Life cycle assessment of aluminium production in new Alcoa smelter in Greenland

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Preface

This LCA report is made by PhD Jannick H Schmidt (2.-0 LCA consultants, Denmark) and PhD Mikkel Thrane (Associate Professor), and with quality review by PhD Lone Kørnøv (Department of Development and Planning, Aalborg University, Denmark) for the Government of Greenland. The study was conducted in the period from October 2008 to April 2009.

Data collection has been carried out in collaboration with experts from Alcoa. We would especially like to thank the following persons involved:

- Marc Montembeault (Environmental and Technical support, Alcoa Deschambault),
- Lise Sylvain (Regional Manager for Environment and Sustainability, Alcoa Canada and Iceland),
- Gudmundur Sveinsson (Environmental Engineer, Alcoa Fjardaal Smelter, Reydarfjordur, Iceland)
- Patrick Grover (Director, Environmental, Health and Safety, Alcoa Global Primary Products, Growth, Energy, Bauxite, and Africa)
- Kenneth J Martchek (Global Life Cycle and Environmental Sustainability Manager, Alcoa Corporate Center in Pittsburgh US)

Besides, we would like to thank Chris Bayliss, responsible for Global Projects and Health in the secretariat for Health, Safety, Environment & Sustainability at the International Aluminium Institute (IAI), for providing useful information and engaging in interesting discussions. The same applies to Eirik Nordheim, Director EHS, from the European Aluminium Association (EAA) in Brussels.

The LCA report has undergone a critical panel review from 20th April to 3rd July 2009.

Terms and abbreviations used are explained in section 15 ‘List of terms and abbreviations’. Cited references are listed in section 16 ’References’.

The front page pictures are provided by Alcoa, and the Greenland map is obtained from:
http://dk.nanoq.gl/Emner/Om%20Groenland/Kort_over_groenland.aspx

Jannick H Schmidt and Mikkel Thrane, August 2009

Contents

Summary in English

The present report is a detailed study of the environmental impacts, seen in a life cycle perspective, of an aluminium smelter with an annual capacity of 360,000 tonnes planned for instalment in West Greenland. The study is initiated by Alcoa and the Government of Greenland. The smelter is still in the planning phase, and will not be operating before 2014, at the earliest.

The study applies the Life Cycle Assessment (LCA) method and it mainly focuses on greenhouse gas (GHG) emissions, or carbon footprint to use a catchier phrase. The focus on GHG emissions is partly a result of the requirements from the commissioner of the study and partly due to the fact that the LCA forms part of a strategic environmental assessment (SEA) in which other types of impacts are assessed separately. Other impact categories such as ozone depletion, acidification, eutrophication, eco-toxicity, and human toxicity are included in the present study and presented as part of the results, but are not assessed as detailed as GHG emissions and are therefore subject to considerable uncertainties.

The objective of the LCA is to provide life cycle-based environmental information on the planned aluminium smelter in relation to the strategic environmental assessment (SEA) process, which is ongoing from 2007 to 2009 (Greenland Home Rule 2007).

The Government of Greenland has commissioned the LCA study, and the target audience involves all interested parties, directly or indirectly involved in the SEA process. This includes the Government of Greenland, Alcoa, citizens of Greenland, citizens of Maniitsoq in West Greenland, where the proposed aluminium smelter is to be situated, and NGOs. The results of the LCA study are also of interest to the negotiating parties, including Denmark and Greenland, in the new climate agreement, which is to replace the Kyoto Protocol.

This summary is divided into three parts. The first part is the background section that describes the context and purpose of the LCA, while the second part explains the scope of study as well as important methodological considerations and choices. The third part presents the main results of the study. These include the estimated GHG emissions of the planned aluminium smelter in Greenland, and GHG emissions related to an alternative aluminium production. The alternative is assumed to be implemented if the Greenland smelter is not established, or to be avoided if the project continues as planned. Finally, part three comprises a sensitivity analysis highlighting the uncertainties of the LCA results.

According to the ISO 14044 standard, an LCA study should undergo a critical panel review if the results are meant to be used to support a comparative assertion intended for public disclosure. The present report has therefore been subject to a panel review from 20th April to 3rd July 2009. Mark Goedkoop (PRé Consultants) has been selected by Klaus Georg Hansen (Government of Greenland) as an external independent expert to act as a chairperson. Mark Goedkoop has independently selected two other interested parties. These are: Eirik Nordheim (EAA, European Aluminium Association) and Pascal Lesage (Sylvatica). The review, including the authors' comments, is available in Appendix 6: Review panel report, including the authors' comments.

Background

Aluminium is a non-ferrous metal and its production requires a significant amount of electricity. According to the International Aluminium Institute (IAI), 1 tonne of virgin aluminium represents, on average, an emission of 10 tonnes of CO2e, including mining and alumina production (see also literature review in section 2). This corresponds approximately to the GHG emissions from one average person during one year in Europe. Hence,

according to the IAI data, the proposed smelter represents GHG emissions equivalent to the emissions from approximately 360,000 persons in Europe during one year (or 3.6 million tonnes of CO2e annually). This is a significant contribution to Greenland's total Carbon Footprint (GHG emissions), and one of the reasons for the commissioning of the present study.

Electricity generation for the planned smelter will be based on two hydropower plants, which will be constructed for the same purpose. In terms of global warming, this is a great advantage, but the construction and operation of hydropower plants also produce GHG emissions. Furthermore, emissions also take place at other life cycle stages, as well as during the production of auxiliary materials (e.g. anodes), during transport, and during the construction of capital goods, such as buildings, machinery, and other types of infrastructure required. To obtain a reliable assessment, it is therefore necessary to make a comprehensive analysis that unveils a representative set of consequences, at all lifecycle stages, and in a larger perspective in which we include aluminium production that is avoided (globally) due to the construction of the Greenland smelter.

Purpose of study: The LCA is made as part of a Strategic Environmental Assessment (SEA). SEAs require that the main alternative is compared with "*reasonable alternatives*" (Directive 2001/42/EC of the European Parliament and the Council on the Assessment of the Effects of Certain Plans and Programmes on the Environment). Hence, the primary purpose of the LCA is to assess and to document the potential environmental impacts with a focus on GHG emissions from the following alternatives:

- Alternative 1: the establishment of an aluminium smelter in Greenland (Alcoa)
- Alternative 0: not establishing the aluminium smelter in Greenland; this means that an equivalent capacity will be installed in another location in the world, and that it may be commissioned by another company. This is also referred to as the marginal production in the present analysis.

Alternative 1) above refers to the main alternative in the strategic environmental assessment carried out by the Government of Greenland, and 0) refers to the 0 alternative.

The fact that the 0 alternative is represented by aluminium production in another location in the world is based on the assumption that aluminium production is driven by the global demand for aluminium. Thus, the decision to approve the aluminium smelter in Greenland will have the effect that a corresponding capacity will not be installed elsewhere. The 0 alternative represents the most likely location and technology that will be installed if the Greenland smelter is not installed. Alcoa may be able to identify another location with access to renewable energy as in the Greenland case, and thereby achieve similar low GHG emissions. However, it is out of the scope of the present study to determine whether Alcoa will search for another location if the Greenland smelter is not approved. Therefore, the present study only compares the specific proposed smelter in Greenland (alternative 1) with the most likely alternative capacity that will be installed elsewhere by an unspecified actor on the market (alternative 0).

Hence, the outcome of any decision made as part of the strategic environmental assessment process in Greenland can only affect local alternatives, such as local location and waste treatment etc., in the location in which new aluminium smelter capacity is installed.

It should be noted that a decision of establishing the smelter in Greenland (Alternative 1) also means that Alternative 0 is avoided, according to the mentioned assumptions about the global supply and demand situation on the aluminium market. The global change in GHG emissions, which results from placing an aluminium smelter in Greenland, is therefore Alternative 1 minus Alternative 0.

Methodology and scope

A life cycle assessment (LCA) is an evaluation of the potential impacts of all emissions arising throughout the life cycle of a product or a service. The LCA is made in accordance with the requirements in the ISO standards 14040 and 14044.

Functional unit and life cycle stages: The unit of study (also known as the functional unit) is 1 kg of virgin aluminium. The LCA involves the life cycle stages; Bauxite mining, alumina production, and aluminium production. Other downstream processes, such as sheet and foil production or aluminium production for consumer products and related waste disposal/reuse/recycling stages, are not included in the study. This is because the study is based on the assumption that the global production volume of aluminium is not affected by the decision whether to build the aluminium smelter in Greenland or not, and hence, the global amount of aluminium waste will not be affected.

It should be acknowledged that the use of aluminium can reduce the environmental impacts of other products, such as cars, significantly. The main reason is that aluminium has a low density, while being relatively durable. Furthermore, aluminium is ideal for recycling, which reduces the GHG emissions per kg by 90-95%. These considerations are, however, not relevant here, considering the purpose and scope of the present study.

Emission types: It has been chosen to categorise the GHG emissions as scopes 1, 2 and 3 according to the Greenhouse Gas Protocol from WRI and WBCSD (WRI and WBCSD 2004).

Scope 1 is the direct emissions from the smelter, which will be the main concern for Greenland in the perspective of the Kyoto Protocol. Scope 2 includes the GHG emissions from purchased electricity (and heat), which, in the case, of Greenland will involve the direct emission from the hydropower plants. The latter will only include GHG emissions of the water reservoirs, which are relatively insignificant. We have therefore also included indirect GHG emissions, related to the construction and operation of the hydropower plant in scope 2. Scope 3 includes all other emissions such as those related to mining, alumina production, transport, production of anodes, auxiliaries, etc.

Data for Greenland Smelter (alternative 1): As the aluminium smelter is not operating yet, data has been obtained from other smelters with a similar type of technology as the one assumed for Greenland. In this regard, Alcoa has provided data for their aluminium smelters in Iceland and Deschambault in Canada. The plant construction in Iceland is probably most similar to the proposed Greenland smelter, because it is the newest plant and because it does not produce anodes – similar to the planned smelter in Greenland. However, in some cases, it has been considered better to use the data from Deschambault, because the Iceland plant has just finished the start-up process and data may not be representative of stable operations in terms of some parameters.

Data for marginal production of aluminium (alternative 0): As mentioned, electricity consumption does, under normal circumstances, represent the largest contribution to GHG emissions in the life cycle of virgin aluminium. For the 0 Alternative, reflecting the alternative production of aluminium, it has therefore been pivotal to obtain reliable data for energy sources used for electricity generation – which again depends on the smelter location and the affected energy sources within the specific region.

A comprehensive analysis is carried out in section 4 to estimate the alternative (marginal) location of the smelters. Large uncertainties are involved, and a number of scenarios have been developed that reflect different methods and data sources (method and data triangulation). The 'recommended scenario' suggests that the alternative location will be a combination of three regions (composite marginal), represented by China by 60%, the Commonwealth of Independent Nations (CIS)[1] by 22%, and the Middle East (ME) by 18%. As electricity production in China is dominated by coal, the marginal electricity mix becomes 62% coal, 29% hydropower and 9% gas, of which half is alternatively assumed to be flared in CIS and the Middle East.

Despite the large number of scenarios, methods, and data sources used, most of the scenarios show rather similar results concerning the marginal electricity mix – with most electricity being based on coal followed by hydropower and gas, in that order. However, less reliable and significantly different scenarios have also been found. This part is elaborated in section 5 and is also reflected in the sensitivity analysis in this summary.

In addition to the considerations about affected energy sources for electricity generation, the analysis reflects technological differences between the relevant regions – both regarding smelter technologies and energy technologies. The study therefore considers other aspects, such as the fact that, e.g., Chinese power plants are less efficient than power plants in Western Europe and that they have different flue gas treatment technologies. For grid electricity used at other life cycle stages (e.g., bauxite mining and alumina production), a separate analysis is carried out that estimates the marginal grid electricity in all relevant regions/countries of the world. This is elaborated in section 6. The reason for distinguishing between electricity to smelter and other processes/stages is based on the fact that aluminium smelters, due to their high electricity consumption, have special contracts with power plants or even a large proportion of self-generated electricity, which arguably makes their electricity mix different from other less energy-consuming industries – even within the same region.

Results and perspectives

The main results for Alternative 1 (Greenland smelter) and Alternative 0 (alternative supply of aluminium) are presented in the following. The results are further described in section 11.

GHG emissions from smelter in Greenland (Alternative 1): The LCA carried out in this study estimates that the planned aluminium smelter will represent a contribution to global warming equivalent to 5.92 kg of CO2e per kg of produced virgin aluminium. Hence, scaling up to the planned annual production of 360,000 tonnes, the total annual contribution is estimated at 2.13 million tonnes of CO2e.

Scope 1 emissions are direct process emissions from the smelter. These amount to 1.66 kg of CO2e per kg of virgin aluminium, which is mainly related to the consumption of the anode, and, to a very limited extent, PFC emissions. The total annual scope 1 emissions relating to a production of 360,000 tonnes of aluminium will sum up to 597,000 tonnes of CO2e.

Scope 2 emissions are related to the generation of electricity at the hydropower plants. This amounts to 0.140 kg of CO2e per kg of virgin aluminium, including the construction and operation of hydropower plants and emissions from reservoirs. This is equivalent to an annual emission of 50,200 tonnes of CO2e.

Scope 3 emissions, related to the smelter stage, mainly include emissions from anode production, transport, services, as well as minor emissions related to waste treatment, etc. These amount to 1.09 kg of CO2e per kg of virgin aluminium, or 391,000 tonnes of CO2e, annually. The total emissions (scopes 1, 2 and 3) related to the smelter stage amount to 2.88 kg of CO2e per kg of virgin aluminium or 1.04 million tonnes of CO2e, annually.

[1] Mainly Russia

The emissions that take place within Greenland, which include the process emissions from the smelter, are estimated at 597,000 tonnes of CO2e. This corresponds to 85% of Greenland's current GHG emissions, which are approximately 700,000 tonnes[2] of CO2e.

To reach the total of 5.92 kg of CO2e per kg of virgin aluminium, we need to include the bauxite mining stage, which represents 0.144 kg of CO2e per kg, and the alumina production representing 2.89 kg of CO2e per kg, of which the major part is related to heat energy (based on fossil fuels).

Compared to other smelters, the GHG emissions from the Greenland smelter are significantly lower – mainly due to the use of hydropower. The GHG emissions related to the aluminium production of other smelters are described in the next section.

GHG emissions from alternative production (Alternative 0): The analysis of the environmental impacts of the marginal aluminium production, which will be implemented if the Greenland smelter is not constructed, shows that this will represent 20.7 kg of CO2e per kg of virgin aluminium, or 7.47 million tonnes of CO2e per year, presuming that 360,000 tonnes of aluminium would be produced in an alternative location. The main reason behind the large contribution is the electricity consumption, which is based on 62% coal, 29% hydropower, and 9% gas (of which half would alternatively be flared). In this scenario, more than 70% of the GHG emissions originate from the electricity production. For the Greenland smelter, this is only approximately 2%.

It is important to stress that the uncertainties related to the results of Alternative 0 are significant. It is not possible to know the exact location of the marginal production or the actual energy sources affected. A large number of sensitivity analyses have therefore been made of alternatives to the recommended scenario. These sensitivity analyses show GHG emissions between 11.6 kg of CO2e per kg of virgin aluminium, representing a production mainly based on hydropower in CIS/Russia, and 29.2 kg of CO2e per kg of virgin aluminium, representing a production in China based on 100% coal. As we cannot rule out any of the scenarios, the results can also be presented as 20.7 ± approx. 9 kg of CO2e per kg of virgin aluminium for Alternative 0. This is further elaborated in section 11.1.

Global change in GHG emissions (Alternative 1 minus Alternative 0): The total change in GHG emissions (in a global perspective) resulting from the placement of an aluminium smelter in Greenland will be the impacts of Alternative 1 minus Alternative 0, i.e. the impacts caused by the smelter in Greenland minus the impacts of placing the aluminium smelter in another location in the world. If we include the uncertainty range explained above, this means that the total change in GHG emissions as a result of implementing the Greenland smelter will cause savings of 2.05 to 8.36 million tonnes of CO2e annually (or savings of 5.34 million tonnes of CO2e annually, if we use the suggested scenario for Alternative 0). In other words, the Greenland smelter will imply that we avoid GHG emissions of about 5 ± 3 million tonnes of CO2e annually, in a global perspective.

Since Greenland's annual CO2e emissions are approximately 700,000 tonnes of CO2e, the planned smelter has the potential for reducing global GHG emissions by 3 to 12 times Greenland's current GHG emissions, despite a nearly doubling of the domestic GHG emissions occurring in Greenland. In this respect, it should be stressed that the consequences of GHG emissions are independent of the location where they occur.

[2] According to UNFCCC (2009), the fossil-based CO_2 emissions in Greenland in 2006 were 682,000 tonnes of CO2e. Based on this, the annual CO2e emission in Greenland today is estimated at 700,000 tonnes of CO2e.

It is possible that equally carbon friendly alternatives (to the Greenland smelter) exist and could be chosen by Alcoa. This includes smelters in areas where it is possible to use 100% hydropower or 100% gas which otherwise would be flared, e.g., in regions such as Russia/Siberia, Africa or the Middle East. However, the present study does only compare the Greenland smelter with no Greenland smelter. Specific alternatives to the Greenland smelter planned by Alcoa are not considered. Instead, the study compares the Greenland smelter with the most likely alternative capacity that would be installed somewhere else as a reaction to changes in the demand for aluminium.

Human Health aspects in Greenland: The study includes a tentative assessment of human health impacts in Greenland – but only related to the external environment (not occupational heath and safety). The assessment shows that the smelter provides a significant contribution to the impact category ‘respiratory inorganics’. Respiratory inorganics include respiratory effects on humans (from inorganic substances such as particles and sulphur dioxide) typically caused by combustion processes. The main contribution from the Greenland smelter is sulphur dioxide, which consequently raises a red flag. This means that we recommend that human health aspects are considered in the strategic environmental assessment (SEA) or in a separate Health Impact Assessment (HIA).

Another potential concern is emissions of hydrogen fluoride (HF). Unless exposed to very large doses, we have not found indications of significant impacts on human health; but considering the possibility of bioaccumulation, it has been considered necessary to discuss this matter as an input to the SEA or HIA. The concern has not been raised by the LCA as such, but is a result of literature studies and interviews conducted as part of the LCA.

Other impact categories: The LCA has also provided a screening of 15 other environmental impact categories – including ozone depletion, nature occupation, acidification, photochemical ozone formation, etc. (see section 11.2). These impacts have not been scrutinized in detail, but the assessment mainly points towards the following impact categories as potentially important:

- Nature occupation
- Human toxicity
- Respiratory inorganics

Concerning nature occupation, the concern mainly originates from a qualitative assessment, and not the quantitative assessment based on the Stepwise LCIA method. Transforming and occupying land in a pristine and probably sensitive environment in Greenland is critical and does raise a red flag.

Concerning human toxicity our analysis suggests that the contribution is mainly related to mining fields, red mud, and landfill sites, where the transfer to humans is relatively insignificant.

For respiratory inorganics, the main contribution comes from sulphur dioxide, particulates, and nitrogen oxides. The emissions are mainly caused by the electrolysis process, the ship transport of raw materials, and the alumina production. It should be noted, however, that the relative importance is likely to be overestimated in the analysis, as the emissions mainly occur in remote places with little human exposure.

It is important to note that the above assessment only reflects a screening and that other impacts could be equally or more important. The impact on cultural and social aspects is another important issue, and it is crucial that the reader addresses the SEA for a more comprehensive assessment of the local, environmental and social impacts related to the planned Greenland smelter.

Eqikkaaneq

Nalunaarusiaq manna tassaavoq avatangiisinut sunniutaasinnnaasunut sukumiisumik misissuineq, Kalaallit Nunaata kitaani aluminiumik aatsitsivimmik 360.000 tons-inik nioqqutissorsinnaasup sanaartorniarneqarluni pilersaarutaasumut atuunnermini sunniutigisinnaasai. Misissuineq Alcoa Kalaallit Nunaannilu Naalakkersuisunit aallartinneqarsimavoq. Aatsitsivik maannakkut pilersaarusiorneqarpoq siusinnerpaamillu 2014-imi atuutilersinnaassalluni.

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Eirik Nordheim (EAA, European Aluminium Association) aamma Pascal Lesage (Sylvatica). Naliliineq allattup oqaaseriumasai ilanngullugut uani takuneqarsinnaavoq: Review panel report, including the authors' comments.

Tunuliaqutaa

Aluminiu tassaavoq aatsitassaq saviminertaqanngitsoq nioqqutissatullu aatsinniarlugu annertuumik innaallagissamik pisariaqartitsisoq. International Aluminium Institute (IAI) naapertorlugu aluminiu ton-i ataaseq agguaqatigiissillugu CO_2-mik 10 tonsinik annertutigisumik aniatitsinermik naleqarpoq, tamatumanili piiaanerit nioqqutissiornerillu ilaallutik (Annertunerusumik paasissutissat uani takuneqarsinnaapput: Afsnit 2-mi). Tamanna GHG-nik aniatitsineq agguaqatigiissillugu Europa-mi inuup ataatsip akiumut aniatittagaanut naleqqiunneqarsinnaavoq. Taamaattumik paasissutissat IAI-meersut naapertorlugit aatsitsivimmit siunnersuutigineqartumit GHG-nik aniatitsineq ukiup ataatsip ingerlanerani Europa-mi inuit 360.000-it aniatittagaannut naleqqiunneqarsinnaalluni (allatut oqaatigalugu ukiumut CO2e 3,6 mio. tons-itut annertutigisoq). Tamanna Kalaallit Nunaanni tamakkiisumik GHG-nik maannamut aniatittakkanik malunnaatilimmik annertusinerussaaq, taamaammallu massuma nalunaarusiap suliarineqarnissaa imissutigineqarsimalluni.

Aatsitsiviup siunnersuutigineqartup innaallagialersornissaa erngup nukinganik marlunnik nukissiorfiliornikkut pissaaq, taakkulu tamannarpiaq siunertaralugu sanaartorneqartussaapput. Nunarsuarmi silap kissatsikkiartornera eqqarsaatigalugu tamanna annertuumik iluaqutaassaaq, taamaattorli erngup nukinganik nukissiorfinnik sanaartornissaq ingerlatsinissarlu aamma GHG-nik aniatitsinermik kinguneqartussaavoq. Ilanngullugu pilersaarutaasup tamakkiisumik ingerlanneqarnerani aniatitsisoqartussaavoq, ilaatigut nioqqutissiornermut atatillugu pilersinneqartussatigut (ass. Anod-it), assartuinikkut, kiisalu tamakkiisumik illorsuarnik, atortorissaarutissanik attaveqarnermullu atorfissaqartitanik sanaartornerup nalaani. Taamaammat naliliineq tutsuiginartoq angussagaanni pisariaqarpoq kingunerisinnaasaanik tamakkiisumik misissueqqissaarnissaq, pilersaarutaasup tamakkiisumik ingerlanneqarnissaa eqqarsaatigalugu, tamassumalu saniatigut nunarsuaq tamakkerlugu eqqarsaatigissagaanni Kalaallit Nunaani aatsitsiviliortoqassappat nunarsuup sinnerani aluminiumik tunisassiornissaagaluap avaqqunneqarnissaa ilanngullugu.

Misissuinerup siunertaa: LCA tassaavoq SMV-mut atatillugu suliarineqartoq. Tunngaviusumik avataangiisinut sunniutissaanik naliliinermut pisariaqarpoq, periarfissaq alla pingaarneq allanut "periarfissanut naleqqutunut" sanillullugu assersuunneqarnissaa (Directive 2001/42/EC of the European Parliament and the Council on the Assessment of the Effects of Certain Plans and Programmes on the Environment). Taamaammat LCA-mi siunertaq pingaarneq tassaavoq periarfissat tulliani eqqaaneqartut iluanni GHG-nik aniatitsinissaq qitiutillugu avatangiisinik sunniuteqarsinnaanissaa nalilersorlugulu uppernarsarniassallugu:

- Periarfissaq 1: Kalaallit Nunaanni aluminiumik aatsitsiviliorneq (Alcoa).
- Periarfissaq 0: Kalaallit Nunaanni aatsitsiviliortoqannginnissaq; Ima paasillugu nioqqutissiorfiup taamatut piginnaassuseqartup nunamut allamut nuunnera, tamannalu sanaartortitsinianit allanit ingerlanneqarsinnaanissaa. Misissuinermi matumani periarfissaq taanna aamma avinngarusimasukkut nioqqutissiorsinnaanissamik taaneqarpoq.

Periarfissaq 1) qulaani eqqaaneqartoq Kalaalit Nunaanni Naalakkersuisut tunngaviusumik naliliisitsinerannut atavoq, taavalu 0) tassaalluni periarfissamut 0-umut atasoq.

Periarfissap 0-up nunarsuarsi piffimmi allami aluminiumik nioqqutissiortoqarsinnaanissaanut attuumassuteqarnera imatut paasineqassaaq nunarsuaq tamakkerlugu aluminiumik pisariaqartitsiuarneq. Taamaammat Kalaallit Nunaanni aatsitsiviliornissamik sanasoqarnissaanik akuersaarneq nunami allami assinganik sanaartorneqarnissaanik pinngitsoortitsissaaq. Periarfissaq 0 tassaavoq Kalaallit Nunaanni aatsitsivimmik pilersitsisoqanngippat inissiffissaa teknologi-lu atorneqartussaq ilimanarnerpaasinnaasut. Imaassinnaavormi Alcoa inissiivissamik allamik Kalaallit Nunaannisulli piujuaannartumik aallaavilimmik nukissiorfittalimmik nassaarsinnaasoq, taamatullu GHG-nik aniatitsinissamik taama appasitsigisumik periarfissaqalersinnaalluni. Kalaallit Nunaannili aatsitsiviliornissaq akuersaarneqanngippat matumani misissuinermi Alcoa-p allamik inissiffissamik ujarlersinnaanissaanut apeqqut ilanngunneqanngilaq. Taamaattumik misissuinermi matumani taamaallaat Kalaallit Nunaanni aatsitsiviliornissamut siunnersuuteqarsimanermut apeqqut (periarfissaq 1) illuatungiliullugulu aappaatut periarfissatut ilimanarnerpaasinnaasoq, tassa piffimmi allami kikkuugaluarnersut aatsitsiviliorusussinnaanissaat (periarfissaq 0) sanilliullugit nalilersorneqarput.

Taamaamat Kalaallit Nunaanni tunngaviusumik avatangiisinut sunniuteqarsinnaaneranik nalilersuinerit tunngavigalugit aalajangiineq suugaluarnersorluunniit piffimmi pineqartumi periarfissanik attuisussaavoq, tassanilu aatsitsiviup nutaap sanaartorneqarnissaani sumerpiaq inissiinissaq, eqqagassat isumagineqarnissaat il.il. apeqqutaalissallutik.

Malugineqassaaq Kalaallit Nunaanni aatsitsiviliornissamik akuersaarneq (periarfissaq 1) ima kinguneqassammat periarfissaq 0-up atorunnaarnissaanik, tamatumani nunarsuaq tamakkerlugu aluminiumik nioqqutissiornermi pilersuineq piumasaqarnerlu eqqaaqqillugit. Nunarsuaq tamakkerlugu GHG-nik aniatitsinikkut allannguutit Kalaallit Nunaanni aatsitsiviliortoqarneratigut tassaasussaapput Periarfissaq 1 Periarfissaq 0-ilu ilanngaatigalugu.

Iliuuseq annertussusaalu

Tamakkiisumik atornissaanik naliliineq tassaavoq nioqqutissiornerup kiffartuussinerulluunniit atuunnera tamakkerlugu silamut aniatitsisinnaaneranik missingersuineq. LCA ingerlanneqartoq ISO standard-it 14040 aamma 14044 naapertorlugit suliarineqarpoq.

Misissugassaq atorneqarneratalu sivisussusaa: Misissugassaq tassaavoq aluminiu attorneqarsimanngitsoq 1 kg-mik oqimaassusilik. LCA-mut ukiut ingerlanerini pisussat misissugassaapput; Bauxit-imik piiaanerit, alumina-mik suliarinninneq kiisalu aluminiu-mik nioqqutissiorneq. Ingerlatsinermi akuusut allat, soorlu sølvpapir-imik taaguutilinnik nioqqutissiornerit nerisassanullu poortuutitut atugassianik nioqqutissiornerit, taakkununngalu atatillugit eqqagasserinerit/atoqqiinerit/aatseriarlugit nutaaliaralugit matumani misissuinermi ilanngunneqanngillat.Tamatumunnga pissutaavoq misissuinerup ingerlanneqarnerani Kalaallit Nunaanni aatsitsiviliornissamik aalajangiinissaq nunarsuaq tamakkerlugu qanoq annertutigisumik aluminiu-mik nioqqutissiornermut apeqqutaasussaanngimmat, taamaammallu nunarsuaq tamakkerlugu tamakkiisumik aluminiu-mik eqqagassat aamma allanngortussaanatik.

Malugeqquneqarpoq aluminiumik atuinikkut nioqqutissat allat, soorlu biilit, avatangiisinut sunniuteqarneri malunnaatilimmik annikillineqarsinnaammat. Tamatumunnga pissutaanerpaavoq aluminiu oqitsunnguugaluarluni sivisuumik atasinnaassuseqarmat. Ilanngullu aluminiu aatseriarlugu nutaaliarinissaanut piukkunnartuuvoq, taamaaliornikkullu GHG-nik aniatitat kg-kkaartumik 90-95%-imik annikillineqartarlutik. Eqqarsaatersuutilli tamakku misissuinermi matumani ilanngunneqanngillat, misissuinerummi siunertaanut killeqarneranullu attuumassuteqanngimmata.

Aniatitassat assigiinngitsut suussusii: GHG-nik aniatitassat WRI-meersoq The Greenhouse Gas Protocol kiisalu aamma WBCSD (WRI aamma WBCSD 2004) najoqqutaralugit ima immikkoortiterneqarsimapput: Scope 1, 2 aamma 3.

Scope 1 tassaavoq aatsitsivimmit toqqaannartumik aniatitat, taannalu tassaavoq Kyoto-mi isumaqatigiissut eqqarsaatigalugu Kalaallit Nunaannut pingaaruteqarnerpaaq. Scope 2 tassaavoq innaallagissiornikkut kiassarnikkullu GHG-nik aniatitsineq, tassanilu Kalaallit Nunaat eqqarsaatigalugu erngup nukinganik nukissiorfinnit aniatitassaq. Kingullermi taamaallaat imeqarfissuarnit GHG-nik aniatitat pineqarput, taakkulu ataatsimut isigalugu suunngillat. Taamaammat Scope 2-mi toqqaannanngikkaluamik GHG-nik aniatitassat ilanngunneqarsimapput, tassaallutik erngup nukinganik nukissiorfiliornerni sanaartornerup ingerlatsinerullu nalaanni pisussat. Scope 3-mi aniatitsinerit allat ilanngussoneqarsimapput: aatsitassiorneq, alumina-mik nioqqutissiorneq, assartuineq, anode-nik nioqqutissiorneq, sulinermi tapertatut ingerlanneqartut il.il.

Kalaallit Nunaanni Aatsitsivik pillugu paasissutissat (periarfissaq 1): Aluminiumik aatsitsivik suli aallartinngimmat paasissutissat Kalaallit Nunaanni pilersaarutaasumut aatsitsivinnit ingerlareersunit teknologikkullu assingusinnaasunik atortunit nunani allani paasissutissanik katersuisoqarsimavoq. Tamanna siunertaralugu Alcoa Island-imi Canada-milu Deschambault-mi aluminiumik aatsitsivinnit paasissutissanik pissarsiorsimavoq. Island-imi aatsitsivimmik sanaartorneq qularnanngitsumik Kalaallit Nunaanni pilersaarutaasumut eqqaanarnerpaavoq, ilaatigut pissutigalugu pilersitani nutaajunersaammat, aammalu anode-nik nioqqutissiortuunngimmat – soorlu taamatut Kalaallit Nunaanni aatsitsivimmi taama pilersaaruteqartoqartoq. Taamaakkaluartoq ilaatigut Deschambault-mit paasissutissat atussallugit iluarineqarneruvoq, pissutigalugu Island-imi aatsaat aallartisarneq naammassimmat, tassanngaanniillu paasissutissat ataavartumik ingerlatsineq eqqarsaatigalugu, misissuinermilu toqqammavissat eqqarsaatigalugit nalorninartoqartutut isigineqarsinnaammata.

Avinngarusimasukkut aluminiumik nioqqutissiornermut atatillugu paasissutissat (Periarfissaq 0): Soorlu eqqaaneqareersoq aluminiumik nioqqutissiorneq tamakkiisumik isigissagaanni nalinginnaasumik ingerlatsinermi innaallagissamik atuineq tassaavoq GHG-nik aniatitsinerpaasoq. Taamaattoq periarfissaq 0 eqqarsaatigalugu, tassa nunami allami aluminiumik nioqqutissiornissaq eqqarsaatigalugu, pingaaruteqarluinnarsimavoq innaallagissiornermi sunik atuineq tutsuiginartumik paasissallugu – tamatumanilu aatsitsviup sumi inissisimanera nunallu immikkoortortaani tassani sutigut nukissiorneq sunut attuinersoq.

Aatsitsivinnik allani inissiisinnaanermut nalilersuinernut sukumiisumik misissueqqissarnerup inernera uani nassaarineqarsinnaavoq: Afsnit 4-mi. Nalorninartut annertuut tassaniipput, misissueriaatsillu arlallit atorneqarsimallutik, taamaaliornikkut periaatsit paasissutissallu aqqutigalugit sumiiffiit takutinniarneqarlutik (periaatsit paasissutissallu atorlugit pingasuniit isigalugu). 'Periusissap siunnersuutigineqartup' allami inissiiffissaq nunap immikkoortui pingasut ataatsimut ataqatigiissinnissaannik imaqarpoq (avinngarusimasoq katitigaq), tamatumani Kina 60%-iulluni, Commonwealth of Independent Nations (CIS)[3] 22%-iulluni kiisalu Kangia Qiterleq (ME) 18%-imik. Kina-mi innaallagissiorneq annertunerpaamik aamarsuarnik aallaaveqarmat, allatut innaallagissamik pilersuinissaq ima agguarneqarsinnaassaaq: Aamarsuit 62%, erngup nukinga 29% kiisalu gas-i 9%, taakkulu affaat illuatungiliullugu CIS-imi ME-milu nassaarineqarsinnaassagunarlutik.

Naak periarfissatut misissuiffigisat, iliuusissat paasissutisallu amerlaqisut atorneqaraluartut naggataatigut innaallagissiornikkut periarfissat katiterneri assigiittorujussuupput – aamarsuit atoraanni inaallagiaq annertunerpaaq pissarsiarineqarsinnaalluni, kiisalu erngup nukinga gas-ilu tulliullutik. Taamaattorli aamma periarfissat tutsuiginannginnerusut allaanerulluinnartullu nassaarineqarsimapput. Tamakkununnga tunngasoq immikkoortumi 5-mi itisilerneqarpoq eqikkaanermilu matumani malussarissuseq pillugu misissueqqissaarnermi aamma takuneqarsinnaalluni.

[3] Annermik Rusland

Kallerup inniliornissamut nukissiuutit sunnerneqartussat pillugit eqqarsaatersuutit qaavatigut misissueqqissaarnerup nunap immikkoortui attuumassuteqartut akornanni teknologiikkut assigiinngissusaat aamma ersersippaa – aatsitsinermi teknologii eqqarsaatigalugu aammattaaq nukissiornikkut teknologii eqqarsaatigalugu. Taamaammat misissuinerup isiginniffiit allat isumaliutigai, soorlu assersuutigalugu Kinami nukissiorfiit Europami Killermi nukissiorfinninngarnit naammassisakinnerusarnerat aammalu putsup gassiata passunneqarnissaanik teknologiit assigiinngitsut atorlugit. Kallerup innera atuunnerup ingerlarnani killiffinni allani atorneqartoq pillugu (soorlu bauxitimik piiaaneq aamma alumina-mik nioqqutissiorneq) misissueqqissaarneq alla ingerlanneqarpoq taassumalu nunarsuarmi nunat immikkoortuini/nunani attuumassuteqarsinnaasuni tamani kallerup innera avinngarusimasumi atorneqartoq naatsorsorpaa. Tamanna immikkoortumi 6-mi itisilernerqarpoq. Kallerup innerata aatsitsivimmukartup suleriaatsinit/killiffinnit allanit immikkoortinneqarneranut pissutaavoq aluminiumik aatsitsiviit, kallerup inneranik annertoorsuarmik atuinertik pissutigalugu, nukissiorfinnik immikkut ittunik isumaqatigiissuteqartarmata imaluunniit allaat kallerup innera nammineq pilersoq annertooq, kallerullu inniutaat taanna tunisassiorfinnit allanit nukimmik atuinnginnerusunit allatut akoorisarsimassagunarpoq – allaat nunap immikkoortuata iluani.

Inerneri siunissamilu pisussat

Periarfissaq 1-mut (Kalaallit Nunaanni aatsitsivik) aamma Periarfissaq 0-mut (aluminiumik pilersuineq periarfissaq alla) inernerit pingaarnerit tulliuttumi saqqummiunneqarput. Inernerit immikkoortumi 11-mi sukumiinerusumik sammineqarput.

Kalaallit Nunaanni aatsitsivimmiit (Periarfissaq 1) GHG-nik aniatitsinerit: Misissuinermi matumani LCA ingerlanneqartup naatsorsorpaa aluminiumik aatsitsivik pilersaarutigineqartoq nunarsuarmi kissatsikkiartuaarnermut aluminiup nutaap nioqqutissiarineqartup kiilup ataatsip CO_2-mut 5,92 kg-mut assersuunneqarsinnaasumik ilanngusseqataasassasoq. Tassa imaappoq, pilersaarutigineqartutuut ukiumut 360.000 tonsinut naatsorsoraanni, taava CO_2-mik ukiumut ilanngusseqataaneq 2,13 million tonsinut naatsorsorneqarpoq.

Aniatitsinerit Scope 1-usut tassaapput aatsitsivimmiit suleriaatsinit aniatitsinerit toqqaannartut. Tamakku annertussuserissavaat aluminiumut nutaamut kiilumut ataatsimut CO2e 1,66 kg, taanna annermik anodemik atuinermut attuumasseteqarluni aammattaaq, assut killeqartumik, aniatitsinernut PFC-usunut. Ukiumut 360.000 tonsinik aluminiumik nioqqutissiornermi aniatitsinerit scope 1-iusut ukiumut tamakkerlugit CO_2 597.000 tonsiussapput.

Aniatitsinerit scope 2-jusut erngup nukinganik innaallagissiorfimmi innaallagialiornermut tunngapput. Taakku aluminiumik nutaamik kiilumut CO_2 0,140 kg angussavaat, erngup nukinganik innaallagissiorfiliornerit ingerlannerilu aammalu imissaqarfinnit aniatitsinerit ilanngullugit. Taakku nalingissavaat ukiumut CO_2 50.200 tonsimik aniatitsineq.

Aniatitsinerit scope 3-jusut, aatsitsinerup nalaanut tunngasut, annermik anodeliornermit, assartuinermit, kiffartuussinernit aammattaarlu eqqakkanik passussinernit il.il. aniatitsinernit annikitsunit pisuupput. Taakku aluminiumik nutaamik kiilumut CO_2 1,09 kg angussavaat, imaluunniit ukiumut CO_2 391.000 tons. Aniatitsinerit tamarmik katinnerat (scope 1, 2 aamma 3) aatsitsinerup nalaanut tunngasut aluminiumik nutaamik kiilumut CO_2 2,88 kg angussavaa imaluunniit ukiumut CO_2 1,04 million tonsiusoq.

Aniatitsinerit Kalaallit Nunaata iluani pisartussat, aatsitsivimmi suleriaatsinit aniatitsinerit ilanngullugit, ukiumut CO_2 597.000 tonsinut naatsorsorneqarput. Tamanna maanna Kalaallit Nunaata GHG-inik aniatitsisarnerata 85%-eraa, CO_2 700.000 tonsit[4] missaanniittoq.

Aluminiumik nutaamik kiilumut katillugit CO_2 5,92 kg angussagaanni bauxitemik piiaaneq ilanngguttariaqarparput, taannalu annertussuseqarluni kiilumut CO_2 0,144 kg, aammattaaq alumina-mik nioqqutissiorneq kiilumut CO_2 2,89 kg-mik annertussuseqartoq, taassuma annersaa kiassarnermut tunngasuusoq (orsussanik ujaranngorsimasunik aallaaveqartut).

Aatsitsivinnut allanut naleqqiullugu Kalaallit Nunaanni aatsitsivimmit GHG-mik aniatitsinerit malunnartumik appasinnerupput – erngup nukinganik atuineq peqqutaanerulluni. GHG-inik aniatitsinerit aluminiumik aatsitsivinnut allanut tunngasut immikkoortumi tullermi nassuiarneqassapput.

Periarfissamit allamit nioqqutissiornermit GHG-nik aniatitsinerit (Periarfissaq 0): Piffimmi (nunami) allami aluminiumik nioqqutissiornermi, Kalaallit Nunaanni aatsitsivik sanaartorneqanngippat atulersinneqartussaq, avatangiisinut sunniutigisinnaasat misissoqqissaarnerata takutippaa tamanna aluminiumik nutaamik kiilumut CO_2 20,7 kg-mik annertussuseqassasoq, imaluunniit ukiumut CO_2 7,47 million tonsit, piffimmi allami aluminiu 360.000 tonsit nioqqutissiarineqarnera tunngavigalugu. Ilanngussinermut taama angitigisumut peqqutaasoq pingaarneq tassaavoq kallerup inneranik atuineq, taanna ima aallaaveqassammat: aamarsuarmit 62%, erngup nukinganit 29% kiisalu gassimit 9% (taassumalu affaa atorneqanngippat ikuallaannarneqartussaalluni). Periarfissami tassani GHG-mik aniatitsinerit 70%-ii sinnerlugit innaallagissiornermit pisuussapput. Kalaallit Nunaanni aatsitsivimmi taanna taamaallaat 2% missaaniissaaq.

Erseqqissaatigissallugu pingaarpoq nalorninartut Periarfissaq 0-p inernerinut tunngasut annertummata. Nioqqutissiorfissap sumorpiaq inissinnissaa nukingilluunniit sunnerneqartussat qanoq agguarsimanissaat nalunarluinnarpoq. Taamaammat malussarissuseq pillugu misissueqqissaarnerit amerlaqisut suliarineqarsimapput periarfissamit unnersuussutigineqartumit piffinnut allanut tikkuussisinnaasut. Malussarissuseq pillugu misissueqqissaarnerit taakku takutippaat aluminiu nutaaq kiilumut CO_2 11,6 kg-p, CIS/Ruslandimi erngup nukinga tunngaviginerullugu tunisassiorneq, aamma CO_2 29,2 kg-p, Kinami aamarsuit 100% tunngavigalugit tunissassiorneq, akornanni GHG-mik aniatitsinerit. Periarfissat arlaannaalluunniit pinngitsoorsinnaannginnatsigu inerneri aamma ima saqqummiunneqarsinnaapput: Periarfissaq 0-mi aluminiu nutaaq kiilu CO_2 20,7 ±. 9 kg miss. Tamanna immikkoortumi 11.1-mi itisilerneqassaaq.

GHG-inik aniatitsinerit pillugit nunarsuarmi allannguutit (Periarfissaq 1 Periarfissaq 0 ilanngaatigalugu): Kalaallit Nunaanni aatsitsivimmik inissiinerup kingunerisaanik GHG-inik aniatitsinerit allanngornerat tamarmiusoq (nunarsuaq tamaat isigalugu) tassaassapput Periarfissaq 1-imi sunniutit Periarfissaq 0-imi sunniutit ilanngaatigalugit, t.i. Kalaallit Nunaanni aatsitsivimmit sunniutit nunarsuarmi piffimmi allami aluminiumik aatsitsivimmik inissiinikkut sunniutit ilanngaatigalugit. Nalorninartorpassuit qulaani nassuiarneqartut ilanngukkutsigit ima isumaqarpoq aatsitsivik Kalaallit Nunaanni atulersinneqartuuppat GHG-nik aniatitsinerit allanngornerat tamarmiusoq ukiumut CO_2 2,05-imiit 8,36 million tonsit tungaannut pinngitsoortitsissasoq (imaluunniit CO_2 ukiumut 5,34 million tonsit siunnersuutigineqartoq Periarfissaq 0 atorutsigu). Allatut oqaatigalugu, nunarsuaq tamaat isigalugu, aatsitsivik Kalaallit Nunaanniittup

[4] UNFCCC (2009) naapertorlugu, 2006-imi Kalaallit Nunaanni ujaranngorsimasut aallaavigalugit CO_2-mik aniatitsinerit CO2e 682.000 tonsiupput. Tamanna tunngavigalugu ullumikkut Kalaallit Nunaanni CO2e -mik ukiumut aniatitsineq 700.000 tonsinut naatsorsorneqarpoq.

kingunerissavaa GHG-nik aniatitsinerit CO_2 5 ± 3 million tonsit missaanniittut ukiumut pinngitsoortittassagivut.

Kalaallit Nunaata CO_2-mik aniatitsinera ukiumut 700.000 tonsit missaanniimmat aatsitsiviup pilersaarutigineqartup nunarsuarmi GHG-inik aniatitsinerit annikillisinnissaannut ilippanaateqarpoq, maanna Kalaallit Nunaata GHG-nik aniatitsinerata 3-12-riaataanik angitigisumik, uffa Kalaallit Nunaanni namminermi GHG-inik aniatitsinerit marloriaatingajaanik annertusigaluarlugu. Tassunga atatillugu erseqqissaatigisariaqarpoq GHG-inik aniatitsinerit kinguneri piffimmit sumit pisuunerat apeqqutaanngimmat.

Imaassinnaavoq (aatsitsivimmut Kalaallit Nunaanniittumut) periarfissanik allanik carbonimik aamma pilersuivallaanngitsunik peqartoq Alcoamillu toqqarneqarsinnaasunik. Taakkununnga ilaapput sumiiffinni aatsitsiviit erngup nukinganik 100%-itimik imaluunniit gassimik 100%-imik pilersorneqarsinnaasut, gassi atorneqanngippat ikuallatsinneqaannartussaalluni, assersuutigalugu nunat immikkoortuini ukunani: Rusland/Siberia, Afrika imaluunniit Kangiani Qiterlermi. Kisianni misissuinerup matumap aatsitsivik Kalaallit Nunaanniittoq aatsitsivimmut Kalaallit Nunaanniinngitsumut taamaallaat naleqqiuppaa. Aatsitsivimmut Kalaallit Nunaanniittumut Alcoamit pilersaarutigineqartumut periarfissat allat tigussaasut isumaliutigineqanngillat. Akerlianik misissuinerup aatsitsivik Kalaallit Nunaanniittoq periarfissaasinnaasunut allanut ilimanarnerpaanut naleqqiuppaa, aluminiumik piumasaqarnerup allanngorsinnaanerata qisuariarfigisariaqarnerata kingunerisaanik.

Kalaallit Nunaanni peqqissuuneq eqqarsaatigalugu: Misissuinermut ilaavoq Kalaallit Nunaanni inuit peqqissusiannut sunniutit misilittaatigalugu nalilernerat – kisianni avatangiisinuinnaq attuumassuteqartut pillugit (sulisilluni peqqissuuneq isumannaatsuunerlu pineqanngillat). Naliliinerup takutippaa aatsitsivik malunnaatilimmik sunniutit immikkoortuannut ‘anersaartuutitigut uumassuseqanngitsu-’nut pilersitsisoq. Anersaartuutitigut uumassuseqanngitsunut ilaavoq inunni anersaartuutitigut sunniutit (sananeqaatinit uumassuseqanngitsunit pisoq soorlu sananeqaatit mikisut aamma svovldioxid) ikumatitaqarluni suleriaatsinit pigajuttartoq. Aatsitsivimmit Kalaallit Nunaanniittumit ilanngussineq pingaarneq tassaavoq svovldioxid, taannalu erfalasumik aappaluttumik nittartitsivoq. Ima isumaqarpoq inuit peqqissusiannut tunngasut pilersaarusiornermut atatillugu avatangiisit nalilersorneranni (SMV) imaluunniit immikkut ingerlanneqartumi Peqqissutsimut Sunniutit Nalilersorneranni (VVH) ilanngullugit isumaliutigineqarnissaat innersuussutigigatsigu.

Isumanerluuteqalersitsisinnaasoq alla tassaavoq hydrogen fluoridimik (HF) aniatitsineq. Annertussutsinut angisoorsuarnut sunnertinneq eqqaassanngikkaanni inuit peqqissusiannut malunnaatilimmik sunniuteqarsinnaasunik nassaarsimanngilagut; uumassuseqartunili katersuukkiartorsinnaanera eqqarsaatigalugu tamanna SMV-imut VVH-mulluunniit ilanngunneqarnissaa oqallisigisariaqartutut nalilerneqarsimavoq. Isumanerluut LCA-mit namminermit pilersimanngilaq atuagassanilli misissuinerup aamma LCA-mut atatillugu apersuinerit ingerlanneqarnerisa inerneralugu.

Allatigut sunniutaasinnaasut: LCA-p avatangiisinut sunniutaasinnaasut immikkoortut 15-it allat aamma pilersissimavai – ilaallutik ozonimik nungusaaneq, pinngortitamik pissarsiarinninneq, seernarsisitsineq, ozonemik fotokemiskiusumik pilersitsineq il.il. (takuuk immikkoortoq 11.2).
Sunniutit tamakku sukumiisumik misissorneqarsimanngillat, taamaattorli naliliineq annerusumik sunniutaasinnaasut immikkoortuinut pingaaruteqaratarsinnaasunut tulliuttunut tikkuussivoq:

- Pinngortitamik pissarsiarinninneq
- Inunnut toqunassuseqarnera
- Anersaartuutitigut uumassuseqanngitsut

Pinngortitamik pissarsiarinninneq pillugu, isumanerluut naliliineq pitsaassutsimik tunngavilik annermik aallaavigaa, naliliineq annertussutsimik tunngavilik periaatsimik Stepwise LCIA-mik tunngaveqartoq aallaaviginagu. Kalaallit Nunaanni avatangiisini innarlerneqanngitsuni immaqalu aserujasumi nunamik allanngortitsineq pissarsiarinninnerlu isornarpoq erfalasumillu aappaluttumik nittartitsilluni.

Inunnut toqunassuseqarnera pillugu misissuinitta takutippaa ilanngussineq nunamut qaartiterusersuinermut, marallummut aappaluttumut aamma nunniorfinnut tunngassuteqarnerusoq, taakkunanilu inunnut nuussineq soorpiarani.

Anersaartuutitigut uumassuseqanngitsut eqqarsaatigalugit ilanngussineq annerpaaq svovl dioxidimit, kusernernit aamma nitrogenoxidinit pissaaq. Aniatitsinerit annermik elektrolysemik suleriaaseqarnermit pinngorfeqarput, sanaassat umiarsuakkut assartornerannit aamma aluminamik tunisassiornermit.
Taamaattorli malugineqassaaq pingaakannissusia misissueqqissaarnermi ingasappallaartumik saqqumeriaannaammat, aniatitsinerimmi alisissumi inunnit tikinneqanngingajattartumi annermik pisarmata.

Eqqaassallugu pingaarpoq naliliineq qulaaniittoq taamaallaat screeningip inernerimmagit taamalu sunniutit allat assinganik anginerusumilluunniit pingaaruteqarsinnaallutik. Kulturimut inooqatigiinnermullu tunngasutigut sunniutaasut tassaapput sammisassat allat pingaartut, pingaarluinnarporlu atuartup SMV saassagaa naliliineq annikitsortaanik aamma ilanngussisoq sumiiffimmut, avatangiisinut inooqatigiinnermullu sunniutit Kalaallit Nunaanni aatsitsivimmut pilersaarutigineqartumut attuumassuteqartut piumallugit.

Sammenfatning på dansk

Nærværende rapport er en detaljeret undersøgelse af miljøpåvirkningerne, set i et livscyklusperspektiv, af et aluminiumsmelteværk med en årlig kapacitet på 360.000 tons der planlægges opført i Vestgrønland. Undersøgelsen er bestilt af Alcoa og Grønlands Selvstyre. Smelteværket er stadig i planlægningsfasen, og sættes tidligst i drift i 2014.

Undersøgelsen anvender livscyklusvurderingsmetoden (LCA) og fokuserer primært på drivhusgas (GHG) emissioner – eller Carbon Footprint for at bruge et mere populært udtryk. Fokus på drivhusgasemissioner skyldes delvist krav fra undersøgelsens bestillere og delvis også den kendsgerning, at livscyklusvurderingen udgør en del af en strategisk miljøvurdering (SMV) hvori andre typer af effekter vurderes særskilt. Andre effektkategorier såsom ozonnedbrydning, forsuring, eutrofiering, økotoksicitet og human toksicitet medtages i denne undersøgelse og præsenteres som en del af resultaterne, men er ikke så nøjagtigt vurderet som drivhusgasemissioner og må derfor tillægges væsentlige usikkerheder.

Formålet med livscyklusvurderingen er at give livscyklusbaseret miljøinformation om det planlagte aluminiumsmelteværk i forhold til den igangværende strategiske miljøvurderingsproces fra 2007 til 2009 (Grønlands Hjemmestyre 2007).

Grønlands Selvstyre har bestilt livscyklusvurderingen, og målgruppen indbefatter alle direkte eller indirekte interessenter i den strategiske miljøvurderingsproces. Disse omfatter Grønlands Selvstyre, Alcoa, den grønlandske befolkning, befolkningen i Maniitsoq i Vestgrønland hvor aluminiumsmelteværket foreslås placeret, og NGO'er. Livscyklusvurderingens resultater er også af interesse for forhandlingspartnerne, inklusiv Danmark og Grønland, i den nye klimaaftale der skal erstatte Kyoto Protokollen.

Sammenfatningen er opdelt i tre dele. Den første del er baggrundsdelen, der beskriver konteksten og formålet med livscyklusvurderingen, mens den anden del redegør for undersøgelsens afgrænsninger samt vigtige metodologiske overvejelser og valg. I den tredje del præsenteres undersøgelsens hovedresultater. Disse indbefatter de estimerede drivhusgasemissioner for det planlagte aluminiumsmelteværk i Grønland samt drivhusgasemissionerne ved en alternativ aluminiumproduktion. Alternativet antages implementeret hvis smelteværket i Grønland ikke opføres, eller antages undgået hvis projektet fortsætter som planlagt. Endelig indeholder del tre en følsomhedsanalyse der belyser usikkerhederne ved livscyklusvurderingens resultater.

Ifølge ISO 14044 standarden skal en livscyklusvurdering gennemgås kritisk af et panel, hvis resultaterne skal bruges til at understøtte en komparativ udvælgelse beregnet for offentliggørelse. Denne undersøgelse er derfor blevet underlagt en panelgennemgang fra 20. april til 3. juli 2009. Mark Goedkoop (PRé Consultants) er blevet udvalgt til panelformand af Klaus Georg Hansen (Grønlands Selvstyre) som en ekstern, uafhængig ekspert. Mark Goedkoop har uafhængigt valgt to andre parter. Disse er: Eirik Nordheim (EAA, European Aluminium Association) og Pascal Lesage (Sylvatica). Panelgennemgangen inklusiv forfatternes kommentarer kan ses i Appendix 6: Review panel report, including the authors' comments.

Baggrund

Aluminium er et ikke-jernholdigt metal, hvis produktion kræver store mængder elektrisk kraft. Ifølge International Aluminium Institute (IAI) tegner 1 ton jomfruelig aluminium sig for gennemsnitligt 10 tons emissioner CO2e, inklusiv udvindingsprocessen og alumina produktion (se også litteraturstudiet i afsnit 2). Dette svarer cirka til den årlige mængde af drivhusgasemissioner fra en gennemsnitsperson i Europa. Således vil det foreslåede smelteværk, ifølge data fra IAI, tegne sig for drivhusgasemissioner svarende til emissionerne fra cirka 360.000 personer i Europa over et år (eller 3,6 millioner tons CO2e årligt). Dette er et væsentligt bidrag til Grønlands totale Carbon Footprint (drivhusgasemissioner), og er en af grundene til at denne undersøgelse er blevet bestilt.

Elproduktion for det planlagte smelteværk vil blive baseret på to vandkraftværker der opføres til dette formål. Set i relation til global opvarmning har dette store fordele, men under vandkraftværkernes opførelse og drift vil der også produceres drivhusgasemissioner. Endvidere fremkommer emissioner i andre livscyklusfaser og ved produktion af hjælpematerialer (f.eks. anoder), under transport og ved produktion af produktionsmidler såsom bygninger, maskiner og andre typer af nødvendig infrastruktur. For at opnå en pålidelig vurdering er det derfor nødvendigt at udføre en omfattende analyse der afdækker et repræsentativt sæt konsekvenser i alle livscyklusfaser, samt i et større perspektiv hvor vi medtager undgået aluminiumproduktion (globalt) forårsaget af opførelsen af smelteværket i Grønland.

Undersøgelsens formål: Livscyklusvurderingen er udarbejdet som en del af en strategisk miljøvurdering (SMV). Til en strategisk miljøvurdering kræves, at hovedalternativet sammenlignes med *"rimelige alternativer"* (Europa-parlamentets og Rådets Direktiv 2001/42/EF om Vurdering af Bestemte Planers og Programmers Indvirkning på Miljøet). Det er således livscyklusvurderingens hovedformål at vurdere og dokumentere de mulige miljøeffekter fra følgende alternativer, med fokus på drivhusgasemissioner:

- Alternativ 1: Etablering af et aluminiumsmelteværk i Grønland (Alcoa)
- Alternativ 0: Ingen etablering af et aluminiumsmelteværk i Grønland, hvilket betyder at en tilsvarende kapacitet installeres et andet sted på kloden, og at dette muligvis udføres af en anden virksomhed. Dette betegnes i denne undersøgelse også som marginalproduktionen.

Ovenstående alternativ 1) svarer til hovedalternativet i den strategiske miljøvurdering foretaget af Grønlands Selvstyre, og 0) svarer til 0-alternativet.

At 0-alternativet repræsenteres ved aluminiumproduktion et andet sted på kloden baserer sig på den antagelse at aluminiumproduktion drives af den globale efterspørgsel efter aluminium. Således vil en eventuel beslutning om at godkende alumiumsmelteværket i Grønland have den effekt at en tilsvarende kapacitet ikke vil blive installeret andetsteds. 0-alternativet repræsenteres ved den mest sandsynlige placering og teknologi som vil blive implementeret hvis smelteværket i Grønland ikke realiseres. Alcoa har mulighed for at identificere en anden placering med adgang til vedvarende energi som det er tilfældet i Grønland og dermed opnå lignende, lave drivhusgasemissioner. Det falder dog uden for grænserne for denne undersøgelses at afgøre om Alcoa vil søge efter en anden placering hvis smelteværket i Grønland ikke godkendes. Denne undersøgelse sammenligner derfor kun det specifikt foreslåede smelteværk i Grønland (alternativ 1) med den mest sandsynlige alternative kapacitet installeret andetsteds af en anden, uspecificeret aktør på markedet (alternativ 0).

Således vil udfaldet af enhver beslutning der træffes som led i den strategiske miljøvurderingsproces i Grønland kun berøre lokale alternativer, såsom detailplacering og affaldshåndtering m.m. i det område, hvor det nye aluminiumsmelteværk installeres.

Det skal bemærkes at en beslutning om at etablere smelteværket i Grønland (alternativ 1) også betyder at alternativ 0 undgås, i overensstemmelse med de ovenfor omtalte antagelser om den globale udbuds- og efterspørgselssituation på aluminiummarkedet. Den globale ændring i drivhusgasemissioner som følge af at placere aluminiumsmelteværket i Grønland er derfor alternativ 1 minus alternativ 0.

Metode og afgrænsning

En livscyklusvurdering er en vurdering af de potentielle effekter af alle emissioner i løbet af livscyklussen for et produkt eller serviceydelse. Livscyklusvurderingen udføres i overensstemmelse med kravene i ISO standarderne 14040 og 14044.

Funktionel enhed og livscyklusfaser: Undersøgelsesenheden (også kaldt den funktionelle enhed) er 1 kg jomfruelig aluminium. Livscyklusvurderingen indbefatter følgende livscyklusfaser: Bauxitudvinding, aluminaproduktion og aluminiumproduktion. Andre nedstrømsprocesser såsom plade- og folieproduktion eller aluminiumproduktion til forbrugerprodukter og dertil hørende affaldsbortskaffelse, genbrug eller genanvendelse, medtages ikke i denne undersøgelse. Det skyldes at undersøgelsen er baseret på antagelsen om at den globale produktionsmængde af aluminium ikke påvirkes af beslutningen om at opføre aluminiumsmelteværket i Grønland eller ej – således vil den globale mængde aluminiumsaffald ikke blive påvirket.

Det skal bemærkes at brugen af aluminium kan nedsætte miljøeffekterne fra andre produkter, såsom biler, væsentligt. Hovedbegrundelsen er at aluminium har en lav densitet samtidig med at det er relativt holdbart. Desuden er aluminium velegnet til genanvendelse, hvilket nedsætter drivhusgasemissioner per kg med 90-95%. Disse overvejelser er dog ikke relevante i denne sammenhæng, undersøgelsens formål og afgrænsninger taget i betragtning.

Emissionstyper: Det er valgt at kategorisere drivhusgasemissionerne som scope 1, 2 og 3 i overensstemmelse med Greenhouse Gas Protocol fra WRI og WBCSD (WRI og WBCSD 2004).

Scope 1 indbefatter de direkte emissioner fra smelteværket som vil være Grønlands hovedinteresse set i forhold til Kyoto Protokollen. Scope 2 indbefatter drivhusgasemissionerne fra indkøbt el (og varme), som i tilfældet Grønland vil indbefatte de direkte emissioner fra vandkraftværkerne. Til det sidstnævnte medtages kun drivhusgasemissionerne fra vandreservoirerne, som er relativt uvæsentlige. Vi har derfor også medtaget indirekte drivhusgasemissioner fra opførelse og drift af vandkraftværkerne i scope 2. Scope 3 indbefatter alle andre emissioner såsom dem der fremkommer ved udvinding, aluminaproduktion, transport, anodeproduktion, hjælpematerialer, m.m.

Data for Grønland-smelteværket (alternativ 1): Idet aluminiumsmelteværket endnu ikke er sat i drift er data blevet indhentet fra andre smelteværker med en lignende teknologi som den der antages brugt i Grønland. Med dette for øje har Alcoa leveret data fra deres aluminiumsmelteværker i Island og Deschambault i Canada. Anlægget i Island ligner sandsynligvis mest det foreslåede smelteværk i Grønland, fordi det er det nyeste anlæg og fordi det ikke producerer anoder – ligesom det planlagte smelteværk i Grønland. I nogle tilfælde har det dog været mest hensigtsmæssigt at benytte data fra Deschambault fordi anlægget i Island netop har afsluttet opstartsprocessen og data herfra af den grund ikke med sikkerhed er repræsentative for stabil drift for nogle parametre.

Data for marginalproduktion af aluminium (alternativ 0): Som nævnt står elproduktion under normale forhold for det største bidrag til drivhusgasemissioner i livscyklussen for jomfruelig aluminium. For 0-alternativet, svarende til en alternativ aluminiumproduktion, har det derfor været afgørende at fremskaffe pålidelige data for energikilder til elproduktion – som igen afhænger af smelteværkets beliggenhed og de berørte energikilder i det aktuelle område.

En omfattende analyse foretages i afsnit 4 for at estimere den alternative (marginale) beliggenhed af smelteværkerne. Mange usikkerheder er involveret, og et antal scenarier er blevet udviklet der afspejler forskellige metoder og datakilder (metode- og datatriangulering). Det 'anbefalede' scenarie peger på at den alternative beliggenhed vil være en kombination af tre områder (komposit marginal), repræsenteret ved Kina med 60%, Fællesskabet af Uafhængige Stater (CIS)[5] med 22% og Mellemøsten (ME) med 18%. Idet elproduktionen i Kina domineres af kul bliver den marginale elektricitetssammensætning 62% kul, 29% vandkraft og 9% gas, hvoraf halvdelen antages at blive afbrændt i henholdsvis CIS og Mellemøsten.

