



A cradle-to-gate life cycle assessment of primary aluminium production at Norðurál

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University of Iceland
2014**

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60 ECTS thesis submitted in partial fulfillment of a
Magister Scientiarum degree in Environment and Natural Resources

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Reykjavik, May 2014

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Bibliographic information:

Anna Margrét Kornelíusdóttir, 2014, *A cradle-to-gate life cycle assessment of primary aluminium production at Norðurál*, Master's thesis, Faculty of Industrial Engineering, Mechanical Engineering and Computer Science, University of Iceland, pp. 78.

Printing: Háskólaprent
Reykjavík, Iceland, May 2014

Abstract

Primary aluminium production is an energy intensive process. While the proportion of fossil fuels as main global energy sources for aluminium production has grown in recent years due to China's increased market share as a producer, Iceland's importance remains as a producer of renewable energy. The promotion of efficient use of material and energy resources and reduction of waste emissions to air, water and soil are becoming great priorities on the environmental global agenda, for industry and among governments and the public as well. This is also the case in Iceland, where life cycle assessment is becoming a more widespread tool for the assessment of environmental impacts and the identification of environmental hot spots, covering the life cycle of products and services. This is the first time a life cycle assessment is conducted and disclosed to the aluminium industry in Iceland.

Two cradle-to-gate life cycle assessments were conducted in order to compare the environmental impacts of the production stages of one metric tonne of primary aluminium at Norðurál with those of an average European smelter, using life cycle inventory data from the European Aluminium Association. By assessing eight different environmental impact categories, it was found in the study that the production of aluminium at Norðurál creates less potential impacts to the environment with regard to global warming, eutrophication, ozone layer depletion and abiotic resource depletion for fossil fuels but not with regard to acidification, photochemical ozone creation, abiotic resource depletion of elements and, finally, primary energy demand of renewable and non-renewable resources. While the energy requirement for primary aluminium remains the source of the industry's greatest environmental burden, this does, inevitably, also present a challenge for stewardship and responsible consumption of resources.

Útdráttur

Framleiðsluferli áls með rafgreiningu er gríðarlega orkufrekt. Hlutfall jarðefnaeldsneytis sem orkugjafa á heimsvísu hefur vaxið undanfarið ár með aukinni álframleiðslu í Kína, þar sem raforka er gjarnan framleidd í kolaorkuverum. Samhliða aukinni umræðu um gildi endurnýjanlegra orkugjafa til að sporna við hnattrænni hlýnun, hlýtur mikilvægi Íslands sem framleiðandi hreinnar orku, þ.e. jarðvarma og vatnsafls að vaxa til jafns. Á heimsvísu er það orðið forgangsratriði í umhverfismálum orkufreks iðnaðar, ríkisstjórna og almennings að stuðla að sjálfbærri nýtingu auðlinda og draga úr losun í loft, vatn og jarðveg. Á undanförunum árum hefur vistferilsgreining rutt sér til rúms á Íslandi sem umhverfisstjórnunartæki og aðferð til að meta umhverfisáhrif, sem og til að greina álagspunkta í heildarumhverfisáhrifum vöru og þjónustu á líftíma þeirra. Þetta mun vera í fyrst skipti sem vistferilsgreining er framkvæmd fyrir íslenska álframleiðslu og niðurstöður gerðar opinberar.

Verkefnið fólst í því að framkvæma vistferilgreiningu á tveimur líkönum frá vöggu þeirra til hliðs. Tilgangurinn var sá að bera saman umhverfisáhrif fimm aðalframleiðslupátta eins tonns af áli framleiddu með rafgreiningu, annars vegar samkvæmt forsendum frá Norðuráli og hins vegar með gögnum frá evrópska álsambandinu EAA. Framlag hvors líkans fyrir sig til átta mismunandi umhverfisþátta var metið og bentu niðurstöður rannsóknarinnar til þess að framleiðsla hjá Norðuráli ylli minni mögulegum áhrifum á hnattræna hlýnun, til næringarefnaauðgunar, til eyðingar ósonlagsins og ólífrænna auðlinda með tillit til jarðefnaeldsneytis og frumorkuþarfar. Umhverfisálag og –áhrif frá álframleiðslu eiga að miklu leyti til uppruna sinn í mikilli orkuþörf framleiðsluferlisins og því mun skynsamleg og sjálfbær nýting auðlinda vera áframhaldandi áskorun fyrir álver á Íslandi og á heimsvísu.

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Abbreviations

ADP	Abiotic resource depletion potential
AP	Acidification potential
EAA	European Aluminium Association
EP	Eutrophication potential
GER	Gross energy requirement
GWP	Global warming potential
IAI	International Aluminium Institute
ISO	International Organization for Standardization
LCA	Life cycle assessment
LCI	Life cycle inventory
ODP	Ozone layer depletion potential
NCV	Net calorific value
PAH	Polycyclic aromatic hydrocarbon
PED	Primary energy demand
PFC	Perfluorocarbon
POCP	Photochemical ozone creation potential
VOC	Volatile organic compound

Acknowledgements

Great thanks go to my three supervisors Larisa Maya Altamira, Ólafur Pétur Pálsson and Marta Rós Karlsdóttir for their guidance, invaluable input and contributions to the project. To my contacts at Norðurál, Einar Friðgeir Björnsson and Steinunn Dögg Steinsen, I would like to give thanks for their enthusiasm for the project and support throughout. Finally, on a personal note, I thank Páll Valdimarsson for sowing the smallest of seeds at a meeting we had *twelve* years ago which this year, hundreds of meetings later, reminds me that “your current safe boundaries were once unknown frontiers.”

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1. Introduction

Aluminium smelting is an energy intensive production process, requiring, in Europe, an average of 15700 kilowatt hours (kWh) of electricity for the production of 1 tonne of aluminium (International Aluminium Institute, 2011a). Roughly 60% of the aluminium produced globally relies on electricity from gas or coal fired power plants (International Aluminium Institute, 2011b). In 2010, Iceland's aluminium production made up about 800 thousand tonnes of primary aluminium, which is 2% of the global market (Icelandic Association of Aluminum Producers, 2013). In this regard, Iceland's importance in the global aluminium production is mainly due to its high share of renewable energy that is used to generate Iceland's electricity. With 30% from geothermal power and 70% from hydropower, the aluminium industry used 71% of the electricity generated in the country in 2011 (National Energy Agency, 2012), and it is therefore reasonable to expect that aluminium production in Iceland is less unfavorable to the global environment. This holds true, particularly with regard to global warming potential, when compared to countries with a lower share of renewable energy in their energy mix. However, other environmental impacts may arise, especially those which affect the local environment and are related to land use, biodiversity loss and depletion of resources.

This study aims to determine how the Norðurál primary aluminium compares to its European counterparts in terms of environmental impacts. Life cycle assessment (LCA) methodology was used to identify environmental hot spots of the primary aluminium cradle-to-gate production stages at Norðurál. The results were compared to those of an average European aluminium smelter, using data from the European Aluminum Association (EAA).

The structure of the thesis is as follows:

- Chapter 2 introduces the aluminium production process, beginning at the extraction of bauxite through to the casting of molten aluminium at production plants, such as that of Norðurál. The properties of aluminium are discussed, as is its important quality of recyclability.
- Chapter 3 presents the operation at Norðurál's production plant at Grundartangi, Iceland. The environmental issues associated with the production processes of electrolysis and casting are discussed, in addition to the company's environmental management and means for controlling and minimizing negative environmental impacts.
- Chapter 4 addresses the field of LCA, its application in the aluminium industry, development and limitations. This chapter also deals with the methodology of LCA and its use, in detail, for the purposes of this study.
- Chapter 5 covers the results of the LCA study undertaken and interpretation thereof.
- Chapter 6 presents final remarks and suggestions for future work related to this study.

Metals industry, future developments

The minerals and metals industries have been under increasing pressure to improve resource efficiency and reduce emissions. In response, minerals and metal producers have looked to examining emissions and energy consumption throughout their whole life cycle. In cradle-to-gate LCAs, assessments of a partial product life cycle, from resource extraction to factory gate, light metals such as titanium and aluminium present the greatest energy requirements and global warming potential (GWP) per kg produced. This is largely due to enormous amounts of energy consumed (Norgate, et al., 2007). Main global energy sources for aluminium production in 2012 were coal (53%), hydropower (37%) and natural gas (7%). A change from 2003, where the sources were 36%, 49% and 9% respectively, this is mainly due to China's quadrupled production (with coal fired power) during the time period (World Aluminium, 2013). It is therefore no wonder that aluminium cradle-to-gate LCAs have focused on energy consumption and greenhouse gas emissions (Liu & Müller, 2012). The energy consumption for the smelting process, which is by far the most energy intensive of the life cycle, has significantly improved in the past decades, through advanced cell design and process control which have allowed higher cell current and smaller anode-cathode distance (Coursol, et al., 2011).

