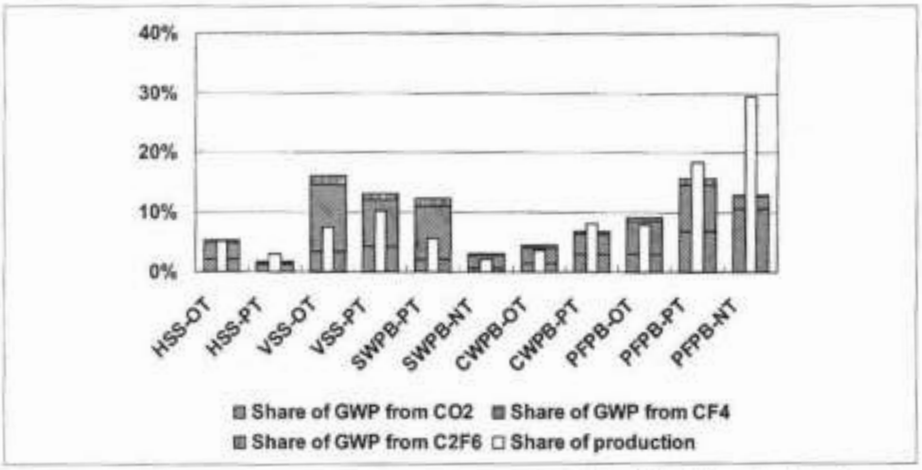

Figure 12: Share of production and emissions of CO_2 and CF_4 caused by different technical smelter categories in 2010 according to case study 1.

The total amount of GWP emitted from smelters increases to 114.9 % of the 1997 value. Certainly the specific amount of GWP emitted decreases to 4.5 t/t Al corresponding to 87.1 % of the 1997 specific value, including 1.8 t/t Al directly as CO_2 arising from anode production and consumption.

Emission of Green House Gases case study 2 for 2010

In case study 2 there is an assumed change in the smelter technology, so aluminium is only produced by smelters in the HSS-PT, VSS-PT, SWPB-PT, PFPB-PT and PFPB-NT categories.

The total amount of GWP emitted from smelters decreases to 96.0 % of the 1997 value. The specific amount of GWP emitted decreases to 3.9 t/t Al corresponding to 74.2 % of the 1997 specific value, including 1.8 t/t Al directly as CO_2 from anode production and consumption.

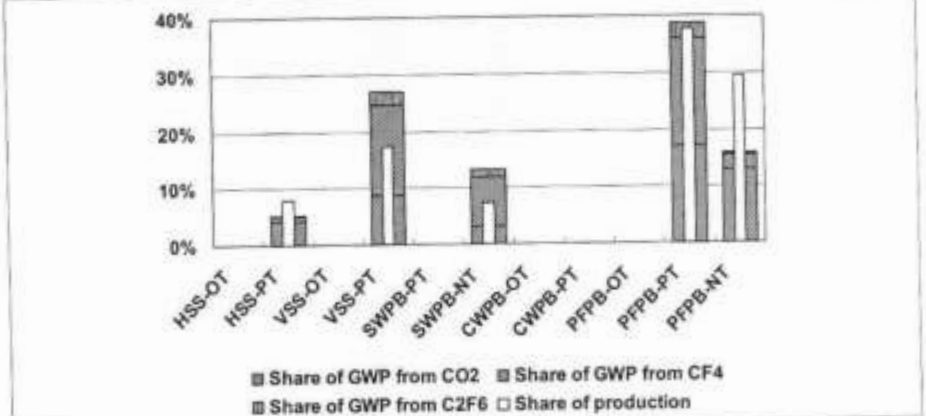

Figure 13: Share of production and emissions of CO_2 and CF_4 caused by different technical smelter categories in 2010 according to case study 2.

Summary and Conclusions

Most of the data from the case studies are shown in Table 10. For case studies 1 and 2 we assume that primary aluminium production will increase from nearly 22 Mt in 1997 to over 28 Mt in 2010, corresponding to 128.2 % of the 1997 amount. With no change in cell operations (case study 1) the specific electrical energy requirements will decrease to 14.6 kWh/kg Al, corresponding to 98.2 % of today's energy consumption, due to the installation of a modern smelter capacity of 3 Mt. At the same time the total electrical energy demand will increase to 126 % of the 1997 amount. With changes and optimisation of the smelter technologies (case study 2) the specific energy amount will decrease to 94.9 %, and the total energy consumption will increase to 121.6 % of the 1997 value. The decrease in the specific energy demand appears to be not very spectacular, but this is based only on the energy requirements of smelters, which are in operation today. Further developments in electrolysis technology are not included, such as larger cells and drained cells with wettable cathodes. Furthermore, 50 % of the aluminium is already produced in PFPB–smelters. Thus the major decreases have been made over the last 20 years due to the installation of this technology. On the other hand the decrease in emissions of gases with global warming potential is much larger, particularly the decrease of CF_4/C_2F_6 emissions. In case study 1, without any change in smelter technology, the specific emissions of CF_4/C_2F_6 will decrease to 85 % of the current value, with a slight increase to 108.7 % of total emissions. If recent existing smelters are optimised (shown in case study 2), the specific as well as the total emissions of CF_4/C_2F_6 will decrease to 61.5 % and 78.9 %, respectively, of the 1997 value. This leads to a decrease of total Green House Gas emissions (including CF_4, C_2F_6 and CO_2 from anode production and consumption) to 96 % of the 1997 value. The specific GWP emissions can be reduced to 74.2 % of the 1997 value.