Til trods for det høje antal benyttede scenarier, metoder og datakilder viser de fleste scenarier sammenlignelige resultater i forhold til den marginale elektricitetssammensætning – hvor det meste af elektriciteten er baseret på kul efterfulgt af vandkraft og gas, i denne rækkefølge. Mindre pålidelige og væsentligt forskellige scenarier er dog også blevet fundet. Denne del uddybes i afsnit 5 og afspejles også i følsomhedsanalysen i denne sammenfatning.

Foruden overvejelserne omkring de berørte energikilder for elproduktion peger analysen på de teknologiske forskelle de forskellige imellem de aktuelle områder– både hvad angår smelteværksteknologier og energiteknologier. Undersøgelsen peger således på andre aspekter, såsom at f.eks. kinesiske kraftværker er mindre effektive end kraftværker i Vesteuropa, og at de har andre behandlingssystemer for røggas. For el fra nettet der benyttes i andre livscyklusfaser (f.eks. bauxitudvinding og aluminaproduktion) er der udført en særskilt analyse, der estimerer den marginale elproduktion fra nettet i samtlige, relevante områder/lande i verden. Dette uddybes i afsnit 6. Begrundelsen for at skelne imellem forbrug til et smelteværk og til andre processer/livscyklusfaser baserer sig på den kendsgerning, at aluminiumsmelteværker i kraft af deres høje elforbrug har særlige kontrakter med kraftværker – eller endda selv producerer elektricitet, hvilket til en vis grad gør deres elektricitetsblanding forskellig fra andre, mindre forbrugende industrier, selv inden for det samme område.

Resultater og perspektiver

Hovedresultaterne for alternativ 1 (smelteværk i Grønland) og alternativ 0 (alternative aluminiumsproduktion) præsenteres i det følgende. Disse resultater uddybes yderligere i afsnit 11.

Drivhusgasemissioner fra smelteværk i Grønland (alternative 1): Livscyklusvurderingen udført i denne undersøgelse anslår at det planlagde aluminiumsmelteværk vil stå for et bidrag til global opvarmning svarende til 5,92 kg CO2e per kg produceret jomfruelig aluminium. Hvis der skaleres op til den planlagde, årlige produktion på 360.000 tons kan det totale, årlige bidrag således anslås til 2,13 millioner tons CO2e.

Scope 1-emissioner er direkte procesemissioner fra smelteværket. Disse svarer til 1,66 kg CO2e per kg jomfruelig aluminium, som hovedsageligt skyldes anodeproduktion og til en mindre grad PFC emissioner. De totale scope 1-emissioner knyttet til en produktion på 360.000 tons aluminium beløber sig til 597.000 tons CO2e.

Scope 2-emissioner stammer fra elproduktion ved vandkraftværkerne. Disse svarer til 0,140 kg CO2e per kg jomfruelig aluminium, inklusiv opførelse og drift af vandkraftværkerne samt emissioner fra reservoirer. Dette svarer til en årlig emission på 50.200 tons CO2e.

Scope 3-emissioner, tilknyttet smeltefasen, indbefatter hovedsagelig emissioner fra anodeproduktion, transport, serviceydelser samt mindre emissioner knyttet til affaldshåndtering, mm. Disse udgør 1.09 kg CO2e per kg jomfruelig aluminium, eller 391.000 tons CO2e årligt. De samlede emissioner (scope 1, 2 og 3) hidrørende fra smeltefasen beløber sig til 2,88 kg CO2e per kg jomfruelig aluminium eller 1,04 millioner tons CO2e årligt.

[5] Hovedsagelig Rusland.

De emissioner der fremkommer inden for Grønland, som også inkluderer procesemissionerne fra smelteværket, anslås til 597.000 tons CO2e. Dette svarer til 85% af Grønlands nuværende drivhusgasemissioner, som er cirka 700.000 tons[6] CO2e.

For at opnå totalen på 5,92 kg CO2e per kg jomfruelig aluminium skal medtages bauxitudvindingsfasen, som står for 0,144 kg CO2e per kg, samt aluminaproduktionen svarende til 2,89 kg CO2e per kg, hvoraf størstedelen knytter sig til varmeenergi (baseret på fossile brændsler).

Sammenlignet med andre smelteværker er drivhusgasemissionerne fra Grønland markant lavere – hovedsagelig grundet brug af vandkraft. Drivhusgasemissioner knyttet til aluminiumproduktion ved andre smelteværker beskrives i det følgende afsnit.

Drivhusgasemissioner fra alternativ produktion (alternativ 0): Analysen af miljøeffekterne fra den marginale aluminiumproduktion der implementeres hvis smelteværket i Grønland ikke bliver opført, viser at disse vil udgøre 20,7 kg CO2e per kg jomfruelig aluminium, eller 7,47 millioner tons CO2e årligt, under antagelse af at 360.000 tons aluminium så ville produceres et alternativt sted. Hovedårsagen til det høje bidrag er elforbruget, som baserer sig på 62% kul, 29% vandkraft og 9% gas (hvoraf halvdelen vil alternativt blive afbrændt). I dette scenarie vil mere end 70% af drivhusgasemissionerne stamme fra elproduktion. For smelteværket i Grønland er det kun cirka 2%.

Det er vigtigt at understrege at usikkerhederne forbundet med resultaterne ved alternativ 0 er væsentlige. Det er ikke muligt at kende den eksakte beliggenhed af den marginale produktion, eller de faktisk anvendte energikilder. Der er derfor foretaget en lang række følsomhedsanalyser for alternativer til det anbefalede scenarie. Disse følsomhedsanalyser viser drivhusgasemissioner mellem 11,6 kg CO2e per kg jomfruelig aluminium, svarende til en produktion hovedsagelig baseret på vandkraft i CIS/Rusland, og 29,2 kg CO2e per kg jomfruelig aluminium, svarende til en produktion i Kina baseret på 100% kul. Da vi ikke kan udelukke nogle af scenarierne kan resultaterne også præsenteres som 20,7 ± cirka 9 kg CO2e per kg jomfruelig aluminium for alternativ 0. Dette uddybes yderligere i afsnit 11.1.

Globale ændringer i drivhusgasemissioner (alternativ 1 minus alternativ 0): Den totale ændring af drivhusgasemissionerne (set i et globalt perspektiv) ved at placere et aluminiumsmelteværk i Grønland vil være effekterne fra alternativ 1 minus alternativ 0, dvs. effekterne fra smelteværket i Grønland minus effekterne fra aluminiumsmelteværket placeret et andet sted i verden. Hvis vi medtager usikkerhedsintervallet som forklaret ovenfor, betyder det at den totale ændring i drivhusgasemissioner som resultat af at implementere smelteværket i Grønland beløber sig til besparelser på 2,05 til 8,36 millioner tons CO2e årligt (eller besparelser på 5,34 millioner tons CO2e årligt, hvis det anbefalede scenarie for alternativ 0 benyttes). Med andre ord vil smelteværket i Grønland betyde at der undgås emissioner for 5 ± 3 millioner tons CO2e årligt i et globalt perspektiv.

Eftersom Grønlands årlige CO2e emissioner udgør cirka 700.000 tons CO2e har det planlagte smelteværk potentiale til at reducere de globale drivhusgasemissioner med 3 til 12 gange Grønlands nuværende drivhusgasemissioner, på trods af at de indenlandske drivhusgasemissioner i Grønland næsten fordobles. I denne henseende skal det understreges, at konsekvenserne af drivhusgasemissioner er uafhængige af, hvor de udledes.

[6] Ifølge UNFCC (2009) var de fossilbaserede CO_2 emissioner fra Grønland 682.000 tons CO2e i 2006. Herudfra anslås de årlige CO2e emissioner i Grønland i dag til at være 700.000 tons CO2e.

Det er muligt, at lige så CO2e-venlige alternativer (til smelteværket i Grønland) findes og kunne vælges af Alcoa. Dette indbefatter smelteværker i områder, hvor det er muligt at bruge 100% vandkraft eller 100% gas som ellers ville blive afbrændt, f.eks. i områder som Rusland/Sibirien, Afrika eller Mellemøsten. Denne undersøgelse sammenligner dog kun smelteværket i Grønland med intet smelteværk i Grønland. Specifikke alternativer til smelteværket i Grønland planlagt af Alcoa medtages ikke. Undersøgelsen sammenligner i stedet smelteværket i Grønland med den mest sandsynlige alternativ kapacitet, der vil blive installeret andetsteds som en reaktion på ændringer i efterspørgslen på aluminium.

Menneskers sundhed i Grønland: Undersøgelsen indeholder en forsigtig vurdering af menneskelige sundhedseffekter i Grønland – men kun set i relation til det ydre miljø (ikke arbejdsmiljø og sikkerhed). Vurderingen viser at smelteværket bidrager væsentligt til effektkategorien ’respiratory inorganics’. Denne effektkategori indbefatter påvirkningerne af menneskers åndedræt fra uorganiske stoffer såsom partikler og svovldioxid der typisk forårsages af forbrændingsprocesser. Det største bidrag fra smelteværket i Grønland er svovldioxid, og som konsekvens heraf hejses et rødt flag. Det fører til at vi anbefaler at menneskelige sundhedsaspekter medtages i den strategiske miljøvurdering eller i en separat sundhedsvurdering (HIA).

En anden mulig betænkelighed udgøres af hydrogenfluorid (HF)-emissioner. Med mindre der sker en eksponering af meget høje doser, har vi ikke fundet indikationer på væsentlige påvirkninger på menneskers sundhed; men hvis risikoen for bioakkumulation tages i betragtning anser vi det for nødvendigt at diskutere dette som et input til den strategiske miljøvurdering eller sundhedsvurdering. Denne betænkelighed fremgår ikke af livscyklusvurderingen som sådan men er et resultat af litteraturstudier foretaget som en del af livscyklusvurderingen.

Andre effektkategorier: Livscyklusvurderingen indeholder yderligere en screening af 15 andre miljøeffektkategorier – deriblandt ozonnedbrydning, naturbeslaglæggelse, forsuring, fotokemisk ozondannelse, mm. (se afsnit 11.2). Disse effektkategorier er ikke blevet undersøgt i detaljer, men vurderingen peger primært på, at følgende effektkategorier som potentielt væsentlige:

- Naturbeslaglæggelse
- Humantoksicitet
- Uorganiske partikler, der påvirker åndedrættet.

I forbindelse med naturbeslaglæggelse stammer betænkeligheden fra en kvalitativ vurdering og ikke den kvantitative vurdering baseret på Stepwise LCIA metoden. Det er kritisk at omdanne og beslaglægge områder i et urørt og sandsynligvis følsomt miljø i Grønland, og der hejses derfor et rødt flag.

I forbindelse med humantoksicitet viser vores analyser, at bidraget knytter sig primært til udvindingsområder, rødt ler og affaldsdeponeringer, hvor overførslen til mennesker er relativt ubetydelig.

For uorganiske partikler der påvirker åndedrættet knytter det største bidrag sig til svovldioxid, partikler og kvælstofoxider. Disse emissioner forårsages primært af elektrolyseprocessen, skibstransport af råmateriale og fra aluminaproduktion. Det skal dog bemærkes at den relative betydning sandsynligvis bliver overvurderet i analysen, idet emissionerne primært fremkommer i afsides områder med meget begrænset eksponering for mennesker.

Det skal noteres at ovennævnte vurdering kun afspejler en screening og at andre effekter kan vise sig at være lige så betydelige eller mere. Effekten på kultur og sociale aspekter udgør en anden vigtig problemstilling, og det er afgørende at læseren henvises til den strategiske miljøvurdering for en mere omfattende vurdering af lokale, miljømæssige og sociale effekter knyttet til det planlagte smelteværk i Grønland.

1 Introduction

This report documents a comprehensive life cycle assessment (LCA) of a planned state-of-the-art aluminium smelter in West Greenland proposed by Alcoa and the Government of Greenland.

The objective of the LCA is to provide life cycle-based environmental information on the aluminium production in the strategic environmental assessment (SEA) process, which is ongoing from 2007 to 2009. The main focus of the LCA is greenhouse gas (GHG) emissions.

The assessment of alternatives in SEAs requires that the main alternative is compared with "*reasonable alternatives*" (Directive 2001/42/EC of the European Parliament and the Council on the Assessment of the Effects of Certain Plans and Programmes on the Environment). The alternatives included in the life cycle assessment are:

- **Alternative 1:** Aluminium smelter in Greenland: The main alternative as proposed by Alcoa
- **Alternative 0:** No aluminium smelter in Greenland

A basic assumption is introduced, i.e. the global production of aluminium is demand-driven. It follows from this assumption that the establishment of a new aluminium smelter in Greenland will not affect the global production of aluminium. Thus, Alternative 0 represents the most likely change in capacity somewhere else in the world, if the Greenland smelter is not established.

The two alternatives are analysed using a range of different sensitivity scenarios that represent likely applied technology mixes. A further third alternative could also have been included**:** the establishment of an increased collection of aluminium scrap and more capacity for the processing of scrap into new aluminium, but this alternative is out of the scope of the Government of Greenland as well as of Alcoa. For further details, see section 3.1.

More details about the project, its location, and supporting facilities are described in the following.

1.1 Location of the project

Three locations of the aluminium smelter in West Greenland have been discussed. The first is close to Nuuk (Godthåb), the second is to the north of Nuuk at Maniitsoq (Sukkertoppen), and, finally, it has been discussed to place the smelter at Sisimiut (Holsteinsborg), even further to the north.

In December 2007, the Government of Greenland issued a draft SEA assessing advantages and disadvantages of locating the aluminium smelter and port in Sisimiut, Maniitsoq and Nuuk, respectively. The period for public comments ended on 15 January 2008, and thereafter, the Government of Greenland recommended that the smelter and port were located in Maniitsoq, see **Figure 1.1** (left). In May 2008, the Greenland Parliament endorsed the recommendation, and the Government of Greenland entered a Memorandum of Understanding (MoU) with Alcoa to conduct feasibility studies and environmental studies of the aluminium project.

The planned smelter will have an annual production capacity of approximately 360,000 tonnes of primary aluminium. The electricity will be supplied by two hydropower plants that will be constructed for the same purpose. One power plant will be situated in Tasersiaq, referred to as the North Hydropower Development, and one power plant will be situated in Imarsuup Isua, referred to as the South Hydropower Development, see **Figure 1.1** right (Environmental Resources Management 2009, Greenland Development 2008 p. 22).

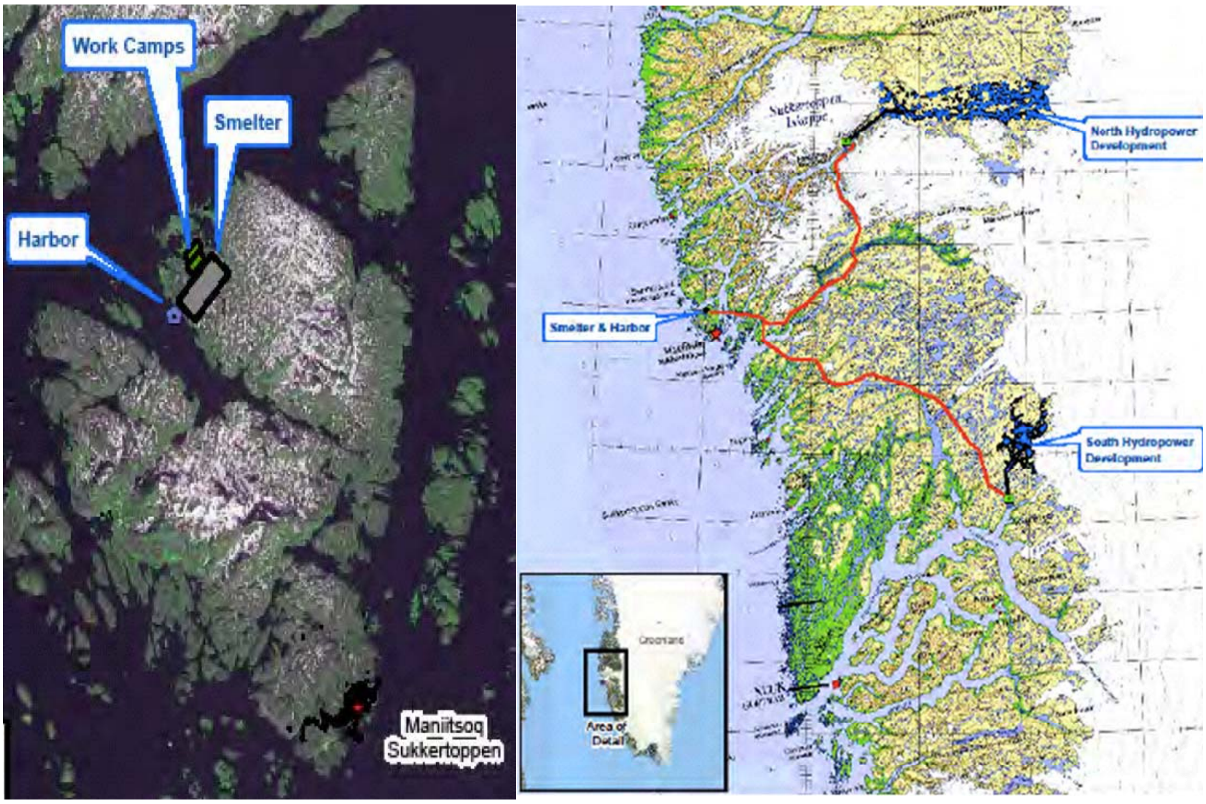

Figure 1.1: Suggested site for aluminium smelter close to Maniitsoq (Sukkertoppen) left, including supporting facilities such as harbour and work camps (left), and sites for hydropower plants (right), to the north-east and south-east of Maniitsoq (Environmental Resources Management 2009).

The supporting facilities include (besides the hydropower plants), transmission lines for electricity, a harbour for import and export of project-related materials, work camps, and different infrastructure elements such as roads, etc.

1.2 Technical details of the project

The expected time horizon for the project is 2015, when it is expected to go into the operation phase. Other important facts concerning project phases, employment, annual production, hydropower capacity, etc., are described in **Table 1.1**.

Project phases	Key figures
Project development phase	2007-2009
Construction phase - hydropower	2010-2014
Construction phase – transmission and smelter	2012-2014
Operation of smelter and hydropower to begin	2014/15
Production and employment	
Annual production of aluminium	>350,000 tonnes
Employment during construction 2010-2014	2,000-5,500 people
Employment in production	Approx. 425
Other employment in development phase	300-400
Hydropower plants	
Number of hydropower plants	2
Hydropower installed capacity	>650 MW
Annual production of electricity	>5 billion KWh
Length of transmission line	>240 kilometre
Total project costs (hydropower + smelter)	19-23 billion DKK (3.8-4.6 billion US$)

Table 1.1: Facts concerning the aluminium project (Greenland Development 2008)

As it appears, the total project costs are estimated at 19-23 billion DKK.

Information about the smelter and supporting facilities

The smelter that is supposed to be constructed in Greenland will most likely represent the same type of technology and smelter design as Alcoa's Fjardaal Aluminium Smelter in Iceland. The port facility will be designed to handle a variety of ship sizes up to vessels of 65,000 tonnes (Greenland Development 2008).

The estimated infrastructure costs related to the smelter involve the construction of a 150 m bridge across Ataa at the estimated costs of 51 million DKK, a 11 km road from quarry to site at the estimated costs of 77 million DKK, a 1 km secondary road at Graveyeard Bay at the estimated costs of 7 million DKK, and finally a 4.5 km water line to the smelter at the estimated costs of 18 million DKK. This gives a total of 153 million DKK (Greenland Development 2008).

Apart from this, the project will include the building of a harbour and working camps. Finally, as mentioned in **Table 1.1**, the total length of transmission lines is supposed to be more than 240 km.

South hydropower plant (Imarsuup Isua)

As illustrated in **Figure 1.1**, the power station for Imarsuup Isua will be located approximately 150 km to the south-east of Maniitsoq. The project involves the building of a 10 km headrace tunnel, which carries water from the reservoir to the generating station turbine, and a 3 km tailrace tunnel after the power station. Water will flow from the reservoir through the headrace tunnel to an underground power house and end up in the Godthåbsfjord. The project will include the building of 6 dams of which the tallest will be about 32 m; 3 canals of which the longest will be 720 m, and 3 tunnels of which the longest will be 2 km. The surface area of the reservoir will be roughly 95 km2. The suggested layout has a main storage reservoir and a smaller reservoir to the south of this that supplies the power tunnel with water (Greenland Development 2008).

North hydropower plant (Tasersiaq)

The power station for Tasersiaq will be located about 100 km to the north-east of Maniitsoq. Water from Lake Tasersiaq will flow through a headrace tunnel of about 30 km to an underground power house. Subsequently, the water will be discharged into Kangerlussuatsiag (the Evighedsfjord). The project will include 2 dams of which the tallest will be 37 m. Also, the Tasersiaq Lake must be raised from its present level. The surface area of the reservoir will be around 190 km^2.

1.3 Methodological approach and structure of report

The environmental assessment carried out in the present report is based on Life Cycle Assessment (LCA) or, more precisely, a state-of-the-art hybrid LCA (see also section 3.3) of a planned aluminium smelter in West Greenland. Special attention is given to the contribution to global warming and the study could also be described as a ‘carbon footprint’ analysis, although it should be stressed that it includes more impact categories apart from global warming. The LCA is conducted in accordance with the ISO 14040 and 14044 standards (ISO 14040 2006, ISO 14044 2006). Further details about methodological considerations and choices are available in section 3. In the following, the content of each of the sections in the report is briefly described.

Section 2) In terms of project structure, the report begins with a review of existing databases and research articles. This serves to provide an overview of the energy consumption and CO2e emissions from aluminium production, according to existing studies. Apart from that, the overview will illustrate the importance of methodological choices; it will guide our data collection, and it will serve as a baseline that can be used for comparison with results obtained in the present study.

Section 3) Section 3 describes the goal and scope of the study and addresses its purpose and the most important methodological choices made in the LCA. The functional unit is described in section 3.2, while section 3.6 describes the data collection, and section 3.7 includes a description of the procedure for critical review of the LCA study. This section, therefore, forms the basis for all subsequent chapters and the basis for the entire study.

Section 4-6) These three sections address marginal aluminium production (smelter stage) including scenarios as well as marginal electricity use for aluminium smelters and for grid electricity, respectively. In section 2, it is shown that electricity use/production is pivotal to the LCA results, and three chapters (4-6) have therefore been devoted to identifying the most likely location of the expansion of aluminium production and the electricity sources affected by this expansion.

Section 7-10) The next four sections represent phase 2 of the ISO standard for LCA - the life cycle inventory phase, i.e. the data collection and modelling phase. Chapter 7 includes inventory data for general processes (or background processes), while the following three chapters address bauxite mining, alumina production, and the aluminium smelter stage (electrolysis, anode and cast house).

Section 11) Section 11 includes the results of the life cycle impact assessment (LCIA) of the planned aluminium smelter in West Greenland (Alternative 1) and the 0 Alternative; i.e. if Alternative 1 is not chosen. The contribution to GHG emissions is the main focus, but other environmental impact categories are also discussed separately.

Section 12) This section includes a brief qualitative assessment of the impacts on human health.

Section 13-14) These two sections include the sensitivity, completeness, and consistency analyses, and the interpretation and conclusions, respectively.

Section 15-16) Section 15 includes a list of terms and abbreviations, and section 16 contains a list of cited references.

Appendices. Appendices 1-5 include data, explanations, and additional results, and Appendix 6 includes the review panel report including the authors’ comments.

2 Review of existing LCA studies

This chapter provides an overview of existing LCA studies of aluminium with a focus on results and how different methodological choices influence these results. The review also serves as the basis for a comparison of the results of existing studies and the present study and provides crucial information about environmental hot-spots that can guide the data collection.

2.1 Databases

A number of databases exist which provide LCI data for aluminium in a cradle-to-gate perspective. The LCA software tool Simapro (version 7.0) includes LCI data for aluminium from the following databases.

- ecoinvent (Classen et al. 2007)
- ETH-96 (Frischknecht et al. 1996)
- Franklin (Franklin Associates USA 2000)
- USA IO-LCA: Primary aluminium (Suh 2004)

In the present study, it is distinguished between data for emissions of scopes 1, 2 and 3, inspired by the definitions used in the Greenhouse Gas Protocol from World Resource Institute (WRI) and World Business Council for Sustainable Development (WBCSD), (WRI and WBCSD 2004).

- Scope 1 emissions include the 'direct' emissions from sources that are owned or controlled by the company in question. These include processes (e.g. chemical processes), burning of fossil fuels or transport in company-owned vehicles.
- Scope 2 emissions include emissions from the generation of purchased electricity and heat
- Scope 3 includes emissions from sub-suppliers (other than scope 2) from transport processes in other parts of the life cycle and from customers or consumers.

In the present LCA, scopes 1, 2 and 3 do not correspond 100% to the GHG protocol's definitions. The LCI data for scope 2 emissions include emissions related to the mining of fossil fuels, transport and transformation of the fuel (pre-combustion processes), while scope 2 emissions, according to the GHG protocol, should only include direct emissions from the electricity or heat production.

Hence, the data provided in **Figure 2.1** (as well as related figures found through the review of databases and literature studies) cannot be translated directly into scopes 1, 2 and 3, as defined by the GHG protocol.

GHG emissions of virgin aluminium

The contributions to global warming measured in CO2e per kg of virgin aluminium (cradle-to-gate) from the four databases mentioned above, divided into scope 1, 2 and 3 emissions, are illustrated in **Figure 2.1**.

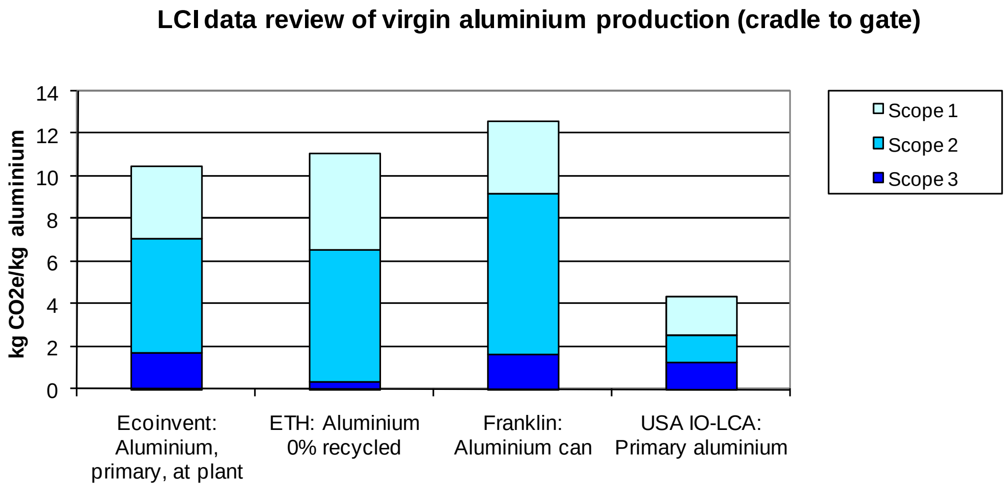

Figure 2.1: The contribution to global warming measured in CO2e per kg of virgin aluminium, according to ecoinvent, ETH, Franklin and USA IO-LCA (Classen et al. 2007, Frischknecht et al. 1996, Franklin Associates USA 2000, and Suh 2004).

The last study mentioned represents data obtained by IO LCA and is therefore fundamentally different in its modelling approach compared to the three process LCAs.

The total emissions (the sum of scopes 1, 2 and 3) vary noticeably. The contributions to GHG emissions in the IO data are considerably smaller, but it should be mentioned that this data includes a mix of recycled and virgin aluminium. Recycled aluminium emits much less GHG compared to the production of virgin aluminium. ecoinvent and ETH suggest quite similar emissions levels (10.5 and 11.1 kg of CO2e per kg of virgin aluminium, respectively). It should be noted that ETH is an older database and therefore reflects older technologies than ecoinvent. In addition, ecoinvent has a more complete coverage of capital goods. The Franklin database suggests the highest emissions of all four databases (12.6 kg of CO2e per kg of virgin aluminium). But it should be stressed that this study represents aluminium 'cans' and not primary aluminium production. Furthermore, the GHG emission level in the Franklin database is related to the electricity mix in the USA in the mid-1990s and must be considered outdated. Apart from the differences explained here, differences can also be seen with respect to electricity mix, databases for background data, etc. **Table 2.1** and **Table 2.2** provide an overview of similarities and differences.

It is worthwhile mentioning that databases are often partially based on existing literature studies. In the case of ecoinvent, which is the most updated database, the background report shows that it is based on data provided by the European Aluminium Association, available in EAA (2000), covering the year 1998. But additional data is also obtained from expert interviews and other literature studies (Classen et al. 2007).

GHG emissions of recycled aluminium

The contributions of recycled aluminium to global warming measured in CO2e per kg of recycled aluminium (cradle-to-gate) from two datasets in the ecoinvent database as well as ETH and Franklin are illustrated in **Figure 2.2**.

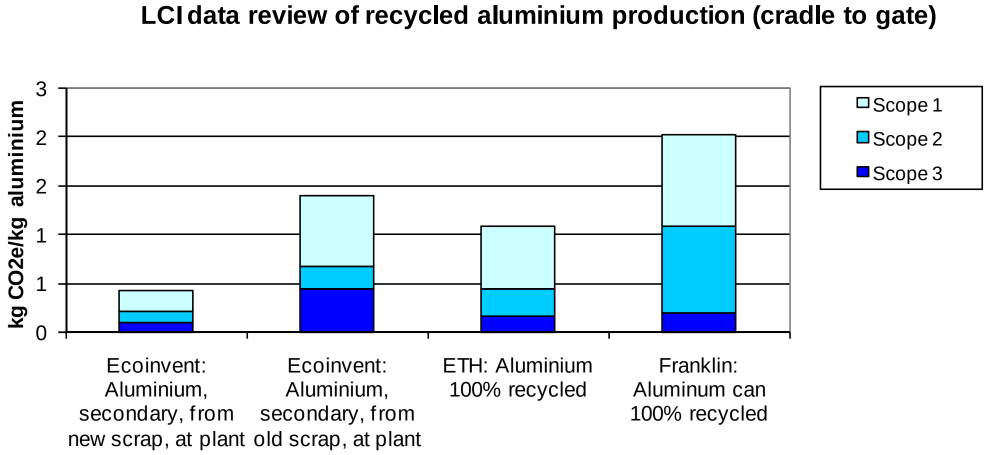

Figure 2.2: The contribution to global warming measured in CO2e per kg of virgin aluminium, according to ecoinvent, ETH, and Franklin (Classen et al. 2007, Frischknecht et al. 1996, and Franklin Associates USA 2000).

GHG emissions vary considerably for recycled aluminium. ecoinvent operates with recycled aluminium based on 'new' and 'old' scrap, where the emissions are 0.4 and 1.4 kg of CO2e per kg of recycled aluminium, respectively. ETH suggests that the emissions are 1.1 kg of CO2e per kg of recycled aluminium; while Franklin suggests 2 kg of CO2e per kg of recycled aluminium. Again, it must be assumed that the data from ecoinvent is most accurate as the database is newer and based on more detailed data, e.g., in terms of the inclusion of capital goods.

If we only consider the ecoinvent data, the emissions from recycled aluminium based on new and old scrap only represent 4% and 13%, respectively, of the emissions from virgin aluminium. Hence, it is clear that virgin and recycled aluminium have very different LCI profiles.

2.2 Literature references

We have also identified a number of literature references with carbon footprint data for aluminium. The most authoritative and updated references include the 'Environmental Profile Report for the European Aluminium Industry - Life Cycle Inventory data for aluminium production and transformation in Europe' (EAA 2008) and the 'Life Cycle Assessment of aluminium: Inventory data for the Primary Aluminium Industry – 2005 update' from the International Aluminium Institute (IAI 2007). Both reports represent data from 2005, but older reports also exist, e.g., from EAA, which represent data from 2002 and 1998 (EAA 2005, EAA 2000).

Other LCA studies (and databases) often use data from EAA or IAI. LCAs have also been made that represent isolated studies, e.g., a study of aluminium production in Australia (Reginald and Hsien 2005).

The contributions of aluminium production to global warming measured in CO2e per kg of virgin aluminium (cradle-to-gate) from Reginald and Hsien (2005), EAA (2008 p. 38) and IAI (2007 p. 41) are illustrated in **Figure 2.3**.

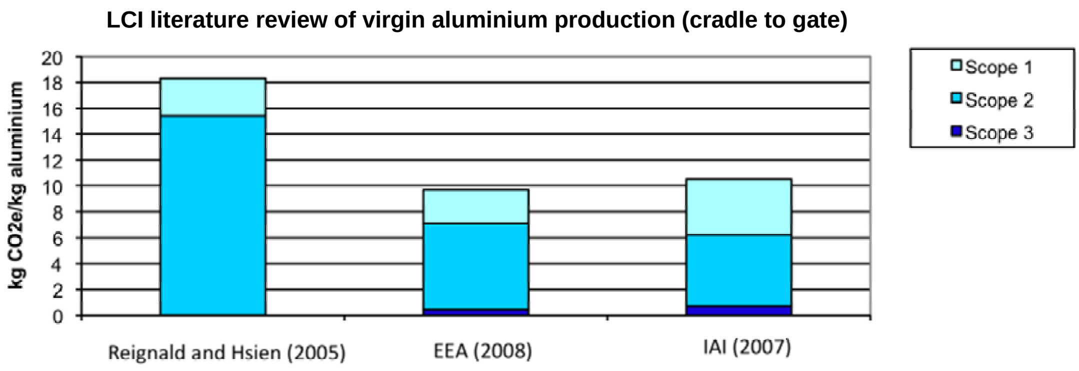

Figure 2.3: Contributions to global warming measured in CO2e per kg of virgin aluminium, according to Reginald and Hsien (2005), EAA (2008 p 38) and IAI (2007 p 41).

In **Figure 2.3**, scope 1 represents direct process emissions, mainly related to the use of heat energy/fossil fuel and PFC emissions. Thermal energy is mainly used in the alumina production and for anode production. The latter is considered as belonging to scope 1 in this context. But it could obviously also be considered part of scope 3, in cases in which the anode production does not take place at the plant. Scope 2 represents emissions related to electricity production, mainly used for the electrolysis at the smelter. Finally, scope 3 represents emissions related to the production of auxiliaries (e.g. NaOH, limestone, petrol coke, pitch production and aluminium fluoride) and transport.

The data from EAA and IAI shows emissions quite similar to those of the ETH and ecoinvent database in **Table 2.1**. The study of Reginald and Hsien (2005) is a special case representing Australia where the main energy source is coal (the data in this study does not include PFC emissions).

As the most notable difference, the scope 3 emissions in the literature studies are significantly smaller compared to the results obtained from the databases. The reason is probably that the databases include capital goods (to a larger extent), and more detailed data for transport processes, etc. It should be mentioned that EAA (2008) has a very limited transport model, which only includes sea transport of bauxite and alumina. In the Australian study, the results in Reginald and Hsien (2005) have been aggregated to such extent that it has only been possible to separate transport data for scope 3. It other words, it must be assumed that some of the emissions that appear to be scope 1 emissions in **Figure 2.3** should actually have been categorised as scope 3.

A more detailed description of the contribution from different processes is available in EAA (2008), which states that 50% of the GHG emissions come from the electricity production. The aluminium processes (mainly anode/paste consumption and PFC emissions) contribute with around 25%, while thermal energy (mainly at the alumina production stage), auxiliary materials and transport account for around 25% of the GHG emissions (EAA 2008 p 38).

A number of studies exist which are not included in this literature review; either because they are older or have another focus than GHG emissions. Here, it is important to mention one study, which focuses on GHG emissions from electricity consumption and different electricity mixes for European aluminium production, namely Koch and Harnisch (2002). Another study that is important to mention is Martchek (2006), which includes data for GHG emissions in the years 1950, 1990 and 2000 as well as scenarios for 2010 and 2020. This study shows a decreasing tendency in emissions from 11.3 kg of CO2e per kg of aluminium in 1950 to 6.8 kg of CO2e per kg of aluminium in 2020, see **Figure 2.4**.

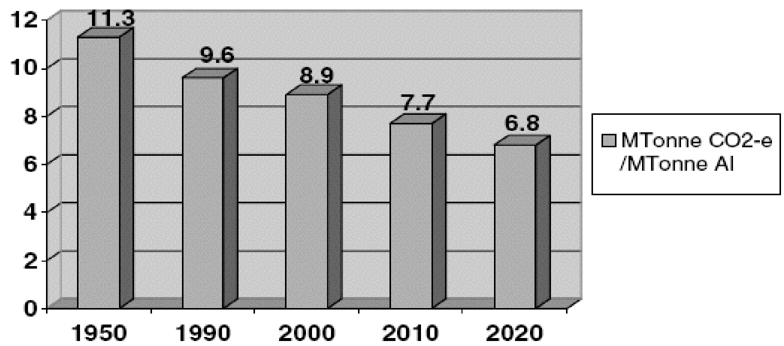

Figure 2.4: Development in emissions of carbon dioxide (tonne) per tonne of primary aluminium (mixed) from 1950 to 2020 (Martchek 2006).

Figure 2.4 is a representation of tonne CO2e per per tonne of semi-finished aluminum products. The greenhouse gas intensity is influenced by the increasing supply of recycled metal (both customer and post-consumer scrap). In 2005, 30% of the metal supply to produce semi-fabricated aluminum products derived from recycled metal and 70% from primary metal (Grover 2009).

The data clearly shows that aluminium production has become significantly more effective over the years. As described by Martchek (2006), the main reasons are increased use of re-cycled aluminium, higher energy efficiency and significant reductions in the PFC emissions, partly due to the switch from Söderberg to Pre-bake technology.

Apart from the review of literature studies and databases, information about aluminium production in China is also obtained during a visit at Beijing University of Technology (BUT). BUT has developed a new LCA material database for China, in which the average emissions of 1 kg of primary aluminium are roughly 21 kg of CO2e in a cradle-to-gate perspective (Gao 2009). The study represents the average of several aluminium plants in China. The emission of the smelter alone contributed with roughly 16 tonnes of CO2e per kg of primary aluminium. The latter was approximately 58% higher than the Japanese aluminium plants with which they have been compared. The energy source in the Chinese study is mainly coal (Gao 2009). Detailed information about the study has not been available, but a paper about GHG emissions of Chinese aluminium production was expected to be published in the journal of "Science in China Series E: Technological Sciences" in May 2009. Generally, the results seems to be reasonable; partly because China probably has less efficient power plants than Australia, where Reginald and Hsien (2005) suggest that the emissions are somewhat lower, despite the use of coal power as well. In this regard, it is also worth mentioning the 'Decision paper for establishment of aluminium smelter in Greenland' from the Government of Greenland. The decision paper was prepared based on a recommendation from Greenland Development. Greenland Development (2008) mentions that CO_2 emissions from a Chinese aluminium smelter are 14.36 kg per kg of primary aluminium, which corresponds to the figures of the Chinese study. It must be assumed that the study mean to say CO2e. Of this total, process CO_2 (from the use of anodes) is assumed to account for 1.4 kg, PFC emissions for 0.3 kg, while the rest is related to electricity generation based on coal.

2.3 Discussion and conclusion of the literature review

The review of databases and literature studies has unveiled that great differences in scope and methodological aspects can be seen in the different studies. **Table 2.1** shows the main differences in scope as well as the representativity of the studies. Some entry fields remain blank, as the data has not been immediately available.

Scope	Technol-ogy	Databases				Literature studies		
		ecoinvent	ETH	Frank-lin	USA-IO	IAI (2007)	EAA (2008)	Reginald and Hsien (2005)
Geo-graphi-cal scope		EU 15 + EFTA	EU 15 + EFTA	US	US	World, ex China	EU 27 + EFTA	Australia
Techno-logical scope	Electricity model	UCPTE	UCPTE			IEI energy survey	Country specific	Company specific
	Electricity mix	53%hydro, 25% coal, 15% nuclear, 5% gas, 3% oil				57% hydro, 28% coal, 9% gas, 5% nuclear, 1% oil	58% hydro, 15% nuclear, 15% coal, 10% gas, 2% oil	100% coal
	Data sources for back-ground data	ecoinvent	BUWAL 250 (1998)				GaBi and Euro-pean Life Cycle Database (LCD)	Buwal and ETH?
	Technol-ogy type	85% Pre-bake 15% Söder-berg				22% Söderberg 78% Pre-bake	27 Pre-bake sites 8 Söderberg sites	
Tempo-ral scope		1998 Based on EAA (2000)	1990s	1990s	1998	2005	2005	
Repre-sentativ-ity						48% of bauxite operation 55% of smelting 59% of alumina production 44% of cast houses	90% of all produc-tion in EU 27/EFTA	Only one plant

Table 2.1: Differences in scope between existing databases and literature studies

As it appears, large differences can be found in the scope of the different studies. But significant differences can also be seen in terms of the methodological approaches regarding functional units, definition of system boundaries, and data categories, see **Table 2.2**.

Method issue	Parameters compared	Databases				Literature studies		
		Eco-invent	ETH	Frank-lin	USA-IO	IAI (2007)	EAA (2008)	Reignald and Hsien (2005)
Functional unit and life cycle stages	Separate data for virgin Al	+	+	+	-	+	+	+
	Separate data for recycled Al	+	+	+	-	-	(-)	-
	Cradle to gate	+	+	+	+	+	+	+
	Cradle to grave	-	-	-	-	-	-	-
System boundaries	Considerations of production con-straints, marginal suppliers etc.	-	-	-	-	-	-	-
	Allocation only by system expansion	-	-	-	-	-	-	-
	Inclusion of capital goods	+	-	-	+	-	-	-
	Avoidance of cut-off	-	-	-	+	-	-	-
LCI data categories	Inclusion of PFC's	+	+	+	+	+	+	-
	Inclusion of transport	+	+	+	+	+	(-)	+

Table 2.2: Overview of methodological approaches related to the inventory phase of LCA in different databases and literature references.

Methodological choices

It appeared from the literature review, **Table 2.2**, that no considerations are made of marginal suppliers in ex-isting studies. We argue that the exclusion of such considerations is undesirable, if one wishes to know the environmental impacts related to the establishment of a new aluminium smelter in Greenland, compared with relevant alternatives. If the simple world average is compared to the new smelter in Greenland, the new smelter will be compared with a production which does not reflect the real alternative. The real alternative is best represented by an alternative location of the new smelter.

Another problem related to most of the existing LCA studies of aluminium production is that capital goods (e.g. machineries and buildings used for aluminium production) and services are not fully included; i.e., most studies have applied a (not well defined and maybe not desirable) cut-off criterion. The only study included in the literature review that has not applied any cut-off criteria is the US IO database. It should be mentioned that it is difficult to see exactly what is included in the various studies in terms of capital goods. Also capital goods can be difficult to define exactly; e.g., anodes which are replaced continuously in aluminium production could be categorized as working materials (not capital goods) as well as capital goods (capital equipment), depending on the perspective (Frischknecht et al, 2007). According to Frischknecht et al. (2007), capital goods are extremely important to renewable energy sources such as hydropower and wind power. It is suggested that 99.4% of the contribution to global warming is associated with capital goods related to hydropower. As hydropower is a very important factor for aluminium production, capital goods should obviously be included here.

Significant life cycle stages/processes

The data which is already available from databases and literature studies indicate that the GHG emissions range from just below 10 kg of CO2e per kg of primary virgin aluminium to more than 18 kg of CO_2 equivalents per kg of primary aluminium in Australia. If we include the Chinese data, it may be as high as 21 kg of CO2e per kg of primary aluminium, but this figure is based only on personal communication.

The electricity consumption is the single most important factor contributing to the emissions of CO2e, and the reason behind the large figures from Australia (and China) is the use of coal as an energy source for electricity production. This data suggests that the marginal aluminium production in a worst-case scenario could represent more than 20 kg of CO2e per kg of primary aluminium.

Based on the analysis in the present section, we can conclude that the most important contributors to GHG emissions are related to the aluminium smelter and alumina production, while the bauxite production represents a relatively small part.

In the case of the smelter, most GHG emissions come from the electricity used for the electrolysis. Electricity (scope 2 emissions) is the overall most important factor contributing to GHG emissions from primary aluminium. But it should be noted that this represents an average situation and that this is not likely to be the case of the electricity consumption at the smelter stage based on hydropower. Apart from that, there are also important direct GHG emissions (scope 1) from the smelter, i.e., process CO_2 from the anode consumption and PFC emissions. The process CO_2 cannot be avoided and is the same for all plants in the world. The PFC emissions are highly dependent on the technology and the operation of the plant. Finally, there are GHG emissions related to the production of the anode. For the alumina production, the emissions are mainly related to the generation of process heat (thermal energy). Apart from this, several small minor inputs of processes (scope 3 emissions) add up to significant GHG emissions. The most significant GHG emission sources are summarised in **Table 2.3**.

Significant processes / life cycle stages	Significant exchanges in life cycle stages
Aluminium smelter (electrolysis)	• Electricity + related emissions of CO2e (scope 2) • Anode consumption/process CO_2 (scope 1) • Anode and paste production + related electricity and fuel use, and CO2e emissions (scope 1 or 3) • Emissions of PFC (scope 1) • Fuel input + related emissions of CO2e (scope 1)
Production of alumina (Al_2O_3)	• Fuel input + related emissions CO2e
IO data (scope 3)	• Several inputs add up to significant impact

Table 2.3: The most significant GHG emission sources in the production of aluminium.

3 Definition of goal and scope

The LCA is carried out in accordance with the ISO standards on LCA: ISO 14040 (2006) and ISO 14044 (2006). According to the ISO standards, an LCA consists of four phases:

1. Definition of goal and scope
2. Life cycle inventory (LCI)
3. Life cycle impact assessment (LCIA)
4. Life cycle interpretation

This section documents the first phase of the LCA of aluminium production in Greenland. The first phase includes a description of the purpose of the study, a definition of the functional unit, an overview of the applied methods, and an overview of the relevant processes (system boundary). This also includes important methodological choices affecting the other phases of the LCA, e.g., the system boundaries affect the data to be collected in phase 2, and the method used for LCIA affects the results calculated in phase 3.

3.1 Purpose of the study

The overall purpose of the present study is to provide decision support in the environmental impact assessment (EIA) process of a new aluminium smelter in Greenland. The main decision to be supported is whether the aluminium smelter should be approved or not. Usually, EIAs do not contain life cycle information. As a supplement to the conventional information provided in the EIA process, the Government of Greenland has requested life cycle information, especially for GHG emissions.

The main question to be answered by the LCA is: "What is the environmental impact of installing the new smelter in Greenland". In EIA, the environmental impact of the proposed project and possibly some alternatives is assessed in comparison with the so-called zero alternative, which represents a situation in which the proposed project is not implemented. In the following, the zero alternative is referred to as Alternative 0. The environmental impact is illustrated in **Figure 3.1** below.

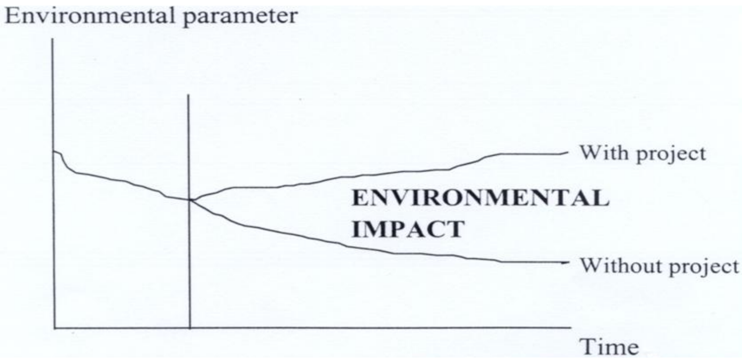

Figure 3.1: The nature of environmental impacts (Glasson et al. 2005, p 19)

It is relatively easy to define the situation in which the proposed project is implemented, which simply corresponds to the scenario proposed by the project commissioner. But when it comes to the zero alternative, it may be more difficult. In the present study, the zero alternative is defined as the situation in which the new aluminium smelter is not installed in Greenland and a corresponding amount of capacity is installed somewhere else in the world. Thus, Alternative 0 is equivalent to the installation of the capacity and annual production of 360,000 tonnes of aluminium somewhere in the world. It is obvious that the identification of the technology and location of Alternative 0 is subject to significant uncertainties. Therefore, several possible versions of Alternative 0 are identified. But all the identified scenarios represent Alternative 0.

It should be noted that the present study does not include any concrete alternatives to the proposed project – only Alternative 0. It is obvious that Alcoa may choose to install new capacity somewhere else in the world if the proposed project is not chosen. Since information on Alcoa's future plans for capacity expansion is confidential, no additional alternatives have been included in the LCA. Therefore, the proposed project in Greenland is compared to a situation in which Alcoa does not install specific capacity in another location. It is clear that Alcoa could achieve an environmental impact similar to the impact of the Greenland smelter if they choose to install a capacity which uses the same technology in another region, e.g., a smelter based on 100% hydro power in Russia. But the assessment of such alternatives lies outside the scope of the present study.

As follows from the above described reasoning, the installation of the Greenland smelter will have the effect that Alternative 0 is avoided and, if the Greenland smelter is not established, then Alternative 0 is affected. The fact that the zero alternative is represented by aluminium production in another location in the world is due to the assumption that aluminium production is driven by the global demand for aluminium, i.e. full elasticity of supply is assumed. In reality, there may be intermediate price differences. The effect of such price differences could be modelled by general economic equilibrium modelling. This would lead to lower impacts of any decision or any change compared to what is modelled in an LCA, but the direction of the change would be the same. It should also be noted that full elastic supply and inelastic demand represent the default assumption in all LCAs.

Assessed alternatives in the comparative LCA

Thus, the primary purpose of the LCA is to assess and to document the potential environmental impacts from:

- Alternative 1) the establishment of the aluminium smelter in Greenland (Alcoa)
- Alternative 0) not establishing the aluminium smelter in Greenland, which means that an equivalent capacity will be installed in another location in the world and will possibly be commissioned by another company

In addition to the two alternatives, Alcoa's existing production in two smelters is included for comparison. This production is analysed in two scenarios; Scenario 2a: Alcoa Deschambault in Canada and Scenario 2b: Alcoa Iceland. It should be noted that these scenarios do not represent actual alternatives to the Greenland smelter, but are included for illustrative and comparative purposes, since most of the data collection is based on data from these two smelters.

Furthermore, an alternative could be the establishment of an increased collection of aluminium scrap and an additional capacity for the processing of scrap into new aluminium. This could eliminate the need for new facilities for the production of virgin aluminium. However, it should be noted that this alternative is out of the scope of both the Government of Greenland and Alcoa – it is more related to structural changes in economy, which may also be regarded as out of scope of this study.

Included scenarios representing the proposed project and the zero alternative

Alternative 1) above refers to the main alternative in the strategic environmental assessment carried out by the Government of Greenland, and 0) refers to the 0 alternative. The fact that the 0 alternative is represented by aluminium production in another location in the world is based on the assumption that aluminium production is driven by the global demand for aluminium. Hence, the outcome of any decision made as part of the strategic environmental assessment process in Greenland can only affect the location of the new aluminium smelter capacity.

It should be noted that a decision of establishing the smelter in Greenland (Alternative 1) also means that alternative 0 is avoided, according to our assumptions about the global supply and demand situation on the aluminium market. The global change in GHG emissions as a result of placing an aluminium smelter in Greenland is therefore Alternative 1 minus Alternative 0.

Alternative 1 is analysed using two different scenarios; a main scenario (Sc1) applying modern technology in the smelter, and an alternative scenario (Sc1a) applying world average existing technology in the smelter. Correspondingly, alternative 0 is analysed using different scenarios. The main scenario (Sc0) applies a mix of aluminium produced in China, CIS/Russia, and Middle East using an identified marginal electricity mix (this is further described in sections 4 and 5). To evaluate the uncertainties in identifying the marginal location and electricity mix, a broad range of sensitivity scenarios are applied, i.e. scenarios Sc0a to Sc0o. For all these scenarios, new smelter technology has been applied. This is supplemented with a scenario (Sc0p) which analyses scenario Sc0, but with existing smelter technology. The two scenarios representing the existing Alcoa smelter in Deschambault in Canada and the smelter in Iceland are termed Sc2a and Sc2b, respectively. **Figure 3.2** below provides an overview of the scenarios used to analyse alternatives 1 and 0.

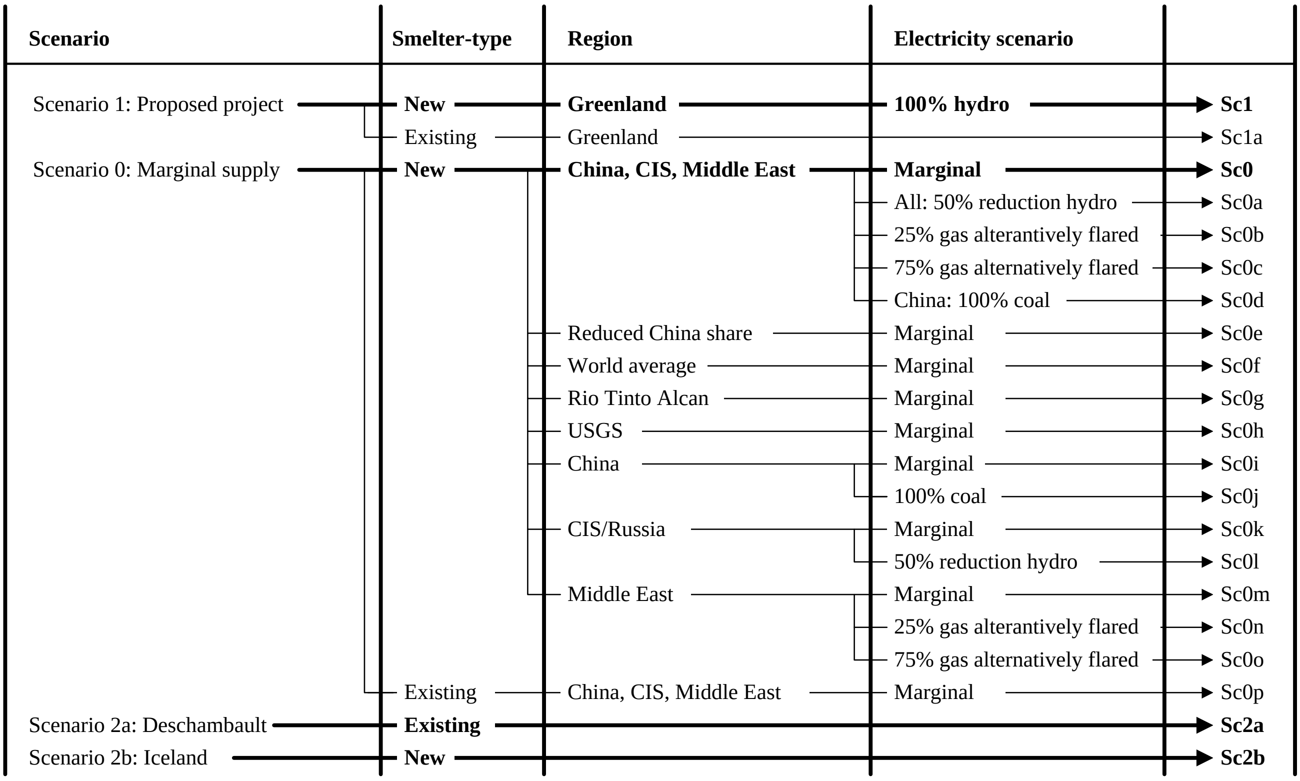

Figure 3.2: Overview of the scenarios for marginal location of smelters (Region), marginal electricity mix (electricity scenario) and scenario names.

3.2 Functional unit: 1 kg of basic aluminium

The function of the product of interest is to supply basic aluminium to the world market, which faces an increased demand. The functional unit is defined as 1 kg of virgin aluminium (ingots) supplied at a plant (100% aluminium, 0% alloying metals). Further processing, downstream manufacture of the aluminium, the use stage and the disposal stage including recycling are not included in the study because these stages are not related to the production of basic aluminium.

The product output, composed of 100% aluminium and 0% alloying metals, is further explained in section 3.4.

3.3 Method for system delimitation

The methodological considerations concerning system delimitation include considerations of consequential LCA versus attributional LCA and considerations on process/input-output/hybrid LCA. This is described in the following.

Consequential vs attributional LCA

In general, two approaches to system delimitation exist: the attributional and the consequential approach (Weidema 2003). This LCA uses the consequential approach.

The attributional approach represents the traditional way of defining system boundaries in LCA, while the consequential approach is developed in light of the fact that cause-effect mechanisms are missing in attributional LCA. Initiated by the Danish Environmental Protection Agency, a project on LCA methodology and consensus has been carried out during the period from 1997 to 2003 (Hansen 2004). The Danish Methodology and Consensus Project advocates the use of the consequential approach.

The main differences between the attributional and the consequential approach are summarised in **Table 3.1**.

Feature	Consequential modelling	Attributional modelling
Nature of the approach to modelling	Attempts to predict to responses to a change in demand	Describes how existing production is taking place
Included processes/suppliers	Marginal (i.e. actual affected suppliers)	Average of present suppliers
Co-product allocation	Co-product allocation is avoided by system expansion	Co-product allocation is most often treated by using allocation factors, and in some cases system expansion may be applied

Table 3.1: Main characteristics of and differences between consequential and attributional modelling in life cycle inventory (obtained from Schmidt 2007 and based on Weidema 2003).

It appears from **Table 3.1** that the consequential approach attempts to predict the responses to a change in demand or to a decision, while the attributional approach simply describes the existing production. In practise, this difference means that the consequential approach only includes the affected processes (or so called marginal suppliers) and avoids co-product allocation by system expansion; while the attributional approach often models average suppliers and allocates between co-products. In this regard, affected processes are the processes that are influenced by the decision alternative being modelled; e.g. to buy organic or non organic food or to incinerate waste or use it for biofuel production. It can be argued that all LCAs concern decision-making in one context or the other and the included processes should be those affected by the decision alternative. In the present report, the decision alternative concerns the building of a smelter in Greenland or not, and included processes should only be those affected by the decision, e.g., alternative marginal production of aluminium (see Chapter 4).

Input-output vs process-based LCA

Three general approaches to identifying data input types can be applied; process LCA, input-output LCA (IO-LCA), and hybrid LCA.

Process LCA: Traditionally, LCAs are performed as a 'bottom-up' process in which the specific processes in a supply chain are linked (Weidema et al. 2005). The processes in a product system are linked via physical relationships/engineering knowledge and information on market mechanisms. As part of this process, it must be decided whether to include aspects such as capital goods, services (such as marketing, accounting, consultancy), business travelling, and possibly some identified less significant inputs of feedstock, ancillaries and energy. The decision of what to include and not is often based on what is referred to as cut-off criteria (ISO 14044). The ISO 14044 standard recommends using well defined cut-off criteria, such as environmental significance. However, the environmental significance can first be known when data is collected - and when data is collected there is no need for excluding this data. In practise, this means that the selection of cut-off criteria and assumptions to be applied is rather arbitrary.

Input-Output LCA (IO-LCA): The principle of linking processes in IO-LCA is exactly the same as in process LCA, but here the processes are linked via information on economic transactions. Information on economic transactions is obtained from statistical agencies. The input-output tables which are used for IO-LCA are constructed using data on the supplies of all products categorised by activities (sectors), and the use of products for each activity within a specified geographical area (typically national) and period of time (typically one year). The so-called supply and use tables are based on reports on products sold and bought, which the statistical agencies receive from the individual industries. An important characteristic of the supply-use tables is the fact that they represent the whole economy, which is balanced in such way that inputs (uses) equal outputs (supplies) both by activities and by products. In addition to the economic IO-table, environmental information is brought into the system as a national emissions inventory, where the emissions are specified per activity in society. Since IO-tables are based on the whole economy and since the added environmental information represents a national emissions inventory, an IO-LCA is complete. In terms of cut-off criteria, this means that IO-LCA uses cut-off criteria at 0%.

In process LCA, the links between processes are measured in different appropriate units, e.g., the use of electricity is usually measured in kWh and the use of metal is usually measured in kilograms. In IO-LCA, all uses are normally measured in monetary units. However, some IO-tables also use different units. In such cases, the monetary transactions are transformed into physical units using price information. Thus, in principle, the only difference between process LCA and IO-LCA is the way data is collected and linked. Once the data is structured in a common LCA data format, there are no differences in the calculations required to carry out the two types of LCA.

Level of detail: Comparing process LCA and Input-Output LCA: It lies in the nature of process LCA, which is basically based on engineering knowledge, that the processes and their related emissions can be modelled very detailed, i.e., as detailed as desired. IO-LCA is based on national accounting, which is always limited by the number of categories of products and activities in economy which are included when the statistical agencies aggregate the reported data from the individual industries.

Figure 3.3 illustrates the difference in the magnitude of results (x-axis) of process, hybrid, and input-output LCAs as well as the correlated uncertainty in the distribution of results (y-axis). It appears that process LCAs have a very narrow uncertainty distribution (because of very detailed and precise modelling), but a very low magnitude of impacts in the results (because many process inputs are not included). Oppositely, input-output LCA shows a magnitude of results closer to “true” value, but has a very wide uncertainty distribution (because product categories represent very different products). The hybrid LCA has a reasonable narrow uncertainty distribution and the magnitude of the result is closer to the “true” value than the magnitude of process LCA.

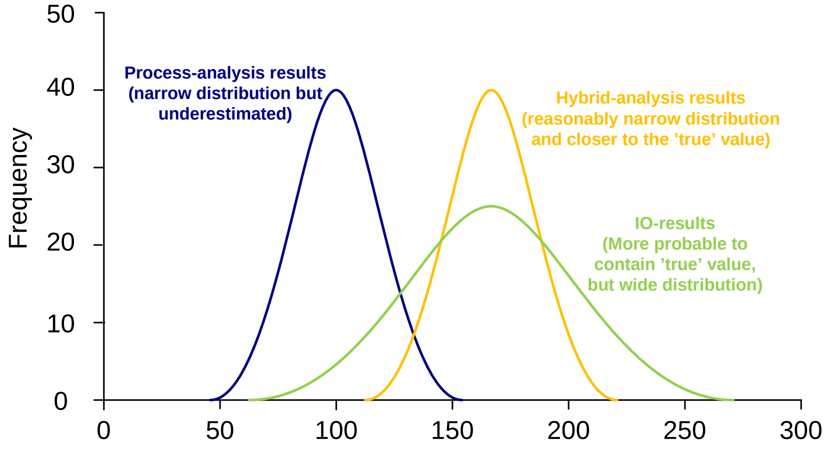

Figure 3.3: Illustration of uncertainty implications of process-LCA, hybrid-LCA and IO-LCA (Suh 2003). The X-axis represents the magnitude of the LCIA result, where the result of process LCA = index 100.

Typically, IO-tables include between 60 and 500 products. Thus, many of the products in IO data include several different types of products; e.g., the US IO-table (which is the most disaggregated to date) presents the following product types:

- '*Primary aluminium*': which includes virgin and recycled aluminium.
- '*Industrial inorganic and organic chemicals*': which among several other chemicals include alumina (Al_2O_3), which is the main feedstock input to the aluminium smelter in aluminium production.
- '*Nonferrous metal ores, except copper*': which among several other ores includes bauxite, which is the main feedstock input to alumina production.

Hence, when using IO data, many specific products are represented by aggregate average data. For very homogeneous product groups, this is not a problem; but for inhomogeneous product groups, such as '*Industrial inorganic and organic chemicals*' as shown above, the average emissions per USD may vary significantly for the different products which belong to the same product group.