Looking to the future and further pressures to move towards sustainability, there are a number of areas along the various production stages of the aluminium production process, from bauxite mining to casting, that present room for improvement for the reduction of environmental impacts. Changing energy sources for electricity generation and a shift away from coal, could reduce the GWP by one quarter to one half per tonne produced and achieve the same reduction in gross energy requirement (GER) owing to increased electricity generation efficiency of natural gas and hydropower and the reduced consumption of primary energy (Norgate, et. al, 2007). Furthermore, the North American aluminium industry is working to replace carbon anodes and reduce greenhouse gases emissions and is currently developing inert anodes. In addition, wetted anodes allow for reduced anode-cathode distances and thus decreased gross energy requirements (The Aluminum Association, 2011), (Green, 2007). Results from Norgate and Jahanshahi (2011) indicate that efforts to reduce greenhouse gas emissions and energy consumption in primary metal production should focus on the metal extraction stage of the life cycle and that therein lies a significant potential for reduction. This holds true for aluminium especially, which has a GER of approximately 220 megajoules (MJ) per kg metal, with metal extraction and refining making up to about 85% of it and mining and mineral processing 15%.

A multiregional model which reflects possible trends in the global primary aluminium industry until 2030 following expected developments in GDP showed rapidly increasing aluminum output accompanied by a threefold increase in emissions (Steen-Olsen, 2009). Climate change and the increasing cost of energy generation in addition to stricter regulations on emissions to the environment remain challenges for the global community to meet. The aluminium industry believes its products serve as part of the solution rather than a contributor (Organization of European Aluminium Refiners and European Aluminium Association, 2007) and will continue, through LCA (Tan & Khoo, 2005), to demonstrate aluminium's value for sustainable development to policy makers, manufacturers and the public alike.

2. The aluminium production process

The life cycle of aluminium begins at the extraction of bauxite ore, which is then treated and refined into alumina (Al_2O_3). Alumina is reduced to aluminium due to an electrolytic reaction during which carbon anodes are consumed. Finally, the molten aluminium is cast according to specification and transported for further processing and manufacture of aluminium goods.

The mass flow for an output of 1000 kg primary aluminium is as follows (Figure 1). On average, 5571 kg of bauxite is required for the production of 1889 kg of alumina. This high demand of bauxite is due to its significant content of water, approximately 20%, and the large amount of bauxite residue produced, nearly 50% by mass or 2614 kg on average (International Aluminium Institute, 2013a).

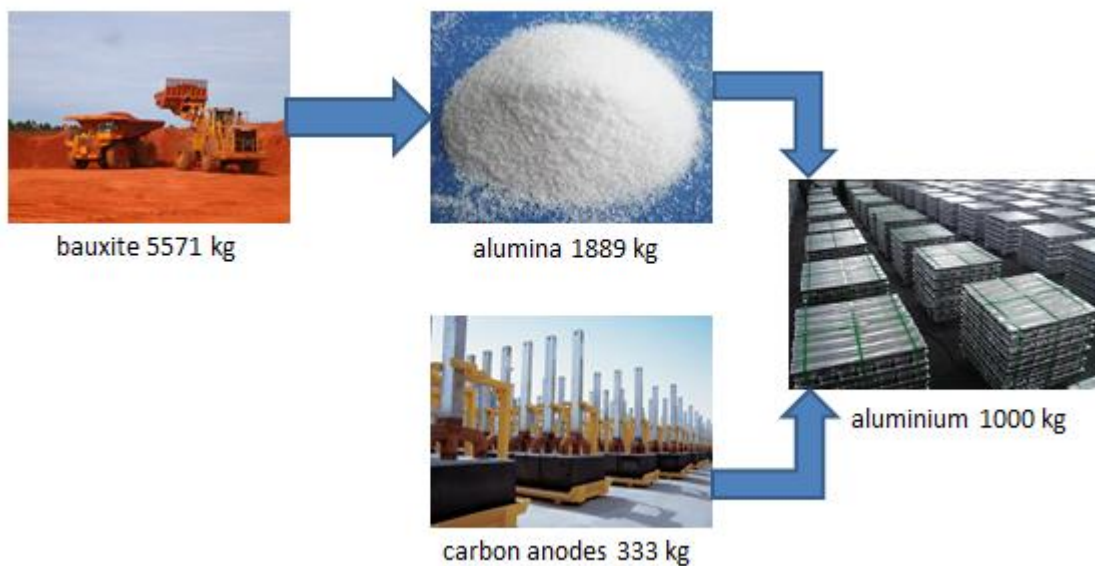
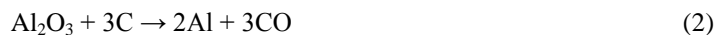


Figure 1 Primary aluminium stoichiometric production mass balance (Figure created from Lamb, 2005; Sai Sharada Marketing Services, 2014; Dubal, 2014 and Quality Foil, 2014)

During the electrolytic process, alumina is chemically reduced according to Equation (1) and requires a stoichiometric minimum of 1889 kg alumina and 333 kg carbon from anodes to produce 1000 kg pure primary aluminium.



The oxygen in alumina is mostly released as carbon dioxide (CO_2) but some of it does, however, form carbon monoxide (CO). Equation (2) occurs in parallel with (1),



Therefore the average net anode consumption is larger (439 kg) than the theoretical amount predicted by Equation (1). The actual production process could therefore be described as a

breakdown of alumina via electrolysis, producing 1000 kg of aluminium, releasing reacted oxygen with the carbon anode as CO₂ (International Aluminium Institute, 2013a).

2.1 From bauxite to alumina

2.1.1 Bauxite mining

Bauxite, the principal ore of aluminium, is a naturally occurring material containing between 45 and 65% aluminium oxides and hydroxides. It is a mixture of minerals, alumina trihydrates such as gibbsite (Al(OH)₃) and alumina monohydrates such as boehmite (AlO(OH)). Monohydrates contain approximately 30% alumina by weight and are found close to the surface, for example, in Australia. Trihydrate alumina contains about 50% alumina and is found at deeper levels. This is the case for Brazilian alumina ore (International Aluminium Institute, 2013b).

Bauxite is typically mined in open pits by removing the overburden (Tan & Khoo, 2005) and is concentrated in deposits in seven bauxite-rich areas globally (Figure 2): Western and Central Africa (Guinea), the Caribbean (Jamaica), South America (Brazil, Venezuela and Suriname), Oceania and South Asia (Australia and India), Central China, the Urals of Russia and the Mediterranean (Greece and Turkey). In 2013, Australia was the largest single producer of bauxite, contributing by 77 million metric tonnes (Mt) to the global bauxite market. China and Brazil were the second and third largest bauxite producers respectively, with 47 and 34.2 Mt respectively (United States Geological Survey, 2014). Known reserves of bauxite ore will sustain the present mining rate for over 100 years (International Aluminium Institute, 2013a).



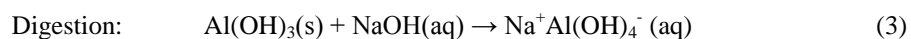
Figure 2 Major bauxite areas globally (UC Rusal, 2014)

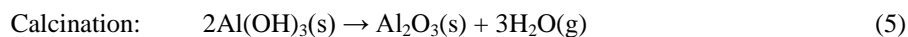
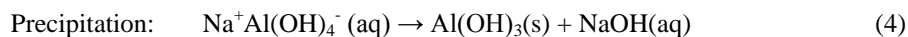
Depending on its hardness and local conditions, the bauxite ore is loosened with explosives. Beneficiation, a grinding and/or washing process for removing impurities and improving ore grade, is required for ores mined in forested sites while grassland areas do not generally call for ore treatment. The waste water from beneficiation processes is retained in a settling pond and recycled for repeated use (International Aluminium Institute, 2013a).

Mining of bauxite ore requires land use change, causing vegetation and habitat loss, with an average of 162 m² of land required to produce 1000 tonnes of bauxite. Furthermore, the process requires water and energy use and generates solid waste, mainly the bauxite residue known as red mud. Currently, 150 MJ of primary energy use are required to produce one dry metric tonne of bauxite, with a range of 40-470 MJ/tonne (dry) (International Aluminium Institute, 2008) and 14200 MJ for a metric tonne of metallurgical alumina (The Aluminum Association, 2011).