It can bee seen from the figures, that the increases of **total** electrical and chemical energy demand, anode consumption and CO_2 emissions are nearly direct proportional to an increased production of aluminium both in case study 1 with no changes in the today applied technology and in case study 2 with changes in the applied technology. The **specific** figures will decrease only little due to the additional production of aluminium in new smelters and changes in the applied technology. The changes of the emissions of CF_4/C_2F_6 are **not** proportional to an increased aluminium production, because there are large differences in the specific emissions of these gases from different smelter technologies. So an increase of aluminium production to 125 % of the 1997 value will result in an increase of the total CF_4 emissions to 108 % only due to the installation of modern smelter with 3 Mt/a aluminium (case study 1). The change in the technology applied today will result in a **decrease** of the total CF4 emissions to 79 %, the specific emissions will reach only 61 % of the 1997 value. These changes will result in a decrease of the emissions of green house gases, calculated as CO2 on a 100 year basis, to 96 % of the 1997 value.

Additionally there are large potentials in reducing the specific and total Green House Gas emissions after 2010 if aluminium is produced only in new PFPB-smelters. But this is unrealisable until 2010 due to the high investment costs for modern smelters. The only technically practicable way is a slightly but consequent installation of these smelters combined with modernizations of the existing installations.

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order to analyse the complex system of metal production and recycling, different models have been developed. Thanks are due to the German Research Council for financial support.

Table 10: Energy content of fuel oil, packing coke and baked anodes, mass requirements for anode production and specific energy consumption for anode production

		1997		Case Study 1 for 2010		Case Study 2 for 2010	
Production	t	21,943,639	100.0%	28,138,639	128.2%	28,138,639	128.2%
Electrical energy	total MWh	326,648,478	100.0%	411,437,178	126.0%	397,304,652	121.6%
	kWh/kg Al	14.9	100.0%	14.6	98.2%	14.1	94.9%
Anode net consumption	t	10,156,939	100.0%	12784597	125.8%	12,616,797	124.2%
	kg/t Al	463.0	100.0%	454.3	98.1%	448.4	96.8%
Chemical energy from anode consumption	t	304,768,167	100.0%	383,537,901	125.8%	378,503,908	124.2%
	MJ/t Al	13,889	100.0%	13,630	98.1%	13,451	96.8%
Chemical energy for Anode baking (Fuel and packing coke)	t	29,450,489	100.0%	39,677,438.0	134.7%	38,887,714.0	132.0%
	MJ/t Al	1,919	100.0%	1,898.0	98.5%	1,852.8	96.5%
Total Chemical Energy Consumption	t	334,218,656	100.0%	423,215,339	126.6%	417,391,622	124.9%
	MJ/t Al	15,808	100.0%	15,520	98.2%	15,303	96.8%
CO_2 from anode consumption	t	37,249,442	100.0%	46,876,855	125.8%	46,261,589	124.2%
	kg/t Al	1,698	100.0%	1,666	98.1%	1,664	98.0%
CO_2 from anode baking (fuel)	t	1,343,815	100.0%	1,810,467	134.7%	1,681,394	125.1%
	kg/t Al	61	100.0%	64	104.9%	60	98.4%
CO_2 from packing coke	t	1,439,802	100.0%	1,939,786	134.7%	1,901,178	132.0%
	kg/t Al	66	100.0%	69	104.5%	68	103.0%
CO_2 total	t	40,033,059	100.0%	50,627,108	126.5%	49,844,161	124.5%
	kg/t Al	1,825	100.0%	1,799	98.6%	1,792	98.2%
CF_4	t	10,032	100.0%	10,907	108.7%	7,913	78.9%
	kg/t Al	0.457	100.0%	0.388	84.9%	0.281	61.5%
C_2F_6	t	1,003	100.0%	1,091	108.8%	791	78.9%
	kg/t Al	0.046	100.0%	0.039	84.8%	0.028	60.9%
GWP from CF_4	t	65,208,182	100.0%	70,896,657	108.7%	51,438,479	78.9%
	kg/t Al	2,972	100.0%	2,520	84.8%	1,828	61.5%
GWP from C_2F_6	t	9,229,466	100.0%	10,034,604	108.7%	7,280,523	78.9%
	kg/t Al	421	100.0%	357	84.8%	259	61.5%
Total GWP	t	114,470,706	100.0%	131,558,368	114.9%	109,442,931	95.6%
	kg/t Al	5,217	100.0%	4,542	87.1%	3,869	74.2%

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