Completeness: Comparing process LCA and Input-Output LCA: As described, process LCA is related to (often arbitrary) cut-off criteria, whereas IO data are complete. This difference is relevant for the choice of one approach rather than another. Not many published comparisons exist. Below in **Figure 3.4**, the only identified officially published comparison of IO-based and process-based LCA results is presented. The comparison shows that the process-based LCA results only comprise around 25-33% of the IO-based results. **Figure 3.4** combined with non-published comparisons of the US98 input-output table (Suh 2004), the Danish 1999 input-output table (Weidema et al. 2005) and the process-based ecoinvent database (ecoinvent 2007) indicates that, in general, process-based results comprise around 30-70% of IO-based results. For very homogeneous products from the primary sectors and products which relate to significant emissions, the difference is generally less pronounced.

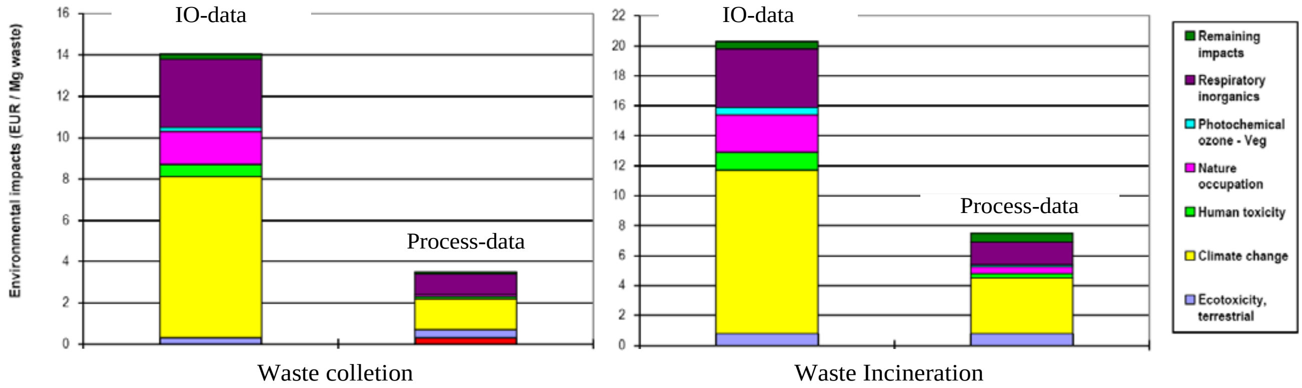

Figure 3.4: Comparison of IO-based and process-based LCA results (end-point monetarised) for waste collection and for waste incineration. The results in terms of monetarised environmental impacts are calculated using the Stepwise method (Weidema 2008, Weidema et al. 2007). The figures are directly obtained from (Institute for Environment and Sustainability 2007, p 156-157).

Hybrid LCA: It appears from the previous comparison of IO LCA and process LCA that IO LCA is complete but not very detailed, while process LCA is incomplete (cut-offs) but can be very detailed. Thus, the optimal LCA would combine the best aspects of the two approaches. This type of LCA, which is called hybrid LCA, is used in this study of an aluminium smelter in Greenland. In this study, the following procedure has been implemented:

1. The best[7] available IO data on primary aluminium is identified. This data is presented in monetary units; i.e., the functional unit or reference flow for the data set is EUR or USD aluminium.
2. Price information on primary aluminium for the relevant period of time and geographical region is identified.
3. A process is expressed in physical units (kg), transforming the monetary reference flow in (1) into mass using the price information in (2).
4. A number of inputs and outputs of the IO data set for the aluminium smelter process are replaced by more detailed process-based LCA data based on:
    a. a screening of the process (contribution analysis made by use of LCA software) and the literature review presented in section 1, and
    b. an identification of the processes of which it is desirable to be able to make detailed modelling (e.g. if it is desirable to be able to make detailed modelling of bauxite production, energy inputs, transportation, or other inputs and outputs which may be either special in the case of Greenland or they may be relevant as parameters in defining alternative technologies to be included in the study)

The procedure of converting an original IO data set into a hybrid data set, as presented above, represents an iterative process in which step (4) can continue as far as desired. However, each time an IO-based input is replaced by a process-based input, it must be considered if the process-based input is significantly less complete than the IO-based input which it replaces. If so, steps (1) to (4) must also be carried out for this specific input.

When a process is described with both IO data and process data, it is presumed that the exchanges taking place in the process are completely described, i.e., cut-off criteria are 0%. If all processes should be completely described in this way, it would require a process LCI database which is completely embedded in an IO database. Currently, such LCI databases do not exist, and it would be a major task to construct such a database. Such a task is not in the scope of this LCA study of aluminium production in Greenland. Instead, it is chosen to describe the anticipated most important processes with both process data and IO data, and then use only process

[7] Here ‘best’ refers to: a) most detailed data, b) most recent data, and c) data for a representative geographical region

data for the remaining processes. Whenever IO data are excluded from the description of processes, this can be characterised as applying cut-off criteria. The applied cut-off criteria are described in section 3.4 under 'Cut-off criteria'.

3.4 System boundary: Life cycle stages and included processes

The included life cycle stages for aluminium production are described in the following section.

Included life cycle stages

The production of aluminium can be divided into three main stages: 1) Bauxite mining, 2) Production of alumina (Al_2O_3), and 3) Aluminium smelter (electrolysis). The downstream processes concerning further processing, final use and disposal are not included in this LCA study. The Alcoa aluminium smelter in Greenland only concerns the stage: 3) Aluminium smelter (electrolysis). The included life cycle stages and the system boundary are illustrated in **Figure 3.5**.

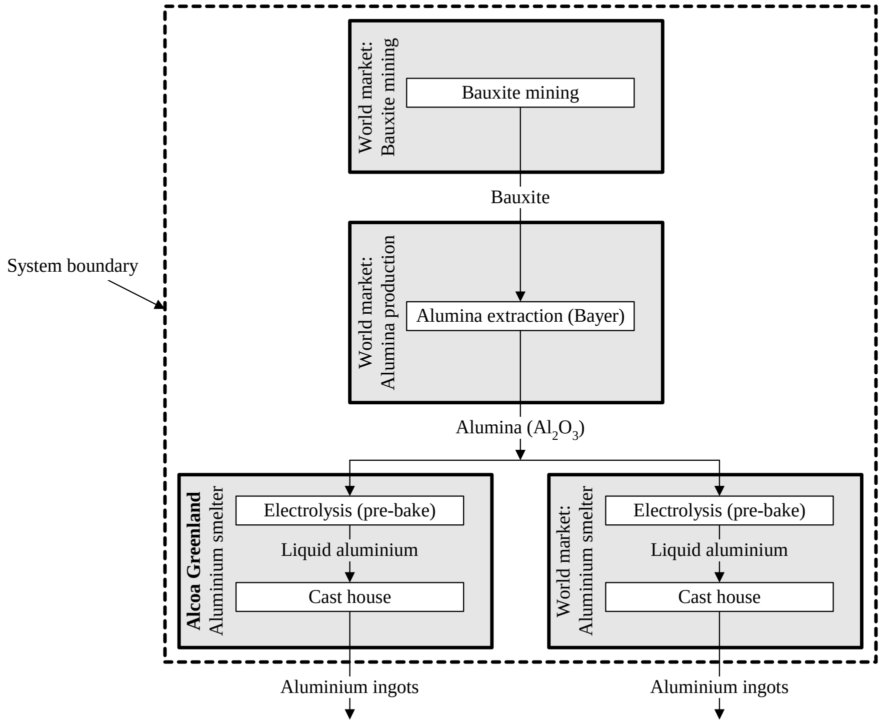

Figure 3.5: System boundary and life cycle stages in the product system of basic aluminium. For each life cycle stage, it is specified whether the life cycle stage is specific for the Alcoa smelter in Greenland, or if it is represented by a supplier on the world market.

The left side of **Figure 3.5** represents Alternative 1: the Greenland smelter, and the right side represents Alternative 0: alternative production of aluminium.

Cut-off criteria

The hybrid approach is adopted in this study, see section 3.3. This implies that the cut-off criterion is 0% for some processes which are selected as the most important ones (IO data combined with process data), while the cut-off criterion is >0% for other processes (only process data is used).

Using IO data implies that many product inputs are described with relatively aggregated product categories, and that these inputs are based on relatively old data. As described in section 3.6, the applied IO data is the US98 IO table, which represents the US economy in 1998 (Suh 2004). Though the data is old, we argue that it is better to have data for 1998 rather than having no data at all for the inputs covered by the IO data.

Based on the literature review and a screening of the ecoinvent (2007) process of primary aluminium production, the following processes have been identified as the most significant contributors to GHG emissions: Electricity, Aluminium smelter, and Alumina production (where process heat is most significant). Based on this, it is chosen to create hybrid processes for these three processes. In order to have consistent modelling of the feedstock chain from bauxite to aluminium, it is also decided to create a hybrid process for bauxite production. All other product inputs in the product system of aluminium production will be described using only process data. **Figure 3.6** provides an overview of the processes described as hybrid processes and those which are only described by use of process data.

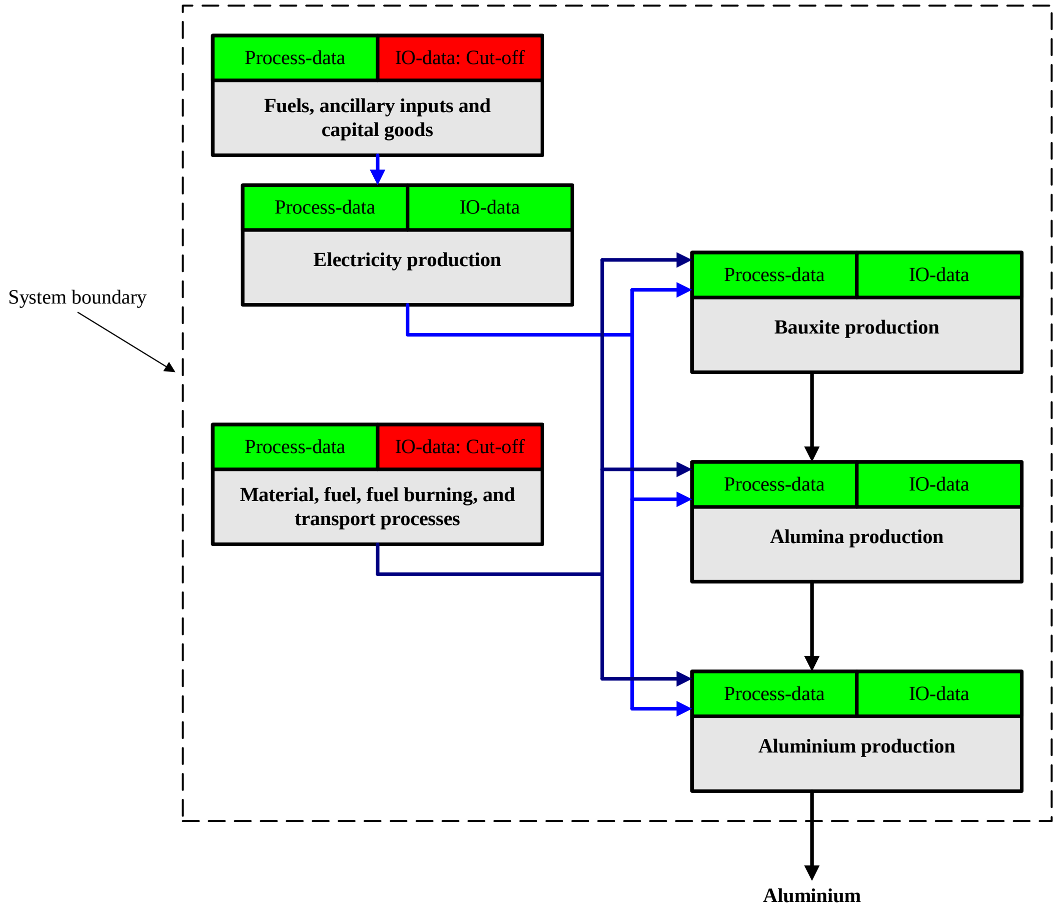

Figure 3.6: Presentation of applied cut-off marked in red. Cut-offs are applied to upstream processes for electricity and processes for materials, fuels, fuel burning and transport.

For the applied process data, the cut-off criteria most often follow the same degree of completeness as in the ecoinvent database (ecoinvent 2007). The ecoinvent database typically includes: material inputs (feedstock and ancillary materials), energy, fuel, and infrastructure (buildings, roads, structures, machinery, and vehicles) as well as the disposal of all inputs. The ecoinvent database (as well as process data in general) does not include service inputs (cleaning, marketing, legal assistance, accounting, business travelling etc.) and office equipment (computers, printers, copy-machines, furniture, pencils, paper etc.). These inputs are not considered in the process data used in this LCA of aluminium production in Greenland.

Product flow between the included life cycle stages

This section briefly provides an overview of the product flow (feedstock chain) between the three product stages: 1) Bauxite mining, 2) Production of alumina (Al_2O_3), and 3) Aluminium smelter (electrolysis). This overview is provided in physical units as well as in monetary units (obtained from the US98 IO model). This also includes a description of the product flow, as it is included in the IO data, as well as some modifications of IO data. The physical flow is illustrated in **Figure 3.7**.

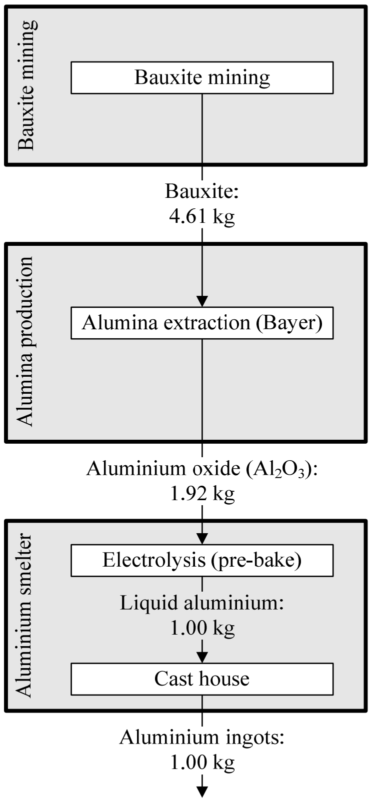

Figure 3.7: Product flow between the life cycle stages. The quantities in the figure are described and documented in sections 9.2 and 10.2.

It should be noted that the cast house process often includes alloying metals for a few per cent of the product output. However, since the input of alloying metals relate to the specific purpose of the use of the aluminium, which is not considered in this study, the input of alloying metals has been eliminated and the analysed product output is assumed to be 100% pure aluminium. The same assumption is applied to the LCA presented in EAA (2008).

According to the procedure for hybrid LCA described in section 3.3 'Method for system delimitation', the starting point for the system boundary is defined by an IO data set of primary aluminium. The identified IO data set is '*Primary aluminium*' in the US98 IO table (Suh 2004). The reasons for choosing this data set and the related US98 IO table as the starting point are described in section 3.6, under 'IO data'. The product flow of the main feedstock (bauxite => alumina => primary aluminium) in the supply chain related to primary aluminium production in the US98 IO table is illustrated in **Figure 3.8**. It should be noted that the process names applied (in the boxes) are the ones from the US98 IO table, whereas the flows are denominated as "Mainly…[flow name]". This name convention is used here, because we know the actual flow, i.e., the contents of the actual flow. E.g. the input flow from the process 'Industrial inorganic and organic chemicals' to the 'Primary aluminium' process mainly consists of alumina. But the flow also includes other chemical inputs, such as aluminium fluoride and cryolite (Classen et al. 2007, part 1). Therefore, we use the term "Mainly".

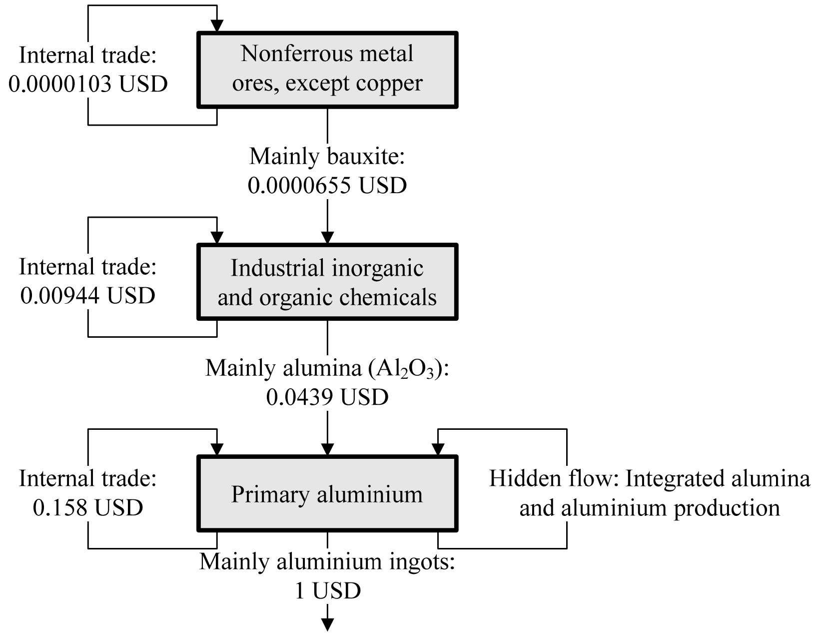

Figure 3.8: Product flow of 'bauxite', 'alumina', and 'primary aluminium' related to 1 USD 'Primary aluminium' in the US98 IO table (Suh 2004).

Internal trade: It appears from **Figure 3.8** that an internal trade takes place of 0.157 USD primary aluminium per supplied USD of primary aluminium. This is mainly assumed to cover the use of aluminium scrap (which in some cases may be classified as primary aluminium) for recycling and the internal trade of liquid aluminium to individual cast houses. Both of the above-mentioned transactions of primary aluminium will appear as internal trade, i.e., input of primary aluminium to primary aluminium. Since recycling is not considered as part of the aluminium smelting process, and since the cast house process is modelled specifically, the internal trade of 0.157 USD is deleted and the reference flow is reduced accordingly by 0.157 USD. Since energy inputs and the main feedstock and ancillary inputs are replaced with process-based data, this modification is regarded as insignificant.

Correspondingly to the internal trade in the 'primary aluminium' process, the internal trade is also eliminated in the 'Industrial inorganic and organic chemicals' and 'Nonferrous metal ores, except copper' processes.

Hidden internal trade: Figure 3.8 also illustrates a hidden internal trade of alumina. This can be interpreted as the internal production of alumina. It has no monetary value, because integrated alumina and aluminium facilities do not pay for their intermediate transactions. We wish to model alumina separately from the smelting process, and therefore, it is desirable to exclude this internal production of alumina from the primary aluminium production process. We are able to identify the presence of integrated production of alumina and aluminium, because the primary aluminium production process includes an input of 'Nonferrous metal ores, except copper'. It is generally known that aluminium smelters do not use metal ores directly - the bauxite is first processed into alumina. The existence of integrated alumina and aluminium production facilities is also referred to by the European Commission (2001, p 275). In order to eliminate the integrated alumina production from the 'Primary aluminium' process, the input of 'Nonferrous metal ores, except copper' is deleted. Other important exchanges related to the production of alumina are fuel inputs and the related direct emissions as well as electricity. All these exchanges are replaced with process-based LCI data. Therefore, no other modifications are necessary.

Processes in US98 IO table in physical units: In order to create meaningful units of the flow between product stages in the IO data, the monetary flows are transformed into physical weight using price information. The data for the product categories in the US98 IO table (column 2 in **Table 3.2**) is expressed in US$98. By using price information from UN (2009), the reference flows (1 US$98) in the IO processes are transformed into physical units (kg), see **Table 3.2**, column 4 and comments in column 5.

Product flow	Product category in US98 IO table	Price	New reference flow of IO process	Comments to price of product flow
Bauxite	Nonferrous metal ores, except copper	0.0312 US$98/kg	1 USD => 32.1 kg	Weighted average of US98 import and export prices of 'Aluminium ores and concentrates' (UN 2009)
Alumina	Industrial inorganic and organic chemicals	0.262 US$98/kg	1 USD => 3.82 kg	Weighted average of US98 import and export prices of 'Aluminium oxide, except artificial corundum' (UN 2009)
Aluminium	Primary aluminium	1.50 US$98/kg	1 USD => 0.667 kg	Weighted average of US98 import and export prices of 'Aluminium unwrought, not alloyed' (UN 2009)

Table 3.2: Changing monetary IO processes for bauxite, alumina and aluminium into physical IO processes using price information.

Based on the processes shown in **Table 3.2**, the product flow in **Figure 3.7**, and the described modifications (elimination of internal trade), the figures in **Figure 3.8** can be transformed into physical units. This is shown in **Figure 3.9**. It should be noted that the monetary flows in **Figure 3.8** cannot be obtained by multiplying the physical flows in **Figure 3.9** by the prices in **Table 3.2**. This is because the flows in **Figure 3.8** do not cover the same as the flows in **Figure 3.9**; e.g., the process 'Industrial inorganic and organic chemicals' in **Figure 3.8** is an average of the whole chemical industry, which of course does not use much bauxite compared to the alumina industry, which is represented in **Figure 3.9**.

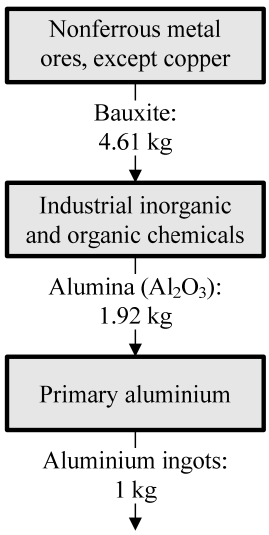

Figure 3.9: Product flow of 'bauxite', 'alumina', and 'primary aluminium' related to 1 kg of 'Primary aluminium' in the US98 IO table.

The processes and the product flow presented in **Figure 3.9** form the backbone and the starting point for the LCA. By using only the data presented in **Figure 3.9**, the LCA would be a pure IO-LCA. As described previously, this data is not suitable for the purpose of this LCA for the following reasons:

- Aluminium smelter stage: The process '*Primary aluminium*' in the US98 IO table includes virgin as well as recycled aluminium.
- Alumina production stage: The process '*Industrial inorganic and organic chemicals*' in the US98 IO table represents the average of the US chemical industry, which is not a desirable level of detail for describing alumina production.
- Bauxite production stage: The process '*Nonferrous metal ores, except copper*' in the US98 IO table represents the average of the US mining of nonferrous metal ores (except copper), which is not a desirable level of detail for describing bauxite mining.

Therefore, in the above-mentioned processes, for all product and resource inputs as well as emissions outputs where more detailed data is available, these exchanges have been replaced with the better process-based data. This hybridisation exercise is described in detail in the individual sections that describe the inventory data for the life cycle stages, see sections 8 to 10. In addition, the hybridisation of electricity data is described in section 7.2.

3.5 Method for life cycle impact assessment (LCIA)

The life cycle impact assessment phase is the third phase of an LCA. In this phase, the interventions (or emissions) per functional unit are transformed into easier interpretable impact categories. The interventions per functional unit are calculated through the life cycle inventory phase – phase 2 in the LCA. The number of interventions included in an LCA is typically several hundred, while the number of included impact categories is more limited. Therefore, LCIA is normally necessary in order to be able to interpret the results. **Figure 3.10** provides an overview of the most commonly included impact categories in LCA as well as examples of some typical interventions.

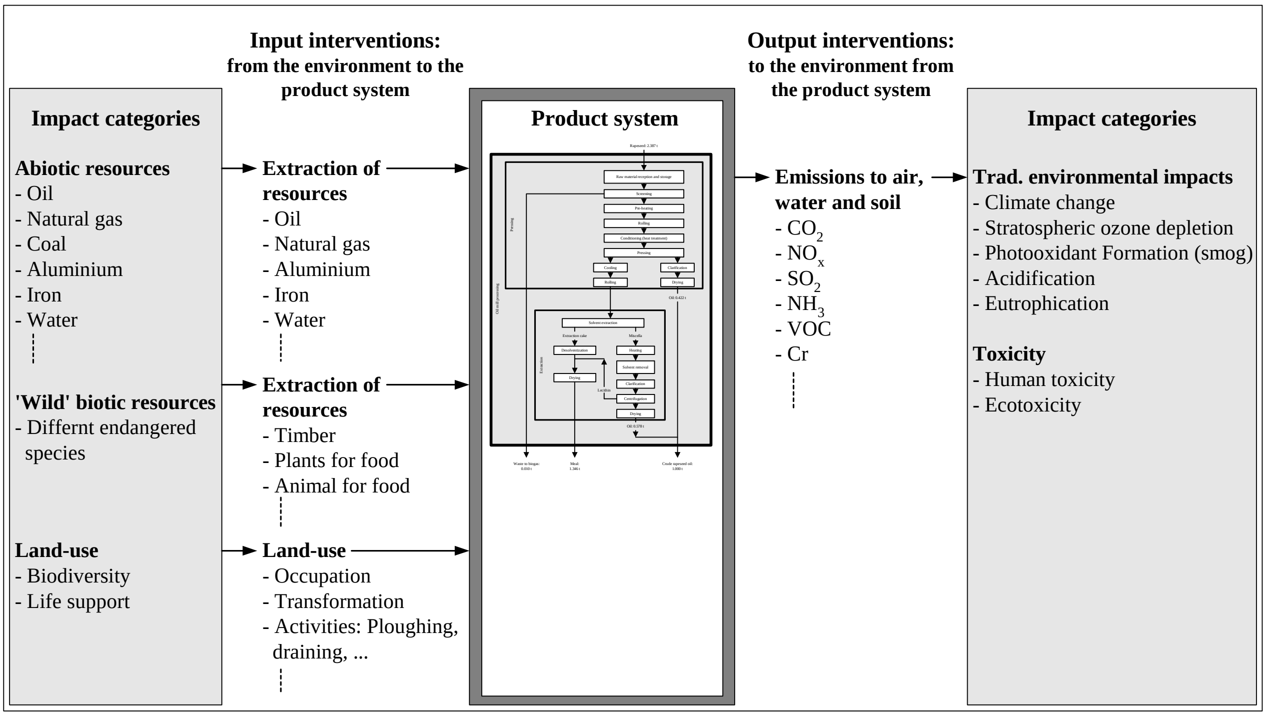

Figure 3.10: Overview of the most common impact categories (Obtained from Schmidt 2007).

The LCIA consist of three steps:

1. Characterisation
2. Normalisation
3. Weighting

Characterisation: Here, the interventions are transformed into impact categories and the results are presented as impact indicators.

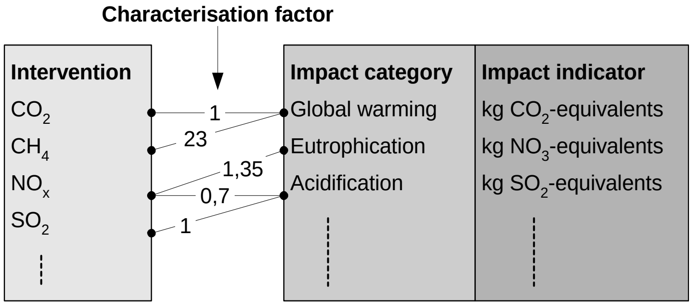

Figure 3.11: Interrelationships between environmental exchanges, impact categories and category indicators / impact potentials (Obtained from Thrane and Schmidt 2007)

Normalisation: Here, the normalised results are divided by a reference (typically the total contribution to the impact category per citizen per year). Hereby, the magnitude of the environmental impact can better be assessed. The unit of the normalised results is person equivalents. It is often easier to have an impression of the magnitude of the contribution from 1 kg of aluminium to acidification if it is expressed in terms of person equivalents than in terms of kg of SO_2-eq.

Weighting: In this step, the normalised results are multiplied by a factor representing the relative importance of the impact category to the other impact categories. Hereby, the magnitude of the different impact categories can directly be compared, and it is possible to point out the most significant impact categories. Sometimes the normalisation step and the weighting step are carried out as one single step.

Presentation of results

The presentation and interpretation of results will be at the level of characterised results. Since normalisation and weighting imply that additional factors are multiplied by the characterised results, these results will be more uncertain. Therefore, these results will not be used for presenting the results of the LCA. However, the weighted results are used for identifying the most significant impact categories.

LCIA method: Stepwise v1.2

The applied LCIA method in the present study is the Stepwise 2006 method, version 1.2. The method is described and documented in Weidema et al. (2007) and Weidema (2009). This method is developed by selecting the best principles of the Danish EDIP2003 method (Hauschild and Potting 2005) and the Impact 2002+ method (Jolliet et al. 2003). Weidema et al. (2007) is available on: http://www.lca-net.com/publications/

In the assessment of environmental impacts of aluminium production, special attention is given to the impact category of global warming. There are several reasons for focussing on GHG emissions:

- This specific focus is of particular interest to the Government of Greenland.
- GHG emissions of an aluminium smelter in Greenland will increase Greenland's domestic GHG emissions significantly, but may lead to avoided emissions in other places which need to be addressed and quantified to get a complete picture of the consequences.
- Other types of impacts, especially other types of local impacts, are assessed as a part of the strategic environmental assessment (SEA), of which the present LCA forms part.
- GHG emissions represent a major environmental issue on the global agenda and GHG emissions calculated by the use of LCA corresponds to carbon footprint (CFP), which is an eco label undergoing rapid development these years (EPLCA 2007; PAS 2050)

Apart from the detailed assessment of GHG emissions (section 11.1), the study includes a screening of local human health impacts (section 12), which was requested by the commissioner of the study. After GHG emissions, which are given first priority in the assessment, the study gives second priority to human health impacts, which include respiratory organics and inorganics as well as human toxicity carcinogenic and non-carcinogenic. Third priority is given to 'other' impact categories included in the Stepwise method. The latter is therefore only considered at a screening level in section 11.2. This does not mean, however, that these issues are of a trivial character (especially not in a pristine environment such as Greenland), but merely that they are not addressed at a detailed level in the present study. Readers who are interested in more detailed assessments of other impacts are referred to the information provided in the SEA. A complete list of the included impact categories as well as information about the level of detail at which they are treated in the study is available in **Table 3.3**.

Impact category	Unit	Level of detail			Comments
		High	Low	Additional	
Global warming	kg CO_2-eq	X			High level of detail. Results are available in section 11.1.
Nature occupation	m^2 agr.land		X		Low level of detail, meaning that it is included in the assessment but only at a screening level. Results are available in section 11.2. Note on land use: We acknowledge that nature occupation (including impacts of land occupation and transformation) may have a significant impact on Greenland's pristine environment due to the building of the smelter itself, but also the construction and maintenance of hydropower plants, transmission lines, roads, harbour etc. However, there are large complexities involved in this type of assessment and it is already handled in other parts of the SEA.
Acidification	m^2 UES		X		
Eutrophication, aquatic	kg NO_3-eq		X		
Eutrophication, terrestrial	m^2 UES		X		
Photochemical ozone, vegetation	m^2*ppm*h		X		
Respiratory inorganics	kg $PM_{2.5}$-eq		X	X	As above, but an additional assessment of impacts occurring locally in Greenland, possibly affecting the population in Greenland, is available in section 12.
Respiratory organics	pers*ppm*h		X	X	
Human toxicity, carcinogens	kg C_2H_3Cl-eq		X	X	
Human toxicity, non-carcinogens	kg C_2H_3Cl-eq		X	X	
Ecotoxicity, aquatic	kg TEG-eqw		X		Low level of detail, meaning that it is included in the assessment but only at a screening level. Results are available in section 11.2
Ecotoxicity, terrestrial	kg TEG-eq s		X		
Ozone layer depletion	kg CFC_{11}-eq		X		
Non-renewable energy	MJ primary		X		

Table 3.3: Overview of impact categories included in the applied LCIA method based on Stepwise 2006, version 1.2. Level of detail refers to the comprehensiveness of our assessment. The level 'Additional' refers to the additional assessment of local impacts occurring in Greenland, which is available in chapter 12. Further explanations of the impact categories are available in 'Appendix 2: Explanation of units in the Stepwise LCIA method' as well in the documentation of the LCIA method Stepwise 2006, version 1.2 (Weidema et al. 2007).

As it appears from **Table 3.3**, global warming is the only impact category that is assessed at a high level of detail. A less comprehensive assessment is made of other impact categories, except for local human health impacts in Greenland, which is treated separately in chapter 12. Considering the potentially significant impacts on nature and landscape in the pristine environment in Greenland, a qualitative discussion of this is included in the discussion of nature occupation in section 11.2. However, it must be stressed that the SEA includes such assessments at a much more detailed level, separately from the present study.

3.6 Data collection

The data collection concerns three types of data, i.e. data on 1) processes within Alcoa, 2) processes outside Alcoa, and 3) input-output data (IO data) which covers the data not included in the first two data types. Note that the specific data collection (and data used in the modelling) is comprehensively documented in sections 4 to 10.

Processes within the Alcoa aluminium smelter

The data collection for Alcoa processes is mainly based on specific requested data provided by Alcoa. Data which is not available from Alcoa is estimated on the basis of other data sources; personal communication with Chris Bayliss from IAI and Eirik Nordheim from EAA as well as other LCA studies such as EAA (2008) and ecoinvent (2007).

Company visit at Alcoa's Deschambault plant in Quebec:
Data collection has taken place in collaboration with Alcoa. A company visit took place at the Alcoa smelter in Deschambault in Quebec from the 10th to the 13th of February 2009. The factory tour took place on the 10th of February and meetings with key staff members took place on the 10th and 11th of February. Participants were:

- Marc Montembeault (Environmental and Technical support),
- Patrick Grover (Director EH&S Virginia – Global Primary Products GEBA)
- Lise Sylvain (Regional Director for Environment and Sustainable development in Alcoa Canada/Iceland),
- Cathrine Daoust (Environmental Engineer in Alcoa ABI plant)
- Louise Pearson (Laboratory, Environment and Engineering Manager)

And on the phone were:

- Jannick Schmidt (2.-0 LCA consultants)
- Kenneth Martchek (Manager – Life Cycle & Environmental Sustainability, Alcoa)

As a result of the visit and subsequent communication, Alcoa has provided detailed life cycle inventory (LCI) data for their aluminium smelters in Deschambault in Quebec and their new state-of-the-art smelter in Iceland (Fjardaál).

Personal communication with Chris Bayliss from IAI:
Apart from continuous email contact with specialists from Alcoa (mentioned above), valuable information about marginal production of aluminium and marginal electricity has been provided by Chris Bayliss, who is responsible for Global Projects and Health in the secretariat for Health, Safety, Environment & Sustainability at the International Aluminium Institute (IAI). Communication has been based on email conversations during January and March 2009. Apart from guidance in the use and interpretation of IAI's statistics, Chris has provided valuable insight into Rio Tinto Alcan's assumptions about future expansions within the aluminium industry.

Personal communication with Eirik Nordheim from EAA:
Valuable information about expected global expansions of aluminium smelters has also been obtained from personal communication with Director EHS Eirik Nordheim from the European Aluminium Association (EAA) in Brussels. Communication has been based on email conversations during January and March 2009.

Processes outside Alcoa

Upstream processes to the aluminium smelter as well as smelter data for Alternative 0 are based on existing LCA data (EAA 2008; ecoinvent 2007), personal communication (see above), statistical information (IAI 2009b), energy outlooks (IEA 2008), as well as general industry information (European Commission 2001).

IO data

All the inputs to the processes in the product system which could not be covered by the above-mentioned process-specific data collection are covered by general IO data for the USA in 1998 (Suh 2004). This relatively old data represents the best compromise between level of detail, regional coverage, and updated data, see section 3.3.

3.7 Critical review

The LCA report has undergone a critical review by a panel of interested parties. Mark Goedkoop (PRé Consultants) has been selected by Klaus Georg Hansen (Government of Greenland) as an external independent expert to act as a chairperson. Mark Goedkoop has independently selected two other interested parties. These are: Eirik Nordheim (EAA, European Aluminium Association) and Pascal Lesage (Sylvatica).

The final draft of the LCA report was sent to the review panel on the 20th of April 2009. The draft review statement report was received by the authors on the 3rd of July 2009. On the 10th of July, the authors sent the revised LCA report and the commented review statement report to the review panel for verification. The final review statement report and verification of the revised LCA report and the commented review statement report were received by the authors on 20th of July 2009. The review panel report including the authors' response is presented in Appendix 6: Review panel report, including the authors' comments.

4 Identification of marginal production of aluminium (smelter stage) and included scenarios

Since electricity is the single factor which contributes most to GHG emissions from aluminium production, it is obvious that the source of electricity is crucial for the result of the LCA.

The 0 alternative represents what is most likely to happen in a global perspective if the Greenland smelter is not established (see also section 3.1). The purpose of the present section is to identify the geographical location of the marginal production of aluminium. This is highly relevant because the mix of electricity sources is dependent on the location of the marginal production.

Since the identification of the marginal supply of aluminium is subject to uncertainties, several candidates for the marginal supply are identified. The marginal electricity mix for the identified countries and regions is analysed in section 5.

4.1 Approach to the identification of marginal production

When identifying the marginal supply of a product, it is important to note whether the marked trend is increasing or decreasing. On increasing markets, the marginal supply can be identified as the most competitive supply, while it is the least competitive supplier on decreasing markets (Weidema 2003). In this regard, it should be noted that the global aluminium demand and production are expected to increase in many years to come, according to most references (USGS 2009b, Aluminium Marketing Research 2009, and Bergsdahl et al. 2004). Personal communication with experts from the International Aluminium Institute (IAI) and the European Aluminium Association (EAA) also confirms this tendency (Bayliss 2009, Nordheim 2009).

The current (year 2009) financial crisis obviously affects the market trend, but in the long term, the aluminium production is assumed to continue to increase, as will be explained in section 4.2. Therefore, the marginal suppliers of aluminium are assumed to be the ‘most competitive’.

Generally, information about which supplier is most competitive is not directly accessible. We have therefore gathered information on where new capacity will presumably be installed. Sometimes, the best way to estimate the expected location of future capacity is to look into statistics. It can be presumed that the locations which have faced the fastest growth in the recent years will also face the highest growth in the future. Hence, to identify the marginal suppliers of aluminium, this section analyses the historical development in aluminium production globally and in different regions of the world, and we discuss the current situation and the expected locations of future expansions. The latter is based on an analysis of historical trends, literature studies and expert interviews. A similar analysis is carried out, specifically of the development in the electricity mix for aluminium smelters (section 5) and of the electricity (section 6). An overview of different scenarios for aluminium production is available in section 4.4.

4.2 Historical development – the last decade

The global production of aluminium has increased significantly over the last decade and is estimated to be roughly 34 million tonnes of primary aluminium and 16 million tonnes based on recycled aluminium in 2006 (IAI 2009a). This gives a total of more than 50 million tonnes of aluminium.

The statistical survey conducted by the International Aluminium Institute, which only covers part of the world's aluminium industry (only IAI members), shows that the production of primary aluminium has increased from a total of 20 million tonnes in 1998 to nearly 26 million tonnes in 2008 – a yearly increase of about 3%. The expansion has especially taken place in Asia and Eastern/Central Europe, see **Figure 4.1**.

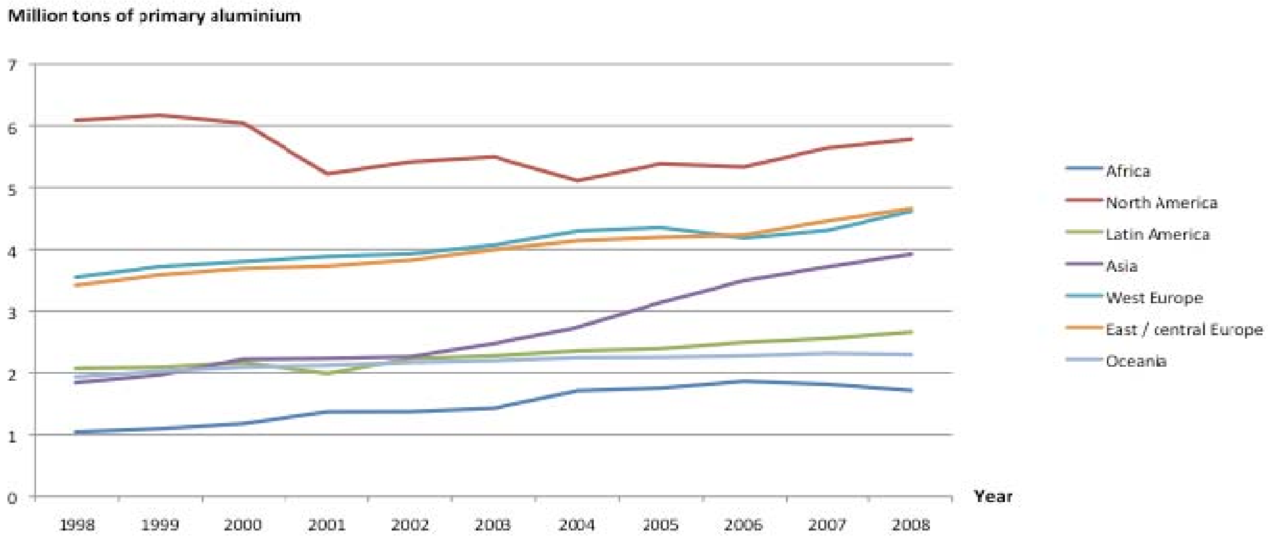

Figure 4.1: Development in primary aluminium production from 1998 to 2008 (IAI 2009b)

The regions referred to in **Figure 4.1** are specified in **Table 4.1**.

Area / region	Countries included in the region
Africa	Cameroon, Egypt, Ghana (1/1980-12/2003), Ghana* (1/2004-12/2005), Ghana (1/2006-1/2007), Mozambique, Nigeria (1/1999-12/2003), Nigeria* (1/2004-1/2007), South Africa
North America	Canada, United States of America
Latin America	Argentina, Brazil, Mexico (1/1980-12/2001), Mexico* (1/2002-12/2003), Venezuela
East Asia	China*, Japan, North Korea*, South Korea*, Tadzhikistan*
South Asia	Azerbaijan*, Bahrain, India, Indonesia (1/1982-12/2002), Indonesia* (1/2003-12/2003), Indonesia (1/2004-1/2007), Iran*, Kazakhstan* (1/2007-1/2007), Turkey (1/1980-12/2004), Turkey* (1/2005-12/2005), Turkey (1/2006-1/2007), United Arab Emirates
Western Europe	France, Germany, Greece, Iceland, Italy, Netherlands, Norway, Spain, Sweden, Switzerland (1/1980-12/2005), United Kingdom
Eastern/Central Europe	Bosnia and Herzegovina*, Croatia*, Hungary (1/1991-12/2005), Montenegro* (1/2006-1/2007), Poland*, Romania*, Russian Federation* (1/1980-1/2003), Russian Federation (1/2004-1/2007), Serbia and Montenegro (1/1997-12/2005), Slovakia, Slovenia, Ukraine* (1/1980-12/2003), Ukraine (1/2004-12/2005), Ukraine* (1/2006-12/2006), Ukraine (1/2007-1/2007)
Oceania	Australia, New Zealand

Table 4.1: Area definition and included countries according to IAI. * indicates that the electrical power used in the primary aluminium production was not reported to the IAI by the company or companies producing primary aluminium solely within that country. Dates given for a country indicate that data was reported or not reported, as appropriate, for the limited period shown. Although a country is shown as reporting data, some smelters operating in that country may not be reporting energy data (IAI 2009b).

The significant increase in the production in Eastern/Central Europe is, according to Bayliss (2009), partly based on the fact that the Russian Federation started to report in 2004. As can be seen in **Table 4.1**, several countries have not reported their electricity consumption in some periods or have started reporting recently.

The data provided in **Figure 4.1** does not cover the production that takes place in China (Bayliss 2009). Separate statistics on the Chinese production are available from the International Aluminium Institute and this data is presented in **Figure 4.2**.

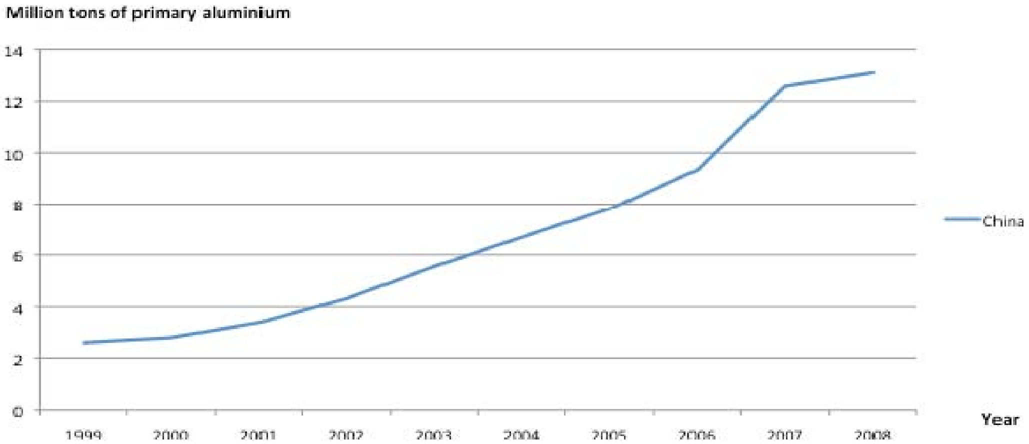

Figure 4.2: Development in primary aluminium production in China by Chinese-owned companies (IAI 2009b)

When comparing **Figure 4.1** and **Figure 4.2**, it appears that China is the world's largest producer of primary aluminium and that China also represents the largest expansion in aluminium production over the last decade, as the increase has been nearly 20% per year since 1999. Adding the numbers from **Figure 4.1** and **Figure 4.2**, the global primary aluminium production can be calculated as close to 40 million tonnes in 2008, which is an average annual increase of almost 6% at the global level from 1999 to 2008. The current production of virgin aluminium in different regions including China is shown in **Table 4.2** (IAI 2009b).

Aluminium Production (million tonne) in 2008								
Africa	North America	Latin America	Asia	Western Europe	East-ern/central Europe	Oceania	China	Total
1.72	5.78	2.66	3.92	4.62	4.66	2.30	13.11	38.76
4%	15%	7%	10%	12%	12%	6%	34%	100%

Table 4.2: Aluminium production in different regions in 2008 (IAI 2009b)

This is in accordance with statistics from the US Geological Survey, which estimate that the total aluminium production was 39.70 million tonnes in year 2008 (USGS 2009c). In addition, the production from recycled aluminium would be approximately 60 million tonnes of aluminium in 2008 (IAI 2009b).

The current financial crisis has obviously affected the aluminium industry. According to the London Metal Exchange (LME), the prices of primary aluminium have plummeted from more than 3,000 US$ per tonne in 2008 to 1,200 US$ per tonne in 2009, see **Figure 4.3**.

Figure 4.3: Development in aluminium prices (US$) per tonne of primary aluminium from March 10th 1998 to March 10th 2009 (LME 2009)

Hence, in the current situation, there is a decline in demand and producers are forced to react.

> *"For Alcoa, this has meant cutbacks in production at the smelter in Rockdale, Texas, USA; alumina production (an intermediate product from which aluminium is made) has been adjusted to reflect lower demand; and plants that are not producing in the optimum manner are constantly monitored. Due to the high prices of the last two years, many firms have commissioned old smelters that are expensive to operate and which pollute the environment, and it is expected that these will be taken out of service once more"* (Greenland Development 2009a, p1).

Based on the fact that the market is currently decreasing and on the statement by Greenland Development shown above, it is possible that a change in production (e.g. an increase) will mainly affect the least competitive aluminium smelters in the short term. This logic is further elaborated in Weidema (2003). However, in this LCA, we assume that the current financial crisis will be intermediate and that the general long-term market trend is an increase in the aluminium production.

4.3 Expected future development and scenarios

Aluminium is a durable, lightweight product with many applications and it can easily be recycled. The main applications are transport, packaging and construction. For transport, the demand can be assumed to increase, because of the focus on reducing fuel consumption (Greenland Development 2009a). For packaging and construction, an increased level of affluence is also likely to lead to an increase in the demand for aluminium packaging – especially in developing countries and new industrialised countries such as China. According to USGS (2009b):

> *"World demand for aluminium is expected to continue to increase, although at a slightly slower pace than in recent years. Demand from China and other developing nations is expected to remain strong, offsetting reduced demand from the housing and automotive sectors in the United States"* (USGS 2009b)

According to Bayliss (2009), the increase in demand and production can be expected to be around 4% per year in the following years. This is supported by Aluminium marketing Research (2009), and is a somewhat smaller increase than we have seen in the last decade.

The following sections include a number of scenarios of future marginal aluminium production, which differ in terms of the geographical location. The first scenario is based on an extrapolation of IAI statistics on the development in aluminium production (smelters) from 1998/99 to 2008. The second scenario is based on an expert assessment from the European Aluminium Association (EAA), and the two last scenarios are based on an assessment from the aluminium producer Rio Tinto Alcan (RTA) and United States Geological Survey (USGS). The last two scenarios include country specific information about future expansions.

Statistics: Extrapolation of IAI world average

The simplest way to estimate where the future expansion of aluminium production will take place, is to extrapolate the historical development of aluminium production (smelters) in different regions of the world including China (**Figure 4.1**and **Figure 4.2**). This has been done in **Figure 4.4** below.

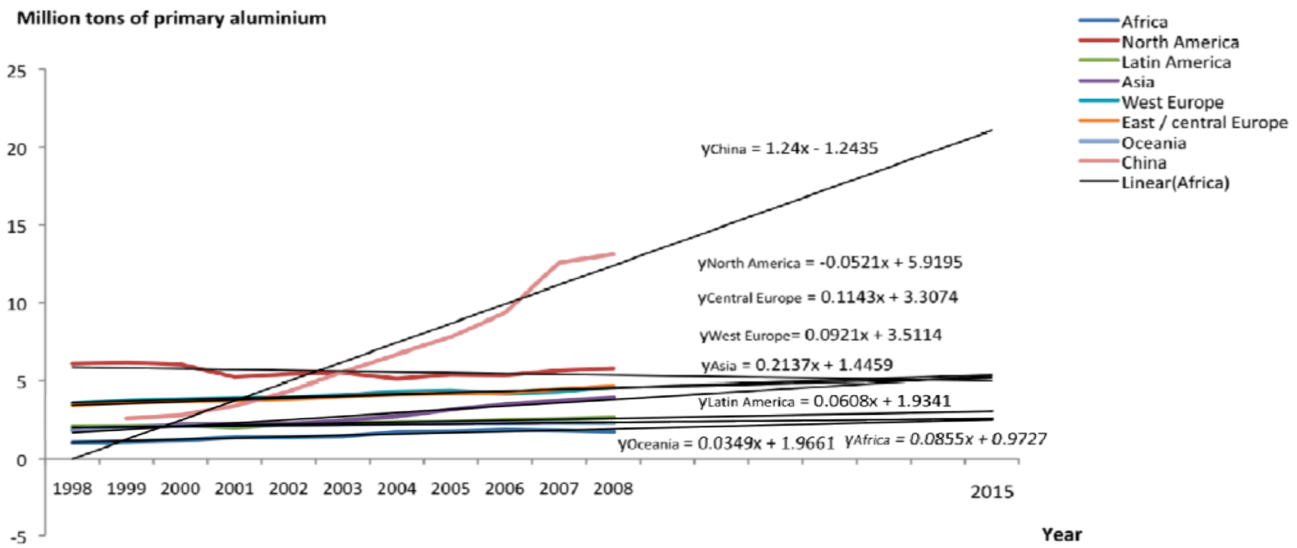

Figure 4.4: Development in global aluminium production including China, and extrapolations to year 2015 (IAI 2009b)

The figure clearly illustrates that China will represent the largest expansion (increase of 1.24 million tonnes per year), followed by Asia (increase of 0.21 million tonnes per year) and Central Europe (increase of 0.11 million tonnes per year). This would suggest that China, or a combination of China, Asia and Eastern/Central Europe are the most competitive regions and therefore represent the marginal production. However, this is not modelled further here, but treated separately in the following scenario based on the assessment of Nordheim from the European Aluminium Association.

Instead we have calculated the relative increase in each region (compared to the total increase) to obtain a global average marginal that reflects the changes in all regions. The total yearly increase is 1.79 million tonnes – equivalent to an increase of about 12.5 million tonnes from 2008 to 2015.

Scenario based on IAI: China (70%), Asia (12%), Eastern/Central Europe (6%), Western Europe (5%), Africa (5%), Latin America (3%), Oceania (2%), and North America (-3%), according to this world average scenario.

Textbox 4.1: Scenario based on extrapolation of IAI world average.

This will be used as one of the scenarios of marginal aluminium production in our analysis.

We have used linear regression for the extrapolations because it is a relatively simple approach, and because more advanced exponential trend lines will not necessarily give a more realistic picture of the development. Specifically for China, the growth does indeed appear to be exponential, but for other regions this might not be the case.

The next scenario takes another approach. It is partly based on an expert assessment and it only covers the regions that are ‘most’ competitive, thus suggesting a ‘narrower’ marginal than suggested above.

Expert assessment: Nordheim from EAA

According to Eirik Nordheim, Director EHS for the European Aluminium Association (Nordheim 2009), many of the planned projects are highly speculative. As an example, he mentions several projects in Africa, which are constrained by political instability, apart from possibly one in Algeria. He also mentions isolated projects in countries like Indonesia, Malaysia, Brunei, Laos, India, and Iran, which may or may not go ahead. He predicts no new smelters in Europe in the foreseeable future, with the possible exception of Iceland and Greenland. Actually, a number of smelters are closing down due to the lack of power contracts at affordable prices in Europe, he says. Nordheim assumes the same to be the case in the US. Nordheim therefore predicts that the main expansion will take place in the following three regions:

- China
- Commonwealth of Independent States (CIS: mainly Russia) [8]
- The Middle East/Gulf region

This prediction is generally in line with the world average scenario, because the Middle East is included in Asia in the IAI statistics, while CIS (mainly Russia) belongs to the region Eastern and Central Europe.

China: Nordheim acknowledges the point that the expansion in China will probably be slower than in recent years, but on the other hand, a number of projects in China are based on national power generation supplied by local coal mines, which is a cheap energy source (Nordheim 2009).

The prediction that the future increase will slow down compared to recent years in China is supported by Aluminium Market Research:

> *“Aluminium demand is expected to rise approximately 3 to 4% annually. The core growth in production is expected to be in countries with less expensive access to power. Despite the enormous growth in Chinese demand for aluminium, it is not expected that the country will increase production radically as the cost of energy within their country is seen as too high. China, however, was the largest producer of aluminium in 2005, with an almost 20% market share”* (Aluminium Marketing Research 2009)

This assessment is supported by USGS (2009b) stating that:

> *“China announced a policy to close smelters and stop construction on smelters in progress that do not meet strict environmental and financing rules or that use obsolete technology. Similar rules also would apply to alumina refineries under the policy. However, many Provincial governments were ignoring the national Government’s efforts to control growth in the aluminium industry. New projects were being allowed to move forward, and those operating in violation of the national Government’s rules were still producing because the Provincial governments desired to increase employment and local economic growth. In August, in an effort to increase aluminium supply in the Nation and reduce electricity use, China imposed a 15% export tax on aluminium bars and rods, while eliminating a 5% tariff on imports of primary aluminium in an effort to reduce exports of products that are energy intensive”* (USGS 2009b)

[8] ’Commonwealth of Independent States (CIS)’ is a regional organisation whose participating countries are former Soviet Republics. It includes Armenia, Azerhaijan, Belarus, Georgia, Kazakhstan, Kyrgystan, Moldova, Russia, Tajikistan, Uzbekistan, Turkmenistan, and Ukraine – but the two latter have not ratified the CIS charter.

Hence, evidence show that China will not face increase rates of 20%, as we have seen in the last decade. On the other hand, it is not likely that the expansion will come to a halt. USGS (2009b) predicts that the Chinese demand for aluminium will remain high and increase further. Also, it appears that the Russian Aluminium producer RUSAL predicts significant increases in the aluminium production in China in the coming years, see **Figure 4.5** (Belsky 2008).

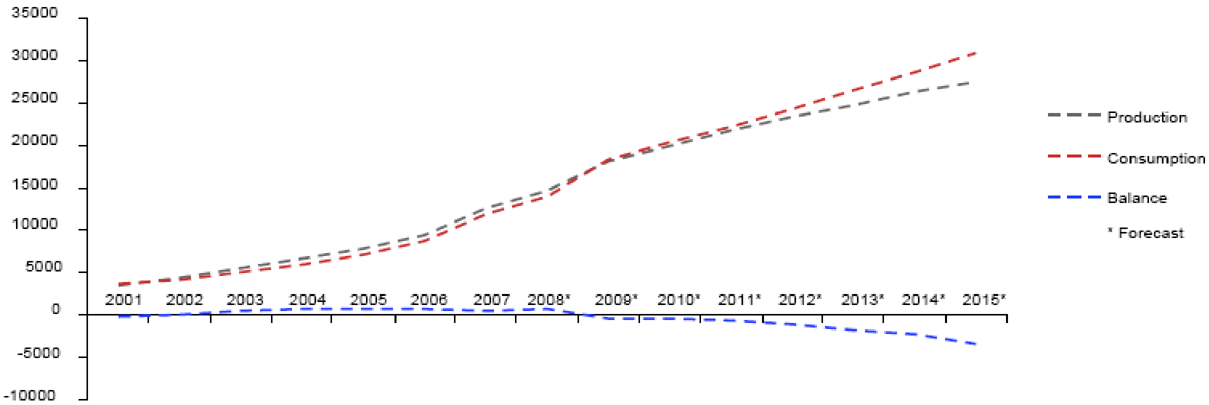

Figure 4.5: Predicted development in the Chinese aluminium consumption and production according to Belsky (2008). Unit: 1000 tonnes

According to Belsky (2008), the Chinese production will increase significantly towards 2015. Reading from the curve, it appears that the predicted increase will be around 10% per year, which is the same increase as China experienced from 2006-2008. According to Belsky (2008), it takes 12 months to build an aluminium smelter with a capacity of 250,000 tonnes per year in China, while it takes 3-5 years in other regions. He also mentions that a large amount of smelting projects are to be finished in 2009, corresponding to a capacity of about 5.8 million tonnes per year. More than 5 million tonnes of this amount are located in major coal-producing areas. Among the barriers to further increase, he mentions environmental problems, competition for energy resources, and a lack of bauxite that China needs to import to increase production.

All in all, we would therefore assume that China will play an important role in future expansions. It is most likely, however, that increase rates will stay under 10%.

The Middle East: Concerning the Middle East, other references support the prediction of increases in production in this region.

> *"….companies are investing heavily to find dedicated power sources to be able to produce aluminium. They are looking even further afield, often in very remote locations to set up aluminium producing operations. Some of these firms, including Rusal and Norsk Hydro are looking to remote spots in Siberia or other locations for new production sites. The new rule seems to be to get closer to the production source as opposed to closer to the customer. The geographic center of gravity continues to shift. The Middle East, as a consequence of its major oil and gas reserves, is expected to significantly grow its aluminium production. With the same objective in mind, Norsk Hydro has teamed up with Qatar Petroleum to expand capacity in Qatar. Alcoa has set up production operations in Iceland where it has better access to hydropower. For the most part, aluminium operations in the Pacific Northwest of North America have been almost shut down due to the high cost of fuel"* (Aluminium Marketing Research 2009)

The statement above also stresses the point that expansions are likely to take place in remote locations with cheap energy sources, such as Siberia.

CIS: Concerning the Commonwealth of Independent States (CIS), it is predicted that most of the expansion will take place in Russia (Nordheim 2009). This is supported by data obtained from the aluminium producer Rio Tinto Alcan (RTA) discussed in the following sub-section and in discussions with Chris Bayliss from IAI (Bayliss 2009).

Expected expansion in each region: Nordheim (2009) has not provided information about the expected difference in expansion in the three regions. But if we assume that the yearly expansion in percentage of current production for each region is the same, the individual weighting of a region can be expressed as the production within the given region divided by the total production of all three regions. Due to the aggregation level in the IAI statistics, the Middle East is represented by the production in Asia (East and South Asia) and CIS is represented by Eastern/Central Europe[9].

Scenario based on expert assessment: This means that future expansion (or marginal suppliers) in this scenario will be represented by an increase of 60% in China, 22% in CIS, and 18% in the Middle East/Gulf region.

Textbox 4.2: Scenario based on expert assessment.

According to Nordheim (2009), this is probably an overestimation of the increase in China. On the other hand, Bayliss (2009) from IAI supports the idea that this is a reasonable scenario in a longer time perspective. Also, it should be noted that CIS and the Middle East are represented by larger regions (Asia and Central/Eastern Europe) with a 'larger production'. This means that CIS and the Middle East are actually weighted higher than they should be – or that we assume higher expansion rates than in China. Finally, the extrapolation of the world's aluminium production (see **Figure 4.4**) suggested an even larger increase in China; actually China represents nearly 80% of the projected increase in the three regions, China, Central/Eastern Europe and Asia.

Acknowledging the large uncertainties involved in future estimates, we consider the estimate in which China represents 60% of the future expansion as the most reasonable estimate. Still, however, we believe that it would be relevant to include an alternative scenario in which the share from China is reduced from 60% to 40%.

Scenario based on expert assessment – reduced share of China: This would suggest a scenario in which 40% of the marginal supplier is located in China, while 33% and 27% are located in CIS (Russia) and the Middle East, respectively.

Textbox 4.3: Scenario based on expert assessment – reduced share of China.

But, apart from assuming that the marginal consists of an average of the three regions, we could also assume that the marginal was represented by only one of the regions – China, CIS, or the Middle East.

Scenarios for individual regions: This suggests that we should include three additional scenarios. A scenario in which the marginal supplier is located in China, CIS (Russia), or the Middle East.

Textbox 4.4: Scenarios for individual regions.

Assessment based on Rio Tinto Alcan (RTA)

We have also obtained access to an assessment of the future expansion in aluminium smelter capacity from the aluminium company Rio Tinto Alcan (RTA). The data in table 4.2 represents RTA's assessment of the future expansion of aluminium smelter capacity over the next 5 years. Expansion in China has not been assessed, and the assessment does therefore not represent a picture of the total global expansion.

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[9] Some CIS countries besides Russia are included under Asia in the IAI statistics, but as Russia is expected to represent the main expansion, we have found that East/Central Europe is a better match for CIS.

Region/country	Company	Expected expansion 2009-2014 (1000 tonnes of primary alu)	(per cent)
Africa			
Egypt	Nag Hammadi	50	
Egypt	National Aluminium Company Limited (NALCO)	115	
Egypt	Vedanta	415	
Total		**580**	**13%**
North America			
Canada	Rio Tinto Alcan (RTA)	60	
Canada	Alcoa	160	
Total		**220**	**5%**
South Asia / the Middle East			
Abu Dhabi	Dubal	700	
Kazakhstan	Eurasian Natural Resources Corp (ENRC)	125	
Qatar	Norsk Hydro	585	
Oman	Rio Tinto Alcan (RTA)	195	
Total		**1,605**	**35%**
Western Europe			
Iceland	Hegulvik	160	
Total		**160**	**3%**
Eastern/Central Europe			
Russia	Rusal	175	
Russia	Rusal	135	
Russia	Rusal	135	
Russia	Rusal	600	
Russia	Rusal	374	
Russia	Rusal	175	
Total		**1,419**	**30%**
Capacity creep			
Capacity creep		**670**	**14%**
Total all		**4,654**	**100%**

Table 4.3: Future expansions (except China) in smelter capacity in the period 2009-2014 according to Rio Tinto Alcan. Data provided by Bayliss (2009).

This assessment supports the point that the Middle East and CIS (including Russia) will represent the largest increase in aluminium production over the next five years. It shows, however, that other regions will increase as well – especially Egypt, representing Africa in the IAI statistics. But if Egypt is considered as a part of the Middle East/Gulf region, it actually supports the estimate that more than 90% of the new installed capacity will come from the CIS and the Middle East/Gulf.

This scenario does not make sense without China. We have therefore included China by using the same weighting factor of 60% for China as previously used. To include capacity creep we have assumed that this will be distributed equally among the regions/countries in **Table 4.3**.

Scenario based on Rio Tinto Alcan (RTA): This means that 60% of the future expansion (or the marginal suppliers) according to this scenario will be situated in China, 16% will be located in Asia (Abu Dhabi, Kazakhstan, Qatar and Oman), 14% in Eastern and Central Europe (Russia), 6% in Africa (Egypt), 2% in North America (Canada), and 2 % in Western Europe (Iceland).