2.1.2 The Bayer process

The process by which bauxite ore is refined to produce alumina is known as the Bayer process, by which 95% of alumina is manufactured globally (World Aluminium and European Aluminium Association, 2013). It involves the digestion of crushed bauxite with concentrated sodium hydroxide (NaOH), also known as caustic soda, according to Equation (3). Digestion takes approximately 1-2 hours. At 270°C aluminium compounds of the ore dissolve in the solution leaving red mud, an insoluble residue. The solution is cooled and stirred for up to three days, allowing crystallization and precipitation of aluminium trihydroxide (Al(OH)₃) (Equation (4)). Finally, the product of precipitation, gibbsite, is washed and calcinated, as stated in Equation (5), to produce alumina (Al₂O₃) (Hind, et al., 1999).





Air emissions related to alumina refining mainly arise from the calcination stage where fuel combustion contributes to emissions of particulates, CO₂, mononitrogen oxides (NO_x) as NO₂, and sulphur dioxide (SO₂) (International Aluminium Institute, 2013a).

Water emissions, roughly 3 m³ per tonne alumina produced in Europe (European Aluminium Association, 2013), are largely due to cooling and the digestion of bauxite while mercury emissions to air and water are due to the mercury content in bauxite ore, and are released during treatment and refining (Green, 2007).

The bauxite residue produced during the Bayer process is a significant environmental load in the aluminium production process, with two tonnes produced per tonne alumina according to Tan and Khoo (2005). Europe, however, generated an average of 706 kg per tonne alumina in 2005, and in 2009, an average of 1142 kg per tonne alumina were generated on a global level (Leroy, 2009). In fact, bauxite residue is the single largest solid waste stream of the entire cradle-to-gate aluminium production system. The high concentration of iron oxides, between 10 and 30%, gives the residue its characteristic red color though it also contains titanium oxide (2-15%) and silicon oxide (5-20%) (International Aluminium Institute, 2012a). The amount of residue produced at individual refineries depends primarily on the source and nature of the bauxite but also on extraction conditions at plants (World Aluminium and European Aluminium Association, 2013). Bauxite residues are also highly alkaline (pH>11) and are high in sodium content due to the use of NaOH during the refining process and contain organic compounds such as polyhydroxy acids, polybasic acids, alcohols and phenols and other acids (Hind, et al., 1999).

In order to reduce pH and extract and reuse the maximum amount of caustic soda and alumina, the residue is washed following the Bayer process. There is no universal method for disposal of residue; this depends on regulatory requirements, geographic conditions, land availability and various other factors. However, the most common practice among refineries has been the containment of bauxite residue in specific facilities known as Bauxite Residue Disposal Areas (BRDA) or Residue Storage Areas (RSA). After washing treatment, one of the following methods is used for drying before storage (International Aluminium Institute, 2012b): filtration to produce a dry cake, high density slurry formation, or dilute slurry pumped into land-based settling ponds, a method known as lagooning. The trend in the industry has been to move away from the storage of residue in wet slurry form towards stacking of dry material since this allows for better recovery of caustic fluid from the residue (Hydro, 2012).

Various methods have been employed for reducing the pH of the residue and decant waters due to the residue's limited reuse potential but the most important barriers to remediation and re-utilization remain its high alkalinity and sodicity (Power, et al., 2011). The construction industry has been one of the main users of recycled bauxite residue; however, the fraction of total residue produced that is recycled makes up less than 1% and is likely to decline as increasing demand for bauxite continues to be met by ore of decreasing quality (International Aluminium Institute, 2013a).

2.2 Anode production

Anode material is consumed during the aluminium electrolysis process. The two types of smelting technologies used are distinguished by the type of anode used: pre-baked or Söderberg anodes, both of which require paste made of petroleum coke, a byproduct of petroleum refining, and a pitch binder, usually coal tar pitch.

The process for making the paste involves the calcining of petrol coke and the subsequent grinding and mixing with coal tar pitch. This aggregate forms a paste which is fashioned into anode blocks for baking or briquettes for direct consumption after cooling (Green, 2007).

For pre-baked anodes, prior to insertion of steel rods, the paste is molded into blocks known as anode butts. The anodes are baked in a gas-fired furnace at a temperature of 1120°C for up to two weeks, forming a solid block of carbon with homogeneous consistency. Steel axial bars are fused to the anodes with molten cast iron; and these hold the anodes in place and are used for the conduction of electricity in the electrolytic process (International Aluminium Institute, 2012c).

Söderberg smelting processes use a single anode which largely covers the top of the electrolytic cell. In the case of Söderberg anodes, the anode paste (or briquettes) is added directly to anode casings and the baking occurs in the electrolysis cells of aluminium smelters. They are, however, less electrically efficient and contribute to greater amounts of volatile organic compounds (VOC) emissions than the pre-baked anodes. Söderberg technology has therefore become less prevalent in the last two decades (International Aluminium Institute, 2013a) and is being gradually phased out as facilities reach retirement. In fact, in 2010, 95% of primary aluminium smelters in Europe were using pre-bake technology (European Aluminium Association, 2013).

Emissions related to anode production include SO₂ due to the coke content of paste, fluorides (gaseous and particulate) from the recycling of residual anode butts and polycyclic aromatic hydrocarbons (PAH), including benzo-a-pyrene (BaP). The combustion of fuels gives rise to emissions to air of particulates, nitrous oxide and SO₂ (International Aluminium Institute, 2013a). Pollution control at anode production facilities is most commonly a type of scrubbing process, using alumina from electrolysis or, in the case of separate anode baking plants, coke and lime (Green, 2007). Solid waste from the production of anodes includes carbon waste, and sludge from scrubbing processes; these are deposited in landfills (International Aluminium Institute, 2013a). Refractory materials are used for linings in baking furnaces in anode production. They are partly recycled and partly landfilled.

According to the European Environment Agency (2009), coke usage was reduced between 2005 and 2010, accompanied by a significant reduction in air emissions over the same time period. Furthermore, fuel and electricity consumption at European production plants has been decreasing and remains below global averages (European Aluminium Association, 2013).

2.3 Aluminium smelting

Primary aluminium is produced by the Hall-Héroult process of reducing pure alumina into aluminium metal in electrolytic cells described by Equation (1) at the beginning of the Chapter.

Carbon cathodes form the bottom of the reduction cell and act as negative electrodes while carbon anodes held at the top of the cell act as positive electrodes. The combination of a fluorinated bath of cryolite (Na_3AlF_6) at 950°C which dissolves the alumina, aluminium fluoride (AlF_3) which lowers the melting point and the carbon anodes under high intensity electric current, causes a reaction that produces molten aluminium metal (U.S. Environmental Protection Agency, 2013b).

At European smelters (2010 data), one metric tonne of primary aluminium requires 1920-1925 kg alumina and the average electricity consumption is 14887 kWh/tonne cast Al (European Aluminium Association, 2013). Smelters in North America require on average 1.9 tonnes of alumina, 437 kg carbon anodes and 15300 kWh of electricity to produce one metric tonne of primary aluminium (The Aluminum Association, 2011). The reduction reaction of alumina and the carbon anodes occurs according to Equation (1) (U.S. Environmental Protection Agency, 2013a), as previously shown at the beginning of the chapter. The reaction provides the minimum stoichiometric requirement of 1889 kg Al_2O_3 for the production of one metric tonne of primary aluminium (International Aluminium Institute, 2013a).

The pre-baked anodes are replaced at regular intervals, when they are down to one third to one quarter of their original size. Once removed and having cooled, the remaining anode butts are cleaned of bath materials, which are recirculated in the potroom, while the butts are crushed for material for new anodes.

The molten aluminium remains below the surface of the cryolite bath until it is siphoned and transferred to a furnace for casting. It is stored in a holding furnace where it is alloyed, if necessary according to specifications, and degassed to remove impurities. The process involves adding a flux of chloride and fluoride salts along with bubbling a mixture of chlorine gas and an inert gas through the molten material, according to the EAA (2013) this amounts to 2.38 kg of the mixture (chlorine, argon and nitrogen) per tonne cast aluminium. The reaction discharges impurities to form hydrochloric acid (HCl), Al_2O_3 and metal chlorides (U.S. Environmental Protection Agency, 2013b). From the holding furnace, the purified molten aluminium is finally cast.

The entire production process of primary aluminium requires enormous amounts of energy, up to 20000 kWh per tonne aluminium. The energy consumption of the Hall-Héroult process accounts for 80% of the total of the primary energy demand in aluminium production (Moors, et al., 2005), 60% of which is generated by fossil fuels on a global level (coal, oil and natural gas) (World Aluminium, 2013; International Aluminium Institute, 2012a). This has implications for global warming, the consumption of renewable and non-renewable energy resources and the depletion potential of abiotic resources (ADP). Energy consumption is thus a significant factor in both cost and environmental load for the aluminium industry, although it has been reduced by half over the last 50 years and by 7% in the last 20 years.

Solid waste generated during the smelting process includes dross, residual anode butts, undissolved alumina and spent pot liners (The Aluminum Association, 2011). The cathode of the electrolysis cell is not consumed during the production process but cathodes do deteriorate with time through electrolyte absorption. Spent pot linings (SPL) from the cathodes are a waste stream

generated at a rate of 15-35 kg per tonne aluminium produced (International Aluminium Institute, 2012a). Approximately one quarter of the total SPL waste is nonhazardous, recyclable refractory material and 20% is made up of a carbon-rich fraction deemed hazardous due to leachable fluoride and cyanide contents. The final mixed 55% of the total cathode waste is also classified as hazardous. No treatment process for SPL has become widespread and, as a result, storage in secure sites is still general practice for many aluminium smelters (Lisbona, et al., 2013).

Pre-baked carbon anodes are not entirely consumed during electrolysis as the carbon paste of Söderberg anodes is. Approximately 20% of the anode is left when the anode is removed from the cell for replacement. This anode waste is returned to the anode production facility where the carbon remnants are crushed and recycled into the anode production process (European Aluminium Association, 2013).

Dross, another waste flow of electrolysis, is made up of a mixture of entrapped aluminium metal, aluminium oxide and salts. When molten aluminium metal comes into contact with air, an aluminium oxide forms an outer layer of the melt and this is termed dross (Das, et al., 2007). The aluminium content varies from 30-60% depending on how carefully skimming from the melt has been done, the composition of the molten alloy and the cooling of the dross (Manfredi, et al., 1997). The dross is usually further processed in order to recover the aluminium metal (International Aluminium Institute, 2013a).

During electrolysis, alumina is replenished to maintain its content in the bath at 2-5%. Should it fall below 1.5-2%, the bath fails to wet the carbon anode and a gas layer forms around the anode, resulting in a rapid voltage increase. This is known as an anode effect. The two perfluorocarbons (PFCs), CF_4 and C_2F_6 , that are produced due to anode effects are greenhouse gases (Alcoa, 2013), and make up approximately one third of all direct greenhouse gases emissions of primary aluminium production (U.S. Environmental Protection Agency and International Aluminium Institute, 2008).

According to the Aluminum Association (2011), the current greenhouse gases level of emissions per tonne primary aluminium is 1.6 tonnes CO_2 , mainly due to anode consumption, and 0.6 tonnes of CO_2 equivalent of PFCs, which can be controlled by optimizing process operations (The Aluminum Association, 2011).

Emissions of NO_x and SO_2 arise from fuel combustion and carbon anode consumption (International Aluminium Institute, 2013a). While SO_2 contributes to acidification potential (AP), NO_x emissions contribute to photochemical ozone creation (POCP) and AP, they also have implications for eutrophication potential (EP), due to the potential chemical conversion of NO_x into nitrate (NO_3^-). Gaseous fluoride, which mostly takes the form of hydrogen fluoride (HF) (Light Metals Research Centre, 2011), accounting for 50-80% of fluoride emissions (European Environment Agency, 2009), is among the pollutants which contribute to AP. It is formed when the AlF_3 part of the molten bath reacts with hydrogen while particulate fluoride is released as bath particles vaporize and condense. Dust is emitted during electrolysis as alumina and cryolite (Light Metals Research Centre, 2011).

Wet scrubbers have been used to control gaseous and particulate fluorides from electrolysis cells (U.S. Environmental Protection Agency, 2013b). Dry scrubbers are used for the same purpose at Norðurál and in the aluminium industry. Furthermore, fluoride scrubbing systems recycling alumina have been shown to improve cell chemistry and process efficiency, which use at the same time is encouraged for an industry committed to a 35% reduction in fluoride emissions per tonne of production between 2006 and 2020 (International Aluminium Institute, 2012a).

2.4 Aluminium casting

Molten aluminium is siphoned from electrolysis pots regularly and transported via crucibles to holding or mixing furnaces in the plant casthouse. Alloying elements are added in the holding furnaces until the desired chemical composition and temperature is reached (European Aluminium Association, 2013). Aluminum as a material is almost always used in alloyed form (The Aluminum Association, 2011). Copper, for example, increases strength, while the addition of silicon reduces melting temperature (ESAB, 2014). In some instances, depending on the intended application and bath composition in the pots, some treatment is required to remove impurities once alloying is complete. Alkali chlorides and fluorides, for example, are used as flux to accomplish impurity elimination and reducing gas content in melting furnaces. The fluxing process removes gases and inorganic particulates by flotation to the metal surface, which are subsequently skimmed off, along with some aluminium metal, forming a waste material known as dross (Green, 2007).

Some primary aluminium is cast using direct chill technology into ingots intended for further treatment and processing such as rolling (typically 6 m long, flat slabs with rectangular profiles (The Aluminum Association, 2014)), extrusion (0.5-1.8 m long billets with circular profiles (Aluminum Extruders Council, 2014)) or for remelting. The liquid metal is poured into open ended molds on a platform which is lowered into a pit filled with water, thus achieving cooling as well. The ends of the cast aluminium products are sawed off and directly recycled within the casthouse and this completes the production of the primary aluminium product which is ready for transport to the customer (European Aluminium Association, 2013).

The most significant waste component from aluminium casting is dross, the surface layer which is skimmed off the molten metal. It is generally recycled internally or sold to independent recyclers.

Filter dust from melting furnace air filtration is partly recovered as byproduct for external recycling and partly landfilled. In the case of the EAA, for example, the amount for recycling is 0.9 kg per tonne cast aluminium and 0.5 kg per tonne cast aluminium disposed of in landfills.

Air emissions from casting arise due to fuel combustion, with the major energy carriers being electricity, natural gas and heavy fuel oil. Particulates, NO_x and SO₂ are the major constituents of emissions to air (International Aluminium Institute, 2013a).

2.5 Properties of aluminium

Aluminium has an atomic number of 13 and atomic mass of 27 g/mole, making it low in density (2.7 g/cm^3) and significantly lower than other common metals such as iron (7.8 g/cm^3) and copper (8.9 g/cm^3). Combined with other elements, such as magnesium, zinc and copper, it forms alloys which have high strength-to-weight ratios and are easily shaped through industrial metalworking processes. It provides permeation and corrosion resistance and exhibits excellent thermal and electric conductivity. Aluminium foil, for example, is completely impermeable, letting neither light, odor nor taste in or out. These characteristics are important to various industries, including automobile, food and aeronautics (The Aluminum Association, 2011).

The metallic structure of aluminium distinguishes it from other materials, since it is not affected by melting processes. That is, the inherent properties and elemental nature of aluminium and its alloys are preserved and make them, as other metals, in principle indefinitely recyclable. In fact, nearly 75% of the aluminium produced since the 1880s is still in circulation (The Aluminum Association, 2011)

Once cast as intermediate products such as ingots or slabs, aluminium can be rolled, extruded or further processed for final use in applications ranging from construction, packaging and machinery and numerous others (de Schrynmakers, 2009). In fact, it is the second most used metal after steel and its applications continue to diversify and grow due to its versatile properties (Liu & Müller, 2012). Aluminium's light weight has become an important feature in transportation, its durability makes it a material of choice for the building sector and due to its good electrical conductivity, it is widely used in wires and cables (de Schrynmakers, 2009).

2.5 Recycled aluminium

Iceland produces only primary aluminium, with three smelters delivering 800 thousand metric tonnes per year. Aluminium scrap from casting is recycled internally, while aluminium products are recycled abroad. Alur, a company located in Reykjanesbær specializing in this recycling treatment, treats approximately 2500 tonnes of dross annually for recovery of aluminium metal (Alur álvinnsla, 2012).

Globally however, over 60% of aluminium used is recycled, most of which comes from products that are easily recycled, such as construction and transport (Moors, Mulder, & Vergragt, 2005). Aluminium's recyclability makes it a preferable choice of material for various products, both with regard to sustainability issues and economic attractiveness. Recycling cuts raw material inputs and reduces waste outputs and land use for landfill sites (de Schrynmakers, 2009). The most important incentive for recycling aluminium is energy savings, which amount to 95% compared to the production of primary aluminium (Liu & Müller, 2012). The avoided environmental load from alumina refinery, red mud waste, also provides a significant incentive. With regard to the Hall-Héroult process, waste gases containing fluorides, SO_2 , various greenhouse gases (CO_2 , CO, PAHs, PFCs) and dust particulates (Moors, et al., 2005) are also avoided. LCA studies in the aluminium industry vary in scope and produce significantly different results according to whether the subject is primary or secondary aluminium. Though the

predominant focus is on energy and greenhouse gas emissions for both primary and secondary aluminium, the studies present different temporal and geographical characteristics and ranges of environmental impacts (Liu & Müller, 2012).