Textbox 4.5: Scenario based on Rio Tinto Alcan (RTA).

The arguments for using 60% have already been presented, but in another context. In the context of the RTA assessment, it would suggest that China will increase its aluminium production by 7.3 million tonnes from 2008 to 2014. This is an increase of 7.5% annually for China. The total global increase (including China) would amount to 5% annually, and without China the increase would be 3% annually. It has previously been argued that the total global increase is more likely to be around 4%. This indicates that either the increase in

China is overestimated or that the increase is overestimated altogether, suggesting that RTA's assessment is too positive. The latter is not so important in this context, because we are mainly interested in the relative increase between regions/countries. Concerning China, an increase of 7.5% annually is not unrealistically high if the increase in the rest of the world is 3% annually. Here, we should remember that China has experienced an annual increase of 20% from 1999 to 2008 and 10% from 2006 to 2008. For further discussion about the expected development in China, see the previous sub-section 'Expert Assessment: Nordheim from EAA'.

Assessment from United States Geological Survey (USGS)

The US Geological Survey Minerals Yearbook 2007 (USGS 2009b and USGS 2009c) also provides information about expected expansions in aluminium production. USGS makes a 'world review' of aluminium production for each country with a focus on recent developments and information about announced projects of which some have a deadline and some are more uncertain. It is not our impression that the review is made with the purpose of making future scenarios – and it is somewhat uncertain what time period the review covers. But as information is available for projects in 2014 as well, we assume that the time frame is roughly the same as the RTA review. The review is descriptive and all the information about future expansions in the period 2009-2014 has to be extracted from the text. Based on this, it has been possible to establish a table about expected future expansions from 2009 to 2014, divided into expansions with a deadline (left columns) and all expansion projects without a deadline/finishing date (right columns). The results are available in **Table 4.4**.

Region/country	Expected expansion 2009-2014 (1000 tonnes of primary alu)	Expected expansion 2009-2014 (percent)	Expected expansion 2009-2014 incl. announcements without deadline (1000 tonnes of primary alu)	Expected expansion 2009-2014 incl. announcements without deadline (percent)
Africa				
Algeria			700	
Cameroon			610	
Congo			800	
South Africa	720		720	
Total	**720**	**10%**	**2,830**	**17%**
North America				
Canada			155	
Total		**0%**	**155**	**1%**
Latin America				
Argentina	105		105	
Brazil	140		140	
Guyana			400	
Trinidad & Tobago			466	
Total	**245**	**3%**	**1,111**	**7%**
East Asia				
Malaysia			550	
Total		**0%**	**550**	**3%**
South Asia				
India	650		1,800	
Iran			110	
Kazakhstan	190		190	
Kyrgyzstan			250	
Qatar	1,200		1,200	
Saudi Arabia			1420	
United Arab Emirates	1,400		2,500	
Total	**3,440**	**47%**	**7,470**	**45%**
Western Europe				
Greenland	340		340	
Iceland	250		250	
Total	**590**	**8%**	**590**	**4%**
Eastern/Central Europe				
Russia	**1,350**	**19%**	**2,400**	**14%**
China				
China	955	**13%**	1,555	**9%**
Total all	**7,300**	**100%**	**16,661**	**100%**

Table 4.4: Expected global future increases in aluminium production according to USGS (2009b) divided in projects/expansion with a deadline (left columns) and all expansions including projects without a deadline (right columns). The latter is considered to be more speculative.

According to this scenario, the Middle East will experience the largest growth, i.e., 47% of the total of 7.3 million tonnes, if we only consider the predicted expansions that actually have a deadline. The second largest increase takes place in Russia (19%) and China (13%). These are the same regions that were predicted would represent the largest increase in the previous scenarios, but China is much less important according to USGS, while the Middle East is dominating. Other regions such as Africa and Western Europe also play a relatively bigger role.

Scenario based on USGS: According to the USGS scenario, the marginal would be composed of 47% in the Middle East, 19% Eastern/Central Europe (Russia), 13% China, 10% Africa, 8% Western Europe, and 3% Latin America.

Textbox 4.6: Scenario based on USGS

If we include projects with no deadline (see **Table 4.4**) the scenario does not change much, apart from the fact that relatively more emphasis is placed on Africa and Latin America. However, the total increase would, in this case, be much bigger, roughly 17 million tonnes.

A global increase of 7.3 million tonnes from 2009 to 2014 is more realistic and represents an annual increase of less than 3%. This is not unlikely. It seems unlikely, however, that China would only experience an increase of less than 1 million tonnes (an annual increase of approximately 1%), considering the annual growth rate of 20% from 1999 to 2008 and 10% from 2006 to 2008.

We have included this scenario, because it is based on a different set of references and sources. However, we do not think that it gives a highly reliable picture of the future expansions. For China specifically, the low expected increase rate could also be a result of a lack of information about projects in China.

4.4 Recommended and alternative scenarios

A number of estimates of the marginal suppliers of aluminium have been presented; and apart from providing an overview of the scenarios, this section also seeks to identify the scenario which we believe would be the best (or recommended) and which alternative scenarios we include. The section also provides the scenarios with names that are used as references in the following sections of the report.

The recommended scenario: Based on the discussions and the analysis made, it is our belief that the most competitive regions are China, CIS (mainly Russia), and The Middle East. Expansion will probably take place in other areas as well, but we are interested in the regions that are most likely to respond to a change in demand. According to Weidema (2003), these are the ‘most competitive’ producers/regions on an increasing market. The most likely scenario, in this context, is, according to our analysis, the scenario based on the assessment of Nordheim from the European Aluminium Association (EAA), in which it is assumed that 60% of the marginal production will be situated in China, while 22% will be situated in CIS (Russia), and 18% in the Middle East (see **Textbox 4.2** in section 4.3). This scenario is therefore chosen as our ‘recommended’ scenario.

Alternative scenarios: Apart from the recommended scenario, we have developed a number of alternative scenarios. The first alternative is similar to the recommended scenario, but with China representing a smaller share. Arguments of Nordheim (2009) suggest that 60% is overestimated, and the USGS scenarios also point in that direction. This scenario is described in **Textbox 4.3**.

The second alternative is described in **Textbox 4.1** and is based on an extrapolation of the development in aluminium production worldwide. This scenario has not been chosen as the recommended one, because it is based on a simple extrapolation without the use of expert knowledge. Also we believe that the production of China is overestimated in this scenario.

The third and fourth alternative scenarios are described in **Textbox 4.5** and **Textbox 4.6**. They are based on assessments of the expansion at country levels and on information from Rio Tinto Alcan (RTA) and USGS, respectively. The latter is considered unreliable for various reasons, which have been presented in section 4.4. The RTA scenarios, however, appear to be reliable. On the other hand, it is noticeable that the expansion in Greenland is not included in their assessment. Also, the RTA assessment does not necessarily point towards the ‘most’ competitive regions. As an example, the assessment includes expansions in North America and Western Europe, which not are considered to be the ‘most’ competitive regions, according to, e.g., Nordheim (2009).

The last three alternative scenarios are described in **Textbox 4.4** and are similar to the main scenarios, but assuming that the marginal supplier is situated in China, CIS (Russia), or the Middle East. These scenarios are mentioned last here; because they are the only scenarios that only represent one region or country. Neither of these is chosen as the main scenario, because all three regions appear to be highly competitive. We have therefore chosen to believe more in a composite marginal reflected by the recommended scenario.

Overview, names and results: To provide an overview, we have listed all scenarios in **Table 4.5**. In terms of names and abbreviations, Sc refers to Scenario. The number (1, 0 or 2) refers to the purpose of study (see section 3.1), where 1 is the scenario in which the aluminium smelter is built in Greenland, and 0) corresponds to the 0 alternatives that represent what will happen if the new smelter in Greenland is not approved. The 0 alternatives are, in other words, different estimates of the marginal production of aluminium. Furthermore, Alcoa's existing aluminium smelters in Quebec and in Iceland are included for reasons of comparison, as scenarios 2a and 2b.

Included scenarios for different regions of aluminium smelters	
Scenario 1: Aluminium smelter in Greenland	
Sc 1: Aluminium smelter in Greenland	Represents the proposed project
Scenario 0 (recommended): The most likely location of the marginal supply of aluminium (recommended scenario)	
Sc 0: Marginal supply of aluminium (average; China, CIS and the Middle East). See **Textbox 4.2**.	China (60%), CIS (22%), and the Middle East (18%). CIS is mainly Russia.
Scenario 0 (alternatives): Alternative locations of marginal aluminium supply of aluminium smelters (alternative scenarios)	
Sc 0e: As above but with reduced share from China. See **Textbox 4.3**.	China (40%), CIS/Russia (33%), the Middle East (27%)
Sc 0f: Marginal supply of aluminium (World average incl. China; IAI). See **Textbox 4.1**.	China (70%), Asia (12%), Eastern/Central Europe (6%), Western Europe (5%), Africa (5%), Latin America (3%), Oceania (2%), and North America (-3%)
Sc 0g: Marginal supply of aluminium (World average; Rio Tinto Alcan). See **Textbox 4.5**.	China (60%), Asia/Abu Dhabi, Kazakhstan, Qatar and Oman (16%), Eastern and Central Europe/Russia (14%), Africa/Egypt (6%), North America/Canada (2%), and Western Europe /Iceland (2 %).
Sc 0h: Marginal supply of aluminium (USGS). See **Textbox 4.6**.	The Middle East (47%), Russia (19%), China (13%), Africa (10%), Western Europe (8%), and Latin America 3%.
Sc 0i: Marginal supply of aluminium (China). See **Textbox 4.4**.	China (100%)
Sc 0k: Marginal supply of aluminium (CIS/Russia). **Textbox 4.4**.	CIS/Russia (100%)
Sc 0m: Marginal supply of aluminium (the Middle East). See **Textbox 4.4**.	The Middle East (100%)
Scenario 2: Scenarios included for reasons of comparison	
Sc 2a: Aluminium production in Alcoa smelter in Quebec	
Sc 2b: Aluminium production in Alcoa smelter in Iceland	

Table 4.5: Included scenarios for different locations of aluminium production (smelter stage). Sc 0 is the recommended scenario.

5 Identification of marginal electricity sources for aluminium smelters

The purpose of this section is to identify the marginal electricity sources for aluminium smelters in different regions of the world. Combined with the information about the expected location of the aluminium production (Section 4), this will create the basis for scenario building at the end of the section.

It should be noted that other studies suggest including the historical average electricity mix as representative for the marginal electricity supply to aluminium smelters (Weidema 2003, p 69-70). This approach is not followed in the present study, however. This is based on the fact that Weidema (2003) concerns the marginal supply of aluminium without considering the marginal location of the smelter and the related local circumstances which may influence the electricity mix. In the present study, the marginal location of aluminium smelters is considered, and hence, it is possible to differentiate the electricity mix between regions, dependent on the location of the smelter.

The present section is structured in a way that reflects the scenarios in terms of the location of the marginal aluminium production established in the last section (Section 4.4). Hence, the first sub-section concerns the marginal electricity related to the recommend scenario (Sc0).

5.1 Approach to identifying marginal electricity mix

It is not an easy task to estimate the marginal electricity mix and one of the challenges has also been to decide whether we should include all energy sources.

Energy sources included: It is assumed that only coal, gas, hydropower, and nuclear are flexible technologies, which can form part of the marginal electricity supply. Oil is not included. This is not due to a lack of flexibility, but because it is assumed that oil is too expensive to form part of the electricity mix for aluminium smelters which consume very large amounts of energy. In some regions, a small percentage of oil is included in the electricity mix, e.g., in the Middle East, but this is disregarded in the modelling. For aluminium smelters, we have not come across any references that mention renewable energy such as wind or biomass as a part of the energy mix, and this has therefore not been included either.

Grid electricity: When establishing the marginal electricity sources, it is generally important to distinguish between self-generated electricity and electricity purchased from the grid, because the marginal electricity supplied by the electricity grid is seldom based on the average electricity mix of the grid, which is often being reported by companies, electricity providers, etc. As an example, it is not reasonable to include electricity from the incineration of household waste (biomass), because the available amount is related to the amount of household waste generated and not small changes in the demand of electricity (Weidema 2003). In the present analysis, it has been possible to establish the percentage of electricity purchased from the grid – but only for each region *or* per energy source. In order to be able to use the marginal electricity mix in the analysis, we need to know the amount of electricity for each region *and* energy source. We have therefore only used the analysis to obtain an indication of the amounts of purchased electricity and the uncertainties involved, which again has been used to develop alternative scenarios for, e.g., the amount of hydropower reported.

Other aspects: Apart from applying expert knowledge about marginal electricity sources to some scenarios, we have assumed that the marginal electricity supply can be represented by the estimated growth of the flexible technologies. The estimated growth has been established by an extrapolation of the development in the last decade, either worldwide or per region, depending on the scenario. The development in electricity consumption per energy source and region is based on data from IAI, and the latter is based on self-reporting from the aluminium smelters. This means that we, in our estimates, indirectly assume that the reported electricity mix from the grid to each smelter reflects the actually affected electricity sources. This might be true in the cases in which contracts are made with the electricity providers. But, there may be cases in which smelters simply report the average electricity mix from the grid, as suggested by the electricity provider. Hence, uncertainties are definitely involved. However, we have made scenarios that reflect the fact that hydropower might be constrained to some extent and that gas is alternatively flared in many cases, see section 5.2.

5.2 Electricity mix for the recommended scenario (Sc0)

The following two sections (5.1 and 5.2) include a number of scenarios of the marginal electricity mix. But before describing the scenarios, we wish to mention some of the basic assumptions of the analysis.

Historical development in electricity mix for IAI regions

The development of the electricity sources for existing aluminium smelters in six different regions of the world is illustrated in **Figure 5.1**. It should be noted that the data only covers the same companies as represented by **Figure 4.1**, and therefore, e.g., excludes the production in China.

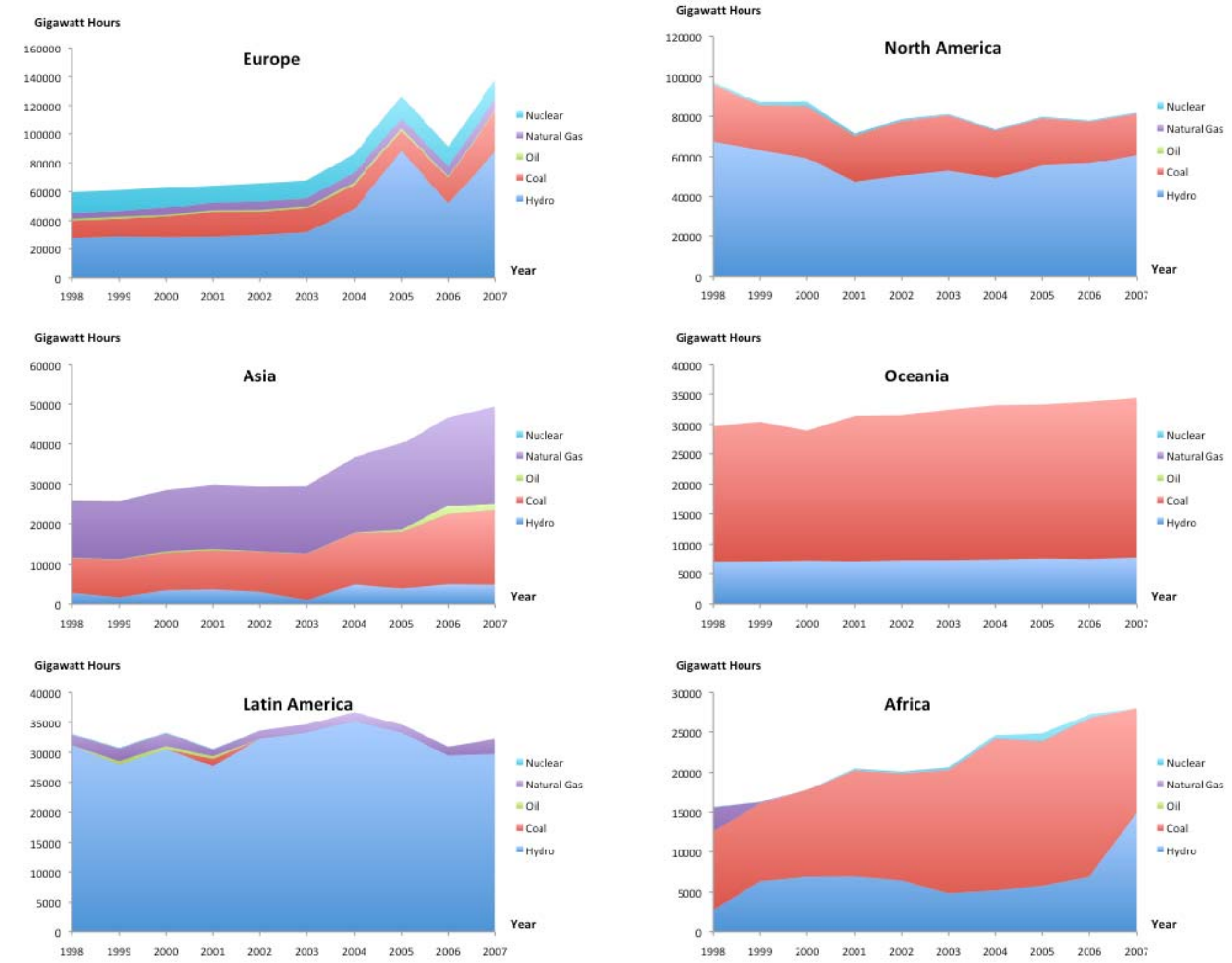

Figure 5.1: Development of electricity sources for aluminium smelters in different regions of the world. The specific countries represented by the regions are specified in **Table 4.1** (IAI 2009b).

The data in **Figure 5.1** represents the electrical power used in primary aluminium production and includes power used for electrolysis in the Hall-Heroult processes (including conversion from AC to DC) and pollution control equipment up to the point at which the liquid aluminium is tapped from the pots. It excludes power used in casting and carbon plants (IAI 2009b).

The development of the electricity mix shows that most of the electricity consumption has been related to the production in Europe (Eastern / Central Europe), North America, and Asia, in that order. But, if China had been included, China would most likely be the largest consumer of electricity. The countries with the relatively largest share of hydropower are Latin America, North America, and Europe, in that order. Coal, on the other hand, dominates in regions such as Oceania, Africa, and Asia, in that order. Natural gas also plays an important role in Asia (which includes the Middle East).

Another observation is that the electricity mix in most of the regions seems to be relatively stable over time. However, a region that shows a significant change in the electricity mix is Europe - in the period after 2004 in which hydropower increases abruptly. But according to Chris Bayliss from IAI (Bayliss 2009), the reason for the increase in hydropower is the fact that existing aluminium plants in Russia started reporting their electricity mix during this period, see also **Table 4.1** (Bayliss 2009). A similar situation may have caused the increase in hydropower in Africa after 2006.

The electricity mix for aluminium production in the different regions as well as the world average is dominated by hydropower, coal, and natural gas, in that order, see **Table 5.1**.

Electricity source	Reported Electrical Power Used (Giga watt Hours)							
	Africa	North America	Latin America	Asia	Europe	Oceania	Total	Total (%)
Hydro	14,982	60,986	29,727	4,85	87,914	7,828	**206,287**	**56.6%**
Coal	13,079	20,274	0	18,676	28,116	26,587	**106,732**	**29.3%**
Oil	0	7	0	1,705	807	2	**2,521**	**0.7%**
Natural Gas	6	281	2,457	24,215	7,552	0	**34,511**	**9.5%**
Nuclear	0	461	0	0	13,638	0	**14,099**	**3.9%**
Total	**28,067**	**82,009**	**32,184**	**49,446**	**138,027**	**34,417**	**364,150**	**100%**

Table 5.1: Electricity mix for different regions (excluding China) in year 2007 as well as the world average according the IAI (2009b).

Apart from the data provided in **Table 5.1**, it is also relevant to know the share of self-generated electricity and the amount purchased from the grid. For self-generated electricity, we can be relatively sure that the specific energy source is the one affected by potential changes in the aluminium production. But for electricity purchased from the grid, it is more uncertain whether the reported energy sources are actually the ones affected by marginal changes in production. In this regard, IAI statistics actually provide information about the percentage of electricity purchased from the grid versus self-generated electricity for different regions, see **Table 5.2**.

Electricity source	Reported Electrical Power Used (per cent)					
	Africa	North America	Latin America	Asia	Europe	Oceania
Self-generated	0.0	30.8	31.2	96.5	7.5	3.4
Purchased - Grid	100.0	64.7	67.3	0.1	90.2	96.6
Purchased - Other	0.0	4.5	1.4	3.4	2.2	0.0
Total	**100**	**100**	**100**	**100**	**100**	**100**

Table 5.2: Self-generated electricity and electricity purchased from the grid and other sources for different regions in year 2007 (IAI 2009b)

From **Table 5.2**, it appears that most of the electricity is reported as being purchased from the grid, especially in Oceania, Africa, and Europe. In Asia, however, 96.5% of the power is self-generated. The amounts of purchased and self-generated electricity for different energy sources are shown in **Table 5.3**.

Electricity source	Reported Energy Source (per cent)				
	Coal	Oil	Natural Gas	Nuclear	Hydro
Self-Generated	24.5	68.3	77.5	0.0	20.3
Purchased	75.5	31.7	22.5	100.0	79.7
Total	**100**	**100**	**100**	**100**	**100**

Table 5.3: Self-generated and purchased electricity for different energy sources in 2007 (IAI 2009b)

As **Table 5.3** does not contain information on different regions, the table can only provide a very rough average estimate on how self-generated electricity is produced. The information on the fuel source of electricity purchased from the grid cannot directly be used, since this represents market averages not taking into account considerations on marginal electricity supplied from the grid.

Existing electricity mix in China

China is not represented by any of the graphs in **Figure 5.1** and historical data has not been available. Information from IAI suggests, however, that aluminium production in China is mainly based on coal and, to some extent, hydropower. A rough estimate suggests a coal share of 80-90% and a hydropower share of 10-20% hydropower, or more specifically 85% coal and 15% hydropower (Bayliss 2009). According to the Wold Energy Outlook, the average electricity mix for China in 2006 was based on 80% coal, 15% hydropower, and 5% oil, nuclear and gas (IEA 2008). This is not far from the IAI estimate, which has a somewhat smaller percentage of coal-based electricity as well as a small percentage of oil, nuclear and gas. The IEA data, however, represents average grid electricity, while the IAI data addresses aluminium production in particular. We therefore assume that the most likely electricity mix for aluminium smelters in China is coal/hydropower (85/15).

Estimation of (future) marginal electricity mix

The prediction of the future marginal electricity mix is subject to uncertainties. Ideally, a distinction should be made between self-generated and purchased electricity from the grid and then different marginal mixes should be identified for the two. However, the data available on self-generated versus purchased electricity presented in **Table 5.2** and **Table 5.3** applies to very aggregate regions; they do not include China and do not include considerations of differences between energy sources per region. Therefore, we argue that we do not have sufficient information to distinguish between self-generated and purchased electricity for aluminium smelters.

Instead, the marginal sources of electricity (the marginal electricity mix) are identified based on a combination of extrapolations of the electricity mix for the aluminium industry (IAI 2009b), outlooks for the electricity mix from the grid (IEA 2008), and expert judgements (Bayliss 2009).

Extrapolation of IAI data: The future marginal electricity mix, on a regional basis, can be estimated based on an extrapolation of the historical development of the electricity mix for each region (see **Figure 5.1**). This is similar to the method of establishing the marginal location of aluminium production described in section 4.3. If a future increase in the electricity consumption (according to the extrapolation) would imply an increase in gas-based electricity of 25% and coal-based electricity of 40%, the marginal electricity mix would, according to this approach, consist of 25/(25+40)% gas and 40/(25+40)% coal. This corresponds to a marginal mix of 38% gas and 62% coal.

According to this approach, the regional electricity mix of the regions relevant for the recommended scenario is as illustrated in **Table 5.4**.

	Electricity mix for aluminium production (smelter stage)				
Region	**Coal**	**Natural Gas**	**Nuclear**	**Hydro**	**Total**
Asia (representing the Middle East)	44%	45%	0%	11%	100%
Europe (representing CIA/Russia)	14%	5%	0%	81%	100%
China	85%	0%	0%	15%	100%

Table 5.4: Marginal electricity mix for Asia and Europe based on an extrapolation of IAI data (IAI 2009b) and separate data from China (Bayliss 2009).

China is not included in the IAI statistics of electricity consumption and, in this case, it is therefore not possible use this approach. But according to the IEA (2008) projections (see Appendix 4: World Energy Outlook; Marginal electricity), the marginal supply of average grid electricity from China consists of 82% coal, 11% hydropower, 5% nuclear, and 2% gas. This marginal supply mix is very close to the current supply mix, according to IEA. This implies that the electricity mix is relatively stable, which is a good argument for using the existing electricity mix for aluminium smelters, which was earlier estimated to be based on 85% coal and 15% hydropower (Bayliss 2009). Based on this approach, the future marginal electricity supply for Chinese aluminium smelters is assumed to consist of 85% coal and 15% hydropower. The estimate of Bayliss is regarded as a better estimate than that of IEA. This is due to the fact that Bayliss represents an expert estimate specific to the aluminium industry, while IEA represents a general energy outlook for the region.

The main weakness of this approach is the fact that the aggregation level of the IAI regions does not match the categories of suggested marginal regions perfectly. In other words, CIS/Russia is not necessarily well represented by Europe, and the Middle East is not necessarily well represented by Asia. It is difficult to say, however, in which direction the analysis would change, if the IAI categories had been more disaggregated. Also, it should be stressed that the suggested electricity mix for CIS (Russia) and the Middle East is relatively close to the suggested electricity mix for the planned aluminium smelters in the regions, as suggested by Bayliss (2009) in relation to the scenario based on Rio Tinto Alcan (Sc 0g).

Marginal electricity mix for the recommended scenario: As suggested in section 4.5, the marginal suppliers of aluminium will be located in a combination of China (60%), CIA/Russia (22%), and the Middle East (18%). Combined with the information about the marginal electricity mix for each region presented in **Table 5.4**, it can be established that the composite marginal electricity mix of the recommended scenario consists of 62% coal, 29% hydropower, and 9% gas, when oil is excluded.

5.3 Estimated electricity mix of ‘alternative’ scenarios

The marginal electricity mix of the alternative scenarios is established in this section, beginning with a version of the recommended scenarios in which China’s share of the aluminium production is reduced from 60% to 40%. A complete list of all scenarios is available in section 5.4.

Marginal electricity – reduced China share (Sc0e)

In the scenario with a reduced China share, the marginal suppliers of aluminium will be located in China (40%), CIA/Russia (33%), and the Middle East (27%), see **Table 4.4**. Combined with the information about the marginal electricity mix for each region presented in **Table 5.4**, it can be established that the composite marginal electricity mix of the recommended scenario consists of 50% coal, 36% hydropower, and 14% gas, when oil is excluded.

Marginal electricity – world average (Sc 0f)

The development of the world’s electricity mix (excluding China) for aluminium smelters in the period 1998-2007, according to IAI, is illustrated in **Figure 5.2**.

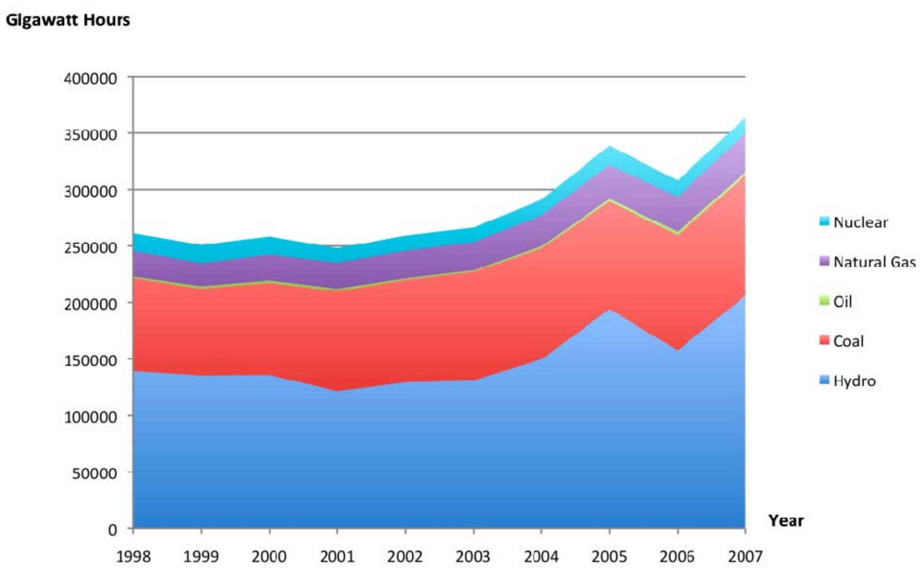

Figure 5.2: Development of the world’s electricity mix (except China) for aluminium smelters in the period 1998-2007 according to IAI.

As it appears, the electricity mix has been relatively stable over the last decade. Still, however, hydropower has experienced a larger increase than other energy sources from 2004 to 2007. As explained earlier, Russian smelters based on hydropower probably cause this increase, as Russia started to report its electricity mix during this period; and it is therefore a result of better statistics rather than a change in the electricity mix. In 2007, the electricity mix was based on nearly 60% hydropower, 30% coal and 10% gas. It should be stressed that this does not include China.

The simplest approach to identifying the marginal electricity mix for aluminium smelters (world average) is to extrapolate the historical development and identify the relative increase from each energy source, just as we did at the regional level in section 5.2. **Figure 5.3** shows the energy mix for aluminium smelters, extrapolated (based on linear regression) to year 2015 on the basis of the historical development from 1998 to 2007.

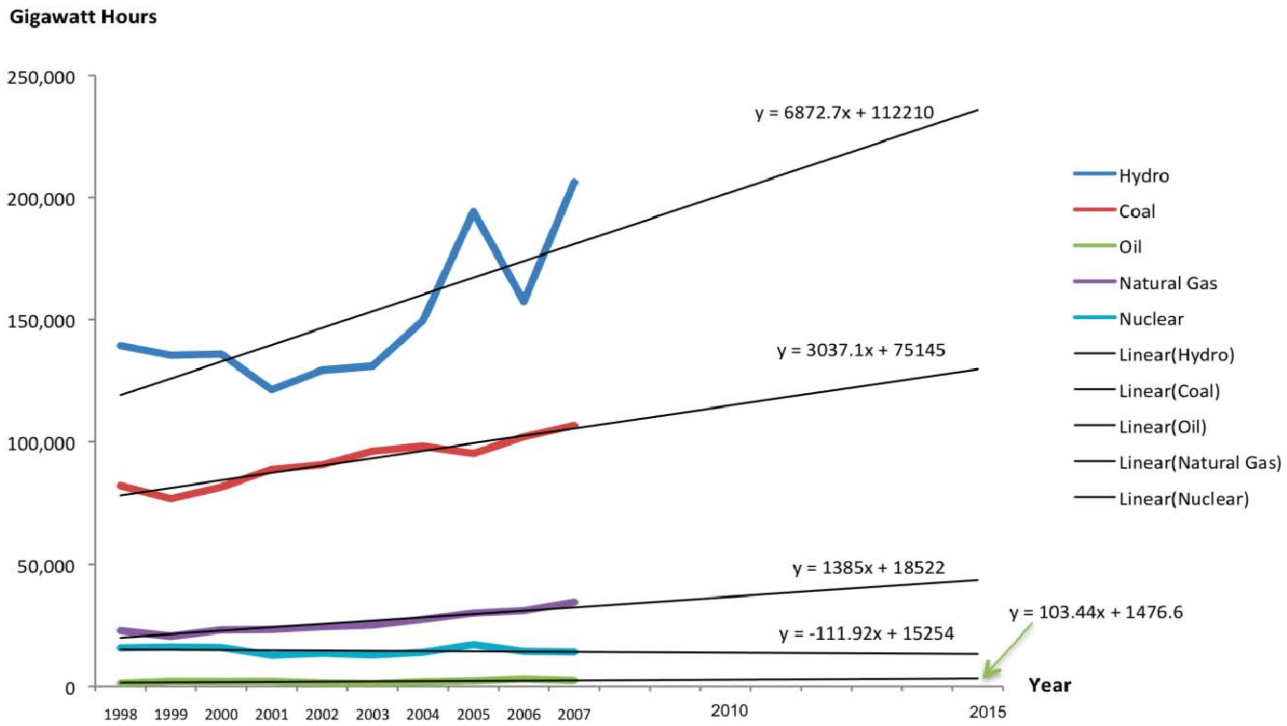

Figure 5.3: Development of the electricity mix for aluminium smelters (world average) from 1998 to 2007 and an extrapolation of data to year 2020, based on data from IAI (2009b)

As the trend line for nuclear energy is negative, we have disregarded nuclear energy. Based on the extrapolation, it appears that only hydro, coal and gas will increase significantly in the future. The trend line equations tell us that hydropower will make up 61% of the yearly increase, while coal and gas will make up 27% and 12%, respectively. Compared to the existing mix in 2008, this reflects a small increase in the gas and hydropower.

China is not included in the IAI model, but it has previously been argued that we can expect a marginal electricity mix for smelters in China of 85% coal and 15% hydropower. In section 4, it was established that China's share was 70% of the production, but this figure is based on an extrapolation from a period in which China experienced a larger growth than is expected in the future. We have therefore chosen to use the figure of a 60% share from China, which is also used in the recommended scenario. This means that the global marginal electricity mix for aluminium smelters would consist of 62% coal, 33% hydropower, and 5% gas, according to this scenario.

It should be noted that the simple projection presented here has significant limitations. In this regard, it is also problematic that the increase in hydropower from year 2004 to a large extent is due to the statistics concerning Russian aluminium smelters, which have been producing for a long time but have just started reporting recently.

Marginal electricity – Rio Tinto Alcan (Sc 0g)

In section 4.3, a scenario based on information obtained from Rio Tinto Alcan (RTA) is presented with country specific information about expansion until year 2014.

Chris Bayliss at IAI (Bayliss 2009) has provided estimates of the marginal electricity used for the different projects listed in **Table 4.3**, suggesting hydropower and coal (80/20) for all projects in Russia, hydropower for the two projects in Canada and one in Egypt (Nag Hammadi). Coal is suggested as the marginal energy source for the two other projects in Egypt as well as the project in Kazakhstan, while gas is assumed to be the energy source in Oman, Qatar, and Abu Dhabi. Iceland's electricity production is based on geothermal energy. Besides, we have previously argued for an electricity mix for China of coal and hydropower (85/15). This type of information has only been available in relation to this scenario and is therefore only used here.

If we combine these estimates with knowledge about the expansions which have taken place in the different regions and assume that China will represent 60% of the total expansion, we reach the following results:

- 60% increase in China (coal and hydro – 85/15)
- 16% increase in the Middle East: Abu Dhabi, Kazakhstan, Qatar, and Oman (gas)
- 14% increase in Russia (hydro and coal – 80/20)
- 6% increase in Egypt (hydropower)
- 2% increase in Canada (hydropower)
- 2 % increase in Iceland (geothermal)

This gives a marginal electricity mix consisting of 54 % coal, 28 % hydro, 16% gas, and 2% geothermal, for this scenario. Geothermal makes up a very small percentage of the electricity mix. In our final scenario, we have therefore assumed that these 2% are hydropower instead of geothermal power. The difference in the environmental impact (CO2e) of geothermal energy and hydropower, respectively, is insignificant.

Marginal electricity mix – USGS (Sc 0h)

The last scenario is related to the assessment of the marginal aluminium production from USGS. For this scenario, no information has been available about the specific electricity mix of each country. We have therefore based the assessment on projections of the regional electricity mix provided by IAI for aluminium smelters, combined with an assumption about the electricity mix for China, consisting of 85% coal and 15% hydropower.

Based on this approach, the marginal electricity mix for each of the relevant regions is presented in **Table 5.5**.

Region	Electricity mix for aluminium production (smelter stage)				
	Coal	Natural Gas	Nuclear	Hydro	Total
Africa	59%	3%		38%	100%
North America	25%			75%	100%
Latin America	8%			92%	100%
Asia	44%	45%		11%	100%
Europe	14%	5%		81%	100%
China	85%			15%	100%

Table 5.5: Marginal electricity mix for each region based on an extrapolation of IAI data (IAI 2009b) and separate data for China (Bayliss 2009).

The suggested aluminium production share of each region was established in section 4.3 (see **Textbox 4.6**), and the average marginal electricity mix, according to this scenario, is based on 41% coal, 36% hydro and 23% gas. It can be noted that the proportion of coal-based electricity is significantly smaller than in the other scenarios, which is due to the low expected growth in China. As indicated earlier, we are sceptical about this assumption.

Marginal electricity - China, CIS (Russia), and Middle East separately (Sc 0i, Sc 0k, and Sc 0n)

The recommended scenario is based on a weighted average of the marginal electricity mix of China, CIS/Russia, and the Middle East. But we have also included three scenarios that represent a marginal which consists of China, CIS/Russia, or the Middle East. This is partly because all regions are perceived as highly competitive and are therefore potential candidates to being most competitive. However, the three alternative scenarios have also been included with the aim to analyse their individual importance to the results (in terms of carbon footprint).

- For China (Sc 0i), we have previously argued that the electricity mix is 85% coal and 15% hydropower.
- For CIS/Russia (Sc 0k), the marginal electricity mix can be represented by Europe, which has a marginal electricity mix of 81% hydro, 14% coal, and 5% gas – see **Table 5.5**
- For the Middle East (Sc 0m), the marginal electricity mix can be approximated by Asia, which proposes an electricity mix of 45% gas, 44% coal, and 11% hydropower – see **Table 5.5**

The previous scenarios have been defined without further considerations about production restrictions in the electricity grid/system and alternative uses of energy resources. Both factors are relevant to discuss, especially in relation to hydropower and gas. The following section therefore addresses special issues related to hydropower and gas.

Marginal electricity – Quebec and Iceland (Sc2a and Sc2b)

In addition to the scenarios that represent alternatives 1 and 0, results for the production of aluminium in Alcoa's smelter in Quebec (Deschambault) and in Iceland are also included.

The energy source of the Deschambault smelter is the Hydro-Quebec electricity grid (Alcoa 2009a). According to Hydro-Quebec, the electricity mix in Quebec in 2007 was composed of 92% hydro, 3% nuclear, 2% gas, 1% coal, and ~2% other sources. New power sources planned to increase the production pool will be based on hydro and wind power (Hydro-Quebec 2009a and 2009b). Since hydropower and wind power are associated with approximately the same amount of GHG emissions, the marginal electricity in Quebec is assumed to be represented by 100% hydro. It should be noted that the results for the aluminium smelter in Quebec are not used in the interpretation and conclusions of this report. Therefore, though the analysis of marginal electricity in Quebec presented above is very rough and simplistic and is subject to uncertainties, this will not affect the results of the current study.

The marginal supply of electricity used in Alcoa's Iceland smelter is based 100% on hydropower. The establishment of a new hydropower plant in Iceland is directly related to the establishment of the aluminium smelter. Moreover, the hydropower plant would not have been built if the aluminium smelter was not established (Alcoa 2009b).

Special issues related to hydropower and gas

The following section addresses production restrictions for hydropower and alternative uses of gas, which are both relevant in relation to the discussion of marginal electricity production for aluminium smelters. Apart from providing knowledge about these aspects, the purpose is to provide the basis for a number of extra scenarios that reflect the uncertainties in this regard.

Hydropower: Some smelters purchase a large proportion of the electricity from the grid. According to IAI (2009b), the share of purchased electricity is especially high in the region Eastern and Central Europe[10]. In some cases, the companies that report to IAI about their electricity consumption may base their assessment of the electricity mix (for the purchased electricity) on country averages for electricity mix. In other cases, it is possible that special contracts exist which they use to calculate the electricity mix. It is somewhat uncertain how this works and uncertain whether the reported electricity mix is a good proxy for the marginal electricity mix.

As mentioned, it also is likely that the hydropower electricity purchased from the grid would have been used by other industries or consumers, if the aluminium smelters had not purchased it. This could even be the case in situations in which the hydropower is self-generated due to the growth of cities in surrounding areas. In this regard, Greenland Development writes the following in their introduction to the aluminium project in Greenland:

> *"The good contracts on energy supply the aluminium industry has secured around the globe are coming under increasing pressure from higher energy consumption and rising energy prices. As the 20-60-year contracts begin to expire, they are becoming increasingly difficult to extend, as there are plenty of others on the market willing to buy energy at a higher price. Private consumers, in particular, are using more and more power"* (Greenland Development 2009b)

Based on the considerations presented above, there are indications that the amount of hydropower reported does not represent the marginal supply in all cases. In some cases, the real marginal (or affected energy sources) could be coal or gas, especially if seen in a longer time perspective. In this regard, it should also be remembered that Russian smelters started reporting in 2004 and that this have caused the rather abrupt increase in hydropower after 2004. Therefore, the amount of hydropower in the marginal supply of electricity to aluminium smelters identified in the following may be overestimated in some cases.

It is difficult (or impossible) to predict the size of the overestimation. Therefore, it has been chosen to supplement the recommended scenario (Sc0) with an alternative scenario in which the amount of hydropower is reduced by 50%. The same is done for the scenarios that only include CIS/Russia (Sc0k). The two additional scenarios are called Sc0a and Sc0l.

For China specifically, it must also be assumed that there is great competition of hydropower resources in the system. On the other hand, the country has plenty of coal reserves. We have therefore developed an alternative scenario for China (Sc0i) in which 100% of the electricity is coal-based. The latter is called Sc0j.

Gas: Gas, which would alternatively be flared or sold as LPG, is often used for smelters in the Middle East (Nordheim 2009). According the Global Gas Faring Reduction Partnership (GGFR 2009), at least 150 billion cubic meters of gas are flared every year. This is roughly 5.7E6 TJ, which is significant considering the fact

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[10] In IAI (2009b) the region East and Central Europe includes Russia and Siberia where many smelters are located.

that the total electricity consumption for all aluminium smelters (according to **Table 5.1**) is around 365,000 GWh or 1.3E6 TJ. Hence, the amount of gas that is currently flared is more than enough to produce the electricity needed for all the smelters in **Table 5.1** (assuming an efficiency factor of 40% in the conversion from gas to electricity). The amount is probably also sufficient if we include all Chinese smelters and other smelters that are not reported to IAI. The top 10 flaring countries appear from **Table 5.6**:

Rank	Top 10 countries	2004 bcm	2005 bcm
1	Nigeria	24.1	25.5
2	Russia (total)	14.7	14.9
3	Iran	13.3	13.0
4	Iraq	8.6	7.2
5	Angola	6.8	6.4
6	Venezuela	5.4	5.4
7	Qatar	4.5	3.9
8	Algeria	4.3	3.5
9	USA	2.8	3.4
10	Kuwait	2.7	3
Total		**87.2**	**86.2**

Table 5.6: The 10 most important countries in the world regarding flaring of gas (GGFR 2009). bcm: billion cubic meters.

It appears from the table that Nigeria and Russia as well as Iran and Iraq flare large amounts of gas. In top 10, there has been a small decrease in emissions of 1 billion cubic meters (bcm) from 2004 to 2005, but in top 20 (not shown here) there has actually been an increase of 0.5 bcm from 2004 to 2005. GGFR is engaged in reducing the flaring; some progress has been made, but they also conclude the following:

> *"For the past 20 years, overall global flaring levels have remained virtually constant, despite many individual governments' and companies' successes in reducing flaring. These efforts have been limited not only because of the increase in global oil production and the associated gas production, but also because of the major constraints that hinder the development of gas markets, gas infrastructure, and flaring reduction projects"* (GGFR 2009)

According to Nordheim (2009), the production of aluminium in the gas flaring regions has traditionally been based on gas which would otherwise be flared; but now these regions increasingly focus on the utilisation of the flared gas for NGL transport to other regions (Nordheim 2009). This suggests that change is on the way, but the development in the last 20 years also shows that it may be a slow process. Hence, despite the efforts to reduce flaring and produce LPG instead, it seems reasonable to assume that a great deal of the gas would be flared (wasted). If this is not taken into account in the gas flaring regions (Middle East and Russia), it is likely that the environmental impacts associated with electricity based on gas are overestimated.

Therefore, when gas is a marginal source of electricity in the Middle East and Russia, it should be taken into account that the gas would alternatively be flared in many cases. This means that part of the energy obtained from gas is represented by the difference between burning the gas in a power plant and by flaring the gas. This is further described in section 7.2. It would definitely be wrong to assume that 0% or 100% of the gas would alternatively be flared. In the recommended scenario (Sc0) and in the scenarios of gas-based electricity in the Middle East (Sc0m) and CIS/Russia (Sc0k), it is therefore assumed that 50% of the gas would alternatively be flared.

Considering the large uncertainties, this is supplemented with scenarios in which it is assumed that 25% and 75% of the gas would alternatively be flared, i.e., Sc0 and Sc0m. Gas does not play a great role for the aluminium smelters in CIS/Russia and alternative scenarios are therefore not developed here.

5.4 Overview of scenarios in terms of electricity mix

A large number of scenarios have been developed and described in sections 4 and 5. **Figure 5.4** illustrates the scenarios for marginal location of smelters (the content of section 4), the marginal electricity mix (the content of section 5) and the smelter type (different levels of efficiency of smelters, which are discussed and modelled in section 10). The right column in the figure shows the abbreviations used for the scenario names.

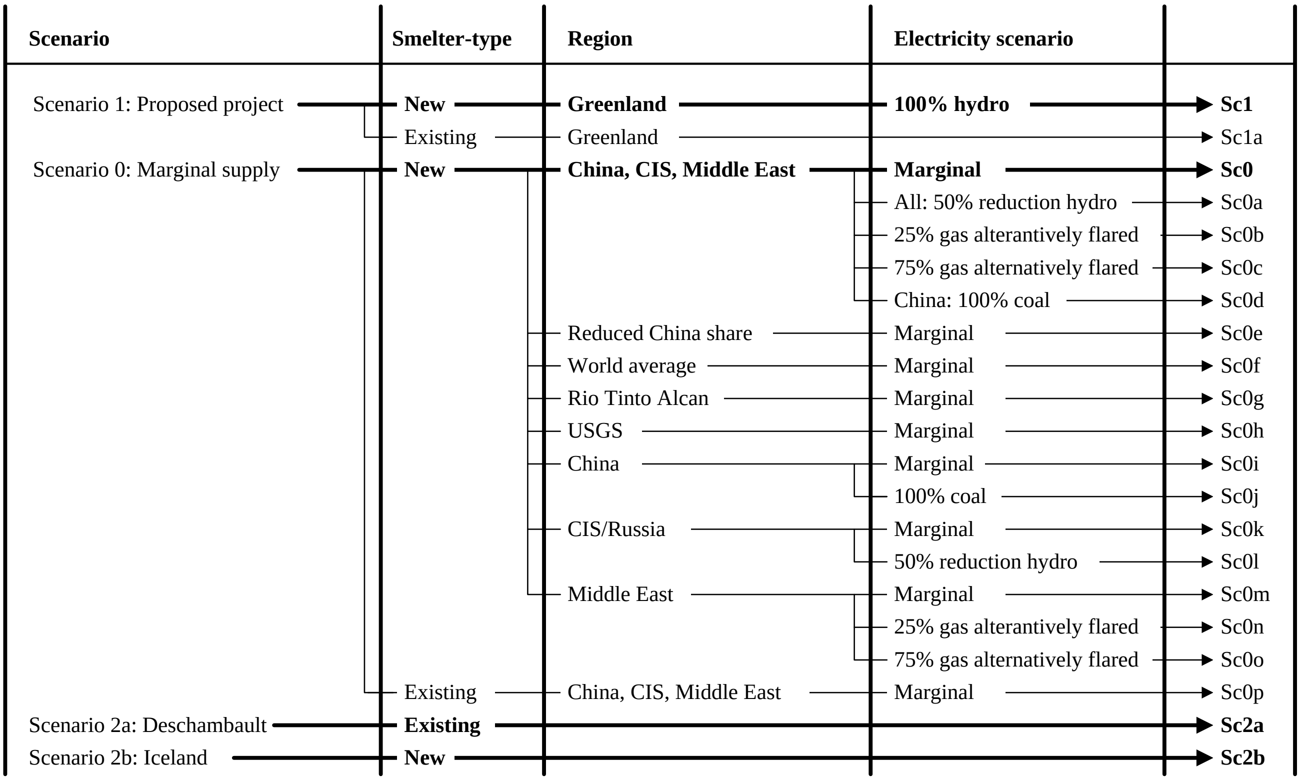

Figure 5.4: Overview of the scenarios for marginal location of smelters (Region), marginal electricity mix (electricity scenario) and scenario names.

The scenario names suggested in the left column in the figure refer to the purpose of study described in section 3.1. The entire exercise of sections 4 and 5 has been to establish the marginal electricity mix or the electricity mix for the marginal production of aluminium with a focus on the smelter stage. This is related to uncertainties, and therefore a large number of scenarios has been developed to analyse the effect of the uncertainties with respect to location and electricity sources on these locations. One scenario has been chosen as the most likely one (Sc0).

Results: The results of the previous section are summarised in **Table 5.7**, which gives an overview of the marginal electricity mix for all included scenarios. For gas, we have assumed that 50% is alternatively flared in the Middle East and CIS, and for the extra scenarios representing 25% and 75% flared gas, respectively, we have indicated this in a separate column for flared gas in the table.

Furthermore, the table shows which share of the electricity mix is related to different regions; e.g., the share of the 62% coal in the recommended scenarios which is related to smelters operating in China (Chi), CIS/Russia (CIS), and the Middle East (ME), respectively. It should be noted that these calculations are not shown. As shown in **Table 7.3** in section 7, we distinguish between energy technologies in 9 countries/regions, which do not match 100% the regions in the present section. In this regard, we have matched regions/countries mentioned in the present section with regions/countries in **Table 7.3** in the following way:

- Africa = Middle East (ME) in **Table 7.3** and **Table 5.7**
- Egypt = Middle East (ME) in **Table 7.3** and **Table 5.7**
- CIS = Russia in **Table 7.3** and **Table 5.7**
- IAI (average of IAI members) = World in **Table 7.3** and **Table 5.7**
- Latin America = Brazil (Br) in **Table 7.3** and **Table 5.7**
- Canada = United States & Canada (USC) in **Table 7.3** and **Table 5.7**
- Iceland (Ic)

Scenario	Coal	Gas	Gas (flare)	Hydro	CO2e/kWh
Sc 1: Aluminium smelter in Greenland	**-**	**-**	**-**	**100%**	**0.0104 kg**
Sc 0: Average; China, CIS (Russia), Middle East RECOMMENDED SCENARIO	**62%** Chi: 51% CIS: 3% ME: 8%	**4%** Chi: 0% CIS: 0% ME: 4%	**5%** Chi: 0% CIS: 1% ME: 4%	**29%** Chi: 9% CIS: 18% ME: 2%	**1.12 kg**
Sc 0a: 50% reduction of hydropower	**73%** Chi: 56% CIS: 9% ME: 8%	**6%** Chi: 0% CIS: 2% ME: 4%	**6%** Chi: 0% CIS: 2% ME: 4%	**15%** Chi: 5% CIS: 9% ME: 1%	1.39 kg
Sc 0b: 25% gas alternatively flared	**62%** Chi: 51% CIS: 3% ME: 8%	**7%** Chi: 0% CIS: 1% ME: 6%	**2%** Chi: 0% CIS: 0% ME: 2%	**29%** Chi: 9% CIS: 18% ME: 2%	1.15 kg
Sc 0c: 75% gas alternatively flared	**62%** Chi: 51% CIS: 3% ME: 8%	**2%** Chi: 0% CIS: 0% ME: 2%	**7%** Chi: 0% CIS: 1% ME: 6%	**29%** Chi: 9% CIS: 18% ME: 2%	1.10 kg
Sc 0d: 100% coal for China	**71%** Chi: 60% CIS: 3% ME: 8%	**4%** Chi: 0% CIS: 0% ME: 4%	**5%** Chi: 0% CIS: 1% ME: 4%	**20%** Chi: 0% CIS: 18% ME: 2%	1.27 kg
Sc 0e: As Sc0 but with share of China reduced from 60% to 40%	**50%** Chi: 34% CIS: 5% ME: 11%	**7%** Chi: 0% CIS: 1% ME: 6%	**7%** Chi: 0% CIS: 1% ME: 6%	**36%** Chi: 6% CIS: 27% ME: 3%	0.952 kg
Sc 0f: Marginal supply of aluminium (IAI + China world average)	**62%** Chi: 51% World: 11%	**2%** Chi: 0% World: 2%	**3%** Chi: 0% World 3%	**33%** Chi: 9% World: 24%	1.05 kg
Sc 0g: Marginal supply of aluminium (according to RTA)	**54%** Chi: 51% CIS: 3%	**8%** ME: 8%	**8%** ME: 8%	**30%** Chi: 9% CIS: 11% ME: 6% USC: 4%	1.05 kg
Sc 0h: Marginal supply of aluminium (according to USGS)	**41%** Chi: 11% CIS: 4% ME: 26%	**11%** ME: 11% CIS: 0%	**12%** ME: 11% CIS: 1%	**36%** Chi: 2% CIS: 22% ME: 9% Br: 3%	0.748 kg
Sc 0i: Marginal supply of aluminium – only China	Chi: 85%	-	-	Chi: 15%	1.48 kg
Sc 0j: 100% Coal – only China	Chi: 100%	-	-	-	1.74 kg
Sc 0k: Marginal supply of aluminium – only CIS/Russia	CIS: 14%	CIS: 2%	CIS: 3%	CIS: 81%	0.440 kg
Sc 0l: 50% reduction of hydropower	CIS: 43%	CIS: 8%	CIS: 9%	CIS: 40%	1.29 kg
Sc 0m: Marginal supply of aluminium – only the Middle East	ME: 44%	ME: 22%	ME: 23%	ME: 11%	0.771 kg
Sc 0n: 25% of gas alternatively flared	ME: 44%	ME: 34%	ME: 11%	ME: 11%	0.876 kg
Sc 0o: 75% of gas alternatively flared	ME: 44%	ME: 11%	ME: 34%	ME: 11%	0.674 kg
Sc 2a: Aluminium production at Alcoa smelter in Quebec	**-**	**-**	**-**	**USC: 100%**	0.0433 kg
Sc 2b: Aluminium production at Alcoa smelter in Iceland	**-**	**-**	**-**	**Ic: 100%**	0.0104kg

Table 5.7: Summary of applied marginal electricity mixes for the included scenarios. The GHG emissions are calculated based on the distributions between regions and technologies shown and the inventory data presented in section 7.2.

As it appears, most of the scenarios show quite similar results concerning the marginal electricity mix, with most electricity being based on coal followed by hydropower and gas, in that order. There are, however, scenarios that differ significantly. These include mainly the scenarios in which CIS/Russia is assumed to be the only marginal supplier, which results in a very large proportion of hydropower (81%), and the scenarios in which the Middle East is assumed to be the only marginal supplier, which results in the largest proportion of energy coming from gas (42%). The USGS scenario is also somewhat different, as it represents less coal and more hydropower and gas compared to the recommended scenario. But it is still mainly based on coal, followed by hydropower and gas, in that order, as in most of the other scenarios.

The uncertainties and sensitivity assumptions behind the different scenarios, concerning location, are discussed in section 4.5. For the electricity mix, uncertainties and sensitive assumptions are discussed in relation to the description of each scenario in the present section. Most of the scenarios are based on extrapolations of the development in the electricity mix experienced in each region. In the case of China and countries included in the RTA scenario, the marginal electricity mix is based on information from Bayliss (2009). For China, a verification of the assumptions has been made by use of data obtained from IEA.

The fact that the RTA scenario shows a relatively similar electricity mix as the recommended scenario, despite the fact that it is based on a very different method to define the region as well as the electricity mix, supports the validity of the recommend scenario.

6 Identification of marginal electricity from the grid

In the previous section, the marginal sources of electricity used in aluminium smelters have been identified. The marginal supply of electricity to aluminium smelters is not the same as the marginal supply of electricity to the grid. Since aluminium smelters use significant amounts of electricity they actively search for cheap and stable electricity sources. Thereby the decision to install new aluminium capacity is often accompanied by an installation of new electricity capacity, which would otherwise not have been installed. Electricity from the grid, which is described in this section, is used by all other electricity-consuming processes in this study, except from the electricity used by aluminium smelters.

The marginal supply of electricity is considered for the regions/countries shown in **Table 6.1**.

Country/region	Reason for considering the region/country
Australia	Considerable shares of the world's bauxite and alumina are produced in Australia, see sections 7 and 8
Brazil	Considerable shares of the world's bauxite and alumina are produced in Brazil, see sections 7 and 8
China	Considerable shares of the world's bauxite and alumina are produced in China, see sections 7 and 8
World	For processes where the location is not known and where electricity (in LCI database) is significant, this is replaced with the world's marginal electricity production

Table 6.1: Considered regions in which the marginal supply of electricity from the grid is identified.

In line with the approach to identifying marginal electricity for aluminium smelters, the identification of marginal sources of electricity supply to the grid is based on energy outlooks for expected types of new capacity. According to Weidema (2003), a marginal supply can be characterised as the most competitive technology among those that are flexible if the market trend is constant or increasing. Thus, the first step is to identify if some technologies are constrained (not flexible); i.e., the production volume is determined by other factors than the demand. It is argued that the production volume of the following energy sources to a large extent is determined by political decisions rather than the general demand for electricity:

- **Biomass;** may generally be constrained by political decisions on increases in renewable energy share, partly with the aim of accommodating climate reductions
- **Waste incineration/landfill gas recovery;** generally constrained by decisions on health and safety as well as decisions made to accommodate climate reductions
- **Wind power;** same as biomass
- **Geothermal energy;** this energy source is not available in many locations and it may also be constrained by political decisions on increases in the renewable energy share, partly with the aim of accommodating climate reductions
- **Solar;** same as biomass
- **Tidal and wave;** same as biomass

The above identification of constraints obviously involves uncertainties. But the facts that the constraints are real in some regions and partly relevant in most regions are considered as considerable assumptions. At least it is evident that the investment in renewable energy is often related to the aim of reducing climate change (IEA 2008, p 155). Assuming that the above-mentioned technologies are constrained, the following technologies can be regarded as flexible:

- Coal
- Oil
- Gas
- Nuclear
- Hydro

According to Weidema (2003), also referred to above, the marginal technology can be identified as the most competitive technology if the market trend is constant or increasing. According to IEA, the market trend is positive; the global electricity generation is projected to increase from 18,921 TWh in 2006 to 33,265 TWh in 2030, corresponding to an increase of 76% (IEA 2008, p 507). All countries/regions included in IEA (2008) are projected to face an increasing market trend on the electricity market during the next two decades.

In order to identify the most competitive technology, prices of electricity generation have been identified in IEA (2008), see **Figure 6.1** and **Figure 6.2**.

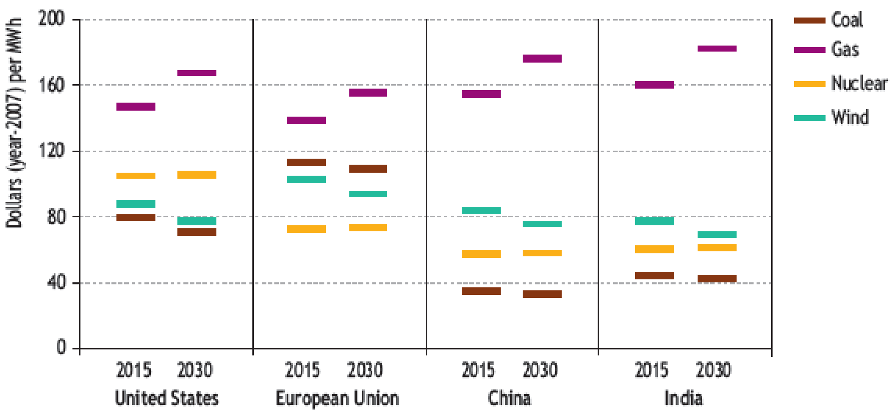

Figure 6.1: Electricity generation costs of different electricity sources in different regions. In the European Union, the costs include a carbon value of \$30/tonnes of CO_2. The figure is directly obtained from (IEA 2008, p 154).

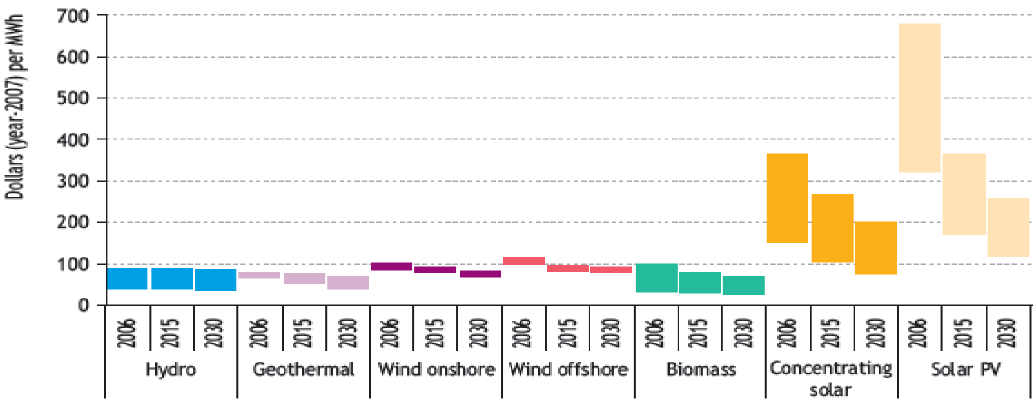

Figure 6.2: Electricity generation costs of renewable energy technologies. The figure is directly obtained from (IEA 2008, p 164).

Based on the prices provided in **Figure 6.1** and **Figure 6.2**, coal turns out to be the cheapest source of electricity in most regions. However, especially in the EU, due to CO_2 taxes, technologies related to low CO2-

emissions such as nuclear and wind power, turns out to be cheaper. It appears from **Figure 6.2** that the prices related to renewable energy sources are subject to significant uncertainties.

Based on the considerations presented above, coal (and in some cases nuclear) could be identified as the marginal source of electricity. However, as pointed out in Lund et al. (2008), new installed electricity capacity will be implemented in an existing energy system. Thus, if installing coal capacity, this may affect a range of different technologies due to temporal differences on the electricity market; e.g., wet/dry season, windy/calm weather, day/night, summer/winter. Also, different technologies may face changing contextual market conditions which may change the marginal source of electricity over time; e.g., changes in subsidies or some technologies may be constrained due to specific political decisions. Therefore, it is chosen, in this LCA study, to adopt a composite marginal reflecting the fact that the marginal source of electricity may be composed of different technologies and that the probability of each technology of being marginal is different; e.g., if it is projected that the probability that coal is the marginal source of electricity is 90%, then this would be included as 90% coal.

An alternative way of identifying the competitiveness of the different technologies, compared to the price inventory presented in **Figure 6.1** and **Figure 6.2**, is to use available information in energy outlooks from the International Energy Agency (IEA), and assume that the projected increase of the production volume of each technology represents the individual technology's share of the composite marginal. Or termed in another way; the projected increases of production volume of each technology represents the probability of the individual technology of being the marginal supply. When adopting this approach, only flexible technologies and only technologies that are projected to increase their production volume are included. Regarding the identification of projected increases in production volume, the time frame from 2006 to 2015 has been chosen. **Table 6.2** shows the outcome of applying this approach to the data for the reference scenario in the World Energy Outlook (IEA 2008). The data is further documented in Appendix 4: World Energy Outlook; Marginal electricity.

Country/region	Coal	Gas	Nuclear	Hydro	GHG emissions
Australia	40%	0%	54%	6%	0.429 kg CO2e/kWh
Brazil	23%	36%	8%	33%	0.598 kg CO2e/kWh
China	82%	2%	5%	11%	1.47 kg CO2e/kWh
World	63%	17%	6%	13%	0.880 kg CO2e/kWh

Table 6.2: Identified marginal supply of electricity using the energy outlook projections IEA (2008). The right column shows the GHG emissions associated with the different marginal supplies of electricity using the LCI data described in section 7.2.