As the amount of aluminium in circulation increases, the importance of recycled, or secondary, aluminium is expected to rise since its production requires less energy. Equally important will be the efficient recycling of aluminium, as energy constraints and environmental concerns continue to grow (Organization of European Aluminium Refiners and European Aluminium Association, 2007).

3. Norðurál primary aluminium production

3.1 Production process

The Norðurál primary aluminium production facility at Grundartangi was launched in 1998 with an initial production capacity of 60,000 metric tonnes per year (mtpy). In 2001, the production was increased to 90,000 mtpy. The facility was acquired by Century Aluminum in 2004 and has since increased its capacity to 294,000 mtpy (Norðurál, 2014a) though its operational permit, issued by the Environment Agency of Iceland, covers the production of up to 300.000 mtpy and is valid until June, 2020 (Environment Agency of Iceland, 2003). Primary aluminium production at Norðurál accounts for 35% of the 800 thousand mtpy produced in 2010 (Icelandic Association of Aluminum Producers, 2013).

Norðurál's main operations are shown in Figure 3. Norðurál receives its alumina from various suppliers globally, depending on prices and availability (item 1 in Figure 3). Sherwin Alumina Company LLC, an American alumina manufacturer located in Gregory, Texas, supplied the majority of Norðurál's alumina in 2012, the reference year for data used in this study. The main country of origin to supply bauxite to Sherwin for their alumina production is Jamaica, and to a lesser extent, Guinea. For the purposes of this study, bauxite mining was modelled in Jamaica and alumina refining in Texas.

Century Aluminum owns through its subsidiaries a 40% share of Baise Haohai Carbon Company, Ltd. in China, which supplies Norðurál with carbon anodes for electrolysis (Century Aluminum, 2014).

Four potrooms house a total of 520 electrolysis cells (item 6 in Figure 3), each with twenty 1200 kg pre-baked carbon anodes which are replaced every 28-30 days. Producing approximately 1.5 metric tonnes per day, the pots are regularly tapped for molten aluminium, which is transported to the casthouse.

Annual production requires approximately 4300 Gigawatt hours (GWh) of electricity (in 2012), nearly one quarter of total electricity generated in Iceland, and is supplied by publicly owned companies Orkuveita Reykjavíkur, Landsvirkjun and HS Orka (Norðurál, 2012). Landsvirkjun provides electricity generated by hydropower, HS Orka produces electricity from geothermal plants Svartsengi and Reykjanesvirkjun (HS Orka, 2010) and Orkuveita Reykjavíkur generates electricity via two geothermal plants, Nesjavellir and Hellisheiði, in addition to two small hydropower plants (Orkuveita Reykjavíkur, 2014).

Once the contents of the casting furnace reach 60 metric tonnes of molten aluminium at 720°C, the furnace is raised to pour aluminium into casting molds. Norðurál's final products are 22 kg pure aluminium cast ingots (Norðurál, 2014b) which are sold under three London Metal Exchange-based (LME) tolling agreements (Century Aluminum, 2013):

- 130.000 tonnes per year to BHP Billiton (contract through 2013)
- 90.000 tonnes per year to Glencore (contract through 2016)

- 40.000 tonnes per year to Glencore (contract through 2014)

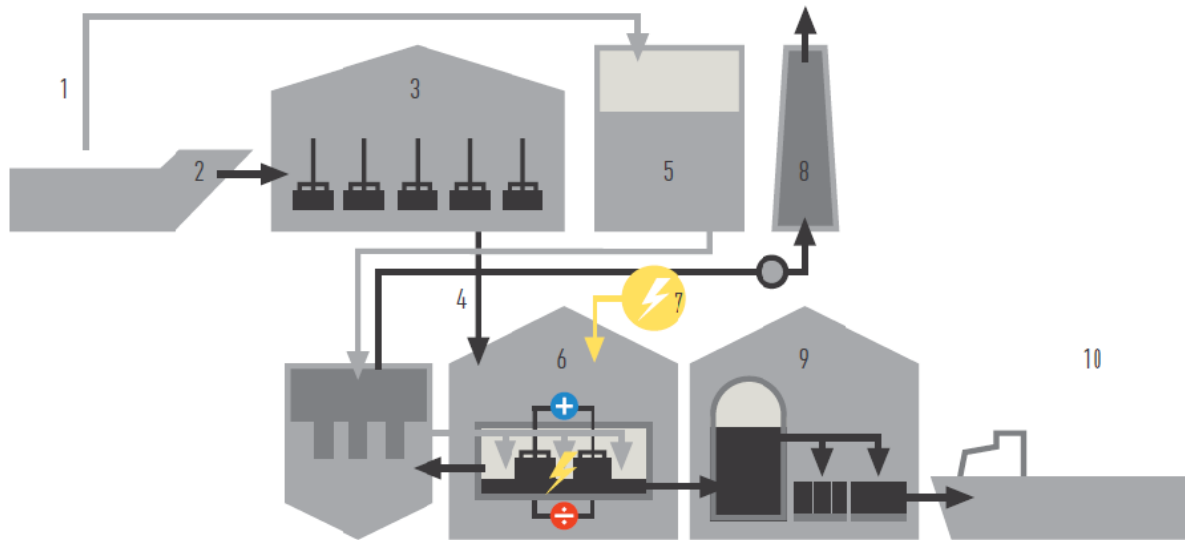


Figure 3 Norðurál production process.

1. Alumina from freight ship discharged to silo; 2. Anodes moved from port to anode shop; 3. Anode assemblies cast to carbon anode with steel; 4. Complete anodes fixed to pots; 5. Alumina conveyed from silo to dry scrubber and potrooms; 6. Aluminium is produced in pots through electrolysis; 7. Electricity reduces the alumina according to Equation (1) and molten aluminium is transported via crucible to the casthouse; 8. CO_2 formed during electrolysis is emitted through dry scrubber stack; 9. Aluminium is cast into ingots and stacked on bundles and stored in containers for shipping; 10. All of Norðurál's products are shipped to European markets. Adapted from (Norðurál, 2012)

Norðurál's product is shipped to Rotterdam where it is sold within the limits of the agreements to Germany, Austria, the Netherlands, Belgium, Hungary, Finland, Poland, Romania, Ireland, France and Slovakia, in order of magnitude of sale (Steinsen, Electronic communication, 2014a).

3.2 Environmental aspects

Norðurál strives to manufacture its products in compliance with Icelandic laws and regulations, meeting buyer demands for quality and making efforts to improve environmental performance. The company's environmental objectives include minimizing emissions to air, increasing employee awareness of environmental issues, increasing the proportion of reused material and responsible waste disposal in addition to boosting the systematic management of chemical use in all operations (Norðurál, 2012). In order to better manage its environmental impacts and pollution prevention measures, Norðurál implemented a certified environmental management system, ISO 14001:2004, as of October 31, 2013 (BSI Assurance UK Limited, 2013).

3.2.1 Emissions to air

Air emissions due to processes upstream of the smelting and casting stages at Norðurál, that is emissions from bauxite mining and alumina refining, are largely contributed by the combustion of fossil fuels during those processes. The main constituents are NO_x , SO_2 , CO_2 and particulates. These emissions are, however, beyond the control of Norðurál aside from contracting other suppliers whose environmental burden is less.

Greenhouse gas emissions related to the production facility at Norðurál are to a great extent due to the electrolysis stage of the production process. The emissions are mainly CO_2 in addition to the fluorocarbons hexafluoroethane (C_2F_6) and tetrafluoromethane (CF_4). Approximately 1.4% of the sulphur contained in pre-baked carbon anodes reacts with oxygen during electrolysis to form SO_2 , another major constituent of potroom emissions. Potroom emissions are not treated or scrubbed for SO_2 (Norðurál, 2012).

Minimizing fluoride emissions from the aluminium production process is important for reducing local environmental effects, improving working environment, in addition to meeting legal limits set by Norðurál's operational permit of 0.5 kg F/t Al (Environment Agency of Iceland, 2003). Norðurál uses dry scrubbing technology from engineering company Alstom for the treatment of potroom emissions, in particular, to minimize gaseous fluoride (in the form of HF) and particulate (dust) emissions.

Alumina for the electrolytic process is conveyed through the dry scrubber before entering the potroom for feeding into electrolysis cells. Exhaust gases from the potrooms are treated in dry scrubber reactors, where HF is adsorbed onto the surface the fresh alumina. The fluoride-enriched alumina and dust are removed through fabric bag filters and returned to the electrolytic process (Paulin, et al., 2009). Thus fluoride is recycled within the production process and less than 1% is emitted to air (Norðurál, 2012). The composition of potroom emissions is significantly improved by the dry scrubbing process, with the amount of fluorides decreasing from 240 mg/Nm^3 to less than 1 mg/Nm^3 for gaseous fluoride and 120 mg/Nm^3 to 0.3 mg/Nm^3 for particulate fluoride as a result of the scrubbing treatment. Moreover, the amount of dust, or particulates, is reduced in the dry scrubber to 3 mg/Nm^3 from 0.5 mg/Nm^3 in untreated potroom gas (Norðurál, 2014c).

As specified in the facility's operational permit (2003), Norðurál carries out regular and continuous monitoring of emissions to air, water and soil (Table 1).

Table 1 Emissions monitoring at Norðurál

Pollutant	Unit	Average	Monitoring frequency
Treated emissions from stack			
gaseous fluoride	kg F/t cast Al	monthly	continuous
particulate fluoride	kg F/t cast Al	annual	annual
dust	kg/t cast Al	monthly	continuous
sulphur dioxide	kg SO ₂ /t cast Al	monthly	continuous
Emissions from potroom roof			
gaseous fluoride	kg F/t cast Al	monthly	continuous
particulate fluoride	kg F/t cast Al	annual	annual
dust	kg/t cast Al	monthly	annual

The operational permit specifies annual and short term limits to averages (monthly averages) for three pollutants: total fluoride, dust and sulphur dioxide.

Table 2 Emission limits specified by Norðurál operational permit (Environment Agency of Iceland, 2003)

Pollutant	Unit	Annual average	Short term average
total fluoride	kg/t cast Al	0.5	0.8
dust	kg/t cast Al	1.0	1.3
sulphur dioxide	kg/t cast Al	21.0	28.0

3.2.2 Emissions to water

Water is used for cooling casting molds in the casthouse; it is continually reused in a closed loop system. Any water used in the production process is filtered for oil and grease prior to discharge into seawater. Sewage is treated in a septic tank and handled by certified outside contractors. Prevention efforts for oil pollution are in accordance with regulation no. 35/1994 on measure to prevent oil pollution due to land operations (Environment Agency of Iceland, 2003).

According to Norðurál's monitoring procedure for 2012-2021, rivers within the designated monitoring area and dilution zone are sampled periodically for levels of SO₄²⁻, Cl⁻, F⁻, conductivity and pH. The monitoring has been carried out periodically since the introduction of industrial processes to Grundartangi with the objective is to assess any possible environmental burdens to air, soil, fresh water and sea water in the area (Environment Agency of Iceland, 2012).

Similarly, Norðurál's seashore landfills are monitored and sampled regularly. The emission constituents sea water samples are evaluated for include cyanide, heavy metals (Cu, Zn, Cr, Ni, Pb, V, As, Al), iron, phosphorus and fluoride. Furthermore, the mussel populations in the fjord where Norðurál is located, are monitored for heavy metal concentrations and PAH (Environment Agency of Iceland, 2012). Monitoring has shown PAH levels to be within limits and the levels of cadmium, mercury and lead have been under the detection limit. However, chromium, copper,

nickel and zinc have been detected in samples but in levels low enough to produce minimal or no effect, according the regulation no. 796/1999 on the prevention of water pollution (EFLA Verkfræðistofa, 2014, 2012).

3.2.3 Waste and byproducts for recycling

In 2012, 75.84% of weighted waste generated by the operations of Norðurál facilities was recycled and 23.75% was disposed of in seashore landfills. The division of the remaining 0.41% waste was as follows: solid waste amounted to 0.36%, hazardous waste accounted for 0.01% and 0.04% went to waste water treatment or collection systems (Norðurál, 2012).

Waste materials from general operations and maintenance of the production facility such as timber, plastics, cardboard and scrap metals are recycled locally by Hringrás if possible or sent abroad for treatment and reuse.

Anode butts constitute the remains of anodes once they have been consumed in the electrolysis process. On average, 20% of the anode is left when it is replaced in the cell. Anode butts are recycled at Norðurál's subsidiary anode production plant in the Netherlands.

Spent pot linings (SPL), carbon and slag dust and mixed bath waste from decommissioned pots are deposited in an on-site seashore landfill in the harbor area of the industrial site at Grundartangi. The landfill is closed off from open water by an embankment. In the landfill, the SPL materials are mixed with shell sand, which reacts with and neutralizes fluoride and cyanide and dilute the material. Associated Icelandic Ports use the residual material for harbor sediment and construction (Norðurál, 2013).

4. Life cycle assessment methodology

The framework provided by ISO 2006 divides the procedure for LCA into four phases: goal and scope definition, inventory analysis, impact assessment and interpretation. Figure 4 describes the relationship between the phases.

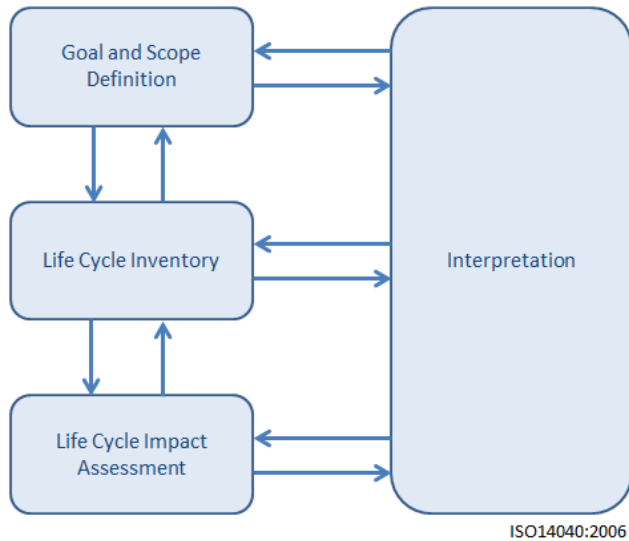


Figure 4 Four phases of LCA (Figure adapted from (ISO, 2006a))

LCA studies shall include all four phases. The definition of the study goal and scope depend on the subject of the assessment and the intended application of the study. The scope describes the methodological choices affecting assumptions and limitations. The second phase, life cycle inventory (LCI), involves creating an inventory of inputs and outputs related to the product system being studied, as defined in the first phase. The life cycle impact assessment phase provides additional information for the assessment of life cycle inventory results and includes the selection of impact categories, category indicators and characterization models, classification and characterization. In the fourth and final phase of LCA, life cycle interpretation, results of LCI are gathered for conclusions and the discussion of limitations, identification of significant issues and recommendations in accordance with the goal and scope definition (ISO, 2006b). All four phases are discussed in detail in relation to this study in Section 4.4.

4.1 Development of LCA

The study of the environmental impacts of consumer goods dates back to the 1960s, when environmental policy became a major issue in industrialized societies, yet the idea of addressing the life cycle of a product did not fully emerge until the 1980s. The 1990s saw a decade of growth and coordination within the field of LCA and the first scientific papers were published (Guinée, et al., 2011). The International Organization for Standardization (ISO) has been

involved in the development of LCA since 1994 and has since then developed a general methodological framework and terminology, described by two international standards for LCA:

- ISO 14040: Environmental Management – Life Cycle Assessment – Principles and framework (ISO, 2006a)
- ISO 14044: Environmental Management – Life Cycle Assessment – Requirements and guidelines (ISO, 2006b)

The ISO standards define LCA as a „compilation and evaluation of inputs, outputs and the potential environmental impacts of a product system throughout its life cycle (ISO, 2006a, p.2).“ LCA does not predict absolute effects on the environment but rather addresses potential environmental impacts. It assists industry, governments and non-governmental organizations in strategic planning, product or process design and environmental management efforts by identifying opportunities to improve environmental performance of products and services (ISO, 2006a).

LCA covers the stages of a product or process system, from material acquisition through production, use and to recycling and waste disposal. The full product life cycle can be divided into the following stages that help define the scope and system boundaries of the study:

- cradle to entry gate (raw material extraction to refining)
- entry gate to exit gate (product manufacture)
- exit gate to grave (product use, recycling and disposal)

The ISO standard describes the selection of a system boundary for LCA studies (PE International, 2010), as detailed in Chapter 4.4.