It is chosen to apply the identified marginal in **Table 6.2**. An argument for using this approach is that it involves less pronounced uncertainties compared to the identification of only one marginal. If choosing only one marginal technology (out of several likely alternatives), the uncertainty is regarded as being more significant compared to the uncertainties related to adopting a mix of the likely alternatives as in **Table 6.2**.

7 Life cycle inventory: General processes

Throughout the life cycle of aluminium, some processes are used at several life cycle stages, such as, e.g., the use of and combustion of fuels, the use of electricity from the grid, and transport by truck and ship. This section describes the inventory data (i.e. the emissions associated with the production of aluminium and related products) for these general processes, also termed background data in some LCAs. Only the data sources for the emissions are presented here, and generally not the emissions themselves. This is because each process is related to several hundred emissions. The emissions can be seen in the LCA software SimaPro 7.1 (Pré 2008), the inventory database (ecoinvent 2007) and the information provided in this section.

Since the use of electricity is the single factor which contributes most to GHG emissions related to the production of aluminium (see section 2), the inventory data of electricity production is described and evaluated more in detail than the other inventory data presented in this section.

7.1 Production and combustion of fuels

Most processes have inputs of fuels. The production and combustion of fuels often involve significant emissions. This section presents the LCI data applied to the production and combustion of fuels. The LCI data presented in this section is used for industrial processes with fuel inputs. LCI data for transport and for electricity is presented separately in sections 7.2 and 7.3.

It is chosen to apply process-based LCI data to the production of fuels. This is because of the fact that no significant difference in emission levels has been identified due to the difference in data; IO data or process data, while the data varies significantly dependent on the country of production (ecoinvent 2007), (see **Table 7.1**).

If no information on the location of the fuel production is available, an average European supply (RER) is used. Only this data is presented in this section. In cases in which fuel inputs to processes, e.g., to the aluminium smelter, are significant and in which information on the location of the fuel production is available, then more site-specific data is used.

In **Table 7.1** below, the applied LCI data on the production of fuels is presented. For GHG emissions, the applied data is compared with IO data obtained from the USA IO database 98.

Refined oils	GHG emission, kg CO2e/kg	LCI data (and property data to have uniform units: kg)	Comment
IO data: Petroleum refining	0.374	'Petroleum refining', USA IO data 98 (Suh 2004) Price: 0.0975 US$98/kg (UN 2009)	-
Process data: Heavy fuel oil	0.448	'Heavy fuel oil, at regional storage/RER' (ecoinvent 2007)	ecoinvent data on crude oil varies from 0.027 to 0.770 kg CO2e/kg oil dependent on country
Process data: Light fuel oil	0.505	'Light fuel oil, at regional storage/RER' (ecoinvent 2007)	
Process data: Diesel	0.508	'Diesel, at regional storage/RER'	
Natural gas			
IO data: Natural gas	0.155	'Natural gas distribution', USA IO data 98 (Suh 2004) Density: 0.802 kg/Nm^3 (Andersen 1981, p 218) Price: 0.0740 US$98/kg (UN 2009)	-
Process data: Natural gas	0.542	'Natural gas, high pressure, at consumer/RER' (ecoinvent 2007) Calorific value: 48.6 MJ/kg (Appendix 1: Data on fuels and flue gasses)	ecoinvent data varies from 0.055 to 0.967 kg CO2e/kg gas dependent on country
Coal			
IO data: Coal	0.214	Coal, USA IO data 98 (Suh 2004) Price: 0.0424 US$98/kg (UN 2009)	-
Process data: Coal	0.286	Hard coal mix, at regional storage/UCTE (ecoinvent 2007)	ecoinvent data varies from 0.163 to 0.937 kg CO2e/kg coal dependent on country

Table 7.1: Comparison of IO-based and process-based LCI data on the production of fuels; refined oils, natural gas and coal. The applied default LCI data is marked by a dotted line.

The data presented above only concerns the production of the fuels – not the combustion. In **Table 7.2** below, the applied emissions data for the combustion of the fuels in **Table 7.1** is shown. The related GHG emissions are also shown.

Fuel	Calorific value, MJ/kg fuel	GHG emission, kg CO2e/kg fuel	GHG emission, kg CO2e/MJ fuel	LCI data for combustion (ecoinvent 2007)
Heavy fuel oil	41.2	3.23	0.0785	'Heavy fuel oil, burned in industrial furnace 1MW, non-modulating/RER'
Light fuel oil	42.7	3.17	0.0742	'Light fuel oil, burned in industrial furnace 1MW, non-modulating/RER'
Diesel	42.7	3.17	0.0743	'Diesel, burned in building machine/GLO'
Natural gas	45.9	2.57	0.0561	'Natural gas, burned in industrial furnace >100kW/RER'
Hard coal	24.0	2.21	0.0922	'Hard coal, burned in industrial furnace 1-10MW/RER'

Table 7.2: Applied inventory data on combustion of different fuels (left column). The related GHG emissions are shown per 1 kg and 1 MJ of the different fuels. The calorific values are from Appendix 1: Data on fuels and flue gasses.

To obtain the complete LCI data for the production and burning of fuels, the data in **Table 7.1** and **Table 7.2** must be combined.

7.2 Production and transmission of electricity

Electricity production is the single factor which contributes most to GHG emissions related to the production of primary aluminium (see literature review in section 1). Therefore, the applied data on electricity is important to the results of the LCA. This section provides information on the applied LCI data on the production of electricity for different technologies. The identification of the marginal technology of electricity used in aluminium smelters as well as supplied from the grid is described in sections 5 and 6. Electricity can be produced using many different technologies, i.e., energy sources; nuclear power, hydropower, wind power, solar power, and combustion of coal, lignite, natural gas, fuel oil, waste, fire wood and other bio fuels, as well as other minor sources of energy.

Overview of the considered technologies and approach to creating hybrid processes

Theoretically, electricity supplying plants in any country in the world may be affected by the aluminium production in the considered locations specified in **Table 4.5** in **section** 4.4. Obviously, electricity used by aluminium smelters will directly only affect the regions in which the smelters are located. But for all upstream processes in the product system, any location in the world may be affected. As indicated in sections 5 and 6, a distinction is made between marginal electricity used by aluminium smelters and all other electricity-consuming processes which use electricity from the grid. **Table 7.3** provides an overview of the countries/regions and technologies considered in this study. The included regions/countries as well as the technologies presented in **Table 7.3** are identified as all the regions/countries and technologies included and mentioned in sections 5 and 6.

	Considered technologies				
Country/region	**Coal**	**Gas**	**Gas, alternatively flared**	**Hydro**	**Nuclear**
Greenland				x	
Iceland				x	
USA/Canada				x	
Russia	x	x	x	x	
Australia	x	x		x	x
Middle East	x	x	x	x	
Brazil	x	x		x	x
China	x	x		x	x
World	x	x		x	x

Table 7.3: Considered supplies of electricity in this study.

The approach to constructing LCI data on electricity involves the creation of hybrid processes. **Table 7.4** below shows the inputs to the electricity processes based on IO data and process data, respectively.

Exchanges	US IO data 98 (Suh 2004)	Process data (ecoinvent 2007))	Other data (IEA 2008)
Fuels		x	
Fuel efficiency		x	x
Chemicals for flue gas treatment		x	
Cooling water		x	
Power distribution		x	
Transport of raw materials		x	
Capital goods (power plant)		x	
Services	x		
Other non-service inputs	x		
Emissions		x	

Table 7.4: Composition of hybrid processes on electricity production and transmission.

It appears from **Table 7.4** that the IO-based and the process-based inputs to the electricity processes differ slightly from the bauxite, alumina and smelter processes; i.e., in these processes capital goods were based on IO data. The reason for this difference is that capital goods (the power plant) significantly vary from one technology to another, e.g., hydropower compared with nuclear or natural gas. Therefore, more accurate data than average US power plants are needed. It is obvious that the IO data on services and other non-service inputs to the average electricity sector in USA in 1998 does not represent high quality data for the considered electricity technologies presented in **Table 7.3**. However, it is argued that it is better to have some data than no data, and it should also be kept in mind that these inputs only relate to 0.30% of the GHG emissions from the created hybrid processes of coal-based electricity in China, see **Figure 7.2**. However, for less CO_2 intensive technologies, such as hydro, the IO-based data accounts for up to 50% of the GHG emissions.

IO-based LCI data on electricity generation and distribution

The US IO data for electricity is related to the process ‘Electric services (utilities)’ (Suh 2004). According to EIA (2009), the price of electricity in the USA in 1998 was 6.74 cents/kWh. With the price information in mind, the monetary units of electricity in the US IO table can be converted into physical units (kWh).

Electric services (utilities): Preparation of US IO data for hybridisation		
Product output	**Amount (US$98)**	**Description of modification**
Electric services (utilities)	1.000	Internal flow (own energy consumption) is eliminated. The supply of the process (1 US$98) is reduced accordingly (1 - 0 = 1 US$98).
Product inputs before deletion of inputs	**Amount (US$98)**	
184 different product inputs	0.5255	
Deleted product inputs	**Amount (US$98)**	**Description of deleted input**
Fuels and energy		
Coal	0.06609	To be replaced with process data on fuels (included in ecoinvent data on electricity and burning of fuels in power plants)
Petroleum refining	0.01086	
Crude petroleum and natural gas	0.003767	
Electric services (utilities)	0.00009531	Internal flow; deleted
Chemicals for flue gas treatment		
Chemical and fertilizer minerals	2.269E-08	To be replaced with process data on chemicals for flue gas treatment (included in ecoinvent data on electricity and burning of fuels in power plants)
Industrial inorganic and organic chemicals	0.009675	
Chemicals and chemical preparations, n.e.c.	0.001405	
Carbon and graphite products	0.0001166	
Lime	0.00003654	
Cooling water		
Water transportation	0.003177	To be replaced with process data on water (included in ecoinvent data on electricity and burning of fuels in power plants)
Water supply and sewerage systems	0.002762	
Power distribution		
Power, distribution, and specialty transformers	0.01059	Power distribution is not included in the processes on electricity; deleted
Transport of raw materials		
Natural gas distribution	0.02993	To be replaced with process data transport (included in ecoinvent data on electricity and burning of fuels in power plants)
Railroads and related services	0.02607	
Trucking and courier services, except air	0.00411	
Natural gas transportation	0.0008687	
Capital goods (power plant)		
New office, industrial and commercial buildings construction	0.09949	
Other repair and maintenance construction	0.0835	To be replaced with process data on capital goods (included in ecoinvent data on electricity and burning of fuels in power plants)
Turbines and turbine generator sets	0.01229	
Relays and industrial controls	0.006735	
Switchgear and switchboard apparatus	0.005287	
Pumps and compressors	0.002306	
Carburettors, pistons, rings, and valves	0.001505	
Blowers and fans	0.001279	
Industrial and commercial machinery and equipment, n.e.c.	0.001118	
General industrial machinery and equipment, n.e.c.	0.000973	
Nonferrous wiredrawing and insulating	0.0008445	
Internal combustion engines, n.e.c.	0.0008135	
Rubber and plastics hose and belting	0.0007342	
Fabricated plate work (boiler shops)	0.0005376	
Conveyors and conveying equipment	0.0003646	
Special industry machinery, n.e.c.	0.000229	
Motors and generators	0.0001069	
Industrial process furnaces and ovens	0.0001028	
Pipe, valves, and pipe fittings	0.00006544	
Sum of deleted inputs	**0.3877**	The sum of the deleted inputs corresponds to 39% of all inputs

Table 7.5: Preparation of US IO data for hybridisation. The table shows the product outputs and inputs of the IO data set. The lower part of the table shows all the product inputs of the IO data set that have been deleted and are to be replaced with more accurate process-based data.

Analysing the original US IO process on electricity in SimaPro using the Stepwise LCIA method, the GHG emissions related to 1 kWh of electricity (6.74 cents) are 0.690 kg of CO2e. After having deleted the scope 1 emissions and the inputs in **Table 7.5**, the GHG emissions are 0.0052 kg of CO2e/kWh. Thus, the deleted emissions and inputs account for 99.2% of the GHG emissions related to the production of electricity in the IO process on electricity.

Process-based LCI data on electricity generation

The applied process data on electricity generation should account for the 99.2% of the emissions not covered by IO data referred to above. The applied process-based LCI data on electricity is data from ecoinvent (2007); and, for some countries where ecoinvent data is not available, the ecoinvent data is adjusted to fit the country specific fuel efficiency which is obtained from IEA (2008). There are different degrees of country specific data availability in the ecoinvent database. These are:

- Country specific data per kWh of generated electricity is available => the data is directly applied
- Country specific data does not exist in ecoinvent => data for the burning of 1 MJ fuel for an anticipated similar country/region is combined with country specific fuel efficiency data obtained from IEA (2008)
- Data on specific technologies/climate is available in ecoinvent (e.g. hydropower in alpine regions) => the anticipated best representative data is applied

The applied ecoinvent data is compatible with the IO data, i.e., when combining the two data types, there is no double counting and no data gaps and the requirements presented in **Table 7.4** are fulfilled without further adjustments. The assumptions regarding the anticipated similar countries and technologies referred to in the three bullets above are described in **Table 7.6**. The process-based LCI data applied to the considered technologies and regions is specified in the table in Appendix 3: Applied process-based LCI data on electricity.

Country/region	Applied process-based LCI data		
	Coal	Gas	Gas, alternatively flared
Greenland	-	-	-
Iceland	-	-	-
USA/Canada	-	-	-
Russia	ecoinvent data for burning coal in Chinese PP combined with actual efficiency in Russian coal PP	ecoinvent data for burning gas in Centrel[11] PP combined with actual efficiency in Russian gas PP	ecoinvent data for burning gas in PP (combined with efficiency in Russian gas PP) minus ecoinvent data for burning gas (flaring)
Australia	ecoinvent data for burning coal in US PP[12] combined with efficiency in Pacific OECD coal PP	ecoinvent data for burning gas in US PP combined with efficiency in Pacific OECD gas PP	-
Middle East	ecoinvent data for burning coal in Chinese PP combined with effi-ciency in Middle East coal PP	ecoinvent data for burning gas in Centrel[11] PP combined with effi-ciency in Middle East gas PP	ecoinvent data for burning gas in PP (combined with efficiency in Middle East gas PP) minus ecoin-vent data for burning gas (flaring)
Brazil	ecoinvent data for burning coal in Chinese PP combined with effi-ciency in Latin American coal PP	ecoinvent data for burning gas in Centrel[11] PP combined with effi-ciency in Latin Americal gas PP	-
China	ecoinvent data for burning coal in Chinese PP combined with actual efficiency in Chinese coal PP	ecoinvent data for burning gas in Centrel[11] PP combined with effi-ciency in Chinese gas PP	-
World	ecoinvent data for burning coal in US PP[12] combined with efficiency in aver. world coal PP	ecoinvent data for burning gas in US PP combined with efficiency in aver. world gas PP	-

Table 7.6: Process-based LCI data on electricity generation applied to this study – table is continued below. Abbreviations: PP (power plant), HP (hydropower), HF (heavy fuel), UCTE countries (see foot note[13]), 'Centrel' countries (see foot note[11])

Country/region	Applied process-based LCI data	
	Hydro	Nuclear
Greenland	ecoinvent data for reservoir HP, alpine region	-
Iceland	ecoinvent data for reservoir HP, alpine region	-
USA/Canada	ecoinvent data for reservoir HP, Finland	-
Russia	ecoinvent data for reservoir HP, Finland	-
Australia	ecoinvent data for reservoir HP, non-alpine region	ecoinvent data for US nuclear PP
Middle East	ecoinvent data for reservoir HP, non-alpine region	-
Brazil	ecoinvent data for reservoir HP, Brazil (CO_2 emission in ecoinvent data deleted, see explanation under **Table 7.7**)	ecoinvent data for Chinese nuclear PP, pressure water reactor
China	ecoinvent data for reservoir HP, non-alpine region	ecoinvent data for Chinese nuclear PP, pressure water reactor
World	ecoinvent data for reservoir HP, Finland	ecoinvent data for US nuclear PP

Table 7.6 - continued: Applied process-based LCI data on electricity generation in this study. Abbreviations: PP (power plant), HP (hy-dropower), HF (heavy fuel), UCTE countries (see foot note[13]), Centrel countries (see foot note[11])

[11] Centrel countries: Hungary, Slovenia, Czech Republic and Poland.

[12] Data for burning of hard coal in the RFC region (Reliability First Cooperation) which represents the largest share of US electricity generation from coal (35.3%) (Dones et al. 2007).

[13] UCTE countries: Austria, Belgium, Czech Republic, France, Germany, Greece, Hungary, Italy, Luxembourg, Nether-lands, Poland, Portugal, Slovakia, Spain, and Switzerland.

The ecoinvent data and data availability for the countries and regions referred to in **Table 7.6** are further described below.

Coal, electricity from; ecoinvent data on electricity generation from coal: Of the considered countries/regions, ecoinvent contains data on electricity generation in the US, the central European electricity grid (Europe), and China. Only the data for US and UCTE is used in this study because the ecoinvent data for China is mainly based on uncertain assumptions (Dones et al. 2007, p 284-285) and the implied efficiency of 35.6% in ecoinvent deviates significantly from the efficiency obtained from IEA (2008, p 530-531) of 28.9%.

Coal, burning of; ecoinvent data on burning of coal in power plants: Besides Europe and the US referred to above, ecoinvent contains LCI data on the burning of coal in coal power plants in China. No country/region specific data exists for Russia, Australia, Middle East, and Brazil. For Australia and world average, it is chosen to use US data; and for the remaining countries/regions, it is chosen to use data on the burning of coal in Chinese power plants combined with information on fuel efficiency in the specific countries/regions.

Natural gas, electricity from; ecoinvent data on electricity generation from gas: ecoinvent contains data on electricity generation from gas in the US and the central European electricity grid (Europe). This data is applied to electricity generation in the US and Europe.

Natural gas, burning of; ecoinvent data on burning of gas in power plants: ecoinvent does not contain data on the burning of natural gas in power plants in other of the considered countries/regions than US and Europe. But data on the burning of gas in power plants in the Central countries (Eastern Europe) exists, and this data is assumed to be representative for countries with less developed flue gas treatment, i.e., for Russia, Middle East, Brazil, and China. For Australia and world average, LCI data on the burning of gas in US power plants has been used.

Natural gas, flaring; ecoinvent data on flaring of refinery gas: ecoinvent contains general (not country specific) emissions data on the flaring of refinery gas.

Hydropower; ecoinvent data on electricity generation from hydropower: ecoinvent contains five different data sets on reservoir hydropower, see **Table 7.7**. In the table, the characteristics of the different geographical regions are considered. Cold climate leads to less methane emissions than warm climate, and sparse vegetation also leads to less methane emissions than forest vegetation (because the reservoir contains less organic material) (Rosa et al. 2004).

In **Table 7.7**, the first column describes the ecoinvent processes for hydropower; the second column shows the regions covered by the ecoinvent processes (ecoinvent 2007). The third column shows a brief characterisation of the differences between the major GHG emissions of the different ecoinvent processes.

Below the table, the different regions represented by the ecoinvent processes are classified with the relevant regions in the present study.

ecoinvent data set on reservoir hydropower	Geographical coverage and climate	Characteristics of emissions
Electricity, hydropower, at reservoir power plant, alpine region/RER	Europe, Alpine (interpreted as cold climate with sparse vegetation)	CH_4: low N_2O: yes CO_2: no
Electricity, hydropower, at reservoir power plant, non alpine regions/RER	Europe, non-Alpine (interpreted as region with aver. climate and vegetation)	CH_4: mid range N_2O: yes CO_2: no
Electricity, hydropower, at reservoir power plant/BR	Brazil (interpreted as warm and wet climate with forest vegetation)	CH_4: high N_2O: no CO_2: yes, from land use change
Electricity, hydropower, at reservoir power plant/CH	Switzerland (interpreted as same climate as Europe, Alpine)	CH_4: low N_2O: yes CO_2: no
Electricity, hydropower, at reservoir power plant/FI	Finland (interpreted as cold climate with forest vegetation)	CH_4: high N_2O: no CO_2: no

Table 7.7: LCI data on characteristics of reservoir hydropower available in ecoinvent (2007).

The applied ecoinvent processes are the ones shown in **Table 7.7**, in which it is assessed which data set best represents the considered country/region. However, the data set for Brazil is not applied directly. This is because the ecoinvent data set for Brazil overestimates the emissions of biogenic CO_2 (and maybe also CH_4), since it includes gross emissions (the actual measurable emissions from the reservoir) rather than net emissions (the actual emissions minus the emissions in case the reservoir was not established) (Bauer et al. 2007, p 100; dos Santosa et al. 2006, p 485). Since no biogenic CO_2 emissions are included in the other ecoinvent data sets for hydropower, and since it is very hard to determine the biogenic CO_2 emissions in case the reservoir was not established, it has been chosen to delete the CO_2 emissions in the ecoinvent data set for hydropower. The following ecoinvent data has been used as representative for the considered countries/regions:

- Europe, alpine, reservoir hydropower: Greenland and Iceland
- Europe, non-alpine, reservoir hydropower: Australia, China, Middle East, and Europe
- Finland, reservoir hydropower: Canada/USA, Russia, and world average
- Brazil, reservoir hydropower (modified): Brazil

Nuclear power; ecoinvent data on electricity generation from nuclear power: ecoinvent contains data on nuclear power for the US, China, and UCTE countries[13]. The following ecoinvent data has been used as representative for the considered countries/regions:

- US nuclear power (average type of reactor): Canada/USA, Australia, and world average
- Chinese nuclear power (pressure water reactor): Russia, Middle East, Brazil, and China
- UCTE countries nuclear power (average type of reactor): Europe

Process-based LCI data on transmission of electricity

The process-based LCI data described so far only concerns the generation of electricity – not the transmission from power plant to end user. LCI data on transmission includes the material inputs to and the maintenance of the grid as well as losses in the grid. Due to the lack of specific data, generic data on the transmission of electricity in all considered countries/regions is used. A distinction is made between the use of electricity from the high voltage grid (150-400 kV) and the medium voltage grid (<60 kV). Large electricity users, such as aluminium smelters, will typically be supplied with electricity directly from the high voltage grid, while less electricity intensive industries will be supplied via the medium voltage grid. According to ecoinvent (2007), the European average loss of the input to the high voltage grid is 1.0%, and the loss of the input to the medium voltage grid is 1.1%. The total loss is 2.1%. The transmission grid and the related losses are illustrated in **Figure 7.1**.

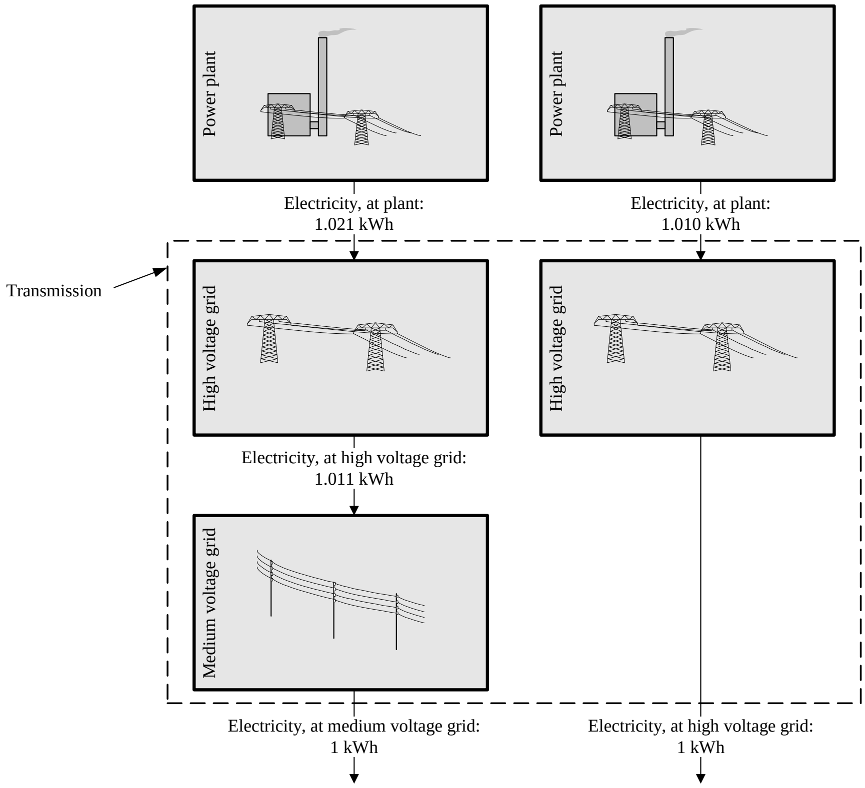

Figure 7.1: Illustration of the two grids from where electricity is supplied and the related losses.

The applied LCI data on the transmission grid is obtained directly from ecoinvent (2007) and it is presented in **Table 7.8**.

LCI data (ecoinvent 2007)	1 kWh electricity, at high voltage grid	1 kWh electricity, at medium voltage grid
Electricity produced, at plant	1.0103 KWh (1.02% loss of input)	1.0213 kWh (2.09% loss of input)
Transmission network, long-distance/UCTE	3.17E-10 km	3.20E-10 km
Transmission network, electricity, high voltage/CH	8.44E-9 km	8.53E-9 km
Transmission network, electricity, medium voltage/CH	-	3.24E-8 km
Sulphur hexafluoride, liquid, at plant/RER	-	6.74E-8 kg

Table 7.8: Used LCI data on production, maintenance and disposal of transmission and distribution to/from the grid in this study.

Summary of LCI data on electricity

In this section, the GHG emissions related to the production and transmission of 1 kWh for all considered technologies and countries/regions are presented, see **Figure 7.2**. The GHG emissions are calculated on the basis of the data presented in section 7.2 and by applying the Stepwise 1.2 LCIA method (Weidema et al. 2007) for analysis of issues related to global warming.

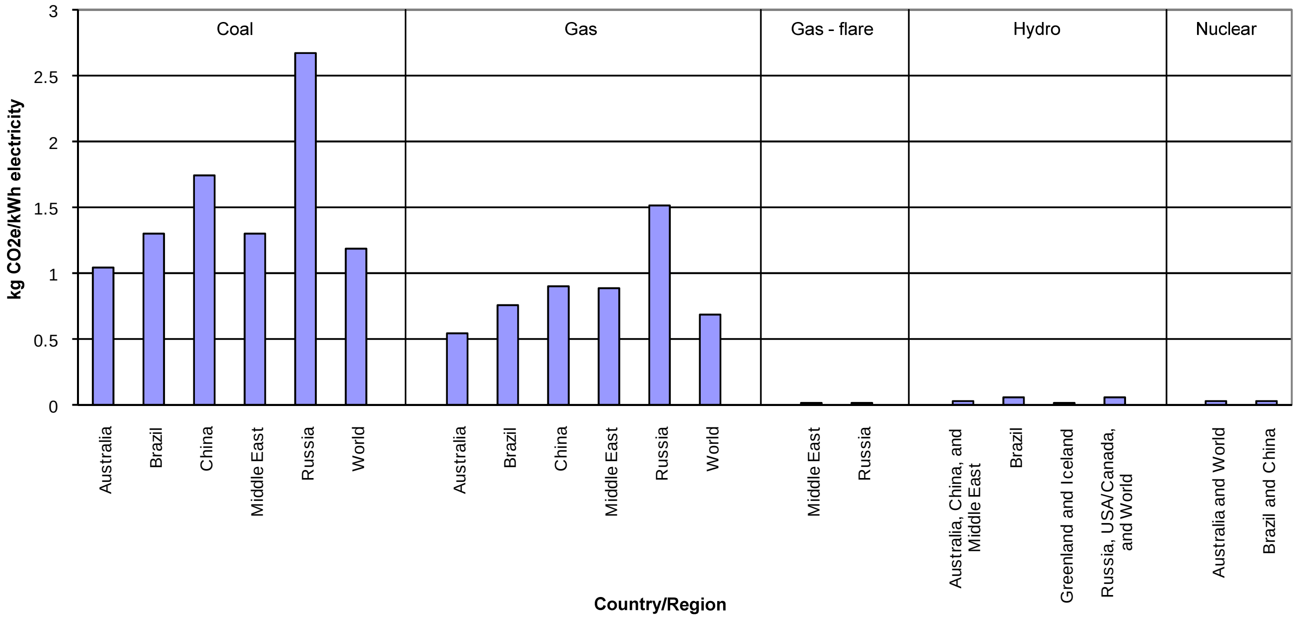

Figure 7.2: Summary of GHG emissions related to the supply of 1 kWh of electricity in high voltage grid in different countries/regions using different technologies.

It appears from **Figure 7.2** that the GHG emissions related to the production of 1 kWh of electricity vary significantly depending on the country/region in which the electricity is produced. The main reason for this variance is the difference in the efficiency of the fuel to electricity generation. In order to obtain an overview of the average performance of the different technologies, **Table 7.9** presents the average, minimum and maximum GHG emission per kWh for the different technologies.

Technology	Average, kg CO2e/kWh	Minimum, kg CO2e/kWh	Maximum, kg CO2e/kWh
Coal	1.54	1.03	2.67
Gas	0.878	0.533	1.51
Gas – alternatively flared	0.00800	0.00738	0.00862
Hydro	0.0316	0.0104	0.0568
Nuclear	0.0178	0.0168	0.0188

Table 7.9: Overview of range of GHG emissions from electricity supply from the high voltage grid of the technologies and countries/regions shown in **Figure 7.2**.

In order to create a general picture of the factors which contribute to the GHG emissions presented in **Figure 7.2** and **Table 7.9**, the total contribution from the electricity supply from the high voltage grid is divided into:

- **Process data:** direct emissions from burning fuel at plant
- **Process data:** emissions related to the production of fuels
- **Process data:** emissions related to capital goods, i.e., power plant and high voltage grid
- **Process data:** emissions related to ancillary inputs at plant
- **IO data:** emissions related to other inputs

The contribution analysis of GHG emissions from the European electricity supply is shown in **Table 7.10**.

Technology	Coal	Gas	Gas - alternatively flared	Hydro	Nuclear
Direct emissions	87%	83%	23%	40%	-
Production of fuels	12%	16%	-	-	36%
Capital goods	0.22%	0.12%	-	29%	18%
Ancillary inputs	0.30%	0.08%	7%	0.60%	8.1%
Other inputs (IO data)	0.48%	0.80%	70%	31%	38%
Total	**100%**	**100%**	**100%**	**100%**	**100%**

Table 7.10: Contribution analysis for electricity supply from high voltage grid (data for Europe are analysed, except gas alternatively flared which is analysed for the Middle East).

It appears from **Table 7.10** that the direct emissions and the production of fuels completely dominates the contribution of coal, oil and gas-based electricity to GHG emissions, while capital goods and other inputs (IO data) play a larger role for hydropower and nuclear power. In addition, the direct emissions from the reservoir are significant in the case of hydropower, while the emissions related to the production of nuclear fuel are significant to nuclear power.

7.3 Transport

Inventory data for transport is only based on process data. The inventory data for transport uses the measurement of tonne kilometre (tkm) as the reference flow. 1 tkm corresponds to the transportion of 1 tonne of goods at a distance of 1 km; i.e., the emissions related to the transportation of 1 kg of goods at a distance of 1000 km are equal to the transportation of 1 tonne of goods at a distance of 1 km. This implies that a generalised load factor (average load) of the trucks is presumed.

The following data is applied:

Road transport with lorry: The applied inventory data is: '*Transport, lorry 16-32t, EURO4/RER*' (ecoinvent 2007). The data represents European lorries (EURO4) operated under Swiss conditions in the year 2005 (Spielmann et al. 2007, p 13). The inventory includes emissions from the production and burning of diesel and other related processes. Capital goods are included (construction, maintenance and disposal of vehicles and roads). The data represents lorries with an average load factor of 5.77 tonnes (Spielmann et al. 2007, p 53; ecoinvent 2007). This means that the trucks in average carry a load of 5.77 tonnes at the total distance they travel. The inventory data is documented in detail in Spielmann et al. (2007).

Sea transport with freight ship: The applied inventory data is: '*Transport, transoceanic freight ship/OCE*' (ecoinvent 2007). The data represents freight ships with a load capacity of 50,000 tonnes, and an average of slow speed engine and steam turbine propulsion (Spielmann et al. 2007, p 171). The inventory includes emissions from the production and burning of fuel oil, harbour operations and other related processes. Capital goods are included (construction, maintenance and disposal of ships and harbour). The inventory data is documented in detail in Spielmann et al. (2007).

8 Life cycle inventory: Bauxite mining

The modelling and the collection of data on emissions from the bauxite mining stage are based on ecoinvent data: ‘Bauxite, at mine/GLO’ (ecoinvent 2007), data on bauxite from EAA (2008), and US98 IO data per USD ‘Nonferrous metal ores, except copper’ (Suh 2004), and a price of 0.0312 US$98/kg (UN 2009).

8.1 Bauxite mining

The first stage of the life cycle of aluminium is the extraction of bauxite from aluminium ores, which are mainly situated in tropical and sub-tropical areas, such as Africa, West Indies, South America and Australia. Aluminium (oxidised form) is the third most abundant element in the earth's crust and there is no immediate risk connected with the depletion of the stocks. Most of the bauxite is extracted from open mines, but closed mines also exist, e.g., in Europe. To access the mines, a layer of 4-6 m of topsoil typically has to be removed, but it can be necessary to remove 70 metres of rock and clay, in some cases. (IAI 2009d)

After that, the bauxite is loosened, which in some cases requires blasting. The bauxite is subsequently loaded onto trucks (or trains) and transported to crushing or washing plants.

Figure 8.1: Pictures from bauxite mining – including excavation from open mine (left), excavation in areas with tropical forest (middle), and rehabilitation of previously mined areas (right) (IAI 2009d).

The bauxite does not require complex processing and the treatment mainly involves the removal of clay by a combination of washing, wet screening, cycloning, and even manual sorting, in some cases. One of the environmental concerns at the mining stage is land use (e.g. related to mining in tropical forest); but according to IAI (2009d), the total mine area was only 20 km^2 in 2002 of which only 2.4 km^2 was located in tropical forest. Rehabilitation is also applied.

8.2 Product flow at the mining stage

The inventory takes its point of departure in the establishment of a product flow diagram for the production of 1 kg of bauxite, see **Figure 8.2**. According to Classen et al. (2007, part I, p 5), the average crude ore of bauxite that is mined contains 53% aluminium oxide (Al_2O_3). This corresponds to 23.6% aluminium (Al)e. Besides the content of Al_2O_3, bauxite contains SiO_2, Fe_2O_3, and TiO_2 (Classen et al. 2007).

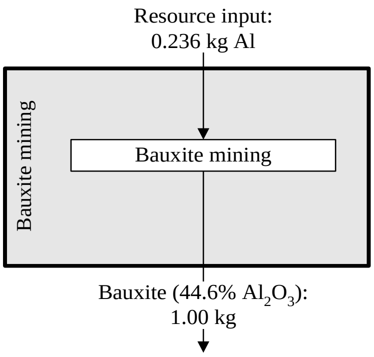

Figure 8.2: Processes and product flow at the bauxite mining stage.

8.3 Hybridisation of the US IO data for the bauxite stage

The product category ‘Nonferrous metal ores, except copper’ defined in the US98 IO model includes bauxite mining. In the IO model, the reference flow of the process is 1 US$98. The price of bauxite in the USA in 1998, calculated as the weighted average of import and export prices, is 0.0312 US$98 per kg (UN 2009). Thus, the reference flow of 1 US$98 can be immediately changed to 32.1 kg.

The following exchanges in the US IO model process for bauxite are deleted and replaced with more detailed data:

- Direct emission outputs
- Direct resource inputs
- Fuel inputs and related emissions
- Electricity inputs

Table 8.1 provides an overview of the product inputs deleted from the IO process ‘Nonferrous metal ores, except copper’.

Process: Nonferrous metal ores, except copper		
Product output	**Amount, US$98**	**Description of modification**
Nonferrous metal ores, except copper	0.8435	Internal flows are eliminated. The supply of the process (1 US$98) is reduced accordingly (1 - 0.1565 = 0.8435 US$98)
Product inputs before deletion of inputs	**Amount, (US$98)**	
120 different product inputs	0.7496	
Deleted product inputs	**Amount, (US$98)**	**Description of deleted input**
Raw materials (feedstock)		
Nonferrous metal ores, except copper	0.1565	Internal flows. The supply of the process (1 US$98) is reduced accordingly (1 - 0.1565 = 0.8435 US$98)
Raw materials (ancillaries)		
-	-	No ancillaries are deleted in the IO process
Fuels and energy		
Electric services (utilities)	0.03177	To be replaced with hybrid-data on electricity (see sections 6 and 7.2)
Natural gas distribution	0.003128	To be replaced with process data on fuels and burning of fuels (see section 7.1)
Petroleum refining	0.01493	
Coal	0.0004591	
Transport of raw materials		
-		No transport services are deleted in the IO process
Waste treatment		
-	-	No waste treatment services are deleted in the IO process
Sum of deleted inputs	**0.2068**	The sum of the deleted inputs corresponds to 28% of all inputs

Table 8.1: Preparation of US IO data for hybridisation. The table shows the product outputs and inputs of the IO data set. The lower part of the table shows all product inputs of the IO data set that have been deleted and are to be replaced with more accurate hybrid or process-based data.

8.4 Energy and fuel inputs

According to section 8.3, the inputs of electricity and fuels included in the IO data are deleted and replaced with process-based LCI data. In **Table 8.2**, different studies of electricity and fuel input to the production of bauxite are compared, and the energy inputs applied to this study are specified.

According to USGS (2009A), almost 60% of the mined bauxite in 2008 was mined in Australia, China and Brazil. Based on that, it is assumed that the electricity used for bauxite production can be modelled as the electricity mix distributed according to the production volumes of bauxite in these three countries (see shares in **Table 8.2**). Data on marginal electricity sources in the three countries is presented in section 6, and LCI data on electricity production and electricity sources in the three countries can be found in section 7.2.

Energy input	Bauxite, at mine/GLO (ecoinvent 2007)	Bauxite (EAA, p 23)	Applied to this study	LCI data
Representativity	Europe 2000-04	World 2005	World 2008	
Electricity	0.0028 kWh	0.0019 kWh	0.0019 kWh	Australian electricity: 52% Chinese electricity: 27% Brazilian electricity: 21% See sections 6 and 7.2
Diesel	0.0439 MJ	0.0470 MJ	0.0470 MJ	See section 7.1
Heavy fuel oil	-	0.0082 MJ	0.0082 MJ	See section 7.1

Table 8.2: Comparison of energy use related to the production of 1 kg of bauxite. The applied energy uses per kg of bauxite are specified. The fuel use in EAA data is converted from mass unit to energy unit using data on calorific value given in Appendix 1: Data on fuels and flue gasses.

8.5 Transport

Data on transport of the used material and fuel inputs is included in the IO data.

8.6 Emissions and resource inputs

As described in section 8.3, inputs of resources (aluminium) and outputs of emissions in the IO data are deleted and replaced with process-based LCI data. Emissions related to electricity and burning of fuels are described in sections 7.1 and 7.2. The only other emission is the emission of dust/particles (EAA 2008, p 23; Classen et al. part I, p 12). The resource input includes the input of aluminium and land use. **Table 8.3** shows the comparison of emission and resource data from two studies and the data applied to this study.

Exchange	**Bauxite, at mine/GLO** (ecoinvent 2007)	**Bauxite** (EAA, p 23)	**Applied to this study**	**Comments**
Representativity	Europe 2000-04	World 2005		
Emissions				
Particulates, <2.5 um	0.16 g	-	0.16 g	
Particulates, >2.5 um, and <10 um	1.44 g	-	1.44 g	
Particulates, >10 um	1.60 g	-	1.60 g	
Particulates, unspecified	-	0.95 g	-	
Resources				
Aluminium resource	0.281 kg	-	0.236	See section 8.2, ecoinvent represents European average while the applied data represents world average
Land occupation	0.000335 m^2 yr	-	0.000335 m^2 yr	Occupation, mineral extraction site
Land transformation	0.000167 m^2	-	0.000167 m^2	Transformation from forest to mineral extraction site

Table 8.3: Comparison of emissions and resource input related to the production of 1 kg of bauxite. The applied data per kg of bauxite is specified.

8.7 Summary of the LCI of the mining stage

The result of the life cycle inventory for 1 kg of bauxite is summarised in **Table 8.4**.

Bauxite mining: 1 kg of bauxite			
Interventions	**Amount**	**Applied LCI data**	
Product outputs			
Bauxite	1 kg	Reference flow	
Energy inputs			
Electricity from grid, Australia	0.000998 kWh	See sections 6 and 7.2	
Electricity from grid, China	0.000507 kWh	See sections 6 and 7.2	
Electricity from grid, Brazil	0.000395 kWh	See sections 6 and 7.2	
Diesel	0.0470 MJ	See section 7.1	
Heavy fuel oil	0.0082 MJ	See section 7.1	
Other inputs			
IO data	1 kg	See section 8.3	
Resource inputs			
Aluminium	0.236 kg	-	
Land occupation	0.000335 m^2 yr	-	
Land transformation	0.000167 m^2	-	
Emissions	**Air**	**Water**	**Soil**
Particulates, < 2.5 um	0.00016 kg	-	-
Particulates, > 2.5 um, and < 10um	0.00144 kg	-	-
Particulates, > 10 um	0.0016 kg	-	-

Table 8.4: Interventions per kg of bauxite.

9 Life cycle inventory: Alumina production stage

The modelling and the collection of data on emissions from the alumina production stage are based on ecoinvent data: 'Aluminium oxide, at plant/RER' and 'Aluminium hydroxide, at plant/RER' (ecoinvent 2007), data on alumina production from EAA (2008), and US98 IO data per USD 'Industrial inorganic and organic chemicals' (Suh 2004), and a price of 0.262 US$98 per kg (UN 2009).

9.1 Alumina production

After the mining stage and transport, the bauxite is refined into aluminium oxide trihydrate (alumina) using the Bayer Process and calcination. It requires around 1.9-2.8 tonnes of alumina to produce one tonne of aluminium (see **Table 9.1**). The alumina is used as a raw material for the aluminium production, but also as an absorbent filter for emissions from the smelter cells, as a thermal insulator for the top of electrolytic cells, and for coating of pre-baked anodes (IAI 2009d).

The production process involves washing and grounding of the bauxite, which is then dissolved in caustic soda (sodium hydroxide) under high pressure and at high temperature. The caustic soda is reused in the process (IAI 2009d).

This generates a liquor containing a solution of sodium aluminate and undissolved bauxite residues (containing iron, silicon, and titanium). The latter deposits at the bottom and is removed as so-called red mud. The clear sodium aluminate solution is pumped into a precipitator, where fine particles of alumina are added to seed the precipitation of pure alumina particles as the liquor cools. The particles sink to the bottom and are subsequently passed through a rotary or fluidised calciner at 1100°C to drive off the chemically combined water (IAI 2009d). The product is alumina, which is a grey/white powder, see **Figure 9.1**.

Figure 9.1: From bauxite (left) to alumina (right), via the Bayer process (IAI 2006).

Apart from the use of significant amounts of energy for heating (from fossil fuels), one of the environmental concerns at this stage includes the waste product 'red mud'. Red mud consists of natural residues from the bauxite as well as traces of alkali. The red colour is due to a high iron content. The amount of red mud is highly dependent on the quality of the bauxite ore (IAI 2009d).

9.2 Product flow at the alumina production stage

The inventory takes its point of departure in the establishment of a product flow diagram for the production of 1 kg of alumina. The quantities of exchanges are based on EAA (2008), Alcoa (2009c), and ecoinvent (2007), see **Table 9.1** below. It appears from **Table 9.1** that the bauxite input per kg of alumina varies significantly depending on the bauxite source and quality. However, the emissions related to bauxite are not significant, and hence, the uncertainty related to the use of bauxite is not significant. According to **Table 11.1** (p 138), bauxite only accounts for 2.4% of the total GHG emissions related to the production of aluminium (Greenland smelter). The applied input of bauxite to alumina production is estimated as a rough average of the data in EAA (2008) and Alcoa (2009c).

Data source	**Bauxite input per output of alumina,** per kg of alumina	**Representativity**
Aluminium, primary, at plant/RER (ecoinvent 2007)	2.142 kg	1990s World
European Commission (2001, p 284)	1.970-2.250 kg	1990s European Union
EAA (2008): World 2005	2.739 kg	2005 World
EAA (2008): Europe 2005	2.199 kg	2005 Europe
Alcoa (Alcoa 2009c)	2.320 kg	2000s for alumina used by Alcoa
Applied bauxite input per kg of alumina	**2.400 kg**	**2008 and future for alumina production**

Table 9.1: Comparison of bauxite input to the alumina process from different data sources. The applied bauxite input per kg of alumina in this study is specified.

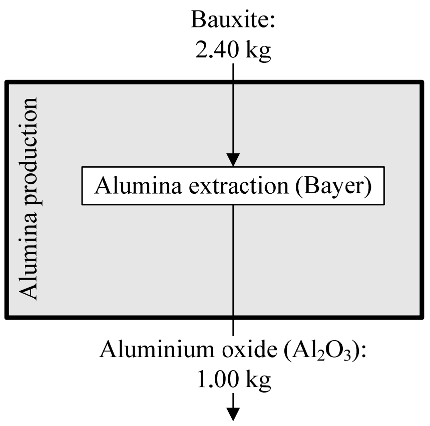

Figure 9.2: Processes and product flow at the alumina production stage.

9.3 Hybridisation of the US IO data for the alumina production stage

The product category 'Industrial inorganic and organic chemicals' in the US98 IO model includes alumina production. In the IO model, the reference flow of the process is 1 US$98. The price of alumina (Al_2O_3) in the USA in 1998, calculated as the weighted average of import and export prices, is 0.262 US$98 per kg (UN 2009). Thus, the reference flow of 1 US$98 can immediately be changed to 3.82 kg.

The following exchanges in the US IO model process for alumina are replaced with more detailed data:

- Direct emission outputs
- Fuel inputs
- Electricity inputs
- Bauxite input
- Material inputs of lime and sodium hydroxide
- Waste treatment (red mud)

Process: Industrial inorganic and organic chemicals		
Product output	**Amount (US$98)**	**Description of modification**
Industrial inorganic and organic chemicals	0.785	Internal flows are eliminated. The supply of the process (1 US$98) is reduced accordingly (1 - 0.215 = 0.785 US$98)
Product inputs before deletion of inputs	**Amount (US$98)**	
337 different product inputs	0.7509	
Deleted product inputs	**Amount (US$98)**	**Description of deleted input**
Raw materials (feedstock and ancillaries)		
Industrial inorganic and organic chemicals	0.215	Internal flows. The supply of the process (1 US$98) is reduced accordingly (1 - 0.285 = 0.785 US$98)
Nitrogenous and phosphatic fertilizers	0.008292	Most of the deleted inputs relate to other 'Industrial inorganic and organic chemicals' than alumina – therefore they are deleted
Copper ore	0.004994	
Chemical and fertilizer minerals	0.00448	
Chemicals and chemical preparations, n.e.c.	0.003556	
Iron and ferroalloy ores, and miscellaneous metal ores, n.e.c.	0.003231	
Nonferrous metal ores, except copper	0.001493	
Lime	0.001241	
Carbon and graphite products	0.0009901	
Products of petroleum and coal, n.e.c.	0.0003896	
Minerals, ground or treated	0.0002745	
Animal and marine fats and oils	0.000213	
Vegetable oil mills, n.e.c.	0.0001744	
Gum and wood chemicals	0.0001342	
Clay, ceramic, and refractory minerals	0.0001123	
Soybean oil mills	0.0001056	
Cellulosic manmade fibres	0.00004891	
Flour and other grain mill products	0.000002157	
Cottonseed oil mills	0.00000186	
Edible fats and oils, n.e.c.	0.000001766	
Sugar	0.000001587	
Gypsum products	0.0000006062	
Fuels and energy		
Electric services (utilities)	0.02139	To be replaced with hybrid-data on electricity (see section 9.4)
Natural gas distribution	0.01746	To be replaced with process data on fuels (see section 9.4)
Crude petroleum and natural gas	0.05231	
Petroleum refining	0.01232	
Coal	0.001325	
Transport of raw materials		
Trucking and courier services, except air	0.01837	To be replaced with process data on transport (see section 9.6)
Railroads and related services	0.007581	
Waste treatment		
Sanitary services, steam supply, and irrigation systems	0.005433	To be replaced with process data on waste treatment, i.e. red mud (see section 9.7)
Sum of deleted inputs	**0.3809**	The sum of the deleted inputs corresponds to 51% of all inputs

Table 9.2: Preparation of US IO data for hybridisation. The table shows the product outputs and inputs of the IO data set. The lower part of the table shows all product inputs of the IO data set that have been deleted and are to be replaced with more accurate hybrid or process-based data.

9.4 Energy inputs

The energy inputs to the alumina production process are identified in Alcoa (2009c), EAA (2008), and ecoinvent (2007). In **Table 9.3**, the identified data is compared, and the data applied is specified.

According to IAI (2009c), the world's production of alumina for metallurgical purposes in 2008 is distributed between China (28%), Oceania (mainly Australia) (25%), Latin America (mainly Brazil) (20%), North America (7%), Asia (7%), Western Europe (7%), Eastern/central Europe (6%), and Africa (1%). The three major suppliers, China, Oceania, and Latin America account for 63% of the total supply. Based on this, it is presumed that the marginal alumina production can be represented by 39% produced in China, 34% produced in Australia, and 27% produced in Brazil.

At the bottom of **Table 9.3**, the total use of fuels for heat production is shown. For comparison, the European Commission (2001, p 284) specifies a total thermal energy input of 8.0 – 13.5 MJ/kg of alumina.

Electricity: The Alcoa (2009c) data on electricity is assumed to best represent the marginal supply of alumina because two out of three of the data sources support this value.

Process heat: The applied fuel mix and total use of process heat is a rough average of EAA (2008) and Alcoa (2009c).

Energy input	**'Aluminium oxide, at plant/RER'** and **'Aluminium hydroxide, at plant/RER'** (ecoinvent 2007)	**Alumina production, world in 2005** (EAA, p 24)	**Alumina production, Atlantic region** (Alcoa 2009c)	**Applied to this study**	**LCI data**
Representativity	**Europe 2000-04**	**World 2005**	**Alcoa specific**		
Electricity	0.225 kWh	0.126 kWh	0.220 kWh	0.220 kWh	Chinese electricity: 39% Australian electricity: 34% Brazilian electricity: 27% See sections 6 and 7.2
Heavy fuel oil	-	4.18 MJ	6.41 MJ	5.00 MJ	See section 7.1
Light fuel oil	7.80 MJ	-	-	-	
Natural gas	0.990 MJ	4.51 MJ	2.39 MJ	3.50 MJ	
Coal	0.312 MJ	2.12 MJ	0.584 MJ	1.50 MJ	
Total thermal energy	**9.11 MJ**	**10.8 MJ**	**9.38 MJ**	**10.0 MJ**	

Table 9.3: Comparison of energy use related to the production of 1 kg of alumina. The energy uses per kg of alumina applied to this study are specified. The fuel use in EAA data is converted from mass unit to energy unit using data on calorific value given in Appendix 1: Data on fuels and flue gasses.

9.5 Material inputs

The material inputs to alumina production are identified by the same data sources as the energy inputs in section 9.4. In **Table 9.4**, the identified data is presented, and the applied data is specified.

Material input	**'Aluminium oxide, at plant/RER'** and **'Aluminium hydroxide, at plant/RER'** (ecoinvent 2007)	**Alumina production, world in 2005** (EAA, p 24)	**Alumina** (European Commission 2001, p 284)	**Alumina production** (Alcoa 2009c)	**Applied in this study**	**LCI data**
Representativity	Europe 2000-04	World 2005	Europe 1990ies	Alumina used by Alcoa		
Calcinated lime	0.0461 kg	0.040 kg	0.035-0.110 kg	0.0419 kg	0.0419 kg	Quicklime, milled, loose, at plant/CH (ecoinvent 2007)
Sodium hydroxide (50%)	0.0301 kg	0.0445 kg	0.033-0.160 kg	0.0430 kg	0.0430 kg	Sodium hydroxide, 50% in H2O, membrane cell, at plant/RER (ecoinvent 2007), remark: ecoinvent data is for 50% solution while the collected data is for 100%
Fresh water	-	7.9 kg	1.0-6.0 kg	-	-	Included in IO data
Sea water	-	0.1 kg		-	-	Included in IO data

Table 9.4: Comparison of material inputs related to the production of 1 kg of alumina. The material inputs per kg of alumina applied in this study are specified.

9.6 Transport

Transport of the material and fuel inputs are described in this section. **Table 9.5** shows the data used for transport, i.e., amount of material transported, assumed transport distance and means of transportation. Alumina is typically produced close to the mining of bauxite. Therefore, a relatively short transport distance with lorry has been assumed for bauxite.

Transported material	Amount	Distance	Transport	Means of transportation	LCI data
Bauxite	2.40 kg	100 km	2,400 kgkm	Lorry	See section 7.3
Heavy fuel oil	0.121 kg	200 km	24.2 kgkm	Lorry	
Coal	0.0364 kg	200 km	7.28 kgkm	Lorry	
Calcinated lime	0.0419 kg	200 km	8.38 kgkm	Lorry	
Sodium hydroxide	0.0430 kg	200 km	8.60 kgkm	Lorry	

Table 9.5: Transport of material input. The fuel uses in **Table 9.3** are converted from energy unit to mass unit using data on calorific value given in Appendix 1: Data on fuels and flue gasses.

9.7 Emissions

The only data source which provides data on emissions which do not originate from the burning of fuels is EAA (2008). The emissions specified here are applied to this study as well, see **Table 9.6**.

Emissions to air	Amount per kg of alumina
Particulates, > 10 um	0.000230 kg
NO_x	0.00122 kg
SO_2	0.00394 kg

Table 9.6: Emissions (not related to the burning of fuels) from the alumina production process (EAA 2008, p 24).

The emissions of particles are assumed to be > 10 um.

9.8 Waste/by-product treatment

The waste and by-product outputs from alumina production include red mud (slurry which contains dissolved aluminate and mixture of metal oxides) as well as tailings, inters, and sand (separated from the bauxite prior to the leaching process) (EAA 2008, p 20). The main treatment of these outputs is landfill (EAA 2008); recycling is increasing but still insignificant. The recycling of red mud includes the utilisation of the mud as an additive in cement and as filler material in road construction (EAA 2008). The same type of recycling is assumed for tailings, inters and sand. In both types of recycling, it is assumed that the recycled material displaces an alternative production of sand.

Waste output	**'Aluminium oxide, at plant/RER'** and **'Aluminium hydroxide, at plant/RER'** (ecoinvent 2007)	**Alumina production, world in 2005** (EAA, p 24)	**Alumina production** (Alcoa 2009c)	**Applied to this study**	**LCI data**
Representativity	Europe 2000-04	World 2005	Alumina used by Alcoa		
Landfill: Red mud	0.719 kg	1.142 kg	0.853 kg	1.00 kg	Disposal, red mud from bauxite digestion, 0% water, to residual material landfill/CH (ecoinvent 2007)
Landfill: Tailings, inters and sand	0.0307 kg	0.025 kg	-	0.0300 kg	Disposal, inert waste, 5% water, to inert material landfill/CH (ecoinvent 2007)
Recycling: Red mud	-	0.0111 kg	-	0 kg	-
Recycling: Tailings, inters and sand	-	0.0056 kg	-	0 kg	-

Table 9.7: Comparison of waste outputs related to the production of 1 kg of alumina. The waste outputs per kg of alumina applied to this study are specified.

9.9 Summary of the LCI of the alumina production stage

The result of the life cycle inventory for 1 kg of alumina is summarised in **Table 9.8**.

Alumina extraction process (Bayer): 1 kg of Aluminium oxide (Al_2O_3)		
Exchanges	**Amount**	**Applied LCI data**
Product output		
Alumina (Al_2O_3)	1 kg	Reference flow
Material inputs		
Bauxite	2.400 kg	See section 8.7
Calcinated lime	0.0419 kg	Quicklime, milled, loose, at plant/CH (ecoinvent 2007)
Sodium hydroxide (50% solution)	0.0430 kg	Sodium hydroxide, 50% in H2O, membrane cell, at plant/RER (ecoinvent 2007)
Energy inputs		
Electricity, China	0.0858 kWh	Electricity from medium voltage grid in China, Australia, and Brazil, see section 7.2
Electricity, Australia	0.0748 kWh	
Electricity, Brazil	0.0594 kWh	
Heavy fuel oil	5.00 MJ	Production of combustion of fuels, see section 7.1
Natural gas	3.50 MJ	
Coal	1.50 MJ	
Transport inputs		
Lorry	2,448 kgkm	See section 7.3
Other inputs		
IO data	1 kg	See section 9.3
Waste to treatment		
Landfill: Red mud	1.00 kg	Disposal, red mud from bauxite digestion, 0% water, to residual material landfill/CH (ecoinvent 2007)
Landfill: Tailings, inters and sand	0.0300 kg	Disposal, inert waste, 5% water, to inert material landfill/CH (ecoinvent 2007)
Emissions to air		
Particulates, > 10 um	0.000230 kg	
NO_x	0.00122 kg	
SO_2	0.00394 kg	

Table 9.8: Interventions in the 'Alumina production (Bayer)' process per kg of aluminium oxide (Al_2O_3).

10 Life cycle inventory: Aluminium smelter stage

The modelling and the collection of data on emissions from the aluminium smelter and cast house are mainly based on data provided by Alcoa (2009a and 2009b), EAA (2008), ecoinvent (2007), and the European Commission (2001).

10.1 Production of aluminium

At the smelter stage, alumina is first stored in large silos. At the Deschambault plant in Quebec, the alumina is used to filter the exhaust gases from the pots, which, apart from removing hydrogen fluoride and PFC’s from the exhaust gases, serves to enrich the alumina, which again has a positive effect on the smelting process and the products (Montembeault 2009).

Electrolysis process

The alumina is reduced into primary or virgin aluminium via an electrolysis process that requires very large amounts of electricity. Due to the high electricity requirement, smelters are typically located in regions with a cheap and stable electricity supply. The process is based on the so-called Hall-Héroult Process, in which alumina is dissolved in an electrolytic bath of molten cryolite (sodium aluminium fluoride) within a steel container known as a "pot", which is lined with carbon or graphite. To improve the performance of the cells, other compounds are added to the cryolite, such as aluminium fluoride (IAI 2009d).

Electric current (with low voltage and high current – typically 200,000 to 350,000 amperes) is passed through a carbon anode (positive) to a cathode (negative) formed by the thick carbon or graphite lining of the pot. The molten aluminium deposits at the bottom of the pot and is extracted periodically. The aluminium is sometimes blended to an alloy before it enters the cast house (IAI 2009d). **Figure 10.1** below shows some of the steps in the electrolysis process.

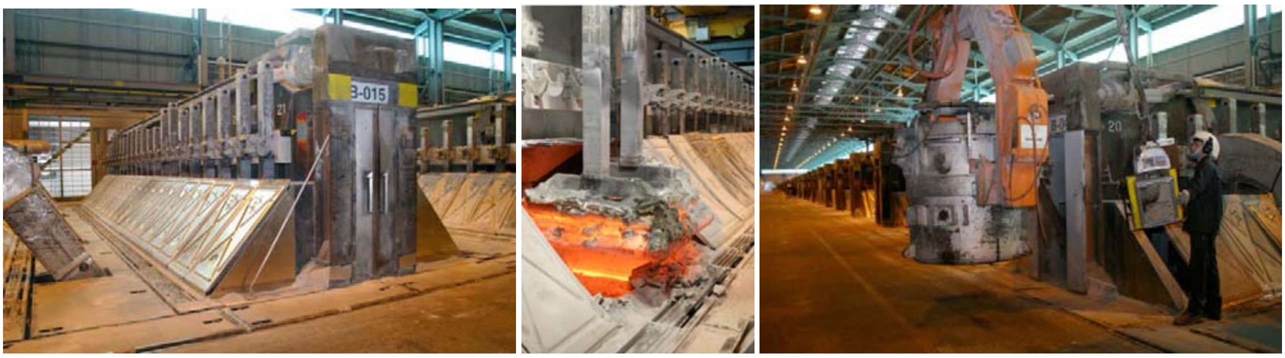

Figure 10.1: Illustration of an aluminium pot with multiple anodes at the Alcoa smelter in Deschambault, Quebec (left); change of used anodes (middle), and extraction of molten aluminium from the pot (right). Pictures are provided by Montembeault (2009) and represent pre-bake technology.

Two technologies are used for the electrolysis process: the pre-bake and the Söderberg design. Due to a lower electric efficiency and higher emission levels, the Söderberg technology is being phased out. The pre-bake design is used in all new aluminium smelters, and will also be applied to the planned Greenland smelter analysed in this project. Alcoa’s smelters in Deschambault and Iceland use the pre-bake technology. In the pre-bake design, anodes for the reduction process are baked in brick-lined pits and the hydrocarbon off-gasses can be captured and burned. The Söderberg design uses a single anode in the reduction process. Anodes are baked by the heat generation in the cells and the off-gasses are more difficult to collect than in the pre-bake design (IAI 2009d).

An aluminium smelter consists of one or several pot lines, which contain around 300 pots. Each pot line typically produces about 150,000 tonnes of aluminium annually. However, some of the newest pot lines are even larger and can produce 200-300,000 tonnes each. The capacity of a smelter is normally around 300,000 tonnes per year and the largest smelters can produce one million tonne (IAI 2009d). During a company visit at Alcoa's Deschambault smelter in Quebec, it was explained that advanced ventilation systems are connected to each pot, which lead the exhaust gases into wet scrubbers and filters before the exhaust gas is discharged through the chimney. During the change of used anodes, double suction is applied to reduce the escape of gases through the factory roof (Montembeault 2009).

The smelting process is continuous and a power supply failure of more than four hours means that metal in the pots will solidify. According to Montembeault (2009), pot linings last 4-7 years and have to be manually rebuilt after this period, which involves the removal of the old lining materials. During a start up of a new aluminium smelter, the life time of the lining will be lower. The lining material is also called 'refractory'.

Environmental concerns at the smelter stage are mainly related to the large consumption of electricity, but also emissions of, e.g., PFCs, CO_2 and hydrogen fluoride (HF) from the plant.

Anode production and rodding

The anode used in the electrolysis process with pre-bake technology is made of petroleum coke and coal tar pitch. The process involves mixing, vibrating and pressing followed by baking under high temperature. Anodes are baked at a temperature of 1120 degrees Celsius. The process, which includes handling, baking and cooling, takes about two weeks (IAI 2009d).

The finished anodes are subsequently attached to three-forked steel rods in a process termed 'rodding'. The rod is attached via the use of molten cast iron. The anodes are then transported via forklift trucks to the pot rooms for use in the smelting pot (IAI 2009d). **Figure 10.2** below shows some of the steps in the anode production process.

Figure 10.2: Attachment of steel rods to anodes (left) and transport of the rodded anodes to the smelter (right). Pictures are provided by Montembeault (2009) and represent pre-bake technology.

In the case of the planned smelter in Greenland, anodes will be imported, but rodding will take place at the plant in Greenland.

Casting process and overview of all processes

The last process at the smelter stage is casting. Many types of casting processes exist, but for generic aluminium ingot, mainly two casting methods are used, either DC cast extrusion or rolling slabs. The first method produces long cylindrical aluminium ingots, while the latter produces rectangular aluminium ingots. DC means direct chill casting technology and means that liquid metal is poured into short moulds on a platform and hereafter cooled, as they are lowered into a water filled pit (EAA 2008). **Figure 10.3** below shows some of the steps in the casting process.

Figure 10.3: Illustration of molten aluminium entering the casting process (left); the casting process itself (middle), and the finished ingots as rectangular blocks (right). Pictures are provided by Montembeault (2009).