The subject has since its inception rapidly gained interest, represented in European Policy (European Commission, 2013; Gao, et al., 2009) and in the United States, the Environmental Protection Agency promotes the use of LCA (U.S. Environmental Protection Agency, 2013a). According to Guinée et al. (2011), the present decade will be one of Life Cycle Sustainability Analysis, broadening the scope of LCA to embrace the three dimensions of sustainability: economic, social and environmental.

4.2 Limitations of LCA

LCA provides a holistic view of ecological effects and this has been regarded as the main strength of the approach, as well as a limitation. As an aggregated technique, it does not fully address localized impacts of systems and does not take into account temporal variations. Therefore, since environmental impacts are not specified in time or space, results from LCA studies are described as potential impacts. Furthermore, the accuracy of the study greatly depends on the quality and availability of data. Liu and Müller's (2012) review of LCA studies in the aluminium industry demonstrated a wide temporal range, with generic industry-wide inventory data being commonly used, despite its infrequent updating, thus limiting its accurate representation of dynamic technological development. Geographical coverage was limited to

Europe, Australia and the United States. These factors can affect comparability between studies and relevance to the industry. Finally, the LCA framework focuses on the environmental aspects of products and processes and does not incorporate social or economic factors or impacts (Guinée, et al., 2002). However, a life cycle costing (LCC) approach has been developed and, LCA is currently evolving into life cycle sustainability analysis (LCSA), a transdisciplinary integrated framework which covers the three dimensions of sustainability: economic, social and environmental. LCSA broadens the scope from product related issues to taking into account social impacts of product and services and associated economic concerns (Guinée, Heijungs, & Huppes, 2011). Social Life Cycle Assessment (SLCA) has emerged as a method to assess social aspects of products and the associated impacts of their production on, for example, workers and entire communities where production takes place (United Nations Environment Programme, 2009). Along with and as a compliment to traditional LCA and LCC, SLCA contributes to the full assessment of goods and services within the framework of sustainable development (Jørgensen, et al., 2008).

4.3 LCA in the aluminium industry

As a consequence of globalization and increased scarcity of resources, trends in consumer demands have changed and the need for resource efficient products with better environmental performance has become great (Burritt & Saka, 2006; Porter & van der Linde, 1995). The aluminium industry started collecting life cycle inventory data early, having the European Aluminium Association (EAA) publishing its first Ecological Profile Report in 1996 (European Aluminium Association, 1996). Since then, other regional and global aluminium associations (International Aluminum Institute (IAI) and the Aluminum Association) have become involved, periodically publishing LCI data sets and environmental sustainability reports (Liu & Müller, 2012).

In the aluminium industry, life cycle thinking has emerged as essential to addressing environmental impacts along value chains, throughout entire life cycles and promoting sustainable development (de Schrynmakers, 2009). The life cycle approach avoids shifting environmental problems or damage between life cycle stages, locations and generations (The Aluminum Association, 2011). Modelling the entire life cycle of a product is essential to understanding the links and interdependencies in the phases of a product's lifetime. This is particularly relevant for aluminium products, since many phases, such as recycling, offer relative savings with respect to environmental load (de Schrynmakers, 2009).

However, this is not the general case with the application of LCA within the aluminium industry. Few studies examine all phases of the product life cycle: from mining and production, to semi-manufacturing and manufacturing, ending with use, waste management and recycling, due to time, data and knowledge constraints. Liu and Müller's (2012) review of LCAs in the aluminium industry found that greenhouse gas emissions intensity ranged from 5.92-41.1 kg CO₂ equivalents (eq) per kg cast primary aluminium ingot. The range is attributed to differences in temporal scope, that is, the fact that generic datasets were infrequently updated and secondly, to the geographical coverage being limited to countries that only account for 20% of global primary aluminium production, Australia, the United States and Europe. System boundary definitions,

technological assumptions and methodological choices played a significant role in the different results among studies.

Norgate and Haque's (2010) LCA of mining and minerals processing for bauxite ore showed that loading and hauling operations were the greatest contributors (approximately 50%) to total greenhouse gas emissions, accounting for 4.9 kg CO₂ eq per tonne ore. Gao et al.'s (2009) cradle-to-gate LCA of an alumina refinery, smelter and casting plant using Chinese data from 2003 revealed a GWP 1.7 times higher than the world's average in 2000, or 21.6 t CO₂ eq/t Al produced in China compared to 12.7 t CO₂ eq/t Al as a global average. This is due to China's coal-dominated energy mix, demonstrating the significance of geographical differences between regions for LCAs with the same system boundaries and functional unit. Schmidt and Thrane's (2009) LCA of a planned new aluminium smelter in Greenland found its potential contribution to global warming to be 5.92 kg CO₂ eq per kg produced aluminium, of which 1.66 kg CO₂ eq would be direct emissions from the smelter. The industry has indeed, due to technological advances in fume treatment (European Aluminium Association, 2013) and improvement in industry performance (International Aluminium Institute, 2013a), seen a significant reduction in air emissions.

LCA has been practiced to model cases of potential improvement of a process' environmental performance in the aluminium industry. Tan and Khoo (2005) used this approach for assessing the supply chain of aluminium production in Australia, consisting of an alumina refinery, smelter and casting plant. The study compared LCA models of four different scenarios to increase the efficiency of plant operation. The application of different sustainable practices and waste reduction measures resulted in reductions in GWP in the order of 2.2% to 21.39% compared to the base case scenario and cumulative reductions in acidification potential (AP) by 2.22-4.49%. The greatest environmental potential improvement in the refining of alumina and casting of primary aluminium proved to be due to the application of clean coal technology to coal fired power plants, and a 50% reduction of bauxite residue from alumina refinery.

Aluminium producers have used LCA and accompanying LCI data to calculate plants' environmental footprint, giving direct input to environmental management. For example, LCA has been the core of Alcan's Life Cycle Management program and product stewardship assessments, aiding in decision-making, benchmarking and improving environmental performance at internal and supply chain levels (Rebitzer & Buxmann, 2005). Moreover, CSIRO Minerals in Australia has used LCA to assess environmental impacts of current and potential production processes for various primary metals, including aluminium (Norgate, et al., 2007).

4.4 Applied LCA methodology to this study

4.4.1 Goal and scope definition

During this stage of the LCA, choices are made which determine the procedure of the assessment. The goal definition states the intended application and the audience of the study, in addition to its justification and objectives for carrying it out (ISO, 2006a). The scope establishes the temporal, geographical and technological boundaries of the system (Guinée, et al., 2002). The product system of the intended study is described in terms of its function, boundaries, reference flows,

allocation procedures, relevant impact categories and data requirements. These elements of the scope also determine the overall sophistication of the study. Since LCA is an iterative procedure, some aspects of the scope may require modification in order to adhere to the goal of the study and to address data collection (ISO, 2006a).

4.4.1.1 Goal

The goal of this LCA study is to quantify the potential environmental impacts of aluminium smelting at Norðurál, and be able to identify the hotspots during all its upstream production stages of its defined product system, which final product is one metric tonne of aluminium ingots. The ingots are 22 kg of pure aluminium cast for remelting; typical dimensions are 750x180x100 mm. This will be the first time an LCA is conducted and disclosed to the aluminium industry in Iceland; until now LCA has mainly been used in the food industry (Smáráson, 2013; Guttormsdóttir, 2009; and Eyjólfssdóttir, et al., 2003, for example) and has in recent years been gaining momentum in other fields.

This LCA study is part of the author's thesis toward a M.Sc. degree in Environment and Natural Resources from the University of Iceland. Hence the study is undertaken for academic reasons and its intended audience is the University and Norðurál's management. The results will provide Norðurál with an overview of the potential cradle-to-gate environmental impacts of its production and will enable the company to identify potential sources of improvement in terms of its environmental performance. Additionally, Norðurál will be able to compare it to that of aluminium smelters globally. Finally, the study will contribute to the growing field of LCA in Iceland.

It is for reasons of comparison that, an additional goal has been identified along the development of this study. This is to compare the potential cradle-to-gate environmental impacts of Norðurál's primary production to the European average (LCA done by the EAA, (European Aluminium Association, 2013)). Caution has been made to establish this comparison by defining the same functional unit.

4.4.1.2 Scope

The LCA model for Norðurál represents a cradle-to-gate system (Figure 5), starting at bauxite mining and ending with the final product of aluminium ingots. The functional unit, which provides reference for inputs and outputs throughout the system, is one metric tonne of cast pure aluminium ingots, 22 kg each and dimensions 750x180x100 mm. This type of pure aluminium ingot is commonly used for remelting and further treatment.

The choice of functional unit allows comparison with corresponding LCA studies focusing on processes within the aluminium industry. This functional unit equals to about 45.4 aluminium ingots of 22 kg each delivered by Norðurál, made of pure aluminium with no alloyed elements.