10.2 Product flow at the aluminium smelter stage

The inventory takes its point of departure in establishing a product flow diagram for the production of 1 kg of aluminium. The aluminium smelter stage is defined as including three different processes; electrolysis, production of anodes and cast house, see **Figure 10.4**. The product flow of alumina feedstock is based on **Table 10.1**.

Data source	Alumina input per output of liquid aluminium, kg alumina/kg aluminium	Representativity
Aluminium, primary, at plant/RER (ecoinvent 2007)	1.920	1990s World (average of pre-bake and Søderberg)
European Commission (2001, p 284)	1.900-1.940	1990s European Union (Pre-bake technology)
EAA (2008)	1.923	2005 World (IAI) (average of pre-bake and Søderberg)
Alcoa Deschambault (Alcoa 2009a)	1.920	2008 for the Alcoa smelter in Deschambault in Canada (Pre-bake)
Alcoa Iceland (Alcoa 2009b)	1.920	2008 for the Alcoa smelter in Iceland (Pre-bake)
Applied data for aluminium	**1.920**	**2008 and future for all aluminium smelters**

Table 10.1: Comparison of alumina input to the electrolysis process per 1 kg output of liquid aluminium from different data sources. The alumina input per kg of liquid aluminium applied to this study is specified.

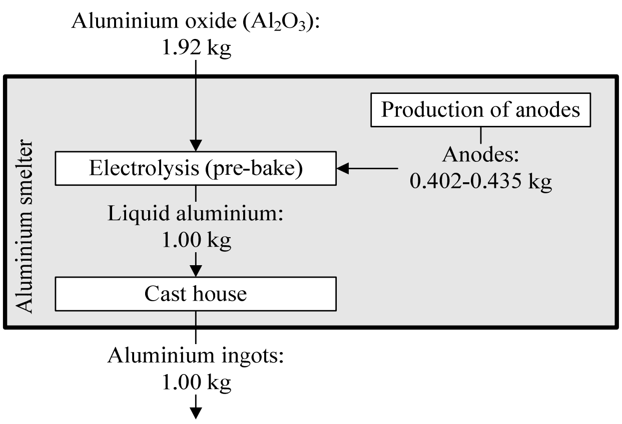

Figure 10.4: Processes and product flow at the aluminium smelter stage. The quantities of exchanges are specified in Table 10.1.

10.3 Hybridisation of the US IO data for the aluminium smelter stage

The approach to constructing LCI data on the aluminium smelter process involves the creation of a hybrid process. **Table 10.2** shows the inputs to the aluminium smelter processes that are based on IO data and those based on process data.

Exchanges	US IO data 98 (Suh 2004)	Hybrid-data	Process data
Raw materials (feedstock)		x	
Raw materials (ancillaries)			x
Fuels and energy			x
Transport of raw materials			x
Waste treatment			x
Capital goods (plant)	x		
Services	x		
Other non-service inputs	x		
Emissions			x

Table 10.2: Composition of hybrid processes in the aluminium smelter.

The product category 'Primary aluminium' in the US98 IO model includes the production of basic virgin aluminium. In the IO model, the reference flow of the process is 1 US$98. The price of aluminium in the USA in 1998, calculated as the weighted average of import and export prices of unwrought unalloyed aluminium, is 1.50 US$98 per kg (UN 2009). Thus, the reference flow of 1 US$98 can be immediately changed to 0.667 kg.

The following exchanges in the US IO model process of primary aluminium are replaced with more detailed data:

- Raw materials (feedstock): Internal flow of primary aluminium, scrap, alumina and bauxite
- Raw materials (ancillaries): Chemicals, cryolite, carbon materials for anodes, refractory
- Fuels and energy: Coal, gas, oil, and electricity
- Direct emission outputs

Process: Primary aluminium		
Product output	**Amount (US$98)**	**Description of modification**
Primary aluminium	0.8423	Internal flows (recycling and reshaping of ingots) are eliminated. The supply of the process (1 US$98) is reduced accordingly (1 - 0.1577 = 0.8423 US$98)
Product inputs before deletion of inputs	**Amount (US$98)**	
229 different product inputs (internal flow of primary aluminium accounts for 0.1577 US$98)	0.7765	
Deleted product inputs	**Amount (US$98)**	**Description of deleted input**
Raw materials (feedstock)		
Primary aluminium	0.1577	Internal flows (recycling and reshaping of ingots). The supply of the process (1 US$98) is reduced accordingly (1 - 0.1577 = 0.8433 US$98)
Scrap	0.07853	To be replaced with hybrid-data on alumina, see section 9. Input of scrap is not relevant to the production of virgin aluminium
Nonferrous metal ores, except copper	0.0012	This represents bauxite used in aluminium smelters, either because the plants are integrated alumina and smelter plants or because the material is used as refractory material.
Primary nonferrous metals, n.e.c.	0.01215	Alloying metals are deleted, see explanation in section 3.4
Primary smelting and refining of copper	0.0007263	
Copper ore	0.0009575	
Industrial inorganic and organic chemicals	0.04391	To be replaced with hybrid-data on alumina, see section 9
Raw materials (ancillaries)		
Products of petroleum and coal, n.e.c.	0.01465	To be replaced with process data on anodes, see section 10.5
Carbon and graphite products	0.007315	
Chemicals and chemical preparations, n.e.c.	0.001246	To be replaced with process data on chemicals, see section 10.5
Chemical and fertilizer minerals	0.000783	
Clay refractories	0.000002138	To be replaced with process data on refractories used in anode production and cast house, see section 10.5
Clay, ceramic, and refractory minerals	1.706E-07	
Nonclay refractories	0.00000232	
Fuels and energy		
Electric services (utilities)	0.08215	To be replaced with hybrid-data on electricity, see sections 5, 7.2, and 10.4
Natural gas distribution	0.01007	To be replaced with process data on fuels, see section 7.1
Crude petroleum and natural gas	0.006108	
Petroleum refining	0.00288	
Coal	0.000433	
Transport of raw materials		
Trucking and courier services, except air	0.05231	To be replaced with process data on transport, see section 7.3
Railroads and related services	0.01322	
Waste treatment		
Sanitary services, steam supply, and irrigation systems	0.006689	To be replaced with process data on waste treatment, see section 10.6
Sum of deleted inputs	**0.4931**	The sum of the deleted inputs corresponds to 62% of all inputs

Table 10.3: Preparation of US IO data for hybridisation. The table shows the product outputs and inputs of the IO data set. The lower part of the table shows all product inputs of the IO data set that have been deleted and are to be replaced with more accurate hybrid or process-based data.

10.4 Energy inputs

Different figures on the use of electricity in aluminium electrolysis and cast house are presented in **Table 10.4** and **Table 10.5**, respectively. The tables also specify the applied energy uses in the included scenarios (lower part of the tables). It should be noted that, in all data provided by Alcoa (2009a and 2009b), the total use of electricity is reported as being used in the electrolysis; i.e., the use of electricity in cast house and anode production appears as being zero. However, since the use of electricity in these two processes is insignificant (see

Table 10.4 and **Table 10.5**), this is not regarded as a problem. Therefore, the data applied to the processes of cast house and anode production will appear as having no electricity use, because this is included in the electrolysis process.

Energy inputs to the electrolysis process

Electricity: It should be noted that the data on electricity from Alcoa used for the electrolysis includes electricity used in cast house (and anode production for smelter in Deschambault). Therefore, when applying the data on electricity provided by Alcoa to the electrolysis process, the anticipated electricity use for the cast house (and for anode production for Deschambault smelter) should be subtracted from the specified electricity use.

Differences in the electricity use for the electrolysis process in scenario 0 are taken into account via scenario 0, which represents a new smelter, and scenario 0p, which represents a smelter with existing technology (current average).

Production of liquid aluminium (electrolysis): 1 kg of liquid aluminium						
Data source	**Electricity**	**Gas**	**Oil, heavy**	**Oil, light**	**Diesel**	**Representativity**
	kWh/kg	MJ/kg	MJ/kg	MJ/kg	MJ/kg	
Alcoa Deschambault (Alcoa 2009a)	14.4*	-	-	-	0.0666	2007 for the Alcoa smelter in Deschambault in Canada (Pre-bake)
Alcoa Iceland (Alcoa 2009b)	13.4*	-	-	-	0.0595	2007 for the new Alcoa smelter in Iceland (Pre-bake)
Aluminium, primary, at plant/RER (ecoinvent 2007)	15.6	0.084	-	0.089	-	1995-2002 World (pre-bake/Søderberg)
European Commission (2001, p 284)	12.9 - 15.5	n.a.				1990s EU (pre-bake)
European Commission (2001, p 284)	14.5-17.0					1990s EU (Søderberg)
EAA (2008, p 27):						
Europe, EAA (1998)	15.6	0.117	-	0.0288	0.0641	1998 Europe (pre-bake/Søderberg)
Europe, EAA (2002)	15.4	-	-	-	-	2002 Europe (pre-bake/Søderberg)
Europe, EAA (2005)	14.9	-	-	-	-	2005 Europe (pre-bake/Søderberg)
World (IAI) (2000)	15.4	-	-	-	-	2000 World (pre-bake/Søderberg)
World (IAI) (2005)	15.3	-	-	-	-	2005 World (pre-bake/Søderberg)
Scenario 1: Data applied to Alcoa smelter in Greenland						
Sc1: Alcoa Greenland smelter	13.3**	-	-	-	0.0595	New Alcoa smelter
Sc1a: Alcoa Greenland smelter (existing smelter)	15.3	-	-	-	0.0666	Existing smelter technology
Scenario 0: Data applied to smelters included in the 0 alternative						
Sc 0: Aluminium smelter (new)	13.3**	-	-	-	0.0595	New smelter, marginal aluminium production, World
Sc 0p: Aluminium smelter (existing)	15.3	-	-	-	0.0666	Existing smelter, World
Scenario 2: Data applied to Alcoa smelters in Deschambault and Iceland (scenarios for comparison)						
Sc 2a: Alcoa Deschambault smelter	14.2***	-	-	-	0.0666	Existing Alcoa smelter
Sc 2b: Alcoa Iceland smelter	13.3**	-	-	-	0.0595	New Alcoa smelter

Table 10.4: Comparison of different data on energy use in aluminium electrolysis (upper part of the table). The data applied to the different scenarios is specified in the lower part of the table.

*The data on electricity from Alcoa includes electricity used for casting

The applied electricity use based on data on the Alcoa Iceland smelter is the specified value minus the electricity use in cast house (see **Table 10.5)

***The applied electricity use based on data on the Alcoa Deschambault smelter is the specified value minus the electricity use in cast house (see **Table 10.5**) and the electricity use in anode production (see **Table 10.8**)

Energy inputs to the cast house process

The energy inputs to the cast house are shown in **Table 10.5**. It appears that the fuel inputs (and process heat), according to EAA (2008), are significantly higher compared to the figures of the other data sources. The reason for the generally higher energy input in the European smelter cast houses is the fact that more clean scrap is remelted and this process requires more energy and a more targeted product spectre, including more treatment and finishing. For all scenarios including new aluminium smelters, it has been assumed that the cast house do not have remelting of scrap. Therefore, the fuel uses, as provided by Alcoa, are assumed to represent new smelters. For the scenarios involving existing smelters (Sc1a and Sc0p), figures of world average in 2005 (EAA 2008) have been applied, except from the fact that heavy fuel oil will not be used in the Greenland smelter Sc1a (Alcoa 2009a). Instead, the 0.235 MJ/kg of alu (heavy fuel oil used in world average 2005) have been added to the use of natural gas; i.e. 1.17 + 0.235 = 1.41 MJ/kg of alu in scenario 1a: Greenland smelter (existing).

Production of aluminium ingots (casting): 1 kg of aluminium ingot							
Data source	**Electricity**	**Gas**	**Coal**	**Oil, heavy**	**Oil, light**	**Diesel**	**Representativity**
	kWh/kg	MJ/kg	MJ/kg	MJ/kg	MJ/kg	MJ/kg	
Alcoa Deschambault (Alcoa 2009a)	n.a.	0.174	-	-	-	-	2007 for the Alcoa smelter in Deschambault in Canada
Alcoa Iceland (Alcoa 2009b)	n.a.	0.0698*	-	-	-	-	2007 for the new Alcoa smelter in Iceland
Aluminium, primary, at plant/RER (ecoinvent 2007)	0.016	0.641	-	-	0.441	-	1995-2002 World
EAA (2008, p 27):							
Europe, EAA (1998)	0.016	0.676	-	0.449	-	0.00427	1998 Europe
Europe, EAA (2005)	0.126	0.987	0.0288	0.317	-	0.0342	2005 Europe
World (IAI) (2000)	0.081	2.02	-	0.412	-	0.00427	2000 World
World (IAI) (2005)	0.083	1.17	-	0.235	-	0.0598	2005 World
Scenario 1: Data applied to Alcoa smelter in Greenland							
Sc1: Alcoa Greenland smelter	0.083	0.0698	-	-	-	-	New Alcoa smelter
Sc1a: Alcoa Greenland smelter (existing smelter)	0.083	1.41	-	-	-	0.0598	Existing smelter technology
Scenario 0: Data applied to smelters included in the 0 alternative							
Sc 0: Aluminium smelter (new)	0.083	0.0698	-	-	-	-	New smelter, marginal aluminium production, World
Sc 0p: Aluminium smelter (existing)	0.083	1.17	-	0.235	-	0.0598	Existing smelter, World
Scenario 2: Data applied to Alcoa smelters in Deschambault and Iceland (scenarios for comparison)							
Sc 2a: Alcoa Deschambault smelter	0.083	0.174	-	-	-	-	Existing Alcoa smelter
Sc 2b: Alcoa Iceland smelter	0.083	0.0698	-	-	-	-	New Alcoa smelter

Table 10.5: Comparison of different data on energy use in aluminium casting (upper part of the table). The data applied to the different scenarios is specified in the lower part of the table. *The gas used at the Alcoa Iceland smelter is propane; it is assumed that the use of propane is associated with the same emissions per MJ as natural gas.

10.5 Material inputs

Material inputs to the electrolysis process

The material inputs to be considered for the aluminium smelter are: Anode, aluminium fluoride, cathode, cryolite, and refractory materials. All other material inputs are regarded as being included via the IO data described in section 10.3. The material inputs in **Table 10.6** only include the inputs to the electrolysis process. The material input to the anode production is specifically dealt with in **Table 10.8**. There are no material inputs to the cast house which are not covered by the IO data. However, one important material input has been excluded, i.e. alloy metals. Data from Alcoa (2009a) and EAA (2008) specifies that around 2% of the feedstock input to the cast house is alloy metals (e.g. copper, zinc, manganese, silicon, and magnesium). However, since the alloy is designed for specific characteristics at the use stage, it would not provide additional information to include the alloy metals here. The purpose of the project is to assess the environmental performance of aluminium production. Since the use of alloy metals can be assumed to be the same in all regions of the world, it is assumed that 100% of the feedstock to the cast house is comprised of liquid aluminium from the electrolysis process. This assumption is in line with the one used in EAA (2008).

In **Table 10.6** below, the use of anodes is specified both as net and gross weight. Gross weight represents the actual use including the amount of anodes which are sent to recycling. When the anode is used, the remaining part is sent to recycling, where the material is used for the production of new anodes. Some data sources only provide the use of anodes as net weight, i.e. gross weight minus the amount which is sent to recycling.

Anode: According to the data sources used, the use of anodes varies between 0.402 and 0.435 kg net weight, i.e. gross input minus amount of used anodes which are recycled into new anodes. Most of the data sources only provide information on the net consumption of anodes. However, this way of modelling does not correspond to the way in which recycling is modelled in this study. The use of anodes will always affect the production of anodes in gross weight, because this is the actual weight of the anodes used. Then, after use, the remaining part of the used anode can be sent to recycling locally in the smelter (as in the Alcoa Deschambault smelter) or shipped to recycling elsewhere (as in the Alcoa Iceland smelter and the planned Greenland smelter). When the used anode is sent to recycling, this is included in the analysis as the avoided production of the corresponding 'virgin' materials. Therefore, the net weight has to be transformed into gross weights. Two data sources provide the use of anodes as both net and gross weight; i.e., EAA (2008, p 27) and Alcoa (2009a). According to EAA (2008), the gross/net weight ratio is 1.244, and according to Alcoa (2009a), the ratio is 1.220. It is assumed that reported net uses of anodes can be converted into gross weight by multiplying the use by 1.244 for the zero alternatives and 1.220 for the Greenland smelter as well as the other Alcoa smelters (Deschambault and Iceland). In **Table 10.6**, the gross weight in anode input is marked with * if it is calculated using the gross/net ratio. The difference between gross weight and net weight is included as anode waste sent to recycling; this is described in section 10.6.

For scenario 1: Alcoa smelter in Greenland, the same use of anodes has been applied as for the Alcoa Deschambault smelter. In scenario 0: new smelter (Sc0) and scenario 0: existing smelter (Sc0p), the anode use in the Alcoa Deschambault smelter and the world average 2005 (EAA 2008), respectively, have been applied.

According to Alcoa, the use of anodes in Deschambault and Iceland differs slightly. However, a slightly higher use in Iceland is caused by the fact that the facility was not yet running optimally, when the data was collected. Therefore, Deschambault figures have been applied to the Iceland smelter.

Aluminium fluoride and cathode: The uses of aluminium fluoride and cathode in the different scenarios follow the same logic as the use of anodes.

Cryolite: Regarding cryolite which is used as bath for the electrolysis process, this is included in the data from ecoinvent (2007) but not in the data from Alcoa and from EAA (2008). The reason that the cryolite is not included as a material input is that a substitute for cryolite is produced on-site as a by-product from alumina residues (sodium). According to Alcoa some smelters have excess production of bath and others have not, depending on the source of the alumina. It is assumed that all aluminium smelters are self sufficient with cryolite substitute. Therefore, the use of cryolite is set to zero.

Production of liquid aluminium (electrolysis): 1 kg of liquid aluminium						
Data source	Anode (net/gross)	Aluminium fluoride	Cathode	Cryolite	Refractory	**Representativity**
	kg/kg	kg/kg	kg/kg	kg/kg	kg/kg	
Comparison of different data sources						
Alcoa Deschambault (Alcoa 2009a)	0.402/0.490	0.0146	0 00512	0	0.00493	2007 for the Alcoa smelter in Deschambault in Canada (Pre-bake)
Alcoa Iceland (Alcoa 2009b)	0.402/0.490*	0.0146	0.00512	0	n.a.	2007 for the new Alcoa smelter in Iceland (Pre-bake)
Aluminium, primary, liquid, at plant/RER (ecoinvent 2007)	0.448/0.548*	0.0187	0.0181	0.00160	n.a.	1995-2002 World (pre-bake/Søderberg)
European Commission (2001, p 284)	0.400-0.440/ 0.490-0.539*	0.015-0.025	n.a.	n.a.	n.a.	1990s EU (pre-bake)
EAA (2008)						
Europe, EAA (1998)	0.448/0.557	0.0187	0.0075	n.a.	0.0086	1998 Europe (pre-bake/Søderberg)
Europe, EAA (2002)	0.447/0.553	0.0190	0.0103	n.a.	0.00988	2002 Europe (pre-bake/Søderberg)
Europe, EAA (2005)	0.428/0.536	0.0189	0.0063	n.a.	0.0086	2005 Europe (pre-bake/Søderberg)
World (IAI) (2000)	0.441/0.540*	0.0174	0.0061	n.a.	0.0061	2000 World (pre-bake/Søderberg)
World (IAI) (2005)	0.435/0.532*	0.0164	0.0080	n.a.	0.0054	2005 World (pre-bake/Søderberg)
Scenario 1: Data applied to Alcoa smelter in Greenland						
Sc1: Alcoa Greenland smelter	0.402/0.490	0.0146	0.00512	0	0.00493	New Alcoa smelter
Sc1a: Alcoa Greenland smelter (existing smelter)	0.435/0.532	0.0164	0.00512	0	0.00493	Existing smelter technology
Scenario 0: Data applied to smelters included in the 0 alternative						
Sc 0: Aluminium smelter (new)	0.402/0.490	0.0146	0 00512	0	0.00493	New smelter, marginal aluminium production, World
Sc 0p: Aluminium smelter (existing)	0.435/0.532	0.0164	0.00512	0	0.00493	Existing smelter, World
Scenario 2: Data applied to Alcoa smelters						
Sc 2a: Alcoa Deschambault smelter	0.402/0.490	0.0146	0 00512	0	0.00493	Existing Alcoa smelter
Sc 2b: Alcoa Iceland smelter	0.402/0.490	0.0146	0.00512	0	0.00493	New Alcoa smelter

Table 10.6: Comparison of different data on material use in the aluminium electrolysis process (upper part of the table). The data applied to the different scenarios is specified in the lower part of the table. *Anode amounts (gross) which are marked with * are calculated by multiplying the net use by 1.244 (scenario Sc0) and 1.220 (scenario Sc1 and Sc2a and Sc2b), as described above the table.

Material inputs to the cast house process

The only material input included in the cast house process is 0.0007 kg refractory per kg aluminium ingot (EAA 2008, ecoinvent 2007).

LCI data on materials

The applied LCI data on the four considered material inputs are shown in **Table 10.7**.

Material input	Applied LCI data
Anode	see **Table 10.8**
Aluminium fluoride	Aluminium fluoride, at plant/RER (ecoinvent 2007)
Cathode	Cathode, aluminium electrolysis/RER (ecoinvent 2007)
Refractory	Refractory, fireclay, packed, at plant/DE (ecoinvent 2007)

Table 10.7: Applied LCI data on material inputs to the aluminium smelter.

The LCI data used for anodes is presented in **Table 10.8**, which also compares data from ecoinvent, EAA, and Alcoa. The data from ecoinvent and from EAA represents anodes containing a share of recycled butts (used anodes). Since the benefits from recycling anodes are included in this study as avoided use of anodes related to the waste from the smelter (see section 10.6), the LCI data used represents virgin anodes. Therefore, the applied data represents up-scaled figures from the data sources which represent anodes containing recycled material. According to the data for Europe 2005 in EAA (2008), anodes are based on 16.3% recycled butts. Therefore, the data should be scaled up accordingly (by multiplying by 1.194). In this respect, it should be noted that only the material inputs of bitumen and petrol coke are scaled up. The remaining exchanges are assumed not to be affected by the creation of a ‘virgin anode’ process based on a ‘partly recycled anode’ process.

It should be noted that the way in which the recycling of anodes is modelled here leads to the same result as if the approach used in ecoinvent and EAA was used. However, we argue that the modelling used here is more correct. This is due to the point that the choice of whether to send used anodes to recycling or not determines the amount of recycled anodes. It is not determined by the use of anodes containing a specified percentage of recycled used anodes.

Generally, the applied LCI data on anodes is based on Alcoa (2009a). In cases in which this data is not applicable, EAA (2008), representing European technology in 2005, has been used. Since most of the ecoinvent data is based on older data from EAA, the EAA (2008) data is preferred over ecoinvent data. In relation to the data on exchanges of refractory (incl. waste treatment), electricity, and process heat, some further comments are needed. These are presented below:

Refractory: The input of refractory is the same as the amount sent to waste treatment.

Electricity: Most aluminium smelters have their own anode production. Thus, the electricity mix is the same as used for the electrolysis process. But exceptions can be found; the smelter in Iceland and the proposed smelter in Greenland do not have their own production of anodes. Therefore, for the anodes used here, the electricity mix used in scenario 0 is applied (marginal aluminium production).

Process heat (fuel oil and gas): The total use of process heat (2.5 MJ/kg of anodes) is assumed to be represented by the data from Alcoa for all included productions of anodes. For the smelter in Greenland (as well as for the other Alcoa smelters which have reported that they use gas), 100% gas is assumed. For scenario 0, 80% gas and 20% fuel oil are assumed, reflecting the mix in Europe in 2005, according to EAA (2008).

Production of anodes: 1 kg of anodes (0% recycled)					
Interventions	**ecoinvent (2007)**	**EAA (2008), Europe 2005**	**Alcoa (2009a)**	**Applied amounts**	**Comments and applied LCI data**
Product outputs					
Anode	1 kg	1 kg	1 kg	1 kg	Reference flow
Material inputs					
Bitumen	0.164 kg	0.173 kg	0.130 kg	0.204 kg	Bitumen, at refinery/RER (ecoinvent 2007)
Petroleum coke	0.649 kg	0.737 kg	0.690 kg	0.871 kg	Petroleum coke, at refinery/RER (ecoin-vent 2007)
Recycled butts	not specified	0.156 kg	0.180 kg	0 kg	-
Water	4.3 kg	4.4 kg	-	-	Included via IO data
Cast iron	0.00781 kg	0.0012 kg	0.00029 kg	-	Included via IO data
Refractory fire clays	0.0101 kg	0.011 kg	0.00496 kg	0.00496 kg	Refractory, fireclay, packed, at plant/DE (ecoinvent 2007)
Energy inputs					
Electricity	0.131 kWh	0.145 kWh	-	0.145 kWh	For Greenland and Iceland smelter, electricity mix for Scenario 0 is used because there is no production of an-odes. For other smelters, the same electricity mix as for the smelter is used, see **Table 5.7**
Heat, light fuel oil	0.935 MJ	-	-	-	-
Heat, heavy fuel oil	-	0.585 MJ	-	2.50 MJ	Sc1: Greenland, 100% gas Sc0:Marginal, 80% gas/20% oil Sc2: Alcoa plants, 100% gas LCI data, see section 7.1
Heat, natural gas	1.9 MJ	2.23 MJ	2.50 MJ		
Diesel, internal transport	-	0.000854 MJ	-	0.000854 MJ	See section 7.1
Transport					
Lorry	83.1 kgkm	-	-	249 kgkm	See section 7.3
Train	166 kgkm	-	-	-	
Capital goods inputs					
Anode production plant	2.5E-10 p	-	-	-	Included via IO data
Various inputs	-	-	-	-	Included via IO data
Service inputs					
Various inputs	-	-	-	-	Included via IO data
Waste service inputs (waste to treatment)					
Asphalt to landfill	0.0007 kg	0.0017 kg	n.a.	0.075 kg	Feedstock (0.204+0.871) minus 1 kg anode. Disposal, asphalt, 0.1% water, to sanitary landfill/CH (ecoinvent 2007)
Refractory material to landfill	0.0039 kg	0.0004 kg	n.a.	0.00496 kg	Same amount as use of refractory: Disposal, refractory SPL, Al elec.lysis, 0% water, to residual material landfill/CH (ecoinvent 2007)
Inert waste to landfill	0.0105 kg	0.0026 kg	n.a.	0 kg	Assumed to be included in refractory material to landfill above
Scrubber sludge to landfill	-	0.0006 kg	n.a.	0.0006 kg	Disposal, inert waste, 5% water, to inert material landfill/CH (ecoinvent 2007)
Refractory material to re-use	-	0.006 kg	n.a.	0 kg	The net use of refractory is applied – therefore reuse is not visible in the fig-ures
Steel to recycling	-	0.0041 kg	n.a.	0.0041 kg	0.0041 kg 'Steel, electric, un- and low-alloyed, at plant/RER' (virgin feedstock deleted) minus 0.0041 'Steel, converter, unalloyed, at plant/RER' (ecoinvent 2007)
Other by-products to recycling (not specified)	-	0.0105 kg	n.a.	0 kg	-

Table 10.8: Applied LCI data on the production of anodes. The table is continued on the next page.

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Interventions	ecoinvent (2007)	EAA (2008), Europe 2005	Alcoa (2009a)	Applied amounts	Comment
Emissions to air					
Benzo(a)pyrene	3.18E-6 kg	1.4E-7 kg	-	1.4E-7 kg	
Carbon dioxide	0.253 kg	-	0.100 kg	0.100 kg	Part of the carbon in the pitch and coke is
Carbon monoxide	0.00104 kg	-	-	0 kg	released from the anodes during baking
Hydrogen fluoride	9.0E-5 kg	-	-	9.0E-5 kg	
Fluoride (as F)	-	5.2E-5 kg	9E-7 kg	-	
Fluoride particulate (as F)	-	3.5E-5 kg		-	
Nitrogen oxides	0.00019 kg	0.00032 kg	-	0.00032 kg	
PAH, polycyclic aromatic hydrocarbons	9.48E-5 kg	5.1E-5 kg	2.6E-6 kg	2.6E-6 kg 5.1E-5 kg	Alcoa smelters: 2.6E-6 kg Scenario 0: 5.1E-5 kg
Particulates, < 2.5 um	8.68E-5 kg	-	-	8.68E-5 kg	
Particulates, > 2.5 um, and < 10um	0.000143 kg	-	-	0.000143 kg	
Particulates, > 10 um	0.00013 kg	-	-	0.00013 kg	
Particles (total)	-	0.00021 kg	-	-	
Sulfur dioxide	0.00084 kg	0.00154 kg	-	0.00154 kg	

Table 10.8 - continued: Applied LCI data on the production of anodes. The table is continued on the next page.

10.6 Waste/by-product treatment

This section describes the waste produced and the waste treatment. Generally, the produced waste accounts for an insignificant contribution to the environmental impacts; e.g., the GHG emissions associated with the waste and related treatments from the electrolysis and cast house for the Greenland smelter account for less than 0.3%. Therefore, for some minor waste outputs, the same waste treatment has been applied to all scenarios, and uncertainties as well as minor inconsistencies when compared with material inputs are accepted. This implies that the recycling of some waste flows has not been included, e.g., recycling of refractory. However, since the landfill of this mainly inert material is not associated with any significant environmental impacts and the recycling of refractory only displaces alternative products of environmentally insignificant materials (mainly sand), then the omission of recycling for minor waste flows is regarded as having insignificant effects on the results of the LCA.

Waste outputs from the electrolysis process

The amount of anode waste to recycling is calculated as the gross use minus the net use of anodes.

Electrolysis: Waste output per kg liquid aluminium	Aluminium, primary, liquid, at plant/RER (ecoinvent 2007)	EAA (2008)	Alcoa (2009a)	**Applied to this study**	**LCI data**
Representativity	Europe 2000-04	World 2005	Alcoa Deschambault		
Used anodes (recycling)	n.a.	0.0048 kg	0.088 kg	Sc1a and 0p: 0.097 kg else 0.088 kg	Avoided: Petroleum coke, at refinery/RER (ecoinvent 2007)
Carbon waste (from dust collectors or from the pots mixed with bath)	0.0012 kg	0.0069 kg	n.a.	0 kg	Assumed to be included in 'scrubber sludge and filter dust (landfill)' below
Refractory (recycling)	n.a.	0.0065 kg	n.a.	0 kg	-
Refractory (landfill)	0.0019 kg	0.0137 kg	0.0157 kg	0.0157 kg	Disposal, refractory SPL, Al elec.lysis, 0% water, to residual material landfill/CH (ecoinvent 2007)
Steel waste (recycling)	n.a.	0.0089 kg	n.a.	0.0089 kg	0.0089 kg 'Steel, electric, un- and low-alloyed, at plant/RER' (virgin feedstock deleted) minus 0.0089 'Steel, converter, unalloyed, at plant/RER' (ecoinvent 2007)
Scrubber sludge and filter dust (landfill)	0.002 kg	0.0047 kg	0.0003 kg	0.002 kg	Disposal, filter dust Al electrolysis, 0% water, to residual material landfill/CH (ecoinvent 2007)
Other inert waste	0.005 kg	0.0026 kg	0.00064 kg	0.002 kg	Disposal, inert waste, 5% water, to inert material landfill/CH (ecoinvent 2007)

Table 10.9: Comparison of waste outputs related to the electrolysis process per 1 kg of liquid aluminium. The waste outputs per kg of liquid aluminium applied to this study are specified.

Waste outputs from the cast house process

In **Table 10.10** below, the waste outputs from the cast house are shown. Recycling of dross is modelled as landfill of hazardous waste, because the recycling includes the recovery of aluminium. As a rough estimate, the recovered aluminium is assumed to constitute only a minor amount of the dross. Therefore, it is modelled as landfill. Also filter dust is assumed to be landfilled.

Cast house: Waste output per kg of aluminium ingot	Aluminium, primary, at plant/RER (ecoinvent 2007)	EAA (2008)	Alcoa (2009a)	**Applied to this study**	**LCI data**
Representativity	Europe 2000-04	World 2005	Alcoa Deschambault		
Dross (recycling)	-	0.0133 kg	0.00626 kg	0.00626 kg	No data is applied: Dross is loss of feedstock input (liquid aluminium). Internal recycling is included since no loss of feedstock is included in the cast house process (100% recycling is assumed in all scenarios)
Dross (landfill)	0.00011 kg	0.0025 kg	n.a.	0 kg	-
Filter dust (recycling)	-	0.00063 kg	n.a.	0 kg	-
Filter dust (landfill)	-	0.00015	0.00001 kg	0.00015 kg	Disposal, filter dust Al electrolysis, 0% water, to residual material landfill/CH (ecoinvent 2007)
Refractory (recycling)	-	0.00024 kg	0.00036 kg	0 kg	-
Refractory (landfill)	-	0.0012 kg	0.00005 kg	0.0014 kg	Disposal, refractory SPL, Al elec.lysis, 0% water, to residual material landfill/CH (ecoinvent 2007)
Other waste	0.00099 kg	0.0002 kg	n.a.	0 kg	-

Table 10.10: Comparison of waste outputs related to the cast house process per 1 kg of aluminium ingot. The waste outputs per kg aluminium ingot applied to this study are specified.

10.7 Transport

Transport of the material and fuel inputs is described in this section. **Table 10.11** shows the data used for transport, i.e., the amount of material transported, assumed transport distances, and means of transportation.

The transport distances are very roughly estimated, and for insignificant transported amounts, e.g. fuels, the same transported amount has been assumed for all scenarios. Transport only accounts for around 8% of the total inputs to the aluminium smelter stage (Greenland smelter) (see **Table 11.1**), and therefore the assumptions are only subject to insignificant uncertainties.

The applied LCI data on transport is described in section 7.3.

Transported material	Amount	Distance	Transport	Means of transportation
Alumina	1.920 kg	10,000 km	19,200 kgkm	Freight ship
Anodes, new				
Sc1	0.490 kg	3000 km	1,470 kgkm	Freight ship
Sc0	-	-	-	-
Sc0p	-	-	-	-
Sc2a	-	-	-	-
Sc2b	0.490 kg	2000 km	980 kgkm	Freight ship
Anodes, used for recycling				
Sc1	0.088 kg	3000 km	264 kgkm	Freight ship
Sc0	-	-	-	-
Sc0p	-	-	-	-
Sc2a	-	-	-	-
Sc2b	0.088 kg	2000 km	176 kgkm	Freight ship
Aluminium fluoride	0.0146 kg	10,000 km	146 kgkm	Freight ship
Cathode	0.00512 kg	3000 km	15.4 kgkm	Freight ship
Refractory	0.00563	3000 km	16.9 kgkm	Freight ship
Fuels (insignificant amount, and same transport assumed for all scenarios)	0.0015 kg	3000 km	4.5 kgkm	Freight ship

Table 10.11: Transport of material input (includes transportation of materials used in electrolysis as well as cast house). The fuel uses in **Table 10.4** and **Table 10.5** are converted from energy unit to mass unit using data on calorific value given in Appendix 1: Data on fuels and flue gasses.

10.8 Emissions

In **Table 10.12** and **Table 10.13**, emissions from the electrolysis and cast house processes in different references are compared, and the data applied to the included scenarios is specified.

Generally, it has been assumed that emission levels of the Iceland smelter serve as the best representation of the anticipated emissions from a new smelter in Greenland as well as the zero scenario (Sc0), and that data for Europe in 2005, as specified in EAA (2008), represents existing aluminium smelters (scenario 0p). Since the CO_2 emissions originate from the net use of anodes, the applied CO_2 emissions are calculated as proportional to the net use of anodes (**Table 10.6**). In this regard, the data provided for the Iceland smelter is used as reference.

Electrolysis: Emissions per kg of liquid aluminium					Applied values			
Emissions to air	**ecoinvent (2007)**	**EAA (2008), Europe 2005**	**Descham-bault: Alcoa (2009a)**	**Iceland: Alcoa (2009b)**	**Sc1 and Sc0**	**Sc1a and Sc0p**	**Sc2a**	**Sc2b**
Benzo(a)pyrene	1.3E-6 kg	1.3E-6 kg	0 kg	-	0 kg	1.3E-6 kg	0 kg	0 kg
Carbon dioxide	1.5 kg	-	1.44 kg	1.44 kg	1.44 kg	1.56 kg	1.44 kg	1.44 kg
Carbon monoxide	0.0917 kg	-	0.09 kg	0.094 kg	0.094 kg	0.094 kg	0.094 kg	0.094 kg
PFCs: Ethane, hexafluoro-, HFC-116	2.8E-5 kg	1E-5 kg	-	-	-	-	-	v
PFCs: Methane, tetrafluoro-, CFC-14	2.52E-4 kg	8.7E-5 kg	-	-	-	-	-	
PFCs: Total, as CO2e	1.77 kg*	0.615 kg	0.0712 kg	-	0.0712 kg	0.615 kg	0.0712 kg	0.0712 kg
Hydrogen fluoride	5.39E-4 kg	-	1.7E-4 kg	2.09E-4 kg	2.09E-4 kg	5.39E-4 kg	1.7E-4 kg	2.09E-4 kg
Fluoride (as F)		0.00056 kg	-	-	-	-	-	-
Fluoride particulate (as F)		0.00044 kg	-	-	-	-	-	-
Nitrogen oxides	6.39E-5 kg	6.5E-4 kg	1.5E-6 kg	1.6E-5 kg	1.6E-5 kg	6.5E-4 kg	1.5E-6 kg	1.6E-5 kg
PAH, polycyclic aromatic hydrocar-bons	4.57E-5 kg	4.1E-5 kg	1.45E-7 kg	-	1.45E-7 kg	4.1E-5 kg	1.45E-7 kg	1.45E-7 kg
Particulates, < 2.5 um	0.00261 kg	-	-	-				
Particulates, > 2.5 um, and < 10um	6.09E-4 kg	-	-	-				
Particles (total)	-	0.0023 kg	0.00018 kg	0.00042 kg	0.00042 kg	0.0023 kg	0.00018 kg	0.00042 kg
Sulfur dioxide	0.00883 kg	0.0082 kg	0.016 kg	0.0107 kg	0.0107 kg	0.016 kg	0.016 kg	0.0107 kg

Table 10.12: Comparison of emissions related to the electrolysis process per 1 kg of liquid aluminium. The emissions per kg of liquid aluminium applied to this study are specified. *PFCs measured in CO2e are calculated using the Stepwise LCIA method for global warming (Weidema et al. 2007).

Cast house: Emissions per kg of aluminium ingot				
Emissions to air	**ecoinvent (2007)**	**EAA (2008), Europe 2005**	**Deschambault: Alcoa (2009a)**	**Applied values**
Hydrogen fluoride	3.0E-6 kg	-	4E-6 kg	4E-6 kg
Nitrogen oxides	-	1.7E-4 kg	-	1.7E-4 kg
Particulates, > 2.5 um, and < 10um	7.0E-6 kg	-	-	-
Particles (total)	-	4.2E-5 kg	6E-6 kg	6E-6 kg
Sulfur dioxide	-	3.2E-4 kg	-	3.2E-4 kg
Hydrogen chloride	-	4.2E-5 kg	-	4.2E-5 kg

Table 10.13: Comparison of emissions related to the cast house process per 1 kg of aluminium ingot. The emissions applied to this study are specified.

10.9 Summary of the LCI of the aluminium smelter stage

Table 10.14 and **Table 10.15** summarise the interventions related to the electrolysis and the cast house processes, respectively.

Electrolysis process: 1 kg of liquid aluminium						
Interventions	**Sc1 (new)**	**Sc0 (new)**	**Sc1a and Sc0p (existing)**	**Sc2a: Descham-bault**	**Sc2b: Iceland**	**Applied LCI data**
Product outputs						
Liquid aluminium	1 kg					Reference flow
Material inputs						
Alumina	1.920 kg					See **Table 9.8**
Anode gross	0.490 kg	0.490 kg	0.532 kg	0.490 kg	0.490 kg	See **Table 10.8**
Cathode	0.00512 kg					Cathode, aluminium elec-trolysis/RER (ecoinvent 2007)
Aluminium fluoride	0.0146 kg					Aluminium fluoride, at plant/RER (ecoinvent 2007)
Refractory	0.00493 kg					Refractory, fireclay, packed, at plant/DE (ecoinvent 2007)
Energy inputs						
Electricity	13.3 kWh	13.3 kWh	15.3 kWh	14.2 kWh	13.3 kWh	Depends on electricity sce-nario, see **Table 5.7**
Diesel	0.0595 MJ	0.0595 MJ	0.0666 MJ	0.0666 MJ	0.0595 MJ	See section 7.1
Transport						
Freight ship	21,117 kgkm	19,383 kgkm	19,383 kgkm	19,383 kgkm	20,539 kgkm	See section 7.3
Other inputs						
IO data	1 kg					See section 9.3
Waste to treatment						
Used anodes to recycling	0.0880 kg	0.0880 kg	Sc1a: 0 kg Sc0p: 0.0901 kg	0.0880 kg	0.0880 kg	Avoided: Petroleum coke, at refinery/RER (ecoinvent 2007)
Used anodes to landfill	-	-	0.0069 kg	-	-	Disposal, bitumen, 1.4% water, to sanitary landfill/CH (ecoinvent 2007)
Refractory (landfill)	0.0157 kg					Disposal, refractory SPL, Al elec.lysis, 0% water, to residual material landfill/CH (ecoinvent 2007)
Steel waste (recycling)	0.0089 kg					0.0089 kg ‘Steel, electric, un- and low-alloyed, at plant/RER’ (virgin feedstock deleted) minus 0.0089 ‘Steel, converter, unalloyed, at plant/RER’ (ecoinvent 2007)
Scrubber sludge and filter dust (landfill)	0.002 kg					Disposal, filter dust Al elec-trolysis, 0% water, to residual material landfill/CH (ecoin-vent 2007)
Other inert waste	0.002 kg					Disposal, inert waste, 5% water, to inert material land-fill/CH (ecoinvent 2007)
Emissions to air						
Benzo(a)pyrene	0 kg	0 kg	1.3E-6 kg	0 kg	0 kg	Emission
Carbon dioxide	1.44 kg	1.44 kg	1.56 kg	1.44 kg	1.54 kg	
Carbon monoxide, fossil	0.094 kg	0.094 kg	0.094 kg	0.094 kg	0.094 kg	
PFCs: Total, as CO2e	0.0712 kg	0.0712 kg	0.615 kg	0.0712 kg	0.0712 kg	
Hydrogen fluoride	2.09E-4 kg	2.09E-4 kg	5.39E-4 kg	1.7E-4 kg	2.09E-4 kg	
Nitrogen oxides	1.6E-5 kg	1.6E-5 kg	6.5E-4 kg	1.5E-6 kg	1.6E-5 kg	
PAH, polycyclic aromatic hydrocarbons	1.45E-7 kg	1.45E-7 kg	4.1E-5 kg	1.45E-7 kg	1.45E-7 kg	
Particles (total)	0.00042 kg	0.00042 kg	0.0023 kg	0.00018 kg	0.00042 kg	
Sulphur dioxide	0.0107 kg	0.0107 kg	0.016 kg	0.016 kg	0.0107 kg	

Table 10.14: Interventions in the electrolysis process per kg of liquid aluminium.

Cast house process: 1 kg of aluminium ingot						
Interventions	**Sc1 (new)**	**Sc0 (new)**	**Sc1a and Sc0p (existing)**	**Sc2a: Deschambault**	**Sc2b: Iceland**	**Applied LCI data**
Product outputs						
Aluminium ingot	1 kg					Reference flow
Material inputs						
Liquid aluminium	1 kg					See **Table 10.14**
Energy inputs						
Electricity	0.083 kWh					Depends on electricity scenario, see **Table 5.7**
Natural gas	0.0698 MJ	0.695 MJ	1.17 MJ	0.174 MJ	0.0698 MJ	See section 7.1
Heavy fuel oil	-	-	0.235 MJ	-	-	
Diesel	-	-	0.0666 MJ	-	-	
Transport inputs						
No transport	-					Insignificant transport of refractory material is included in electrolysis process
Waste to treatment						
Filter dust (landfill)	0.00015 kg					Disposal, filter dust Al electrolysis, 0% water, to residual material landfill/CH (ecoinvent 2007)
Refractory (landfill)	0.0014 kg					Disposal, refractory SPL, Al elec.lysis, 0% water, to residual material landfill/CH (ecoinvent 2007)
Emissions						
Hydrogen fluoride	4E-6 kg					emission
Nitrogen oxides	1.7E-4 kg					
Particles (total)	6E-6 kg					
Sulfur dioxide	3.2E-4 kg					
Hydrogen chloride	4.2E-5 kg					

Table 10.15: Interventions in the cast house process per kg of aluminium ingots.

11 Life cycle impact assessment (LCIA): Aluminium from Alcoa's new smelter in Greenland

In this section, the LCIA results for the production of aluminium are presented. As described in the goal and scope (section 3.5), the main focus is on GHG emissions, partly because this has been requested by the commissioner of the study and partly because other impacts are (or at least should be) covered by other elements of the Strategic Environmental Assessment (SEA). Therefore, GHG emissions are specifically dealt with in detail in section 11.1. Other impacts are described in section 11.2. The other impacts are not evaluated at the same level of detail as the GHG emissions, but a separate assessment of human health impacts (occurring locally in Greenland) is available in section 12. As a consequence of the less detailed assessment of other impacts than GHG-emissions and local human health, it follows that the presented results and conclusions for these impacts are subject to uncertainties.

11.1 GHG emissions

Scenario 1: New aluminium smelter in Greenland

The calculated GHG emissions per kg aluminium ingot from the proposed new smelter in Greenland are 5.92 kg CO2e/kg aluminium. Scaling up to the expected annual production of 360,000 tonnes at the aluminium smelter in Greenland, this corresponds to 2.13 million tonnes of CO2e/year or approximately 3 times the GHG emissions in Greenland in 2006 (UNFCCC 2009).

Of the 5.92 kg CO2e/kg aluminium only 1.66 kg CO2e/kg aluminium is emitted in Greenland[14]. The remaining emissions take place outside Greenland, mainly in China, Australia and Brazil where the alumina is produced. The 1.66 kg CO2e/kg aluminium in Greenland mainly comes from CO_2 emitted from the use of anodes in the electrolysis process. Thus, when scaling up the local GHG emission in Greenland, the 1.66 kg CO2e/kg aluminium corresponds to 597,000 tonnes CO2e/year emitted in Greenland. This corresponds to approximately 85% of Greenland's GHG emissions in 2006 (UNFCCC 2009).

Of the three life cycle stages (bauxite mining, alumina production, and aluminium smelter), two account for almost 100% of the contribution; i.e. the aluminium smelter stage (49% of total contribution) and the alumina production (49% of total contribution). The process contribution is further specified in **Table 11.1**. It appears from the table that the processes contributing significantly to GHG emissions are process emissions (CO_2 from the use of anodes) in the aluminium smelter (28%) and emissions related to process heat used in the production of alumina (27%). Other important contributions come from the transportation of bauxite to the alumina process (12%), the production of anodes (8%), and other inputs calculated on the basis of the IO data in the aluminium smelter (6%). Within the IO data, the most important contributor is the input of 'Blast furnaces and steel mills', i.e. capital goods.

[14] The 1.66 kg CO2e includes only scope 1 emissions from the smelter in Greenland. Other insignificant GHG emissions will take place in Greenland; emissions from the hydro power reservoir, part of the emissions from transport at the smelter stage, and possibly part of the processes covered by IO data.

Sc1: Aluminium smelter in Greenland						
Life cycle stage		**Specification**	**Scope 1**	**Scope 2**	**Scope 3**	**Total**
Bauxite	**0.144**				0.144	0.144
Alumina	**2.89**	Process heat (production and burning fuels)			1.61	1.61
		Transport (lorry)			0.716	0.716
		Electricity			0.372	0.372
		IO data			0.179	0.179
		Other inputs (IO data and other inputs)			0.0187	0.0187
Smelter	**2.88**	Process emissions (mainly CO_2 from anode)	1.66			1.66
		Anode			0.494	0.494
		IO data			0.371	0.371
		Transport (freight ship)			0.227	0.227
		Electricity		0.140		0.140
		Other inputs (mainly benefits from recycling of waste)			-0.0065	-0.0065
Total	**5.92**		1.66	0.140	4.12	5.92

Table 11.1: GHG emission (kg CO2e) per kg aluminium, Greenland smelter.

Scenario 0: No aluminium smelter in Greenland

Scenario 0 represents the situation in which no aluminium smelter is built in Greenland and no specific assumptions are made about alternative decisions (or actions) that could be taken by Alcoa. Here, it is merely assumed that similar smelter capacity is being installed in another region (or regions) where future expansions are most likely to take place as a response to increased demand. No considerations have been made about who will be responsible for this expansion. Hence, it could be Alcoa or other aluminium producers as well as a combination that represent this ‘marginal’ production of aluminium.

In this scenario, it is presumed that a corresponding production capacity will be installed somewhere else in the world – by Alcoa or by another company. This can take place in several locations using several different technologies for electricity generation (e.g. coal, gas, hydro) and aluminium smelters (new technology or existing technology). The most likely location and technology, which will be used if the Greenland smelter is not installed, is referred to as the marginal supply of aluminium. In section 4, the most likely (marginal) location of aluminium smelters is identified; and corresponding to this, the most likely (marginal) electricity mix is identified in section 5. The marginal technology used in the aluminium smelter is assumed to be modern technology (new), mainly represented by the Alcoa Iceland smelter. All the variables presented in the identification of the marginal supply of aluminium are evaluated through several sensitivity scenarios. This evaluation is presented in the next section. The most likely marginal supply of aluminium, according to section 5, will take place in a weighted average of China, CIS/Russia, and the Middle East, and the electricity mix is identified as being 62% coal, 4% gas, 5% gas which would alternatively have been flared, and 29% hydropower. The GHG emissions related to the marginal supply of aluminium are presented in **Table 11.2**.

Sc0: China, CIS/Russia, and Middle East						
Life cycle stage		**Specification**	**Scope 1**	**Scope 2**	**Scope 3**	**Total**
Bauxite	**0.144**				0.144	0.144
Alumina	**2.89**	Process heat (production and burning fuels)			1.61	1.61
		Transport (lorry)			0.716	0.716
		Electricity			0.372	0.372
		IO data			0.179	0.179
		Other inputs (IO data and other inputs)			0.0187	0.0187
Smelter	**17.7**	Electricity		15.0		15.0
		Process emissions (mainly CO_2 from anode)	1.66			1.66
		Anode			0.499	0.499
		IO data			0.371	0.371
		Transport (freight ship)			0.208	0.208
		Other inputs (mainly benefits from recycling of waste)			-0.0070	-0.0070
Total	**20.7**		1.66	15.0	4.11	20.7

Table 11.2: GHG emission (kg CO2e) per kg aluminium, Scenario 0: Marginal supply of aluminium (China, CIS/Russia, Middle East).

The calculated GHG emissions per kg aluminium ingot from the marginal supply are 20.7 kg CO2e/kg aluminium. This is significantly (3.5 times) higher than in the Greenland scenario. Scaling up to the expected production volume of 360,000 tonnes of aluminium per year at the Greenland smelter, this corresponds to 7.47 million tonnes CO2e/year.

It appears from **Table 11.2** that the use of electricity in the aluminium smelter accounts for 72% of the total contribution to GHG emissions. No other contributing processes deviate significantly from the scenario with the Greenland smelter (**Table 11.1**).

Scenarios 2a and 2b: Alcoa Deschambault and Iceland smelters

This section presents the results in terms of GHG emissions from Alcoa's existing smelters in Deschambault and Iceland. The scenarios presented in this section do not represent scenarios that will be affected by the establishment of the Greenland smelter. The scenarios of Alcoa's existing smelters in Deschambault and Iceland are included for reasons of comparison. The GHG emissions from the Deschambault smelter are presented in **Table 11.3**, and the GHG emissions from the Iceland smelter are presented in **Table 11.4**.

Sc2a: Alcoa Deschambault						
Life cycle stage		**Specification**	**Scope 1**	**Scope 2**	**Scope 3**	**Total**
Bauxite	**0.144**				0.144	0.144
Alumina	**2.89**	Process heat (production and burning fuels)			1.61	1.61
		Transport (lorry)			0.716	0.716
		Electricity			0.372	0.372
		IO data			0.179	0.179
		Other inputs (IO data and other inputs)			0.0187	0.0187
Smelter	**3.28**	Process emissions (mainly CO_2 from anode)	1.66			1.66
		Anode			0.418	0.418
		IO data			0.371	0.371
		Transport (freight ship)			0.208	0.208
		Electricity		0.672		0.672
		Other inputs (mainly benefits from recycling of waste)			-0.0522	-0.0522
Total	**6.31**		1.66	0.672	3.98	6.31

Table 11.3: GHG emission (kg CO2e) per kg aluminium, Scenario 2a: Alcoa Deschambault smelter.

Sc2a: Alcoa Iceland						
Life cycle stage		**Specification**	**Scope 1**	**Scope 2**	**Scope 3**	**Total**
Bauxite	**0.144**				0.144	0.144
Alumina	**2.89**	Process heat (production and burning fuels)			1.61	1.61
		Transport (lorry)			0.716	0.716
		Electricity			0.372	0.372
		IO data			0.179	0.179
		Other inputs (IO data and other inputs)			0.0187	0.0187
Smelter	**2.88**	Process emissions (mainly CO_2 from anode)	1.66			1.66
		Anode			0.494	0.494
		IO data			0.371	0.371
		Transport (freight ship)			0.220	0.220
		Electricity		0.140		0.140
		Other inputs (mainly benefits from recycling of waste)			-0.0065	-0.0065
Total	**5.92**		1.66	0.140	4.12	5.92

Table 11.4: GHG emission (kg CO2e) per kg aluminium, Scenario 2b: Alcoa Iceland smelter.

It appears from **Table 11.3** and **Table 11.4** that the GHG emissions from Alcoa's existing smelters in Deschambault and Iceland are very similar to the expected emissions from the proposed Greenland smelter (**Table 11.1**).

Sensitivity scenarios 0a to 0o: Localisation and electricity mix

From the results in **Table 11.1** and **Table 11.2**, it clearly appears that electricity generation is the main contributing factor to GHG emissions (unless it is based on 100% hydro) and that its contribution to GHG emissions is highly sensitive to the location/technology in question. For this reason, a range of sensitivity scenarios are carried out. The changed parameters and assumptions in the different sensitivity scenarios are described in sections 4 and 5. The contribution to GHG emissions per kg of aluminium in the sensitivity analyses are presented in **Figure 11.1**.

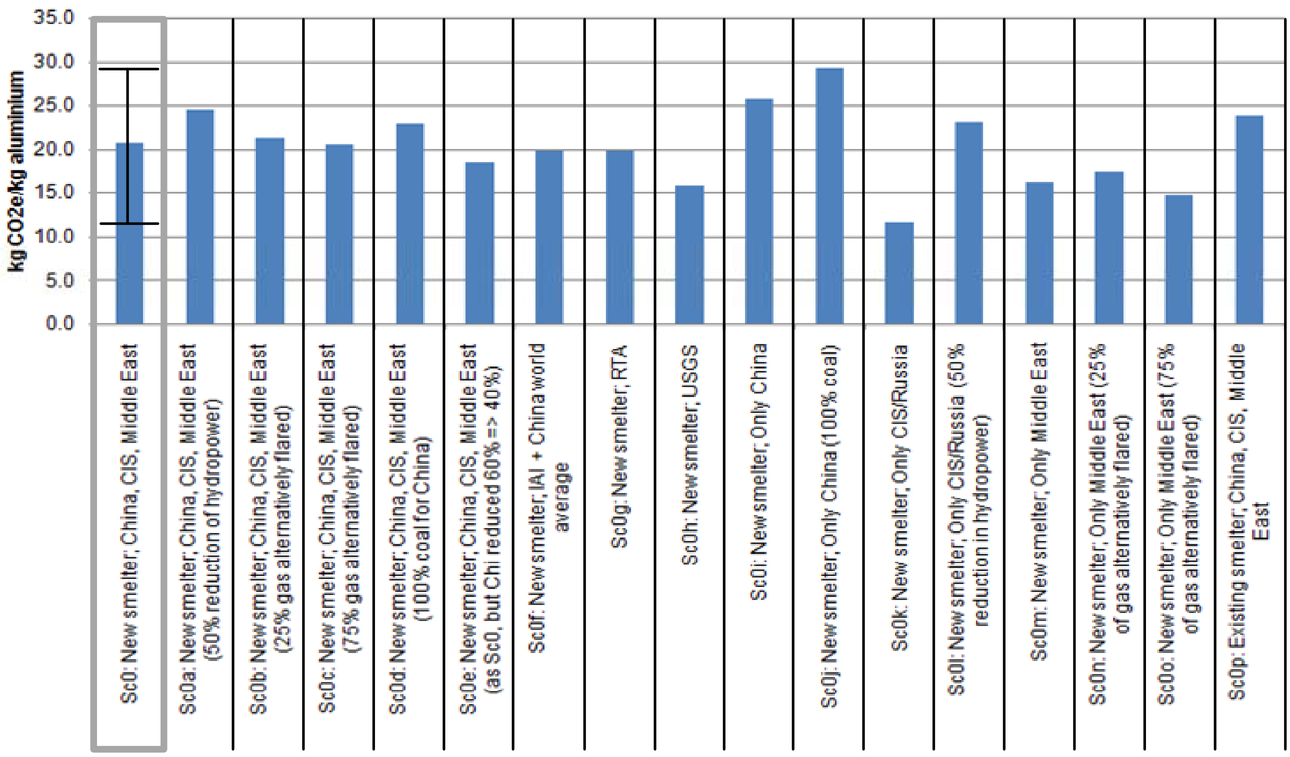

Figure 11.1: Sensitivity analyses relating to the electricity mix in scenario 0. The anticipated most likely marginal supply of aluminium (Scenario 0) is marked in a grey frame to the left, and the range of GHG emissions calculated in Sc0a to Sc0o are illustrated by an uncertainty bar.

It appears from **Figure 11.1** that the GHG emissions in the different sensitivity analyses of scenario 0 vary between 11.6 and 29.2 kg CO2e/kg aluminium. The figure also shows that the GHG emissions in the suggested scenario 0 are close to the midrange[15] value of the sensitivity analyses. Thus, the suggested scenario 0 does not represent an extreme situation in the interval.

Since all the sensitivity scenarios included in **Figure 11.1** are regarded as likely options of the marginal supply of aluminium, the results in **Figure 11.1** also show that the GHG emissions related to the marginal supply of aluminium are 20.7 ± approx 9 kg CO2e/kg aluminium.

Based on the sensitivity analyses of the electricity mix, it can be concluded that the identification of the location of marginal aluminium production and the associated marginal electricity supply is subject to significant uncertainties. Therefore, precaution must be taken when conclusions are drawn from the comparison of the Greenland smelter and the marginal supply of aluminium (scenario 0). As a minimum, the uncertainty interval referred to above (20.7 ± approx 9 kg CO2e/kg aluminium) should be addressed.

Sensitivity scenarios 0p: New vs existing technology at aluminium smelter

In section 10 inventory data for new smelters is compared with data for existing smelters. The applied inventory data in scenario 1 (Greenland smelter) as well as in scenario 0 (marginal supply of aluminium) is data representing new technology. Generally, the data on new smelters is based on figures from the Alcoa Iceland smelter. Existing technology is estimated mainly on the basis of data on European average and world average aluminium smelters in 2005 described in EAA (2008). The characteristics of new and existing technology concern differences with respect to:

- Energy: Electricity, gas, and heavy fuel oil
- Materials: Anodes and aluminium fluoride
- Emissions: Benzo(a)pyrene, Carbon dioxide, PFCs, PAH, particles and sulphur dioxide

In **Table 11.5**, new and existing smelter technologies are compared for scenarios 0 and 1.

Process contribution, kg CO2e/kg alu		**Greenland**		**Marginal aluminium supply**	
	Smelter technology	Sc1: New	Sc1a: Existing	Sc0: New	Sc0p: Existing
Bauxite		0.144	0.144	0.144	0.144
Alumina		2.89	2.89	2.89	2.89
Aluminium smelter					
	Electricity	0.140	0.160	15.0	17.2
	Process emissions	1.66	2.32	1.66	2.32
	Anode	0.494	0.536	0.499	0.542
	IO data	0.371	0.371	0.371	0.371
	Transport (freight ship)	0.227	0.228	0.208	0.208
	Other inputs	~0	~0	~0	~0
Total		**5.92**	**6.74**	**20.7**	**23.8**

Table 11.5: Comparison of GHG emissions (kg CO2e/kg aluminium) from new and existing technology in smelters in scenarios 0 and 1.

It appears from **Table 11.5** that the results are not significantly sensitive to uncertainties relating to new versus existing technologies in the aluminium smelter. For both the Greenland smelter and for the marginal supply of aluminium, the existing technology has around 13-15% higher GHG emissions than new technology. For sce-

[15] midrange = (maximum value + minimum value)/2

nario 0, this is relatively insignificant compared with the uncertainties related to the identification of the marginal electricity mix.

For the Greenland smelter, the difference between new and existing technologies represents the effect of environmental improvements, assuming that the potential improvements are represented by the difference between new and existing technologies. The main reason for the difference is the varying PFC emissions from the smelter. As explained in the next section, this mainly relates to the management of the smelter. Thus, the difference between new and existing technologies for the Greenland smelter mainly represents the difference between good and less good management.

Influential factors on the GHG-emissions from aluminium production

In **Table 11.6**, the range of the GHG emissions of each of the contributing processes in all included scenarios is shown. Furthermore, the variation expressed as the difference between the maximum value and the minimum value is given. The variation indicates which of the contributing factors could be optimised, either technologically or by localisation of the aluminium smelter.

Process contribution, kg CO2e/kg alu		Range	Variation	Comment
Bauxite		0.144	0	
Alumina		2.89	0	
Aluminium smelter				
	Electricity	0.140-23.3	23.2	**Min:** Sc1: Alcoa Greenland (100% hydropower) **Max:** Sc0j: Only China (100% coal)
	Process emissions	1.66-2.32	0.660	**Min:** Sc2a: Alcoa Deschambault **Max:** Sc0p: Existing aluminium smelter
	Anode	0.418-0.544	0.126	**Min:** Sc2a: Alcoa Deschambault **Max:** Sc0j: Only China (100% coal)
	Transport (freight ship)	0.208-0.227	0.019	**Min:** Sc0: China, CIS/Russia, Middle East **Max:** Sc1: Alcoa Greenland
	IO data	0.371	0	
	Other inputs	~0	0	

Table 11.6: Contributing processes and the range of GHG emissions (kg CO2e/kg aluminium) in all scenarios included in the study. The variation is expressed as the maximum value minus the minimum value.

It appears from the table that almost all improvement options lie in the electricity mix, which is closely related to the localisation of the aluminium smelter. Besides the electricity mix, the most important improvement option is to reduce process emissions. Part of the process emissions are CO_2 and CO from the use of anodes, corresponding to approximately 1.7 kg CO2e/kg aluminium. These emissions cannot be avoided. The remaining part of the contribution to GHG-emissions from process emissions relate to PFC emissions. During a company visit at Alcoa's plant in Deschambault (Quebec), it was explained that PFC emissions can be almost eliminated by proper management of the smelter combined with advanced ventilation over the smelters and various simple solutions which can reduce the emissions from the used anodes. The PFC emissions occur when process instability arises, i.e. as an anode effect. The other improvement options relate to the use of anodes (which can be improved by ensuring recycling) and to transport optimisation of raw material inputs and transport of waste including anodes to recycling.

The effect of approving/not approving the Greenland smelter

The decision to build the Greenland smelter will obviously cause emissions from the Greenland smelter, but it will also contribute to avoided emissions from the marginal supply (scenario 0), based on our assumptions about supply and demand (see section 3.1). Therefore, the decision to build the smelter will cause GHG emissions of 2.13 million tonnes CO2e/year minus 7.47 million tonnes CO2e/year, equalling -5.34 million tonnes CO2e/year. This means that the Greenland smelter will save 5.34 million tonnes CO2e/year in a global perspective. This saving will include an increase of 597,000 tonnes CO2e/year emitted in Greenland (scope 1 in **Table 11.1**) and savings of 5.93 million tonnes CO2e/year outside Greenland.

It must be kept in mind that the GHG emissions related to scenario 0 are subject to substantial uncertainties. The different scenarios included (scenario 0a to 0p), which represent other likely marginal supplies of aluminium, show GHG emissions ranging from 11.6 to 29.2 kg CO2e/kg aluminium. This means that the annual GHG emissions saved as a consequence of establishing the Greenland smelter range between 2.05 and 8.36 million tonnes CO2e/year. Hence, the scenarios included indicate that the Greenland smelter will be associated with substantial GHG emission savings regardless of the uncertainties related to the identification of the marginal supply of aluminium.

It should be stressed, however, that the alternative sensitivity scenarios are generic in the sense that they represent an average marginal, because no information has been available about alternative decisions or actions that would be taken by Alcoa. It is indeed possible that Alcoa could make other decisions with a similar carbon footprint as the planned smelter in Greenland. This could be the installation of smelter capacity based on 100% hydropower in other locations of the world where unutilised hydropower resources are available, e.g., in Siberia. It could also be the installation of smelter capacity in areas with gas resources that would alternatively be flared, e.g., the Middle East, Russia or Africa. When compared with such alternative 'deliberate' choices, the Greenland smelter could have GHG emissions close to those of the alternatives. But, since the purpose of the present LCA study is to compare a new aluminium smelter in Greenland with no smelter, it is meaningless to guess which other specific decisions Alcoa would make. We can only conclude that a 'similar' level of GHG emissions could theoretically be obtained by implementing other alternatives as a consequence of deliberate decision-making by Alcoa.

11.2 Other impacts

This section evaluates the contribution of the scenarios to other environmental impact categories than GHG emissions. Initially, it should be mentioned that these 'other impacts' are far from trivial when dealing with an aluminium smelter in a pristine environment such as Greenland. Nevertheless, a detailed assessment of the impacts on the local ecosystem is out of the scope of the present study, see section 3.5. Other types of impacts, including social impacts, are (or should be) dealt with in the SEA. It is also important to be aware of the fact that the present study forms part of the complete SEA.

Overview of characterised results

An overview of the characterised results for 6 key scenarios is available in **Table 11.7.** Among the 6 key scenarios, 100% coal in China represents the worst case, while CIS/Russia with 81% hydropower represents the best case based on the sensitivity analyses of scenario 0 as well as the analysis of the two existing Alcoa smelters on which a large part of the data collection is based. In 'Appendix 5: Characterised results for all scenarios', the characterised results are shown for all scenarios listed in **Figure 5.4**, p 87.

Impact category	Unit	Sc 1: Greenland smelter	Sc 0: Marginal supply of aluminium	Sc 0j: Worst case: Marginal supply of aluminium	Sc 0k: Best case: Marginal supply of aluminium	Sc 2a Alcoa Deschambault	Sc 2b Alcoa Iceland
Human toxicity, carcinogens	kg C_2H_3Cl-eq	0.228	0.357	0.385	0.328	0.228	0.227
Human toxicity, non-carc.	kg C_2H_3Cl-eq	1.94	2.36	2.63	2.08	1.94	1.94
Respiratory inorganics	kg $PM_{2.5}$-eq	0.00792	0.0294	0.0439	0.0150	0.00805	0.00790
Respiratory organics	pers*ppm*h	0.0106	0.0194	0.0246	0.0142	0.0114	0.0106
Ionizing radiation	Bq C-14-eq	29.7	32.0	33.5	30.5	29.6	29.7
Ozone layer depletion	kg CFC11-eq	3.40E-06	3.53E-06	3.43E-06	3.51E-06	3.41E-06	3.40E-06
Ecotoxicity, aquatic	kg TEG-eq w	1636	1676	1701	1651	1640	1636
Ecotoxicity, terrestrial	kg TEG-eq s	17.1	34.3	45.1	23.1	17.0	17.1
Nature occupation	m^2 agr.land	0.245	0.411	0.515	0.303	0.245	0.245
Acidification	m^2 UES	0.888	3.38	5.14	1.68	0.964	0.886
Eutrophication, aquatic	kg NO_3-eq	0.00425	0.00744	0.00953	0.00531	0.00422	0.00424
Eutrophication, terrestrial	m^2 UES	0.592	2.09	3.08	1.09	0.576	0.589
Photochemical ozone, vegetat.	m^2*ppm*hours	97.6	201	264	137	103	97.5
Non-renewable energy	MJ primary	87.6	220	289	138	86.9	87.5
Mineral extraction	MJ extra	0.0335	0.0382	0.0416	0.0357	0.0340	0.0335

Table 11.7: Overview of characterized results for 'other' impact categories of 6 key scenarios, according to the Stepwise 2006 (version 1.2) LCIA method.

It appears from **Table 11.7** that the impact potential of the planned smelter in Greenland is among the lowest of all impact categories, only surpassed (by a very small margin) by the existing smelter in Iceland, which also uses 100% hydropower. **Figure 11.2** shows that the Greenland smelter performs better than the best sensitivity scenario (Sc0k), while it is several times better than the worst case scenario 0j.

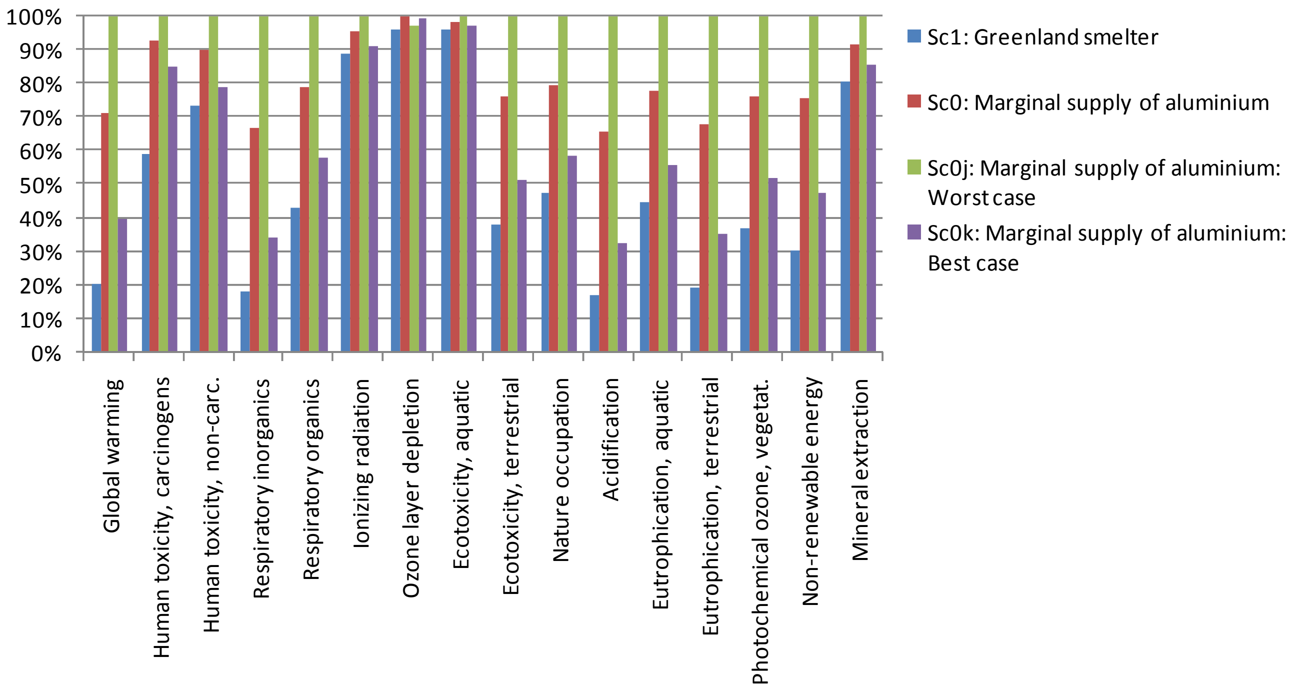

Figure 11.2: Graphical representation of the characterised results for scenarios 1 and 0 as well as the best and worst case of the sensitivity scenarios of marginal aluminium production – scenarios 0j and 0k.

It appears that the global warming potential is a good proxy for the other impact categories as well and that the solution with the lowest carbon footprint also has the lowest impact potential in the other impact categories analysed. Hence, no significant shift-of-burden problems can be identified. However, most of the impact categories are highly site-dependent and the environmental consequences depend on the fate of the emissions, the exposure as well as the sensitivity of the receiving environment. The latter can vary significantly (orders of magnitude), and in the case of a pristine environment like Greenland, it may be different than in other less vulnerable regions. Each of the impact categories are separately assessed at the screening level for scenarios 1 and 0 in the following.

Human toxicity, non-carcinogenic

This impact category covers toxic effects on humans (excluding carcinogenic effects). The contributing substances are shown in **Table 11.8.**

Emissions	**Scenario 1:** Greenland smelter	**Scenario 0:** Marginal supply of aluminium
Arsenic to soil	68%	56%
Arsenic ion to water	31%	42%
Arsenic to air	0.3%	1%
Dioxins to air	0.3%	0.6%
Other emissions	<1%	<1%

Table 11.8: Emissions contributing to Human toxicity, non-carcinogenic, in scenarios 1 and 0.

In both the Greenland smelter scenario and scenario 0, the arsenic emissions to soil mainly originate from the mining of what the IO data categorises as 'non ferrous metal ores (except copper)'. These non ferrous ores are mainly used in the production of copper, which again is used in several processes. The emissions of arsenic to water almost entirely take place in the landfill of red mud from the alumina production.

Fate and exposure: The emissions are likely to take place in mining fields and on landfill sites where the transfer to humans is regarded as being relatively insignificant compared to general arsenic emissions, which is the basis for the characterisation factors in the Stepwise method.

Human toxicity, carcinogenic

This impact category covers carcinogenic effects on humans. The contributing substances are shown in **Table 11.9**.

Emissions	**Scenario 1:** Greenland smelter	**Scenario 0:** Marginal supply of aluminium
Arsenic to soil	55%	35%
Arsenic ion to water	25%	27%
Hydrocarbons, aromatic to air	9%	6%
PAH to air	3%	26%
Other emissions	<8%	<6%

Table 11.9: Emissions contributing to human toxicity, carcinogenic, in scenarios 1 and 0.

The sources of the arsenic emissions to soil and water shown in **Table 11.9** are described under 'Human toxicity, non carcinogenic'. The emissions of PAH in scenario 0 mainly originate from the production of anodes. It should be noted that the emissions of PAH in the anode production process in scenario 0 are significantly higher than in the Greenland scenario, see **Table 10.8**, p 129.

Fate and exposure: As for the previous impact category.

Respiratory organics

This impact category covers respiratory effects on humans caused by organic substances. The contributing substances are shown in **Table 11.10**.

Emissions	**Scenario 1:** Greenland smelter	**Scenario 0:** Marginal supply of aluminium
Carbon monoxide	75%	42%
Nitrogen oxides	18%	35%
Methane	4%	20%
Volatile organic compounds	2%	1%
Non methane volatile organic compounds	1%	1%
Other emissions	<1%	<1%

Table 11.10: Emissions contributing to respiratory organics in scenarios 1 and 0.

In scenario 0, the contribution to respiratory organics is partly related to the electrolysis process and the electricity production based on hard coal. In scenario 1, the contribution is chiefly related to the electrolysis process and the related emissions of especially carbon monoxide. As these emissions occur locally in Greenland they are potentially important.

Fate and exposure: Respiratory organics cover the impact on human health from photochemical ozone formation. The impact is expressed as the accumulated exposure above the threshold of 60 ppb multiplied by the number of persons that are exposed as a consequence of the emission (see also Appendix 2: Explanation of units in the Stepwise LCIA method). As the emission takes place in a sparsely populated area with a low background concentration of NO_x (a catalyst for ozone formation), we would assume that the effect is expected not to be significant.

Respiratory inorganics

This impact category covers respiratory effects on humans caused by inorganic substances. The contributing substances are shown in **Table 11.11.**

Emissions	**Scenario 1:** Greenland smelter	**Scenario 0:** Marginal supply of aluminium
Sulfer dioxide	36%	35%
Particles	35%	37%
Nitrogen oxides	27%	26%
Other emissions	~2%	~2%

Table 11.11: Emissions contributing to respiratory inorganics in scenarios 1 and 0.

In both the Greenland smelter scenario and scenario 0, the emissions mainly originate from the electrolysis process, from ship transport of raw materials (both bauxite to the alumina production and alumina to the aluminium smelter), and from the alumina production.

Fate and exposure: The emissions are likely to take place in remote places where the population density is low. The smelter in Greenland will only affect a limited number of people. Moreover, ship transport mainly takes place away from densely populated areas.

Ionizing radiation

This impact category covers ionizing radiation and the contributing substances are shown in **Table 11.12.**

Emissions	Scenario 1: Greenland smelter	Scenario 0: Marginal supply of aluminium
Radon-222	76%	75%
Carbon-14	21%	21%
Cesium-137	3%	3%
Other emissions	<1%	<2%

Table 11.12: Emissions contributing to ionizing radiation in scenarios 1 and 0.

In both the Greenland smelter scenario and scenario 0, the emissions mainly originate from electricity production based on nuclear power, which is included in the electricity mix of several of the ecoinvent database processes in both product system, e.g., for the production of the refractory and anodes.

Fate and exposure: It is highly unlikely that the Greenland region will be affected by the radiation as the nuclear plants in question are situated on other continents. Also, it should be noticed that hydropower by far represents the largest electricity generation source of the Greenland smelter, and in scenario 0, the electricity generation is based on coal, gas and hydro. Therefore, the amounts of electricity based on nuclear power are small in both scenarios and these amounts only relate to some upstream processes which are modelled with default data in the ecoinvent database.

Ozone layer depletion

This impact category covers ozone layer depletion caused by, e.g., emissions of CFC gases. The contributing substances are shown in **Table 11.13**.

Emissions	Scenario 1: Greenland smelter	Scenario 0: Marginal supply of aluminium
Ethane, 1,1,1-trichloro-, HCFC-140	32%	30%
Methane, tetrachloro-, CFC-10	24%	24%
Methane, dichlorofluoro-, HCFC-21	16%	16%
Methane, bromotrifluoro-, Halon 1301	14%	14%
Ethane, 1,2-dibromotetrafluoro-, Halon 2402	4%	3%
Other emissions	<11%	<13%

Table 11.13: Emissions contributing to ozone layer depletion in scenarios 1 and 0.

In both scenarios, the emissions mainly originate from a large number of small sources in the IO-LCA database. No significant direct sources of ozone depletion have been identified in the direct product system of aluminium production (here referred to as the processes: bauxite mining, alumina production, aluminium smelter, and electricity generation). Therefore, the impact category ozone layer depletion is regarded as insignificant and no further considerations about fate and exposure are made here.

Eco-toxicity, aquatic

This impact category covers ozone layer depletion caused by, e.g., emissions of CFC gases. The contributing substances are shown in **Table 11.14**.

Emissions	Scenario 1: Greenland smelter	Scenario 0: Marginal supply of aluminium
Copper to soil	89%	87%
Chromium VI to water	2%	3%
Zinc, ion to water	2%	2%
Arsenic, ion to water	1%	2%
Other emissions	<5%	<7%

Table 11.14: Emissions contributing to aquatic eco-toxicity in scenarios 1 and 0.

In both scenarios, the emissions mainly originate from copper mining, as shown in the IO-LCA database. Bauxite mining, in the IO-data, uses for some reason significant amounts of copper ore. This seems unrealistic, and when comparing with ecoinvent data for bauxite mining, there are no copper emissions (ecoinvent 2007). Therefore, the copper emission is regarded as based on inadequate data. Chromium to water originates from the landfill of red mud.

Fate and exposure: If the landfill is not properly secured, chromium emissions may lead to high exposure in nature.

Eco-toxicity, terrestrial

This impact category covers terrestrial eco-toxicity caused by toxic emissions. The contributing substances are shown in **Table 11.15**.

Emissions	**Scenario 1:** Greenland smelter	**Scenario 0:** Marginal supply of aluminium
Nickel to air	29%	21%
Zinc, fume or dust to air	23%	12%
Copper to air	22%	18%
Zinc to air	14%	33%
Chromium to air	3%	3%
Other emissions	<9%	<14%

Table 11.15: Emissions contributing to terrestrial eco-toxicity in scenarios 1 and 0.

The most important contributions are air emissions of nickel, zinc and copper, caused by electricity production based on coal in scenario 0. For scenario 1, the largest contribution comes from blast furnaces and steel mills related to the IO data.

Fate and exposure: As it appears from **Figure 11.2,** the emissions are significantly larger in scenario 0 compared to scenario 1, and it must be assumed that relatively small emissions will occur in the region of Greenland.

Nature Occupation

Since nature occupation is not related to emissions, the contribution analysis is shown in terms of contributing processes instead of substances. Note that the Stepwise method only includes interventions related to occupation and that transformation impacts are included via a severity factor embodied in the characterisation factor (Weidema et al. 2007).

Process	**Scenario 1:** Greenland smelter	**Scenario 0:** Marginal supply of aluminium
Aluminium smelter plant	12%	3%
Alumina plant	0.1%	0.02%
Bauxite mine	3%	0.6%
Transport, roads	23%	5%
Landfill	19%	6%
Hardwood mainly used in coal mines	5%	24%
Coal mine	5%	47%
Crude oil production plant	5%	1%
Other processes	<28%	<14%

Table 11.16: Processes contributing to nature occupation in scenarios 1 and 0.

Note that the contribution of transport may be overestimated. Additional transport does not necessarily lead to a corresponding additional occupation, because much transport of raw materials takes place where the roads have an unused capacity for additional transport.

Site-specific considerations: As illustrated in **Figure 11.2**, the contribution to the impact category 'nature occupation' is smaller in scenario 1 compared to all other scenarios, including the best-case scenario from the sensitivity analysis. However, it should be noted that the Stepwise LCIA method represents a rough modelling of nature occupation. Transforming and occupying land in a pristine and probably sensitive environment in Greenland is very different from placing an aluminium smelter in, e.g., an industrial area in China. It is also questionable if it makes sense to use area or biodiversity as indicators of nature occupation. Thus, from a land use perspective, it is highly questionable if the indicator used in the Stepwise method provides the most relevant information about land use impacts. From a 'common sense' point of view, it is highly critical to situate a large industrial facility with associated hydropower plants, roads and other types of infrastructure in a pristine environment in Greenland. The impact on cultural and social aspects is another important issue, and it is imperative that the reader addresses the SEA for a more comprehensive assessment of the local, environmental and social impacts. It should be noted, however, that other equally carbon-friendly alternatives based on 100% hydropower in, e.g., Siberia would possibly also affect pristine nature.

Acidification

This impact category covers acidification caused by emissions, e.g. sulfur dioxide emissions. The contributing substances are shown in **Table 11.17**.

Emissions	**Scenario 1:** Greenland smelter	**Scenario 0:** Marginal supply of aluminium
Sulfur dioxide	77%	74%
Nitrogen oxides	11%	11%
Hydrogen fluoride	5%	3%
Hydrogen chloride	4%	11%
Other emissions	<3%	<1%

Table 11.17: Emissions contributing to acidification in scenarios 1 and 0.

The contribution to acidification is mainly related to electricity production (burning of hard coal) in scenario 0, while the relatively small contribution from scenario 1 (according to **Figure 11.2**) is mainly related to the production of anodes and ship transport.

Fate and exposure: In scenario 1, no significant emissions occur in the Greenland region as anode production and ship transport take place outside the region. The exposure of acidifying emissions in scenario 0 may be significant, but the specific locations are not known.

Eutrophication, aquatic

This impact category covers aquatic eutrophication caused by, e.g., nitrogen and phosphorus emissions. The contributing substances are shown in **Table 11.18**.

Emissions	Scenario 1: Greenland smelter	Scenario 0: Marginal supply of aluminium
Phosphorus to water	66%	38%
Nitrogen oxides to air	28%	59%
Nitrate to water	3%	2%
Ammonia to air	1%	1%
Other emissions	<2%	<2%

Table 11.18: Emissions contributing to aquatic eutrophication in scenarios 1 and 0.

The contribution to aquatic eutrophication is mainly related to electricity production (hard coal burning) in scenario 0 (e.g. nitrogen oxides to air), while it is mainly related to the process ‘food grains’ in the IO data dataset for scenario 1, which also has a smaller contribution to this impact category. It must be noted that aquatic eutrophication typically is an issue in food production systems (mainly agriculture), and that we probably deal with relatively low contributions from aluminium production in general. Since the main contributions are originating from IO-data, some of these may also be subject to significant uncertainties due to a high level of aggregation of the IO-data, e.g. that alumina belong to ‘Industrial inorganic and organic chemicals’ which also covers the production of chemicals based on agricultural crops.

Fate and exposure: In scenario 1, no significant emissions occur in the Greenland region. No significant direct sources of emissions have been identified in the direct product system of aluminium production (here referred to as the processes: bauxite mining, alumina production, aluminium smelter, and electricity generation). Therefore, the impact category aquatic eutrophication is regarded as being insignificant.

Eutrophication, terrestrial

This impact category covers terrestrial eutrophication caused by, e.g., nitrogen and phosphorus emissions. The contributing substances are shown in **Table 11.19**.

Emissions	Scenario 1: Greenland smelter	Scenario 0: Marginal supply of aluminium
Nitrogen oxides	98%	95%
Ammonia	2%	5%
Other emissions	<1%	<1%

Table 11.19: Emissions contributing to terrestrial eutrophication in scenarios 1 and 0.

The contribution to terrestrial eutrophication is mainly related to electricity production (hard coal burning) in scenario 0, which mainly involves nitrogen oxide emissions to air. In scenario 1, terrestrial eutrophication is mainly related to sea transport (also nitrogen oxide emissions to air). The contribution from scenario 0 is significantly higher than the contribution from scenario 1.

Fate and exposure: In scenario 1, no significant emissions occur in the Greenland region. The emissions in scenario 0 are higher and may have a relevant effect. However, the main contributor to terrestrial eutrophication is typically agriculture, and therefore, the contribution from aluminium production to this impact category is considered to be insignificant.

Photochemical ozone formation, vegetation

This impact category covers damage on vegetation caused by ozone. The contributing substances are shown in **Table 11.20**.

Emissions	**Scenario 1:** Greenland smelter	**Scenario 0:** Marginal supply of aluminium
Carbon monoxide	64%	31%
Nitrogen oxides	28%	50%
Methane	2.3%	15%
Other emissions	~6%	~4%

Table 11.20: Emissions contributing to photochemical ozone formation (vegetation) in scenarios 1 and 0.

In both the Greenland smelter scenario and scenario 0, the carbon monoxide emissions almost entirely originate from the electrolysis process. The emissions of nitrogen oxide originate from ship transport of raw materials (both bauxite to the alumina production and alumina to the aluminium smelter) and to a lesser extent from alumina production.

Fate and exposure: Ozone formation mainly occurs in the presence of sunlight and a high background level of NO_x. While sunlight is present in abundance (at least half of the year), the existence of a high background level of NO_x in Greenland is not likely. Concerning the exposure to vegetation, it is possible that sensitive natural vegetation may be affected.

Non-renewable energy

This impact category covers the impact category 'non-renewable energy' caused by the use of fossil and nuclear energy resources. The contributing resources are shown in **Table 11.21**.

Emissions	**Scenario 1:** Greenland smelter	**Scenario 0:** Marginal supply of aluminium
Crude oil	63%	26%
Natural gas	21%	12%
Hard coal	11%	59%
Uranium	4%	2%
Other non-renewable energy resources	<1%	<2%

Table 11.21: Emissions contributing to the impact category non-renewable energy in scenarios 1 and 0.

For the impact category non-renewable energy, the most important contribution in scenario 0 is the use of hard coal related to electricity production at the smelter stage, while it is the use of oil for anode production (petroleum coke) in scenario 1. It is not relevant to discuss fate and exposure in relation to this impact category. Since primary aluminium production is associated with high energy inputs, the impact category 'non-renewable energy' may be significant, especially in cases in which the electricity is not based on hydropower.

Mineral extraction

Emissions	**Scenario 1:** Greenland smelter	**Scenario 0:** Marginal supply of aluminium
Aluminium	46%	42%
Nickel	34%	37%
Iron	15%	16%
Copper	4%	4%
Other minerals	<2%	<2%

Table 11.22: Emissions contributing to mineral extraction in scenarios 1 and 0.

For the impact category mineral extraction, the major contribution in both scenarios is the use of aluminium (bauxite) and reinforcement steel used for hydropower plants and coal-based power plants. The impact category represents an estimate of extra primary energy needed for the extraction of minerals from lower grade ores in the future. Hence, it is not relevant to discuss fate and exposure in relation to this impact category. As it appears from **Figure 11.2,** there is no significant difference in the total impact from the different scenarios.

Final remarks about results on the characterisation level

Based on the characterised results and the subsequent contribution analysis, it is difficult to draw an overall conclusion about the individual importance of the impact categories. But, it can be concluded that no impact indicators in the Stepwise model suggest that scenario 1 (the Greenland smelter) has a higher impact potential than scenario 0, including all sensitivity scenarios of scenario 0. As most of the impact potentials are energy-related, this is not a surprising conclusion. But, a red flag should be raised for the impact category 'nature occupation' – not because the Stepwise method suggests that we should be concerned about its impact potentials, but because we are dealing with land transformation and occupation in a pristine environment in Greenland. In addition, based on the LCIA, the following impact categories are expected to be less significant than the other impact categories included:

- Respiratory organics
- Ionizing radiation
- Ozone layer depletion
- Eutrophication, aquatic
- Eutrophication, terrestrial

It should be noted that the LCIA of other impacts than GHG emissions in this chapter is subject to significant uncertainties. However, these uncertainties do not alter the general conclusion that the Greenland smelter performs better or similar than scenario 0 in terms of the assessed impact categories. There may be impact categories in which the fate and exposure as well as the local conditions in Greenland lead to opposite results; i.e., scenario 0 performs better than the Greenland smelter. This is mainly an issue regarding land use.

11.3 Weighted results

As a supplement to the identification of significant issues in the LCIA of the characterised results, the weighted results are shown in this section. It should be noted that the ISO 14044 standard weighting shall not be used in LCA studies intended for comparative assertions which must be disclosed to the public. Therefore, the following section only provides supplementary information to the LCIA on the characterised results presented in sections 11.1 and 11.2.

The relative importance of the individual impact categories is assessed using the normalisation and weighting factors in the LCIA method Stepwise, version 1.2 (Weidema 2009). Weighting in LCIA means that the individual impact categories are ascribed a relative weight in order to make them comparable. This makes it possible to assess whether, e.g., 1 kg of CO2e emission is more or less significant than 1 m^2UES acidification[16]. The common unit of the weighted results in the Stepwise method is Euro (2003 currency), and it reflects monetarised environmental impacts. The methodology of monetarising environmental impacts is described in Weidema (2009). The weighted results for the Greenland smelter (scenario 1) and for the marginal supply of aluminium (average supply from China, CIS/Russia, and Middle East: Scenario 0) are shown in **Figure 11.3**.

[16] The units of the characterised LCIA results are explained in Appendix 2: Explanation of units in the Stepwise LCIA method

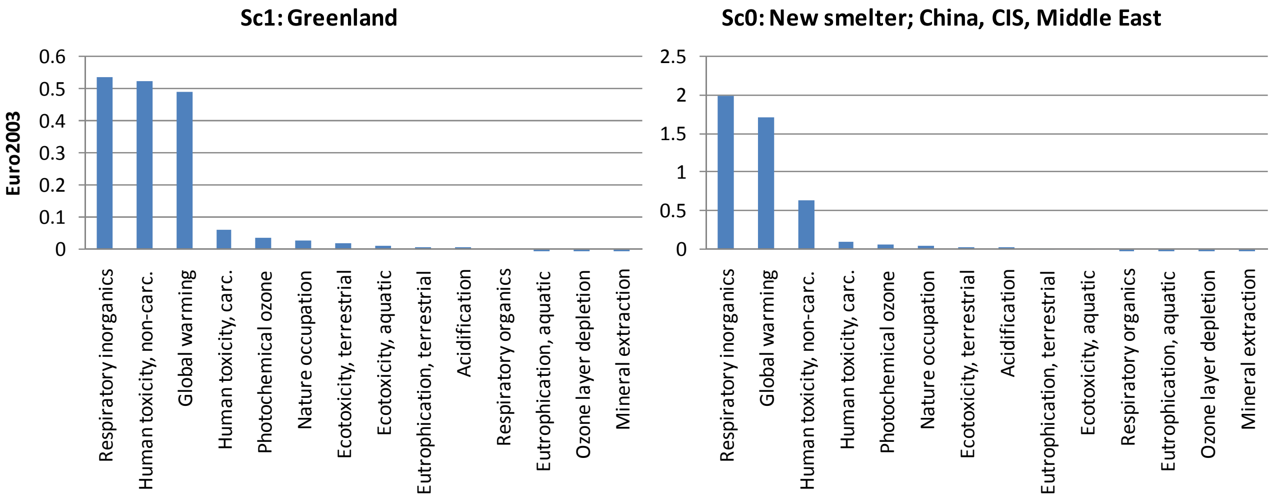

Figure 11.3: Weighted results in EUR2003 per kg of aluminium for the Greenland smelter (scenario 1) and the marginal supply of aluminium (scenario 0).

In **Figure 11.3,** the impact categories are sorted into decreasing order. It appears from the figure that the most significant environmental impacts are respiratory inorganics, human toxicity non carcinogenic, and global warming for both scenarios. Minor contributions to human toxicity carcinogenic and photochemical ozone vegetation can also be seen. Compared to these five impact categories, the remaining impact categories appear to be less significant, but as the weighting methods involve inherent uncertainties and value judgements they shall not be used to make any strict conclusions in this regard. However, the weighted results indicate that the GHG emissions and the human health effects (which are assessed in section 12) are significant. Thus, there is an overlap of the impact categories identified as the most significant in the weighting and in the LCIA based on the characterised results.

12 Human health aspects

This section focuses on human health impacts that, to some extent, are covered by the LCIA in section 11.2, as well as a clarification of the human health aspects not covered by the LCIA. It should be stressed that LCAs, despite recent advances in LCIA modelling, only provide a limited insight into human toxicity impacts, and that the uncertainties related to the analysis of these impacts are very high[17]. The intention is to deliver input about health impacts that potentially could be important and therefore should be addressed by the SEA or a separate Health Impact Assessment (HIA).

Focus will be on local impacts on human health (except Occupational Health and Safety) occurring in the vicinity of the smelter.

12.1 Local impacts on human health covered by the LCA

Several impact categories are directly (or indirectly) related to human health and they will be discussed in the following. It should be stressed that all of the impact categories covered by the LCA are related to emissions to the external environment. In other words, the LCA does not cover Occupational Health and Safety (OH&S).

Respiratory impacts: In terms of local impacts on human health in Greenland, four impact categories are particularly interesting to the LCA:

1. Respiratory organics
2. Respiratory inorganics
3. Human toxicity, carcinogenic
4. Human toxicity, non carcinogenic

Ad 1) Respiratory organics: Respiratory organics mainly cover impacts related to photochemical ozone formation as a result of, e.g., emissions of carbon monoxide (CO) or volatile organic compounds (VOCs), typically from combustion processes. This is also known as summer smog because the ozone formation requires the presence of sunlight and NO_x at the same time.

The LCA shows that the total weighted contribution to this impact category from all life cycle stages is less than 1% of the total weighted impact potential; thus, suggesting that this impact category is insignificant in our study. The largest contribution (81%) is related to the smelter stage, mainly due to emissions of carbon monoxide (CO). However, it must be assumed that small background levels of NO_x can be found in Greenland, due to the low population density. Hence site-specific considerations support the point that the contribution is insignificant. All in all, there are not reasons to raise a red flag for this impact category.

Ad. 2) Respiratory inorganics: Respiratory inorganics reflect respiratory effects on humans caused by inorganic substances, e.g., particle pollution from cars and combustion processes, construction sites, and other physical processes that generate dust. It is caused by emissions of, e.g., particles, NO_x, SO_x, ammonia, or CO.

The weighted results show that the impact potential of respiratory inorganics is important. A process contribution analysis unveils that the largest contribution comes from the alumina stage, from ship transport, and other processes that do not occur in Greenland. The emissions that come directly from the aluminium smelter con-

[17] According to Humbert, Margni and Jolliet (2005) the state of the art in human toxic assessment enables a precision of about a factor 100 (two orders of magnitude). Thus all flows that have an impact over 1% of the total score should, according to the authors, be considered potentially important

tribute with less than 15% of the impact potential. This is, however, still a significant contribution and is caused by emissions of sulphur dioxide (11%), particulates (3%) and carbon monoxide (1%). The emissions of sulphur dioxide are related to the consumption of the anode that contains sulfur.

The specific initial compartment of the emissions in the LCA is poorly specified, e.g. are the particles emitted via a chimney or as fugitive emissions (through the roof), and can they be captured using filters if desired?
We can therefore only conclude that emission of sulphur, carbon monoxide and particulates is an issue of concern and something that should be analysed further. Also, it should be noticed that ship transport contributes significantly to the impact category. Also emissions from ships that transport materials to and from the plant in Greenland should ideally be taken into consideration. A red flag is therefore raised here.

Ad. 3 and 4) Human toxicity: Human toxicity, carcinogenic and non-carcinogenic, reflects emissions that can potentially cause effects on human health. The total weighted impact potential of this impact category is also about one third of the total impact potential for all impact categories. However, the contribution from processes taking place in Greenland is virtually zero. Almost 100% of the contribution to human toxicity (carcinogenic and non-carcinogenic) comes from arsenic to soil and arsenic ion to water mainly related to mining outside Greenland. This is further elaborated in section 11.2.

Hydrogen fluoride (HF): It should be stressed that LCIA models do not include air emission of hydrogen fluoride (HF), which is considered one of the most important emissions from the aluminium industry. The emissions of HF are caused by the cryolite (sodium aluminium fluoride) used as a catalyst for the processes in the smelter. According to the UK Environmental Agency: *"Hydrogen fluoride emissions can cause damage to plants and be harmful to cattle and other domestic animals. It is very corrosive in solution. Fluoride accumulates in the teeth and bones of animals and high doses can cause abnormalities such as discoloration of teeth and skeletal deformities*". In relation to possible effects on human health it is mentioned that *"Excessive exposure to hydrogen fluoride may affect the bone, eye, heart, lung, nose, skin and throat."* (Environmental Agency 2009).

An analysis of the aluminium smelter in Deschambault in Quebec carried out in 2006 shows signs of light and moderate damage to sensitive vegetation in the buffer zone very close to the plant, but not signs of damage outside this area (Montembeault 2009). It appears that HF should mainly be a matter of concern to the local environment if sensitive vegetation grows close to the smelter and/or grazing animals are found nearby, since fluoride could accumulate in the vegetation during the growing season. It is therefore necessary to raise a red flag for HF emissions to the air, despite the lack of LCA results in this area.

Waste water and solid waste

In relation to the water compartment, it should be mentioned that Alcoa's aluminium plant in Deschambault (Quebec) does not discharge process water, which leaves the plant as steam. The only waste water that is discarded derives from rain water that falls on the premises. The latter, however, does have a content of HF and is treated before being discharged. It is assumed and recommended that a similar system is be used for the Greenland smelter (Ministry of Environment 1998; Montembeault 2009).

An aluminium plant generates large amounts of solid waste that can possibly be hazardous. This includes, e.g., spent pot lining (refractory), filter dust, and sludge from waste water treatment. In the LCA, it has been assumed that all waste fractions are properly treated, mainly through controlled landfills. It should be noted that the LCA results do not include landscape effects from waste. It should also be noted that landfill sites sometimes represent very concentrated emission sources. The LCA results do not take such local pollutions into account. Therefore, the environmental significance of local waste treatment should be addressed outside the LCA study.

12.2 Other Health aspects

Health aspects addressed by the SEA: Aluminium production potentially impact human health in different ways during: Construction, temporary stay/living and operation. Further health impacts can be found at earlier stages (e.g. mining of bauxite) and at the final close-down of the aluminium smelter. Examples of health impacts are shown in **Textbox 12.1**.

1. Construction
   - Occupational health
   - Injuries and hazards (fires and spills during transport and handling of materials)

2. Temporary stay/living
   - Living conditions, sanitation etc.
   - Non-communicable diseases (e.g. cancer and asthma)
   - Communicable diseases (e.g. infections)
   - Mental health and stress due to changes in social conditions and demographic changes leading to health impacts like, e.g., changes in alcohol consumption

3. Operation
   - Injuries (explosions, fires, spills etc.)
   - Air emissions to external environment
   - Air emissions to internal production facilities
   - Waste water emissions
   - Solid waste
   - Noise (transport, smelting ventilators)
   - Illumination
   - Odour

Textbox 12.1: Examples of health impacts of the construction of the aluminium smelter; contemporary stay/living and operation. Impact categories included in the LCA are highlighted.

As it appears, there is a long list of health impacts of which the LCA only addresses air and water emissions as well as solid waste.

Besides impacts on physical health, impacts on mental health are also likely to occur. Especially during the construction phase in which mainly foreign labour workers are accommodated temporarily. The groups at risk of health impacts are mainly workers and local residents. In connection to the Strategic Environmental Assessment (SEA) (Greenland Home Rule 2007), a baseline study of human health in Greenland and a scoping of potential health impacts were undertaken. A specific assessment, including mitigating measures, is not published yet.

Important health aspects not covered by the LCA: Occupational Health and Safety is not covered by the LCA. Hence, human health impacts induced by, e.g., magnetic fields, dust, and noise occurring inside the smelter or during the construction phase are not assessed. Injuries related to, e.g., road traffic and work are included in the Stepwise model, but as the LCI has not included data concerning injuries, this impact category has not been applied. The contribution from the smelter and its supporting facilities to injuries could be significant – both during construction and operation.

12.3 Red flags raised by the LCA

Two groups of emissions have made us to raise red flags for human health impacts in Greenland.

Sulphur dioxide: The first is emission of *sulphur dioxide, particulates and carbon monoxide* – which can have respiratory effects on humans. However, a deeper analysis is necessary to estimate, e.g., dispersion and local concentration. We can therefore only conclude that this emission is an issue of concern and something that should ideally be considered in the SEA or in a separate HIA.

Hydrogen fluoride: The second 'red flag' is the emission of *hydrogen fluoride (HF*), which is mainly emitted through the factory roof. Presuming that the smelter in Greenland will have a similar design as the plant in Deschambault (Quebec), HF emissions from process water will not be an issue, as all process water will be evaporated. However, rainwater from the premises will also contain HF and this should obviously be considered together with the HF already present in the steam generated by the process water. According to Montembeault (2009), the water used in the cast house does not contain HF; in the anode plant, water is in contact with fluoride. In Greenland, however, there will not be an anode plant. Unless exposed to very large doses, we have not found evidence that HF emissions will have significant impacts on human health, but considering the possibility of bioaccumulation, it has been considered necessary to consider this as input to the SEA or HIA. The concern has not been raised by the LCA as such, but is a result of literature studies and interviews conducted as part of the LCA. According to feedback from Alcoa experts (see Preface), HF is an issue of ecotoxicity more than human toxicity. Existing aluminium smelters make studies of fluoride concentration in local vegetation and in ambient air. In the case of the smelters in Deschambault and Iceland, there are no concerns about human toxicity.

Other issues: As part of the study, the Deschambault aluminium factory in Quebec was visited, where it was observed that workers involved in dismantling used refractory were exposed to (what appeared to be) significant amounts of dust. In an OH&S perspective, this would be relevant to address in the SEA.

Also, attention should be paid to the handling of solid and hazardous waste produced at the plant. Plans should be made for how to handle and treat this – probably outside Greenland.

13 Sensitivity, completeness and consistency checks

According to ISO 14044 (2006), an evaluation in the interpretation phase including sensitivity, completeness and consistency check must be carried out in order to establish confidence in the results of the LCA.

13.1 Sensitivity check

The objective of the sensitivity check is to assess the reliability of the results and how they are affected by uncertainties in data, assumptions and LCIA methods (ISO 14044 2006). Sensitivity has been assessed at three levels: System boundaries (identification of marginal supply of aluminium), uncertainty related to data, and LCIA methods. The different aspects of sensitivity are evaluated in the following.

The main focus of the present LCA is on GHG emissions. Therefore, the sensitivity analysis mainly focuses on GHG emissions. In this respect, it should be mentioned that the presented results and conclusions related to other impact categories are subject to significant uncertainties.

Sensitivity: Location of marginal supply of aluminium

The LCA report mainly compares the proposed Greenland smelter (Alternative 1) with marginal supply of aluminium (Alternative 0). When identifying the marginal supply, two parameters are crucial; the location of the marginal aluminium production and the marginal supply of electricity used in the identified regions. **Table 13.1** presents the eight included sensitivity scenarios representing uncertainties in the identification of the location of the marginal aluminium production.

Location scenario	**Share of included locations**	**GHG emissions** kg CO2e/kg alu
Sc 0: Average; China, CIS (Russia), Middle East, RECOMMENDED SCENARIO	China (60%), CIS (22%), and the Middle East (18%). CIS is mainly Russia.	20.7
Sc 0e: As Sc0 but with share of China reduced from 60% to 40%	China (40%), CIS/Russia (33%), the Middle East (27%)	18.5
Sc 0f: Marginal supply of aluminium (IAI + China world average)	China (70%), Asia (12%), Eastern/Central Europe (6%), Western Europe (5%), Africa (5%), Latin America (3%), Oceania (2%), and North America (-3%)	19.8
Sc 0g: Marginal supply of aluminium (according to RTA)	China (60%), Asia/Abu Dhabi, Kazakhstan, Qatar and Oman (16%), Eastern and Central Europe/Russia (14%), Africa/Egypt (6%), North America/Canada (2%), and Western Europe /Iceland (2 %)	19.8
Sc 0h: Marginal supply of aluminium (according to USGS)	The Middle East (47%), Russia (19%), China (13%), Africa (10%), Western Europe (8%), and Latin America 3%	15.8
Sc 0i: Marginal supply of aluminium – only China	China (100%)	25.7
Sc 0k: Marginal supply of aluminium – only CIS/Russia	CIS/Russia (100%)	11.6
Sc 0m: Marginal supply of aluminium – only the Middle East	The Middle East (100%)	16.1

Table 13.1: Included sensitivity analyses concerning uncertainties in the identification of the location of the marginal supply of aluminium.

The GHG emissions from the recommended scenario (Sc0) are 20.7 kg CO2e/kg alu, and they vary from 11.6 kg CO2e/kg alu (Sc0k: only CIS/Russia) to 25.7 kg CO2e/kg alu (Sc0i: only China). It should be noted that scenarios 0k and 0i represent extremes which are not as likely to appear as the first five scenarios shown in **Table 13.1**. The GHG emissions from these scenarios vary from 15.8 kg CO2e/kg to 20.7 kg CO2e/kg. It appears that the results of the sensitivity scenarios vary significantly from the result of the recommended scenario. Therefore, the identification of the location of the marginal supply of aluminium is a potentially significant contributor to uncertainties.

Sensitivity: Electricity mix used in marginal supply of aluminium

As mentioned in the section above, the electricity mix is crucial for the calculated results of the LCA. Therefore, different sensitivity scenarios relating to the identification of the marginal electricity supply have been carried out as subsets to scenario Sc0 (the recommended scenario) and the three country specific scenarios; Sc0i (China), Sc0k (CIS/Russia), and Sc0m (Middle East).

Electricity scenario	**GHG emissions** kg CO2e/kg alu
Sc 0: Average; China, CIS (Russia), Middle East RECOMMENDED SCENARIO	**20.7**
Sc 0a: 50% reduction of hydropower	24.4
Sc 0b: 25% gas alternatively flared	21.2
Sc 0c: 75% gas alternatively flared	20.5
Sc 0d: 100% coal for China	22.8
Sc 0i: Marginal supply of aluminium – only China	25.7
Sc 0j: 100% Coal – only China	29.2
Sc 0k: Marginal supply of aluminium – only CIS/Russia	11.6
Sc 0l: 50% reduction of hydropower	23.0
Sc 0m: Marginal supply of aluminium – only the Middle East	16.1
Sc 0n: 25% of gas alternatively flared	17.5
Sc 0o: 75% of gas alternatively flared	14.8

Table 13.2: Included sensitivity analyses concerning uncertainties in the identification of the marginal electricity mix used in aluminium smelters.

Uncertainties related to Scenario 0 (recommended scenario): The sensitivity scenarios that concern uncertainties in the electricity mix used in scenario 0, i.e. sensitivity analyses Sc0a to Sc0d, show GHG emissions varying from 20.5 kg CO2e/kg (Sc0c) to 24.4 kg CO2e/kg (Sc0a). It appears that the result is most sensitive to the share of hydropower; if the share of hydropower is reduced by 50% the GHG emissions increase by 18% from 20.7 to 24.4 kg CO2e/kg. The results are not sensitive to (i.e. weakly affected by) changes in the amount of gas that would alternatively have been flared. This is because the gas that would alternatively have been flared only accounts for 5% of the applied electricity mix. There share of coal in China may moderately affect the result; if 100% coal in China is applied instead of 85%, the GHG emissions increase by 10% from 20.7 to 22.8 kg CO2e/kg alu.

Uncertainties related to scenario 0i (China): It appears from **Table 13.2** that the GHG emissions increase by 14% if the share of coal is changed from 85% to 100%. Since the identification of the marginal electricity supply in China is subject to uncertainties, the share of coal in China's marginal electricity mix is identified as a significant contributor to uncertainties in the results.

Uncertainties related to scenario 0k (CIS/Russia): It appears from **Table 13.2** that the GHG emissions increase by approximately 100% if the share of hydro is changed from 81% to 40%. As mentioned in section 5, the share of hydropower in the marginal electricity mix may be overestimated in some cases, because some hydropower plants would have been built regardless of the establishment of aluminium smelters. Therefore, the identification of the share of hydropower is subject to significant uncertainties.

Uncertainties related to scenario 0m (Middle East): It appears from **Table 13.2** that the GHG emissions vary with ±9% when changing the share of gas that would alternatively have been flared from 50% to 25% and

75%. Since the identification of the amount of gas that would alternatively have been flared is subject to uncertainties, this is identified as a significant contributor to uncertainties in the results.

Since all sensitivity scenarios in **Table 13.2** represent likely representatives for the marginal supply of electricity (through some are more likely than others), the range from 11.6 kg CO2e/kg to 29.2 kg CO2e/kg is regarded a likely uncertainty range relating to electricity mix and location. The recommended scenario is approximately of the mid-range value.

Sensitivity: Technology in aluminium smelter

In section 10, data for two types of smelter technology have been collected/estimated; new smelter technology (mainly represented by Alcoa's new smelter in Iceland) and existing smelter technology (mainly based on world and European average smelters). The effect on GHG emissions from the two types of technologies is evaluated in section 11.1, under 'Sensitivity scenarios 0p: New vs existing technology at aluminium smelter'.

It appears from **Table 11.5** (on page 141) that the results are not significantly sensitive to uncertainties relating to new versus existing technology in the aluminium smelter. For both the Greenland smelter and for the marginal supply of aluminium, the existing technology shows around 13-15% higher GHG emissions than new technology. For scenario 0, this is relatively insignificant compared with the uncertainties related to the identification of the marginal electricity mix.

Sensitivity: Bauxite

According to **Table 11.1**, the production of bauxite only accounts for 2.4% of the total GHG emissions related to the production of aluminium (Greenland smelter). For other more GHG-intensive scenarios, this will even be less. Therefore, uncertainties related to the production of bauxite are regarded as being insignificant.

Sensitivity: Alumina

According to **Table 11.1**, 56% of the GHG emissions related to the production of alumina originate from the production and burning of fossils fuels to produce process heat. According to **Table 9.3**, different data sources suggest that different fuel mixes are used in the alumina production. The GHG emissions related to the production of 1.92 kg alumina (this is required per kg aluminium) using the suggested fuel mix in **Table 9.3** are 2.89 kg CO2e. If only natural gas is used, the GHG emissions are 2.58 kg CO2e; and if only heavy fuel oil is used, the GHG emissions are 3.00 kg CO2e. This variation is regarded as insignificant. Further, the applied fuel mix is based on world average, and it has been confirmed by Alcoa (2009a) that the fuel mix will be similar for the alumina used in the Greenland smelter.

Sensitivity: Transport

According to **Table 11.1**, the transport of raw materials (mainly bauxite to the alumina stage, and alumina to the smelter stage) accounts for 0.942 kg CO2e/kg aluminium – only 0.227 kg CO2e/kg relates to the transport of alumina to the smelter stage.

Generally, the transport distances have been estimated at the high end (transport distance alumina at 10,000 km). The same transport data applies to alumina in all analysed scenarios, and only minor differences in GHG emissions from transport are identified for the smelter stage; 0.208-227 kg CO2e/kg alu, see **Table 11.1**, **Table 11.2**, **Table 11.3**, and **Table 11.4**.

Though transport figures may be overestimated, the uncertainties related to transport are regarded as being insignificant. In addition, only negligible differences between the scenarios have been found in terms of transport.

Sensitivity: IO-based data

To account for all the inputs that are typically excluded from the LCA due to more or less well defined cut-off criteria, the process-based data has been supplemented with IO-based data (see sections 7.2, 8.3, 9.3, and 10.3). This data accounts for inputs of furniture, office equipment, business travelling, and other service inputs, e.g., accounting and legal services. IO data supplements process data in the following processes: aluminium smelter stage, alumina stage, bauxite stage, and in the production of electricity. For each of these processes, the same IO data (per kg or per kWh) has been applied to all scenarios. Thus, the above-mentioned types of inputs are regarded as being the same in Greenland as in other parts of the world. This is obviously a rough estimate subject to uncertainties. Furthermore, the IO data is based on relatively old data on the US economy in 1998; it may be questioned how representative this is for the current and future economy. However, the hybrid approach is regarded as the only desirable way of including these 'hard to quantify' inputs, and it is argued that it is better to include uncertain data than not including any data. **Table 13.3** shows the GHG emissions related to the IO data.

IO data	**GHG emissions** kg CO2e/kg aluminium
Electricity, IO data	0.0696-0.0826
Bauxite, IO data	0.116
Alumina, IO data	0.179
Smelter, IO data	0.371
Total, IO data	**0.736-0.749**

Table 13.3: GHG emissions related to the inputs included in the product system via IO data.

It appears from **Table 13.3** that the GHG emissions caused by the inputs identified through IO data account for 0.736-0.749 kg CO2e/kg aluminium. The variation in the GHG emissions from electricity production is due to different electricity uses in scenarios with new smelter technology and existing smelter technology, respectively. The GHG emissions are directly proportional with the electricity use.

Compared to the total GHG emissions of 5.92 kg CO2e/kg aluminium from the Greenland smelter, the contribution from IO data is relatively high; it comprises 12% of the GHG emissions. Since the applied IO data is subject to inaccuracies, as mentioned above, the uncertainties related to IO data are regarded as being significant. However, since the contribution from IO data is almost the same in all scenarios, these uncertainties do not affect the results in terms of the comparison of scenarios.

Sensitivity: LCIA method

Characterisation: The main focus of this LCA study is on GHG emissions. Since the characterisation factors for GHG emissions are based on the IPCC global warming potential (100 year time horizon)[18] in almost all LCIA methods, differences between LCIA methods regarding characterisation are regarded as insignificant.

Weighting: The weighted results have been used as supplementary information to the assessment of the characterised results. The weighted results show that the most significant impacts categories are: Global warming,

[18] It should be noted that the Impact2002 method (Jolliet et al. 2003) uses a 500-year time horizon. But this is only relevant for non-CO_2 emissions. Since 91% of the GHG emissions related to aluminium production in Greenland are caused by CO2, this difference is insignificant.

respiratory inorganics, human toxicity, and photochemical ozone formation (impact on vegetation). In order to assess the validity of this compared with other weighting methods, a comparison of the weighted results has been made by use of the EcoIndicator and the Impact 2002 methods.

In order to compare the weighted results using different LCIA methods, the impact categories included in the LCIA methods have been aligned, see **Table 13.4**. The actual comparison of weighted results (as percentage of contribution to sum of all weighted results/single score) is presented in **Figure 13.1**.

Stepwise	EcoIndicator	Impact 2002
Respiratory inorganics	Resp. inorganics	Respiratory inorganics
Human toxicity, non-carc.	n.a.	Non-carcinogens
Global warming	Climate change	Global warming
Human toxicity, carcinogens	Carcinogens	Carcinogens
Photochemical ozone, vegetat.	n.a.	n.a.
Nature occupation	Land use	Land occupation
Ecotoxicity, terrestrial	Ecotoxicity	n.a.
Ecotoxicity, aquatic	n.a.	Aquatic ecotoxicity
Eutrophication, terrestrial	Acidification/ Eutrophication	Terrestrial acid/nutri
Acidification	n.a.	n.a.
Respiratory organics	Resp. organics	Respiratory organics
Eutrophication, aquatic	n.a.	n.a.
Ozone layer depletion	Ozone layer	Ozone layer depletion
Mineral extraction	Minerals	Mineral extraction
n.a.	Fossil fuels	Non-renewable energy
n.a.	Radiation	Ionizing radiation
n.a.	n.a.	Terrestrial ecotoxicity

Table 13.4: Key for comparison of weighted results using different LCIA methods.

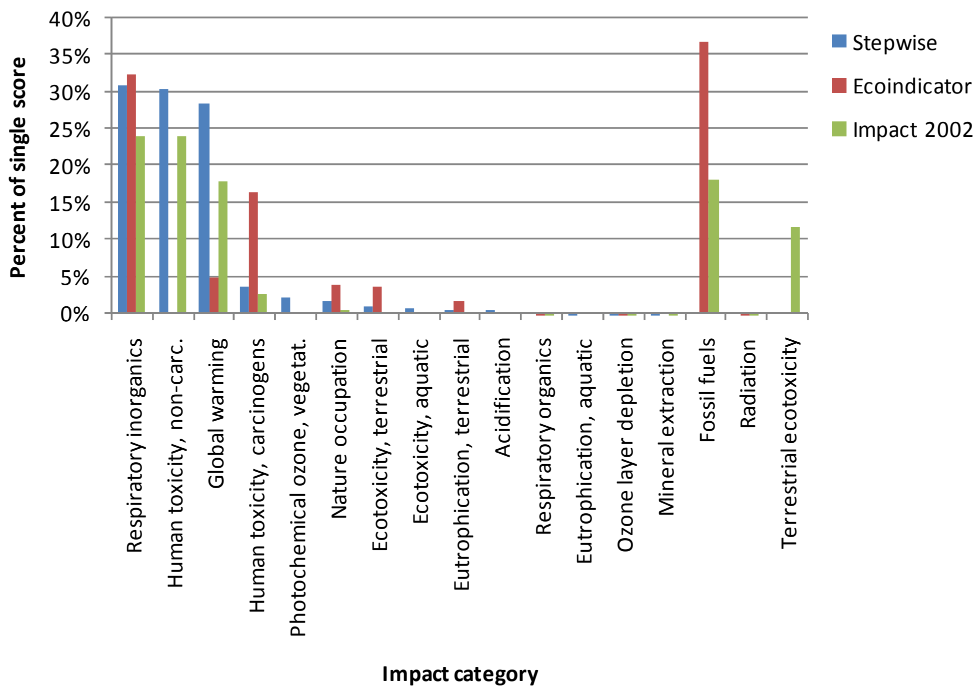

Figure 13.1: Comparison of weighted results using different LCIA methods; Stepwise, EcoIndicator, and Impact 2002. The weighted results are shown for the Greenland smelter. The unit of the y-axis is the percentage of the contribution to the sum of weighted impacts (also referred to as the single score).

It appears from **Figure 13.1** that the identification of respiratory inorganics, human toxicity, and global warming as significant impact categories is relatively consistent among the included LCIA methods. It should be noted that the identification of significant impact categories is not based on weighted results; instead the assessment of characterised results, red flag raising based on qualitative assessment, and additional heath assessment are used. Therefore, the uncertainties related to weighting in LCIA methods are not regarded as being significant.

13.2 Completeness check

The objective of a completeness check is to ensure that the information provided in the difference phases of the LCA are sufficient in order to be able to interpret the results (ISO 14044 2006).

Life cycle inventory

The point of departure for each life cycle stage is that all processes and data of environmental relevance are included in the inventory. Environmentally relevant means relevant to the impact categories included in the study. In order to achieve completeness in the LCI data, the hybrid approach to system delimitation has been applied. However, for some input categories, only process data is used. For these input categories, the LCI data does not represent a complete set of inputs. **Figure 13.2** provides an overview of the processes which are described as hybrid processes and which are only described using process data.

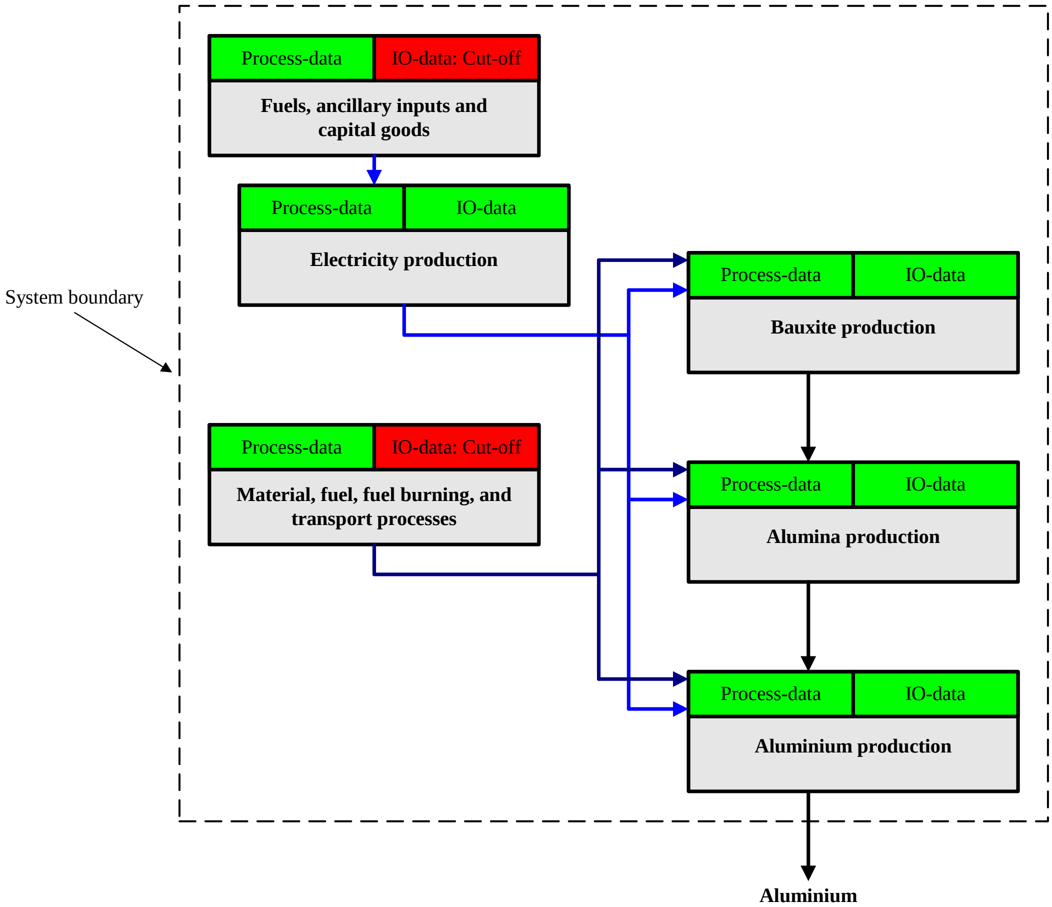

Figure 13.2: Presentation of applied cut-offs marked in red. Cut-offs are applied to upstream processes to electricity and materials, fuels, fuel burning and transport processes.

Since the most important product flows (in terms of monetary flows relating to primary aluminium production) are covered using the hybrid approach, the data is regarded as being relatively complete. The additional GHG emissions that should be added to the result, if the hybrid approach was applied to all inputs, are estimated as being insignificant.

Life cycle impact assessment

The main focus of this study is on GHG emissions. No present GHG emissions which are not included in the Stepwise method have been identified. Only one present type of emission which is not included in the Stepwise method has been identified; i.e. hydrogen fluoride (HF). However, the impact from this emission is considered separately, and therefore, the applied LCIA method combined with the additional qualitative assessments is regarded as being complete.

As a consequence of the less detailed assessment of other impacts than GHG emissions and local human health impacts, it follows that the presented results and conclusions related to these impacts are subject to significant uncertainties.

13.3 Consistency check

The objective of the consistency check is to verify that assumptions, methods and data used are consistent with the goal and scope of the study. Especially, the consistencies regarding data quality along the product chain, regional/temporal differences, allocation rules/system boundaries, and LCIA are important (ISO 14044).

Data quality along the product chain: The point of departure for the data collection of each life cycle stage is that no processes are omitted; i.e., the hybrid approach has been applied. Only very few interventions have not been included in the study. These are marked in red in **Figure 13.2**.

Regional differences: Regarding regional differences, the location of the marginal supplier of aluminium has been identified and the sensitivity to the related uncertainties has been evaluated. IO data for the USA in 1998 has been used as representative for all included regions. No regional differences have been included in the scenarios for the production of bauxite and alumina – the same marginal supplier has been assumed for all scenarios.

Temporal differences: Regarding temporal differences, the results are intended to provide decision support in relation to the establishment of a future aluminium smelter (from year 2014 to ?). Inputs of materials and energy to the life cycle stages are based on data for 2005-2008, and electricity mixes are based on projections (energy outlook and expert assessments) reflecting the relevant time horizon. Background data describing the exchanges related to these inputs is based on older data: energy efficiencies in power plants are based on data for 2006; most of the applied LCI data from databases is from 2000-2004, and the applied IO data is from the USA in 1998. Generally, the newest available data or future projections have been used. Therefore, the temporal differences between the technology described in the used data and the actual technology in the product system relating to the Greenland smelter are not regarded as being significant.

Allocation and system delimitation: Regarding allocation and system delimitation, the consequential approach has consistently been applied to most included inputs. However, the ecoinvent database uses average technology and allocates by use of allocation factors which do not comply with the consequential approach. The effect of using allocation factors and of applying average technologies has been assessed in the cases of all applied LCI data from ecoinvent. This method is regarded as being insignificant because the applied data has been sufficiently disaggregated and based on detailed modelling before the ecoinvent database was used; e.g., electricity technologies are modelled separately, the location of aluminium smelters is modelled in detail, and electricity efficiencies are modelled in detail.

14 Interpretation and conclusions

As a general comment to all results, it should be noted that the impact potentials shown in this study are generally significantly higher compared to existing studies reviewed in section 2. The reason is, partly, that we have used consequential modelling and marginal electricity sources, which, on average, tend to reflect a higher share of electricity based on fossil fuels. Furthermore, the application of the hybrid LCA approach without cut-offs means that more processes (including capital goods) are included in our model, compared to existing LCAs.

14.1 Significant Issues

Several potentially significant issues are related to aluminium production (in Greenland), of which this study pays special attention to GHG emissions. The following includes a detailed description of the results for GHG emissions, followed by a shorter and, due to the nature of the study, more uncertain assessment of other impact categories.

GHG emissions from Alternative 1: The results show that the planned aluminium smelter (Alternative 1), will represent emissions of 5.92 kg CO2e per kg produced virgin aluminium, equivalent to an annual emission of 2.13 million tonnes of CO2e, presuming an annual capacity of 360,000 tonnes of virgin aluminium. These emissions can be divided into the following:

- Scope 1 emissions (directly from the smelter) which amount to 0.597 million tonnes,
- Scope 2 emissions (from electricity use) that amount to 0.0502 million tonnes, and
- Scope 3 emissions (related to everything else including the mining and alumina stages), which amount to 1.48 million tonnes

GHG emissions from Alternative 0: If the Greenland smelter is not constructed (Alternative 0), the production is assumed to take place alternatively in a weighted combination of China, CIS and the Middle East, according to our suggested scenario (Scenario 0). This will represent emissions of 20.7 kg CO2e per kg virgin aluminium or 7.47 million tonnes of CO2e per year, assuming the same capacity as above.

This solution, however, involves some uncertainty and the results of Alternative 0 are highly sensitive to one assumption in particular – namely the energy sources used for electricity generation. Therefore, a number of alternative scenarios have been developed, both in terms of location and energy sources. This shows that the result varies from 11.6 to 29.2 kg CO2e per kg virgin aluminium, depending on the assumptions applied on location and energy mix, see **Figure 14.1**.

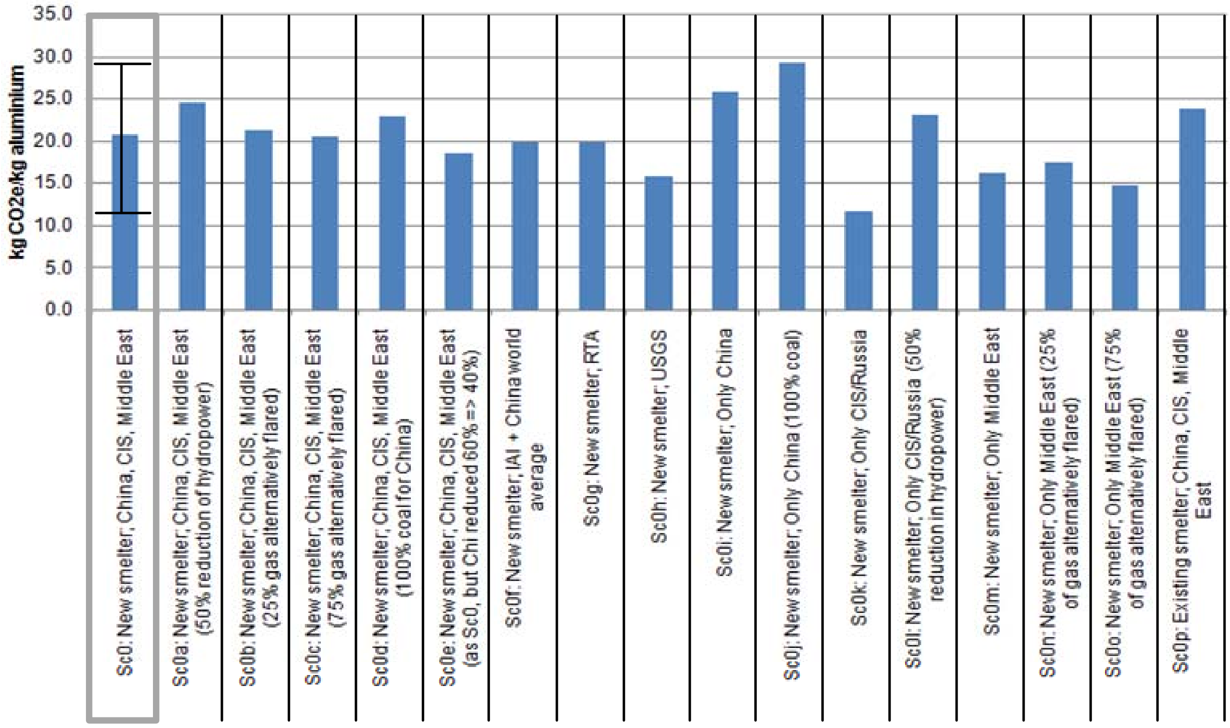

Figure 14.1: Sensitivity analyses relating to the electricity mix in Scenario 0. The anticipated marginal supply of aluminium (Scenario 0) is marked in a grey frame to the left, and the range of GHG emissions calculated in Sc0a to Sc0o is illustrated by an uncertainty bar.

The lowest GHG emissions of 11.6 kg CO2e per kg virgin aluminium would come from a production mainly based on hydropower in the Commonwealth of Independent States (CIS)/Russia. The GHG emissions of 29.2 kg CO2e per kg virgin aluminium represent a production in China based on 100% coal power. A more fair way of showing the result is therefore 20.7 ± approx. 9 kg CO2e per kg virgin aluminium for Scenario 0.

GHG emissions in a global perspective (Alternative 1 minus Alternative 0): The total change in GHG emissions (in a global perspective) which results from the placement of an aluminium smelter in Greenland will be the impacts of Alternative 1 minus the impacts of Alternative 0, according to the applied assumptions on the global supply and demand situation on the aluminium market. If we include the uncertainty range explained above, this means that the total amount of GHG emissions 'saved' as a result of implementing the Greenland smelter is between 2.05 and 8.36 million tonnes of CO2e, annually (or 5.34 million tonnes of CO2e annually, if referring to the suggested scenario). In other words, the Greenland smelter will imply a reduction in GHG emissions of about 5 ± 3 million tonnes of CO2e annually.

To put this into perspective, Greenland's current annual GHG emissions amount to approximately 700,000 tonnes (UNFCCC 2009, Statistics Greenland 2005). Hence, the planned smelter has the potential for reducing global emissions by a figure which corresponds to approximately 8 times Greenland's total GHG emissions (or 3-12 times, if we include the sensitivity range mentioned above).

It is possible that equally carbon friendly alternatives (to the Greenland smelter) exist and could be chosen by Alcoa. This includes smelters in areas where it is possible to use 100% hydropower or 100% gas which otherwise would be flared, e.g., in regions such as Russia/Siberia, Africa or the Middle East. However, the present study does only compare the Greenland smelter with no Greenland smelter. Specific alternatives to the Greenland smelter planned by Alcoa are not considered. Instead, the study compares the Greenland smelter with the most likely alternative capacity that would be installed somewhere else as a reaction on changes in the demand for aluminium.

Other Impacts: Despite the focus on global warming, the LCA has also provided results for 15 other environmental impact categories, including ozone depletion, nature occupation, acidification, photochemical ozone formation, etc. (see section 11.2). These impact categories have not been scrutinized in detail, but the screening mainly points towards human toxicity (non-carcinogenic) and respiratory inorganics as potentially important. Our analysis suggests that, while the latter can be important to humans, human toxicity is mainly related to mining fields, red mud, and landfill sites, where the transfer to (or contact with) humans is relatively insignificant.

For respiratory inorganics, the main contributing emissions are sulphur dioxide, particulates, and nitrogen oxides. The electrolysis process, the ship transport of raw materials, and the alumina production cause most of these emissions. It should be noted that the relative importance is likely to be overestimated in the analysis, as the emissions occur in remote places, such as the Atlantic Ocean, with little human exposure. The emissions that come from the smelter in Greenland are discussed in the following.

Human Health impacts in Greenland: The study includes a tentative assessment of potential human health impacts occurring locally in Greenland – but only related to the external environment (not occupational health and safety). The assessment shows that the smelter contributes somewhat significantly to the impact category 'respiratory inorganics'. Respiratory inorganics are typically caused by combustion processes and various types of particle emissions. The main contribution from the Greenland smelter is sulphur dioxide, which consequently raises a red flag. The latter means that we recommend that this is considered in the strategic environmental assessment (SEA) or a separate Health Impact Assessment (HIA).

Another potential concern is emissions of hydrogen fluoride (HF). Unless exposed to very large doses, we have not found indications that HF emissions have significant impacts on human health, but considering the possibility of bioaccumulation, it has been considered necessary to discuss this as an input to the SEA or HIA. The concern has not been raised by the LCA as such, but is a result of literature studies and interviews conducted as part of the LCA.

14.2 Evaluation; Sensitivity, completeness and consistency

Sensitivity check: The sensitivity check in section 13.1 shows that the main uncertainty is related to the choice of the marginal electricity production for the aluminium smelter in Alternative 0. The GHG emissions from the smelter stage can vary from 8.6 to 26.1 kg of CO2e per kg of virgin aluminium. The first result represents a situation in which the marginal aluminium comes from CIS (more than 80% hydropower), while the latter figure refers to a situation in which the marginal aluminium comes from China and the marginal electricity source is 100% coal. In a cradle-to-gate perspective, this gives a variation from 11.6 to 29.2 kg of CO2e per kg of virgin aluminium, as mentioned previously.

In the suggested scenario for Alternative 0, GHG emissions amount to 20.7 kg CO2e per kg virgin aluminium. However, this may vary from 20.5 to 24.4 kg CO2e per kg virgin aluminium depending on choices made regarding gas and hydropower, even when the assumed country mix is constant (China, CIS/Russia and Middle East). The first figure represents a situation in which 75% of the gas is alternatively flared (instead of only 50%), and the latter refers to a situation in which the amount of hydropower is reduced by 50% (see section 5.3 for explanations).

The sensitivity check shows that the results are most sensitive to assumptions concerning the amount of actually affected hydropower. As it has not been possible to rule out any of the scenarios, we have included all scenarios to represent a realistic uncertainty range (11.6 to 29.2 kg CO2e per kg virgin aluminium). The suggested scenario amounts to 20.7 kg CO2e per kg virgin aluminium, which is close to the mid-range value.

Assumptions regarding the applied technology are also somewhat important, as the results for Alternatives 0 and 1 may vary by 13-15%, depending on whether the applied technology can be described as ‘existing’ or ‘new’. Uncertainties also apply to the mining stage, to alumina production, to transport, as well as to the IO-based data that has been applied. However, the uncertainty range of these inputs is generally considered insignificant compared to the uncertainties related to the electricity mix needed for the smelter. The same applies to the LCIA modelling. A Monte Carlo assessment has not been performed that could have weighed the complete set of uncertainties together and provided an uncertainty distribution. However, since the most significant contributor to uncertainties has been identified and quantified, it is assessed that no crucial additional information would be achieved through a Monte Carlo analysis.

The uncertainty range of Alternative 1 is relatively small compared to Alternative 0, because the energy source is known. The uncertainties here are mainly related to the fuel types used in the production of alumina and the use of anodes. However, the use of fuels in anode production has been verified by Alcoa (2009a) and it is identical in all alternatives and scenarios. Furthermore, the use of anodes is also verified by Alcoa and it varies insignificantly in the scenarios representing ‘existing’ and ‘new’ technologies.

Considering the limited magnitude of the uncertainties related to the assumptions about electricity mix and technologies, we have not performed a separate assessment of uncertainties related to data quality.

Completeness check. The completeness analysis carried out in section 13.2 shows that the completeness of the inventory is high due to the application of the hybrid approach to most processes. Additional completeness, which could have been obtained by applying the hybrid approach to all processes, is assessed to be insignificant. Moreover, the applied LCIA method combined with the additional qualitative assessment of hydrogen Fluoride (HF) is considered to be complete.

Consistency check. A consistency check has been carried out in section 13.3 of data quality along the product chain, including regional differences, temporal differences, co-product allocation, and system delimitation. The check shows that assumptions, methods and data are consistent with the goal and scope of the study.

14.3 Conclusion and perspectives

Table 14.1 provides an overview of the results according to the suggested scenario. Here, the size of the GHG emissions from different life cycle stages in the two alternatives 1) and 0) can be seen. The last row represents the difference between the alternatives: Alternative 1) minus Alternative 0), which shows the global consequences of building the Greenland smelter. The amounts are also presented as relative (in percentage) to Greenland’s current annual GHG emissions of approximately 700,000 tonnes of CO2e.

GHG emissions (million tonnes of CO2e)	A) Mining	B) Alumina	C) Smelter	Within Greenland (scope 1)	Sum (A+B+C)
Alternative 1) Construction of smelter in Greenland	0.0520 7%	1.04 149%	1.04 148%	0.597 85%	2.13 305%
Alternative 0) No smelter in Greenland	0.0520 7%	1.04 149%	6.37 911%	0	7.47 1067%
Alternative 1) minus Alternative 0) Total global consequences	0	0	-5.34 -762%	0.597 85%	-5.34 -762%

Table 14.1: Overview of GHG emissions from decisions concerning Alternative 1, Alternative 0 and Alternative 1 minus 0.

It appears from the figures that most emissions occur at the alumina and smelter stages. The smelter's contribution to GHG emissions occurring within Greenland's geographical boundary (Scope 1) corresponds to 85% of the current annual total GHG emissions of Greenland.

However, global warming is a global problem, which ideally should be dealt with in a global perspective. In a global perspective, our estimate is that the smelter will contribute to 'avoided' emissions in China, CIS/Russia and the Middle East, equivalent to 7.47 million tonnes of CO2e, which corresponds to more than 10 times Greenland's current GHG emissions (1067%). As mentioned, the total net benefit will amount to 5.34 million tonnes of CO2e annually, with an estimated uncertainty range of approximately ±3 million tonnes of CO2e.

The quantitative assessment of other impact categories, according to the Stepwise LCIA method, suggests that no significant trade-offs with other impact categories can be found – and it appears that GHG emissions represent a good indicator for other impacts as well. But this conclusion is based on a less detailed assessment of other impacts. Also, it should be stressed that the study has compared a decision of establishing a smelter in Greenland (scenario 1) with the decision 'not' to install it, a non-decision (Scenario 0). However, as a result of conscious decision-making, it is possible that Alcoa could find alternatives to scenario 1 that are equally carbon friendly and maybe even more sustainable in a larger perspective. But the identification of specific alternatives to Alcoa's planned smelter in Greenland is out of the scope of the study.

Discussion and perspectives: Based on the assessment of its contribution to global warming, we can conclude that the proposed aluminium smelter would represent a significant reduction of GHG emissions in a global perspective, despite the burden it puts on Greenland's domestic carbon footprint.

It should be noted that local effects, like large concentrations of hazardous emissions from waste on a local scale, as well as effects on landscape and occupational safety and heath are not included in the LCA. Therefore, the environmental significance of local waste treatment should be addressed outside the LCA study, as well as local health and safety aspects should be addressed in specific assessments. All results of the LCA are calculated assuming that waste is disposed off at controlled landfills or recycled, and that the production is well managed, as in Alcoa's other aluminium smelters.

15 List of terms and abbreviations

Attributional (LCA) modelling:	See section 3.3
Capital goods:	Buildings, production machinery, transport vehicles, infra structure etc.
Carbon footprint:	The same as CO2e and can be related to a process, a specific stage of a product life cycle, or all the life cycle stages from cradle to gate or cradle to grave
Chi	China
CIS	Commonwealth of Independent States (CIS). Former Soviet Republics (Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Moldova, Russia, Tajikistan, Uzbekistan, Turkmenistan, and Ukraine).
Consequential (LCA) modelling:	See section 3.3
Co-product allocation:	The partitioning and distribution of the interventions (e.g., inputs and outputs) of a multi-product process over its co-products
CO2:	Carbon dioxide
CO2e:	Carbon dioxide equivalents
Cut-off (criteria):	Cut off (criteria) refers to a specification of the amount of material or energy flow or the level of environmental significance associated with unit processes or product systems to be excluded from a study
Elementary flow:	Material or energy entering the system being studied that has been drawn from the environment without previous human transformation, or material or energy leaving the system being studied that is released into the environment without subsequent human transformation
Functional unit:	Quantified performance of a product system for use as a reference unit
GD	Greenland Development. GD is a project organization established to assist the Government of Greenland in a wide range of areas of activity in relation to the aluminium project.
Hybrid LCA:	See section 3.3
Interventions:	Input and outputs as well as non-flow related exchanges such as land use
IO LCA:	Input-output LCA, see section 3.3
LA	Latin America
LCA:	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA:	Life Cycle Impact Assessment

Life cycle:	The stages from e.g. raw material extraction to product (cradle-to-gate) or raw material extraction to use and disposal of the product (cradle-to-grave)
Marginal production/suppliers:	Production or suppliers that is most likely to be affected by a marginal change in demand
ME	Middle East
N.a.	Not applicable
OH&S	Occupational Health and Safety
Pre-bake	In the Pre-bake design anodes for the reduction process are baked in brick-lined pits and the hydrocarbon off gasses can be captured and burned.
Primary aluminium:	This term represents virgin aluminium
Process LCA:	See section 3.3
Product system:	Collection of unit processes with elementary and product flows, performing one or more defined functions, and which models the life cycle of a product
Unit process:	Smallest element considered in the life cycle inventory analysis for which interventions are quantified
Sc	Scenario
Scope 1	Scope 1 emissions include the ‘direct’ emissions from sources that are owned or controlled by the company. This includes processes (e.g. chemical processes), burning of fossil fuels or transport in company owned vehicles
Scope 2	Scope 2 emissions include emissions from the generation of purchased electricity and heat. The scope 2 emissions presented in this report also includes emissions upstream from the power plant
Scope 3	Scope 3 includes emissions from sub-suppliers (other than scope 2), from transport processes in other parts of the life cycle and from customers or consumers
Secondary aluminium:	This term represents recycled aluminium
Smelting technology	Two types of aluminium smelting technologies distinguished by the type of anode used in the reduction process: Söderberg and Pre-bake.
SEA	Strategic Environmental Assessment.
System boundaries:	See section 3.3
Söderberg design	Söderberg design uses a single anode in the reduction process. Anodes are baked by the heat generation in the cells and the off gasses are more difficult to collect than for the Pre-bake design.
WBCSD	World Business Council for Sustainable Development

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Appendix 1: Data on fuels and flue gasses

Fuel	Density	Energy content (lower heating value)	
Fuel oil, heavy	951 kg/m^3	41.2 MJ/kg	39.2 MJ/litre
Fuel oil, light	850 kg/m^3	42.7 MJ/kg	36.3 MJ/litre
Natural gas	0.802 kg/m^3	45.9 MJ/kg	36.8 MJ/Nm^3
Propane	1.96 kg/m^3	46.2 MJ/kg	90.7 MJ/Nm^3
Diesel	870 kg/m^3	42.7 MJ/kg	37.2 MJ/litre
Hard coal**	801 kg/ m^3	24.0 MJ/kg	19.2 MJ/litre

Appendix table 1: Density and lower calorific values for different fuels. Densities are obtained from Andersen et al. (1981, p 218) and calorific values (pr kg for solid and liquid fuels, and per Nm^3 for gaseous fuels) are obtained from ecoinvent (2007) except propane which is based on Andersen et al. (1981, p 218). The calorific values obtained from ecoinvent (2007) are from the following processes: Heavy fuel oil is based on 'Heavy fuel oil, burned in power plant/RER', Light fuel oil is based on 'Light fuel oil, burned in industrial furnace 1MW, non-modulating/RER', natural gas is based on 'Natural gas, high pressure, at consumer/RER', diesel is based on 'Diesel, burned in building machine/GLO', and hard coal is based on 'Hard coal, burned in power plant/DE'.

Appendix 2: Explanation of units in the Stepwise LCIA method

This appendix briefly explains the impact categories included in the applied LCIA method: Stepwise 2006 (version 1.2) (Weidema et al. 2007). If no literature reference is given in the table, this means that the information is obtained from Weidema et al. (2007).

Impact category	Unit	Original source		Explanation
		EDIP 2003	Impact 2002+	
Global warming	kg CO_2-eq	x		The unit is GWP100 (kg CO_2 equivalents) based on the IPCC status reports.
Nature occupation	m^2 agr.land		x	The unit 'm^2-equivalents arable land', represents the impact from the occupation of one m^2 of arable land during one year. Impact 2002+ (Jolliet et al. 2003) has obtained the method for LCIA from EcoIndicator (Goedkoop and Spriensma 2001) where the impact is assessed on the basis of the duration of the occupation of the area (m2*years) multiplied by a severity score, representing the potentially disappeared fraction (PDF) of species in that area during the specified time. In order to include the impacts from transformation, the Stepwise method introduces an additional severity of 0.88 to represent the secondary impacts from this transformation (deforestation), calculated as the nature occupation during the later relaxation from deforestation.
Acidification	m^2 UES	x		The unit expresses the area of the ecosystem within the full deposition area (in Europe) which is brought to exceed the critical load of acidification as a consequence of the emission (area of unprotected ecosystem = m^2 UES). The impact indicator is based on modelling of deposition in Europe. (Hauchild and Potting 2005, p47)
Eutrophication, aquatic	kg NO_3-eq	x		The aquatic eutrophication potentials of a nutrient emission express the maximum exposure of aquatic systems that it can cause. The aquatic eutrophication potentials are expressed as N- or P-equivalents. (Hauchild and Potting 2005, p 73-74)
Eutrophication, terrestrial	m^2 UES	x		Same as for acidification.
Photochemical ozone, vegetat.	m^2*ppm*h	x		The impact is expressed as the accumulated exposure (duration times exceed threshold) above the threshold of 40 ppb times the area that is exposed as a consequence of the emission.The threshold of 40 ppb is chosen as an exposure level below which no or only small effects occur. The unit for vegetation exposure is m^2*ppm*hours. (Hauchild and Potting 2005, p 93)
Respiratory inorganics	kg $PM_{2.5}$-eq		x	The impact on human health related to respiratory inorganics is expressed as equivalents of particles ($PM_{2.5}$).
Respiratory organics	pers*ppm*h	x		The category covers the impact on human health from photochemical ozone formation. The impact is expressed as the accumulated exposure above the threshold of 60 ppb times the number of persons which are exposed as a consequence of the emission. No threshold for chronic exposure of humans to ozone has been established. Instead, the threshold of 60 ppb is chosen as the long-term environmental objective for the EU ozone strategy proposed by the World Health Organisation, WHO. The unit for human exposure is pers*ppm*hours. (Hauchild and Potting 2005, p 93)
Human toxicity, carcinogens	kg C_2H_3Cl-eq		x	The impact on human health related to carcinogens is expressed as equivalents of chloroethylene (C_2H_3Cl). The Impact2002+ method determines the damage on human health in terms of DALY (disability adjusted life years). Since there is no real mid-point for human toxicity, the Impact2002+ method has chosen C_2H_3Cl-eq. as a reference substance. (Jolliet et al. 2003)

Human toxicity, non-carc.	kg C_2H_3Cl-eq		**x**	Same as for human toxicity, carcinogens
Ecotoxicity, aquatic	kg TEG-eq w		**x**	The impact on ecosystems related to ecotoxicity is expressed as equivalents of chloroethylene triethylene glycol (TEG) into water. The Impact2002+ method determines the damage on ecosystems in terms of PAF (potentially affected fraction). Since there is no real mid-point for ecotoxicity, the Impact2002+ method has chosen TEG-eq. into water as a reference. (Jolliet et al. 2003)
Ecotoxicity, terrestrial	kg TEG-eq s		**x**	Same as for ecotoxicity, aquatic
Ozone layer depletion	kg CFC_{11}-eq		**x**	The unit is equivalents of CFC11 which is an important contributor to ozone layer depletion.
Non-renewable energy	MJ primary		**x**	Total use of primary non-renewable energy resources measured in MJ.

Appendix table 2: Explanation of the impact categories in the LCIA method Stepwise 2006 (version 1.2).

Appendix 3: Applied process-based LCI data on electricity

Specification of the applied process-based LCI data on electricity generation for the considered technologies and regions in this study.

Country/region	Applied process-based LCI data		
	Coal	Gas	Gas – alternatively flared
Greenland	-	-	-
Iceland	-	-	-
USA/Canada	-	-	-
Russia	Hard coal, burned in power plant/CN & Efficiency 18.8% for Russia (IEA 2008, p 526-527)	Natural gas, burned in power plant/CENTREL & Efficiency 18.8% for Russia (IEA 2008, p 526-527)	Natural gas, burned in power plant/CENTREL (Efficiency 18.8% for Russia, IEA 2008, p 526-527) minus Refinery gas, burned in flare/GLO
Australia	Hard coal, burned in power plant/RFC & Efficiency 36.9% for Pacific OECD (IEA 2008, p 514-515)	Natural gas, burned in power plant/US & Efficiency 44.6% for Pacific OECD (IEA 2008, p 514-515)	-
Middle East	Hard coal, burned in power plant/CN & Efficiency 38.7% for Middle East (IEA 2008, p 534-535)	Natural gas, burned in power plant/CENTREL & Efficiency 32.4% for Middle East (IEA 2008, p 534-535)	Natural gas, burned in power plant/CENTREL (Efficiency 32.4% for Middle East, IEA 2008, p 534-535) minus Refinery gas, burned in flare/GLO
Brazil	Hard coal, burned in power plant/CN & Efficiency 38.7% for Latin America (IEA 2008, p 538-539)	Natural gas, burned in power plant/CENTREL & Efficiency 37.8% for Latin America (IEA 2008, p 538-539)	-
China	Hard coal, burned in power plant/CN & Efficiency 28.9% for China (IEA 2008, p 530-531)	Natural gas, burned in power plant/CENTREL & Efficiency 31.9% for China (IEA 2008, p 530-531)	-
World	Hard coal, burned in power plant/RFC & Efficiency 32.1% for aver. world (IEA 2008, p 506-507)	Natural gas, burned in power plant/US & Efficiency 34.6% for aver. world (IEA 2008, p 506-507)	-

Appendix table 3: Applied process-based LCI data on electricity generation in this study. Table is continued in **Appendix Table 4**

Country/region	Applied process-based LCI data	
	Hydro	**Nuclear**
Greenland	Electricity, hydropower, at reservoir power plant, alpine region/RER	-
Iceland	Electricity, hydropower, at reservoir power plant, alpine region/RER	-
USA/Canada	Electricity, hydropower, at reservoir power plant/FI	-
Russia	Electricity, hydropower, at reservoir power plant/FI	-
Australia	Electricity, hydropower, at reservoir power plant, non alpine regions/RER	Electricity, nuclear, at power plant/US
Middle East	Electricity, hydropower, at reservoir power plant, non alpine regions/RER	-
Brazil	Electricity, hydropower, at reservoir power plant/BR (modified: CO2 emission eliminated)	Electricity, nuclear, at power plant pressure water reactor/CN
China	Electricity, hydropower, at reservoir power plant, non alpine regions/RER	Electricity, nuclear, at power plant pressure water reactor/CN
World	Electricity, hydropower, at reservoir power plant/FI	Electricity, nuclear, at power plant/US

Appendix table 4: Applied process-based LCI data on electricity generation in this study.

Appendix 4: World Energy Outlook; Marginal electricity

In the following tables, the applied marginal (right column in the tables) is calculated as the shares represented by the flexible (column 7) growths 2006-2015 (column 5) relative to the total of flexible growths.

Identification of marginal electricity at grid: World

World: Identification of marginal electricity							
	Share 2006	**Generation 2006**	**Generation 2015**	**Growth 2006-15**	**Growth 2006-30**	**Flexible**	**Applied marginal**
Fuel	(%)	(TWh)	(TWh)	(TWh)	(% p.a.)		(%)
Coal	41	7756	11100	3344	1.4%	yes	63%
Oil	6	1096	1046	-50	-0.2%	no	0%
Gas	20	3807	4725	918	0.9%	yes	17%
Nuclear	15	2793	3134	341	0.5%	yes	6%
Hydro	16	3035	3734	699	0.8%	yes	13%
Biomass and waste	1	239	418	179	2.3%	no	0%
Wind	1	130	664	534	6.7%	no	0%
Other: Geotermal, solar, tide and wave	0	64	153	89	3.5%	no	0%

Identification of marginal electricity at grid: China

China: Identification of marginal electricity							
	Share 2006	**Generation 2006**	**Generation 2015**	**Growth 2006-15**	**Growth 2006-30**	**Flexible**	**Applied marginal**
Fuel	(%)	(TWh)	(TWh)	(TWh)	(% p.a.)		(%)
Coal	80	2328	4445	2117	2.6%	yes	82%
Oil	2	52	57	5	0.4%	no	0%
Gas	1	26	83	57	4.8%	yes	2%
Nuclear	2	55	176	121	4.8%	yes	5%
Hydro	15	436	715	279	2.0%	yes	11%
Biomass and waste	0	3	18	15	7.4%	no	0%
Wind	0	4	62	58	11.6%	no	0%
Other: Geotermal, solar, tide and wave	0	0	4	4	0.0%	no	0%

Identification of marginal electricity at grid: Brazil

Brazil is represented by the region Latin America in IEA (2008).

Brazil: Identification of marginal electricity							
	Share 2006	**Generation 2006**	**Generation 2015**	**Growth 2006-15**	**Growth 2006-30**	**Flexible**	**Applied marginal**
Fuel	(%)	(TWh)	(TWh)	(TWh)	(% p.a.)		(%)
Coal	3	30	97	67	4.8%	yes	23%
Oil	11	107	95	-12	-0.5%	yes	0%
Gas	13	123	226	103	2.5%	yes	36%
Nuclear	2	21	43	22	2.9%	yes	8%
Hydro	68	654	748	94	0.5%	yes	33%
Biomass and waste	2	20	33	13	2.0%	no	0%
Wind	0	1	9	8	9.2%	no	0%
Other: Geotermal, solar, tide and wave	0	3	5	2	2.1%	no	0%

Identification of marginal electricity at grid: Australia

Australia is represented by the region OECD Pacific in IEA (2008).

Australia: Identification of marginal electricity							
	Share 2006	**Generation 2006**	**Generation 2015**	**Growth 2006-15**	**Growth 2006-30**	**Flexible**	**Applied marginal**
Fuel	(%)	(TWh)	(TWh)	(TWh)	(% p.a.)		(%)
Coal	37	656	749	93	0.5%	yes	40%
Oil	8	147	131	-16	-0.5%	yes	0%
Gas	21	368	367	-1	0.0%	yes	0%
Nuclear	25	452	579	127	1.0%	yes	55%
Hydro	7	128	141	13	0.4%	yes	6%
Biomass and waste	1	25	32	7	1.0%	no	0%
Wind	0	4	22	18	7.1%	no	0%
Other: Geothermal, solar, tide and wave	0	6	17	11	4.3%	no	0%

Appendix 5: Characterised results for all scenarios

The two tables below present the characterised results for all scenarios listed in **Figure 5.4**, p 87.

Scenario / Impact category	Global warming	Human toxicity, carcinogens	Human toxicity, non-carc.	Respiratory inorganics	Respiratory organics	Ionizing radiation	Ozone layer depletion	Ecotoxicity, aquatic	Ecotoxicity, terrestrial
Unit	kg CO2-eq	kg C2H3Cl-eq	kg C2H3Cl-eq	kg PM2.5-eq	pers*ppm*h	Bq C-14-eq	kg CFC-11-eq	kg TEG-eq w	kg TEG-eq s
Alternative 1: Greenland smelter									
Sc1: Greenland	**5.9**	**0.23**	**1.9**	**0.008**	**0.011**	**30**	**3.4E-06**	**1,636**	**17**
Sc1a: Existing smelter; Greenland	6.7	0.42	1.9	0.010	0.011	30	3.5E-06	1,649	17
Alternative 0: Marginal supply of aluminium									
Sc0: New smelter; China, CIS, Middle East	**20.7**	**0.36**	**2.4**	**0.029**	**0.019**	**32**	**3.5E-06**	**1,676**	**34**
Sc0a: New smelter; China, CIS, Middle East (50% reduction of hydropower)	24.4	0.37	2.5	0.034	0.021	33	3.6E-06	1,686	38
Sc0b: New smelter; China, CIS, Middle East (25% gas alternatively flared)	21.2	0.36	2.4	0.030	0.020	32	3.6E-06	1,677	34
Sc0c: New smelter; China, CIS, Middle East (75% gas alternatively flared)	20.5	0.36	2.4	0.029	0.019	32	3.5E-06	1,676	34
Sc0d: New smelter; China, CIS, Middle East (100% coal for China)	22.8	0.36	2.4	0.033	0.021	32	3.5E-06	1,682	37
Sc0e: New smelter; China, CIS, Middle East (as Sc0, but Chi reduced 60% => 40%)	18.5	0.35	2.3	0.025	0.018	32	3.6E-06	1,669	31
Sc0f: New smelter; IAI + China world average	19.8	0.43	2.3	0.027	0.018	33	3.4E-06	1,680	32
Sc0g: New smelter; RTA	19.8	0.35	2.3	0.027	0.019	32	3.6E-06	1,673	33
Sc0h: New smelter; USGS	15.8	0.34	2.2	0.020	0.016	31	3.7E-06	1,661	27
Sc0i: New smelter; Only China	25.7	0.37	2.5	0.039	0.023	33	3.4E-06	1,691	41
Sc0j: New smelter; Only China (100% coal)	29.2	0.38	2.6	0.044	0.025	34	3.4E-06	1,701	45
Sc0k: New smelter; Only CIS/Russia	11.6	0.33	2.1	0.015	0.014	31	3.5E-06	1,651	23
Sc0l: New smelter; Only CIS/Russia (50% reduction in hydropower)	23.0	0.36	2.4	0.030	0.020	33	3.8E-06	1,681	36
Sc0m: New smelter; Only Middle East	16.1	0.34	2.2	0.017	0.016	31	4.0E-06	1,660	26
Sc0n: New smelter; Only Middle East (25% of gas alternatively flared)	17.5	0.34	2.2	0.019	0.016	31	4.4E-06	1,661	26
Sc0o: New smelter; Only Middle East (75% of gas alternatively flared)	14.8	0.34	2.2	0.016	0.015	30	3.7E-06	1,658	26
Sc0p: Existing smelter; China, CIS, Middle East	23.8	0.56	2.4	0.034	0.021	33	3.6E-06	1,695	37
Results from Alcoa's existing production									
Sc2a: Alcoa Descambault	6.3	0.23	1.9	0.008	0.011	30	3.4E-06	1,640	17
Sc2b: Alcoa Iceland	5.9	0.23	1.9	0.008	0.011	30	3.4E-06	1,636	17
Key figures									
Average of all scenarios	**17.62**	**0.35**	**2.26**	**0.02**	**0.017**	**31.56**	**0.00**	**1,669**	**30**
Max% higher than average	65%	60%	16%	84%	42%	6%	22%	2%	50%
Min% lower than average	66%	35%	14%	67%	39%	6%	6%	2%	43%

Scenario / Impact category	Nature occupation	Acidification	Eutrophication, aquatic	Eutrophication, terrestrial	Photochemical ozone, vegetat.	Non-renewable energy	Mineral extraction
Unit	m2 agr.land	m2 UES	kg NO3-eq	m2 UES	m2*ppm*hours	MJ primary	MJ extra
Alternative 1: Greenland smelter							
Sc1: Greenland	**0.25**	**0.9**	**4.2E-03**	**0.59**	**98**	**88**	**0.034**
Sc1a: Existing smelter; Greenland	0.25	1.1	4.3E-03	0.62	100	92	0.036
Alternative 0: Marginal supply of aluminium							
Sc0: New smelter; China, CIS, Middle East	**0.41**	**3.4**	**7.4E-03**	**2.09**	**201**	**220**	**0.038**
Sc0a: New smelter; China, CIS, Middle East (50% reduction of hydropower)	0.45	4.0	8.2E-03	2.45	225	256	0.040
Sc0b: New smelter; China, CIS, Middle East (25% gas alternatively flared)	0.41	3.5	7.5E-03	2.14	204	227	0.039
Sc0c: New smelter; China, CIS, Middle East (75% gas alternatively flared)	0.41	3.3	7.4E-03	2.07	199	215	0.038
Sc0d: New smelter; China, CIS, Middle East (100% coal for China)	0.44	3.8	7.9E-03	2.32	216	238	0.039
Sc0e: New smelter; China, CIS, Middle East (as Sc0, but Chi reduced 60% => 40%)	0.38	2.8	6.8E-03	1.80	183	204	0.037
Sc0f: New smelter; IAI + China world average	0.40	3.3	7.2E-03	1.97	190	210	0.039
Sc0g: New smelter; RTA	0.40	3.1	7.1E-03	1.95	192	216	0.038
Sc0h: New smelter; USGS	0.34	2.2	6.1E-03	1.45	160	184	0.036
Sc0i: New smelter; Only China	0.47	4.5	8.7E-03	2.70	239	259	0.040
Sc0j: New smelter; Only China (100% coal)	0.52	5.1	9.5E-03	3.08	264	289	0.042
Sc0k: New smelter; Only CIS/Russia	0.30	1.7	5.3E-03	1.09	137	138	0.036
Sc0l: New smelter; Only CIS/Russia (50% reduction in hydropower)	0.42	3.4	7.6E-03	2.18	211	249	0.040
Sc0m: New smelter; Only Middle East	0.33	1.8	5.8E-03	1.33	154	199	0.034
Sc0n: New smelter; Only Middle East (25% of gas alternatively flared)	0.33	2.1	6.1E-03	1.47	164	224	0.035
Sc0o: New smelter; Only Middle East (75% of gas alternatively flared)	0.33	1.5	5.5E-03	1.20	145	176	0.034
Sc0p: Existing smelter; China, CIS, Middle East	0.44	3.9	8.0E-03	2.35	218	244	0.040
Results from Alcoa's existing production							
Sc2a: Alcoa Descambault	0.25	1.0	4.2E-03	0.58	103	87	0.034
Sc2b: Alcoa Iceland	0.25	0.9	4.2E-03	0.59	97	88	0.034
Key figures							
Average of all scenarios	**0.37**	**2.72**	**6.6E-03**	**1.72**	**176**	**195**	**0.037**
Max% higher than average	39%	89%	44%	79%	50%	48%	12%
Min% lower than average	34%	67%	36%	66%	45%	56%	10%

Appendix 6: Review panel report, including the authors' comments

In the following, the review panel report is shown. Each issue raised in the review report is commented by the authors of the LCA report (Jannick H Schmidt and Mikkel Thrane). The authors' comments are inserted in the review report, so that the reviewers' comments are immediately followed by the authors' comments. The authors' comments are marked in grey.

1 Draft critical review statement on the “LCA of Aluminium Production in New Alcoa Smelter in Greenland” study

By:
Mark Goedkoop, PRé Consultants, the Netherlands (chair)
Eirik Nordheim, European Aluminium Association, Belgium
Pascal Lesage, Sylvatica, Canada

1.1 Problems regarding the scope of the study

The review team is generally impressed by the high quality of the work, but has major problems with the scope of the study. These major problems need to be addressed in order to consider this study to be in line with the ISO 14040 and 14044 standards. The major problems are as follows.

1.1.1 Comparison of alternatives

In chapter 3.1, in the purpose the purpose is defined as assessing the impact of two alternative scenario’s:

- Scenario 1: Building the smelter in Greenland
- Scenario 0: Building the smelter elsewhere, apparently commissioned by another company,
- Scenario 2.a (Canada) or 2.b (Greenland), in case Alcoa builds an alternative.

To the reviewers it is essential to understand the reasoning behind these choices, and they are not clear and not clearly presented. Especially the scenario 0 is very unclear, as it somehow follows out of the marginal LCA approach used, as the reader learns in chapter 4 and 5. In chapter 5 the reader also learns that there are different and relatively concrete alternatives, like using flaring off gas and 100% hydropower in Russia.

We think that choosing the alternatives deserves much more deliberate attention in the goal and scope section, and should not just follow from the marginal analysis. The reader should be able to understand clearly what the alternatives are and why they are or are not taken into consideration in this comparison. Alcoa has the option to make the same investment elsewhere, and the reader must be informed of the consequences of building the smelter in Greenland versus other choices Alcoa has, and not just between one Alcoa option and the marginal alternative.
Authors’ comment: It seems like the reviewers has not fully understood the purpose and the scope of the study. This is possibly because of insufficient descriptions in section 3.1. Therefore the following text will displace the current section 3.1:

_____new text_____

The overall purpose of the parent study is to provide decision support in the environmental impact assessment (SEA) process of a new aluminium smelter in Greenland. The main decision to be supported is whether the aluminium smelter should be approved or not. Usually, SEAs do not contain life cycle information. As a supplement to the conventional information provided in the SEA process, the Home Rule of Greenland has requested life cycle information, especially for GHG-emissions.

The main question to be answered by the LCA is: “What is the environmental impact of installing the new smelter in Greenland”. In SEA, the environmental impact of the proposed project and possible some alternatives are assessed towards the so-called zero alternative, which represents the situation without the proposed project. In the following the zero-alternative is referred to as Alternative 0. The environmental impact is illustrated in **Figure X** below.

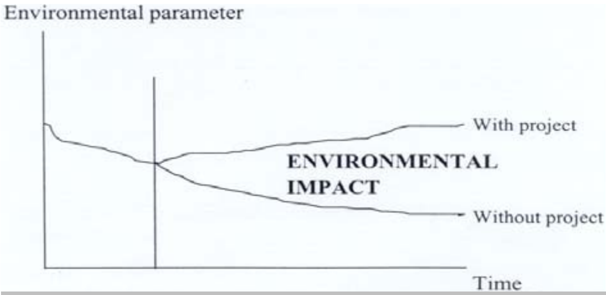

Figure X: The nature of environmental impacts (page 19 in: Glasson J, Therivel R, and Chadwick A (2005), Introduction to Environmental Impact Assessment. 3rd edition. Routledge).

It is relatively easy to define the situation with the proposed project which is simply what is proposed by the project commissioner. But when it comes to the zero-alternative, it may be more difficult. In the parent study, the zero-alternative is defined as the situation if the new aluminium smelter is not installed in Greenland and a corresponding amount of capacity is installed somewhere else in the World. Thus, Alternative 0 is equivalent to installation of capacity and annual production of 360,000 tonne aluminium somewhere in the World. It is obvious that the identification of the technology and location of Alternative 0 is subject to significant uncertainties. Therefore, several candidates of Alternative 0 are identified. But all the identified scenarios represents Alternative 0.

It should be noted that the parent study does not include any concrete alternatives to the proposed project – only Alternative 0. It is obvious that Alcoa may choose to install new capacity somewhere else in the World if the proposed project is not chosen. Since information on Alcoa's future plans for capacity expansion are confidential, no additional alternatives have been included in the LCA. Therefore, the proposed project in Greenland is compared to a situation where Alcoa does not install specific capacity in another location. It is clear that Alcoa could achieve a similar environmental impact to the Greenland smelter if they choose to install capacity which uses the same technology in another region, e.g. a smelter based on 100% hydro power in Russia. But the assessment of such alternatives lies outside the scope of the parent study.

It follows from the above described reasoning, that the Greenland smelter will have the effect that Alternative 0 is avoided. And if the Greenland smelter is not established, then Alternative 0 is assumed to be installed. The fact that the 0-alternative is represented by aluminium production another location in the world is due to the assumption that aluminium production is driven by the global demand for aluminium, i.e. full elasticity of supply is assumed. In reality there may be intermediate price differences. The effect of such price differences could be modelled by general economical equilibrium modelling. This would lead to lower impacts of any decision or any change compared to what is modelled with an LCA, but the direction of the change would be the same. It should also be noted, that fully elastic supply and inelastic demand represent the default assumption in all LCAs.

Assessed alternatives in the comparative LCA
Thus, the primary purpose of the LCA is to assess and to document the potential environmental impacts from:

- Alternative 1) the establishment of aluminium smelter in Greenland (Alcoa)
- Alternative 0) not establishing the aluminium smelter in Greenland, which means that an equivalent capacity will be installed on another location in the World, and possibly be commissioned by another company

In addition to the two alternatives, Alcoa's existing production in two smelters are included for comparison reasons. This is analysed in two scenarios 2a: Alcoa Deschambault in Canada and scenario 2b: Alcoa Iceland. It should be noted that these scenarios do not represent actual alternatives to the Greenland smelters, but that the scenarios are included for illustrative and comparative purposes since most of the data collection is based on data from these two smelters.

Further, an alternative could be the establishment of increased collection of aluminium scrap and more capacity for the processing of scrap into new aluminium. This could eliminate the need for new facility for production of virgin aluminium. However, it should be noted that this alternative is out of the scope for the government of Greenland as well as for Alcoa – it is more related to structural changes in economy, which may be regarded as out of scope of this study.

Included scenarios representing the proposed project and the zero-alternative
... existing text in section 3.1...

_____new text_____

We suggest the following solutions for these problems:

1. Change the title of the study, and include the terms "comparison of alterative locations to the Greenland smelter" or similar, as the current title does not make clear that you are comparing different sites
   Authors' comment: We have decided not to change the title because any attempt make the title capture an explanation of what is compared in the study have turned out to lead to more confusion than clarification. A correct title would be "Comparative LCA of aluminium production in Greenland and unspecified/marginal supply of aluminium". However, it is clear that such a title does not provide sufficient information.

2. Make very clear from the start that this study aims to compare the Greenland location with a range of alternative locations, and we suggest to explicitly choose some extremes, like 100% coal in China, 100% hydro in Russia and 100% flare-off gas in the Middle East, and of course some of the mixed scenario's that are used already now.
   Authors' comment: Indeed, this is not the aim of the study! We compare production of aluminium in Greenland with the marginal supply of aluminium – which will be the supply that will be affected by any decision. However, we will make it clearer what we compare: We have implemented the improved explanation in section 3.1 (see above), and the following text is included in section 1: Introduction: "*A basic assumption is introduced, i.e. the global production of aluminium is demand driven. It follows from this assumption that the establishment of a new aluminium smelter in Greenland will not affect the global production of aluminium. Thus, Alternative 0 represents the most likely change in capacity somewhere else in the world, if not the Greenland smelter is established.*"

3. Compare these alternatives in the interpretation and discussion, and draw specific conclusions per alternative. In chapter 11 where results are presented this is not done, there is no mentioning in the text about the Iceland alternative, apart from table 11.7. also the following chapters do not pay attention to alternative scenario 2a and 2b
   Authors' comment: Again, the purpose of the study is only to compare the Greenland smelter (Sc 1) with the marginal supply of aluminium (Sc0). Scenarios Sc1a and Sc0a-p represents sensitivity analyses of Sc1 and Sc0, and scenarios Sc2a-b are included for illustrative and comparative purposes (these scenarios do not represent actual alternatives to the Greenland smelter). This is explained in the new text in section 3.1 (see above).
   In order to make it clearer what is the environmental impact from each of the sensitivity scenarios, a new table is included in section 11.2 showing the characterised results for 6 key scenarios and all impact categories in the Stepwise method. This information is used to qualify robustness and uncertainty the LCIA of the Greenland smelter (Sc1) and the marginal supply of aluminium (Sc0). In addition a new appendix (appendix 5) is added, showing the characterised results for all scenarios and all impact categories.

In the study, it is assumed that the production of aluminium is completely driven by the demand (fully elastic supply, inelastic demand). Although this type of assumption is not unusual in LCA, it would be beneficial to mention that this is a simplification of reality, and to present a (very brief) discussion of the potential rebound effects associated with the increase in production of aluminium and how these rebound effects could affect the results.

Authors' comment: As described above, the following text is added in section 3.1: "*...It follows from the above described reasoning, that the Greenland smelter will have the effect that Alternative 0 is avoided and if the Greenland smelter is not established, then Alternative 0 is affected. The fact that the 0-alternative is represented by aluminium production another location in the world is due to the assumption that aluminium production is driven by the global demand* *for aluminium, i.e. full elasticity of supply is assumed. In reality there may be intermediate price differences. The effect of such price differences could be modelled by general economical equilibrium modelling. This would lead to lower impacts of any decision or any change compared to what is modelled with an LCA, but the direction of the change would be the same. It should also be noted, that fully elastic supply and inelastic demand represent the default assumption in LCA...*"

1.1.2 Impact assessment

The main focus of the study is on GHG. This is somewhat strange, as it is rather obvious that a plant that uses 100% hydropower has a lower impact than a plant using any energy supply mix that contains fossil fuel, and this study this is the case in all alternative scenario's, except scenario 2b. **Authors' comment:** We have specifically been commissioned to focus on GHG emissions, which is not a trivial issue for Greenland as the planned aluminium smelter (in a national perspective) almost will double Greenland's GHG emissions. The parent study provides a much needed insight in the consequences in a global life cycle perspective.

On the other hand it is far from trivial what the other impacts are, when a large hydropower and smelter facility is placed in a potentially vulnerable and yet unspoiled area as Greenland. In chapter 11 very little is said about the impacts on ecosystem, and the lack of attention is mainly based on the implicit weighting in the Stepwise monetarisation principles. This means the conclusions in this comparison assertion are very much based on a weighting procedure, and this is clearly not in line with the ISO 14044 (section 4.4.5) rules The same problem occurs in the sensitivity analysis in chapter 13, where weighted results are used to present significant or less significant issues. **Authors' comment:** It is true that 'other impacts' are far from trivial when dealing with an aluminium smelter in a pristine environment such as Greenland. Nevertheless, a <u>very detailed</u> assessment of the impacts on the local ecosystem is out of the scope of the parent study. Apart from a screening of local human health impacts, we have only been commissioned to consider GHG emissions. Other types of impacts, including social impacts, are taken into consideration in the SEA. It is important to stress that the parent study is a part of the complete SEA and that we deliberately have delimited the scope of our study to focus on GHG emissions, because of the complexities and challenges involved in assessing other types of impacts in Greenland.

However, to accommodate the critique, all impact categories are now discussed separately on characterization level in chapter 11.2. The normalised and weighted results are now given second priority as supplemental information and only mentioned briefly in the end. Reservations to ISO 140544, section 4.4.5 are also made clear. The impact category 'nature occupation' is given special attention – including a discussion of impacts related to land use. Also chapter 12, still includes a separate screening of human health impacts locally in Greenland.

Further, the summary, the LCIA, and the conclusion specifically stress that the results regarding other impacts than GHG-emissions and local human health in Greenland are subject to significant uncertainties.

In section 13.1 'Sensitivity check' it is also stressed that "*The main focus of the parent LCA is on GHG-emissions. Therefore, the sensitivity analysis mainly focuses on GHG-emissions. In this respect it should be mentioned that the presented results and conclusions other impact categories are subject to significant uncertainties.*".

It is confusing that in the graphs and in the assessment and conclusions scenario 2a and 2b do not play any role, and that scenario 1 is only compared to scenario 0
Authors' comment: See the added text in section 1.1.1 here in the review statement.

We propose the following solution:

1. The study clearly identifies the issues of concern, as required in the standard, and clearly describes why impact categories are selected, or ignored. This should be done in the goal and scope section, and cannot just be based on the Stepwise outcome or other weighting methods. The selection should certainly include the impacts of land conversion and land use, as relatively large areas are converted and used. It should also discuss some of the problems in assessing the fate and effect of emissions in the Greenland region, and we cannot accept that all ecosystem damages are written off as insignificant.

2. The characterisation results are discussed per impact and/or endpoint category, and does this per alternative scenario. This also means a differentiation is needed per scenario. This is not done, for instance in table 11.7 the results for Iceland and Greenland are almost identical.

We do realise that this is not an easy task, but instead of proving the obvious GHG benefit, the report would become much more informative if these more difficult issues are clearly addressed.

Authors' comment: It is acknowledged that we should pay more attention to the selection of impact categories in the goal and scope phase. As a consequence, we have made a revision of section 3.5. As it will appear, we distinguish between GHG-emissions that are assessed with a high level of detail and other impacts that are assessed on screening level (lower level of detail). Local human health impacts in Greenland are separately assessed in section 12 and represent a level of detail between the two.

Also see comments under 1.1.2.

Concerning characterisation results, they are now discussed per impact category in chapter 11.2. The section begins with an overview of all 'other' impact categories for 6 key scenarios. Subsequently, each impact category is discussed separately for scenarios 1 and 0. It has been chosen to only include these two scenarios because scenario (0a-0p) must be considered as sensitivity scenarios. A new appendix 5 show the characterised results for all included scenarios (including the sensitivity scenarios 0a-0p). Scenarios 2a and 2b are only included for illustrative and comparison reasons because a large share of the data collection is based on these aluminium smelters.

Concerning the comments that the Iceland scenario 2b and the Greenland scenario 1 are too similar, we would like to emphasize that the Iceland scenario is only included for comparison and illustration reason because a large part of the data collection is based on this smelter. Also, in terms of GHG-emissions it has not been possible to identify a significant difference between the two.

A completely different alternative solution would be to stop considering this to be an LCA and use the GHG standard like ISO 14064 as a basis, but this would have major implementations for the study and the verification.

Authors' comment: This is not considered as an option.

1.2 Some general observations

Although well written, the text does contain many typos and some spelling/grammar errors. The study could greatly benefit from a revision of the text by a native English speaker.
Authors' comment: Parallel to the panel review process, the report has undergone a language proof.

It should be noted that the majority of the critical review panel (2/3 members) were not interested parties, and one of the reviewers is also mentioned in the text as data provider.

1.3 Comments per chapter.

1.3.1 Chapter 3, Input-output vs. process based LCA.

Figure 3.2 suggests that a hybrid approach would result in impacts that would not only be more precise than those of an IO approach (narrower distribution) but also *lower*. Hybrid results will only necessarily be significantly lower than pure IO results if the process-based data used is significantly less complete than the IO data, which is something that is stated as needing to be avoided (see section on hybrid LCA). Perhaps a better representation would be to show the hybrid results (orange) distribution with the same or at least a similar mean as that of IO.
Authors' comment: We agree, this is implemented in Figure 3.2

1.3.2 Chapter 5, table 5.7.

The CO2 figures appear to come from the data given in section 7.2. Particularly the calculation of emissions from hydro reservoirs is difficult and disputed. We miss a justification for the figures used here.
Authors' comment: In Table 5.7, a clear reference is made to section 7.2. The explanations of emissions from hydro reservoirs are made clearer in Table 7.7 in section 7.2.

The applied assumptions for hydropower in different regions gives rise to difference in GHG-emissions from hydropower from 10 g CO2e/kWh to 57 g CO2e/kWh. The differences are mainly due to different levels of hydro reservoir GHG-emissions which depend on climate and biomass in water. However, since hydropower is associated with significant lower GHG-emissions compared to coal and gas, any introduced uncertainties in GHG-emissions from hydro reservoirs will have insignificant effect on the results. If the Greenland hydropower is associated with the same GHG-emissions as the Brazil hydropower (which has the highest GHG-emissions), then the results would change from 5.92 kg CO2e to 6.54 kg CO2e per kg aluminium.

1.3.3 Chapter 7

The heating value used (see Appendix 1 and Table 7.2) for natural gas, as derived from "Natural gas, high pressure, at consumer/RER", seems to be wrong. The process indicates that 0.0272 m3 = 1 MJ, giving 36.8 MJ/Nm3, while the report states 39 MJ/Nm3. This has the effect of reducing the impacts of natural gas production and combustion in the study by about 6%. This should not alter the conclusions of the study.
Authors' comment: The 39 MJ/Nm3 is the higher calorific value, it is correct that it should have been 36.8 MJ/Nm3. This is corrected in Table 7.2. This has no implications for any calculations or results since the ecoinvent emissions data are per MJ as well as the data collection is also per MJ.

For transmission impacts associated with the Maniitsoq plant, it would be preferable to use the actual expected losses on the grid and to scale the actual grid impacts to the known length of the distribution network. These would likely be lower than the data actually used. It is acknowledged by the critical reviewers that this should not significantly affect the results of the study for Sc0.
Authors' comment: The electricity related GHG-emissions in the Greenland smelter scenario are 0.140 kg CO2e per kg aluminium out of a total of 5.92 kg CO2e per kg aluminium. This corresponds to 2.4%. The applied grid loss is 2% (see Figure 7.1). A grid loss at 0% would reduce the electricity related GHG-emissions from 0.140 to 0.137 kg CO2e per kg aluminium, and a very high grid loss at 10% would increase the electricity related GHG-emissions from 0.140 to approximately 0.152 kg CO2e per kg aluminium. Both of these extreme grid losses have insignificant effect on the results. Therefore, no more efforts are made to increase the accuracy of the applied values. In section 7.2 it is explicitly added, that the same grid losses are assumed for all countries.

The use of Australia, China and Brazil as representative of all bauxite mining seems to be overly gross, as these three represent only 60% of total production. However, it is recognized that a finer-grained mix would not change the conclusion of the study. It is simply suggested that the text in Section 8.4 better account for the simplifying nature of the assumption.
Authors' comment: The use of Australia, China and Brazil as representative for bauxite is only used in order to identify a relevant electricity mix. In this respect it should be noted that electricity only accounts for 0.073% of the total GHG-emissions related to the production of bauxite. Therefore, the effect of this assumption is insignificant.

The data on Bauxite mining seems to be incomplete when compared with the ecoinvent 2.1 data. Please justify the exclusion of the inputs from the technosphere "Blasting" and "Recultivation", as well as the inputs from the ecosphere "Water" and "and transformation, from arable (irrigated and non-irrigated). It is recognized that blasting is not necessary in all mines, and that mines are often restored after use, but this should be clarified. We do understand that these issues will not affect the conclusions of the study.
Authors' comment: The inputs of 'Blasting', 'Recultivation', and 'Water' are included via the IO-data. Generally, the data quality and significance of these data are relatively poor in the ecoinvent processes. Therefore, these inputs have been included via the IO-data.

The transport distances assumed for inputs to the production of alumina (other than that of bauxite) seem low. However, it is recognized that this will not affect the conclusions of the study.
Authors' comment: This comment relates to the transportation of heavy fuel oil, coal, Calcinated lime, and sodium hydroxide. The used ecoinvent data on heavy fuel oil and coal are processes that represents '*... at regional storehouse*'. Thus, the transport of these materials from the production site near to the use site has been included. Therefore, it is only the transport of Calcinated lime and sodium hydroxide which may be underestimated. These two inputs accounts for 3.2% of the material input to the alumina process. Therefore, this is assumed to have an insignificant effect on the results.

1.3.4 Chapter 9

Chapter 9.4 The alumina produced in China is all used locally, but Chinese alumina production generally requires higher energy input.
Authors' comment: No data to support this has been identified. Therefore, this is not further addressed in the study.

Chapter 9.6, table 9.5: Transport of bauxite over 100 km distances would normally not be done by lorry.
Authors' comment: Based on communication with Alcoa, alumina production typically take place close to the bauxite mine. The 100 km represents a very rough estimate – it could be less, so we still argue it should be lorry.

1.3.5 Chapter 10

Chapter 10.4, Energy input to the electrolysis process: We miss a discussion of the possible difference in energy requirements and process emissions in scenario 0. It is here assumed that this is equal to Scenario 1
Authors' comment: The following text is added: "Differences in the electricity use in scenario 0 in the electrolysis process are taken into account via scenario 0 which represents a new smelter and scenario 0p which represents a smelter with existing technology (current average)."

Chapter 10.4, Energy input to the cast house: The explanation for higher energy input to the cast house in Europe with reference to the EAA report is wrong.
The reason for generally higher energy input in European smelter cast houses is more remelting of clean scrap requiring more energy and more targeted product spectre requiring more treatment and finishing.
Authors' comment: This is corrected.

Chapter 10.5, table 10.6: Is the anode consumption, aluminium fluoride consumption and cathode consumption the same for Deschambault and Iceland?
Authors' comment: The following text is added: "According to Alcoa, the use of anodes in Deschambault and Iceland differs slightly. However, a slightly higher use in Iceland is because the facility was not yet running optimal when collecting the data. Therefore, Deschambault figures has been applied for the Iceland smelter."

Chapter 10.5, table 10.8: In the table for emissions to air, the source for the particle size distribution is unclear as there is no industry data on this.
Authors' comment: As specified in the top of the table, the particle size is based on data from ecoinvent (2007).

Chapter 10.9, table 10.14: For Scenario Sc1a and Sc 0p is used a world average for emissions. It would be more correct to use a world prebake average, but this is more difficult to find.
Authors' comment: Due to lack of data availability, this was not possible.

1.3.6 Comments about the conclusions, Chapters 11,12 and 13.

Chapter 11.1 Scenarios 1 and 0: In both scenarios is used the same figure for transport of alumina. The transport distances for China, Middle East Russia are potentially shorter than for transport to Greenland. On the other hand transport to Russian and Chinese smelters would be partly by ship and partly by rail.

Authors' comment: The transport of alumina to the smelter only accounts for 0.227 kg CO2e for the Greenland smelter. Minor differences in transport distances will have insignificant effects. The exact assumptions on transport distances of all materials to the aluminium smelter are described in Table 10.11.

Chapter 11.1 Influential factors on the GHG emissions from aluminium production: The PFC emissions occur when there is process instability, an anode effect. The contribution from replacing anodes or during cooling is negligible for PFC emissions, but important for fluoride emissions.
Authors' comment: Corrected.

Chapter 12: We agree that for the human health impact it is more relevant to conduct a local health impact assessment. This will also be mainly relevant for the situation where there are considerable differences in local population density between the different scenarios.
Authors' comment: Yes, and this will hopefully be done more in detail as part of the SEA.

Chapter 13. Sensitivity electricity mix.
As mentioned earlier we think including scenarios with 100% hydro power for Russia and 100% gas for Middle East would be relevant. This would particularly affect the Russia scenario.
Authors' comment: This is true, but it should be remembered that these scenarios only are sensitivity scenarios for scenario 0. It is not 'completely' unrealistic that the marginal would be 100% hydropower in e.g. Russia, but it is VERY unrealistic – see section 4 and 5. It could be 100% hydropower as a result of conscious decision-making by Alcoa, but as mentioned it is out of the scope of the study to include such assessments.

The sensitivity analysis comparing the weighted results using different impact assessment methods shows some differences with the Stepwise method: it would behove the authors to summarily discuss the issues that appear important in other impact assessment methods.
Authors' comment: In section 11.2 all impact categories are now assessed.

Chapter 13. Technology in smelters.
I would suggest also a consideration of the choice of new technology, i.e. would the new technology used in Russia, Middle East and China have the same emissions as the one chosen for Greenland.
Authors' comment: Yes. Based on discussions with experts at Alcoa it is our understanding that there are only minor technological differences between new smelters in different regions of the world. But there can be significant differences in the way the smelters are run, which may have an effect on e.g. PFC emissions. However, this has not been taken into account.

General conclusions Chapters 13 and 14.
We think the conclusions need to be redrafted in the light of the comments on goal and scope.
Authors' comment: Section 13 and 14 as well as the report summary has been redrafted in the light of the comments about goal and scope and LCIA.

Final remarks on critical review statement on the "LCA of Aluminium Production in New Alcoa Smelter in Greenland" study

By:
Mark Goedkoop, PRé Consultants, the Netherlands (chair)
Eirik Nordheim, European Aluminium Association, Belgium
Pascal Lesage, Sylvatica, Canada

The review panel discussed the way the comments have been dealt with, and would like to make the following final remarks:

1. The review panel thinks the scope of the study has been better defined, but is still worried that the study can create the false impression that, of all the available options, a smelter in Greenland is the best option. The ALCOA assignment has a much more narrow scope, it asks to compare between a known and an unknown location, driven by market forces. With that the study does not say there are no better options.
   Authors' comment: It is correct that the assessment 'only' concerns the decision alternatives to establish a smelter in Greenland versus not establishing a smelter in Greenland (the 0-alternative). It is out of the scope of the parent study to identify alternative (and possible better) options to the Greenland smelter. The purpose of the study is to assess the proposed project in Greenland and to compare with the zero alternative, i.e. not to build the smelter in Greenland.

2. The better explanation of the other impact categories is a major step forward. We still think the conclusions (and summary) should clearly address the fact that there is a trade off between conversion/occupation of land and lower greenhouse gas emissions.
   Authors' comment: It is true that there is a possible trade-off between conversion/ occupation of land (land use) and lower GHG emissions, but we think this has been empasized adequately in the report as well as in the summary and conclusion.

3. The better description of the impact categories reveals that the IO data play a much bigger role that thought and dominates the human and ecotoxicity categories, the ozone layer depletion, and aquatic eutrophication. This both shows the usefulness of trying to fill data gabs, but also the problem that the IO solution can suddenly dominate the other impact categories.
   Authors' comment: IO-data provides relevant information, but it is also true that IO-data, due to the aggregation level, can add unwanted distortion. In the parent study, however, this has not been a significant problem in relation to the assessment of GHG-emissions, and the problems for other impact categories have been identified and addressed in the life cycle impact assessment.

4. We can agree with the way the other comments have been dealt with.
   Authors' comment: -

The review panel also would like to add a few words regarding its own independency, as each members have some links that could potentially be interpreted as a conflict of interest:

- LCA 2.-0 has a business relationship with PRé Consultants, as it resells the software from PRé in Denmark
- LCA 2.-0 has recently established (or refreshed) an informal collaboration agreement with Sylvatica (links are made on each other website)
- Eirik Nordheim, is quoted in the report as the provider of some data, and was thus somewhat involved in the writing of the report.

All three members have however been critical without any limitation due to these relationships, and have been completely independent in making their comments.