This study qualifies as an attributional LCA, as it describes the environmentally relevant physical flows to and from the processes associated with the life cycle of the pure aluminium ingots, in this case from cradle-to-gate.

Flow diagram for primary aluminium

Legend:

Grey represents processes for which databases are used (background system)

Blue represents processes with primary data (foreground system)

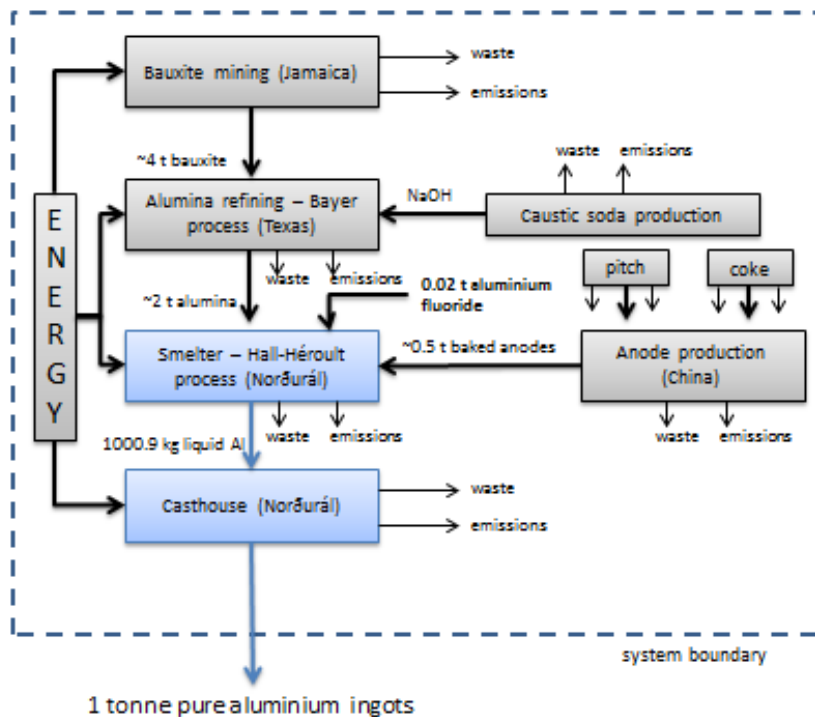


Figure 5 Flow diagram for production of aluminium at Norðurál from cradle-to-gate

In Figure 5, the blue color denotes processes within the foreground system, for which primary data from Norðurál has been attempted to be used. The grey color refers to the background system, which was modelled using secondary data from the GaBi 6 Education database (PE International, 2013), and the EAA's LCI environmental data from 2010 (European Aluminium Association, 2013).

The system boundary and geographical scope includes:

- Bauxite mining in Jamaica and transport of bauxite by sea to Texas
- Alumina refining in Texas by the Bayer process and transport of alumina by sea from the Port of Corpus Christi to Grundartangi
- Production of pre-baked anodes by Baise Haohai Carbon Co., Ltd in China and transport by sea from Qinzhou Port to Grundartangi
- Aluminium smelting by the Hall-Héroult process (at Norðurál)
- Aluminium casting (at Norðurál)
- Electricity and thermal energy generation and supply for all background processes, according to their related country of origin
- Electricity generation and supply locally (in Iceland) for aluminium smelting and casting
- Disposal of waste from mining, refining, pre-baking, smelting, casting, energy generation and from all the background processes included in the study, by re-use, recycling, incineration, landfill and/or deposit

- Disposal or treatment of wastes

The system boundary does not include:

- Capital equipment and maintenance of production facility
- Maintenance and operation of equipment
- Human labor
- Internal transportation of materials
- Distribution of the product
- Use phase of the product
- End-of-life phase of the product
- Recovery of used products, including energy recovery

The focus of the study is on the aluminium smelting and casting processes which take place at Norðurál's production facility in Iceland, thus their definition as the foreground system. The bauxite mining, alumina refining and anode production processes form the background system. As primary data were not available for bauxite mining, alumina refining, anode production and auxiliary processes, secondary data was used from the EAA environmental LCI dataset (European Aluminium Association, 2013), IAI environmental LCI dataset (International Aluminium Institute, 2013a) in addition to the GaBi 6 Education database (2013).

The CML 2001 impact assessment methodology, last updated in November 2010, was applied in GaBi 6.0 Education software.

The EAA product system shown in Figure 6, is similar to that of Norðurál. It is made up of solely secondary data from the report of the EAA (2013) and the IAI (2013a). The functional unit is the same, one metric tonne of pure aluminium cast ingots, but the geographical scope is different. Bauxite mining occurs in Australia, while alumina refining, anode production, electrolysis and casting take place in the EU. Electricity grid mix and energy specific to the location, in this case Australia and EU-27, have been selected in order to reflect the environmental burden of energy generation as closely as possible.

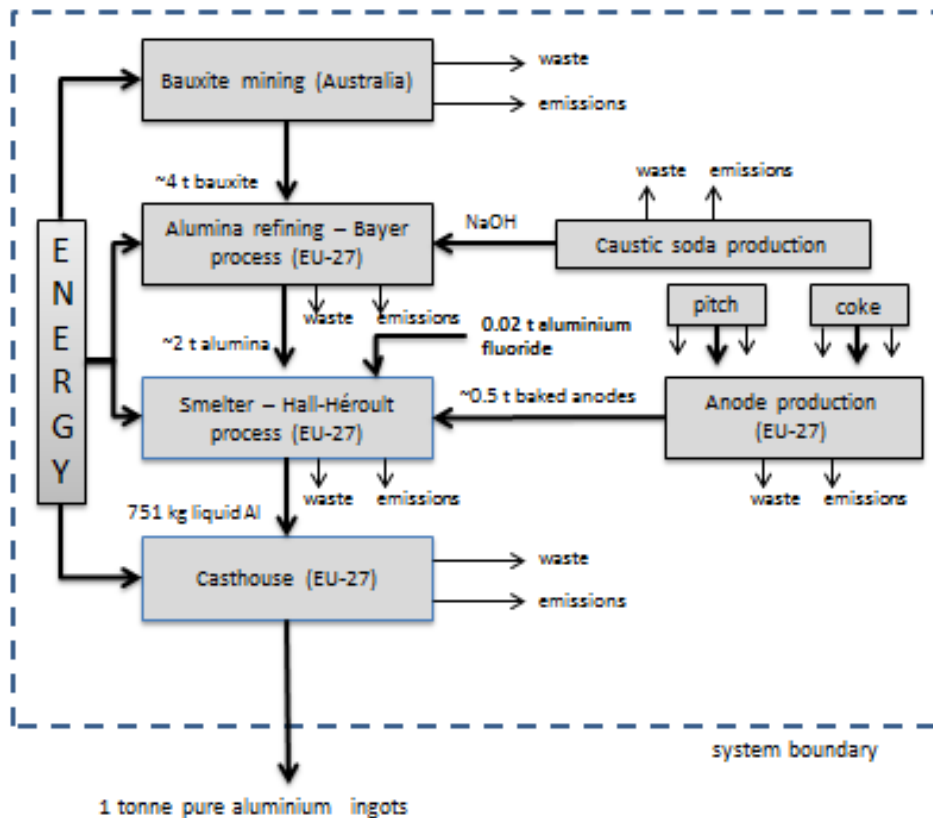


Figure 6 Flow diagram of EAA model for production of aluminium from cradle-to-gate

4.4.1.3 Assumptions and procedures

Allocation procedures

Most processes are multifunctional or generate more output than just the intended product. Similarly, most processes involve inputs that are intermediate products or waste from other processes. Allocation is one possible solution to the problem of multifunctionality and involves „the partitioning of input or output flows of a process or product system between the product system under study and one or more other product systems (ISO, 2006b).“ It should reflect the underlying physical relationships between the different products or functions and their respective shares of environmental burden. Allocation can be avoided by dividing unit processes into two or more processes, a method referred to as subdivision, or by system expansion, a method by which the boundaries of the product system are expanded to include the impacts of alternative and/or additional functions of co-products.

In the case of primary aluminium, alumina production involves inputs such as bauxite, lime and caustic soda, anode production involves petrol coke, pitch and recycled anode butts, and aluminium scrap is a byproduct of aluminium casting. During the course of this LCA study, allocation has been avoided as far as possible by modeling internal reuse or recycling of secondary products or waste, net consumption within the inventory analysis and system expansion when byproducts were sent for external recycling. System expansion, a method to

account for the use of secondary material which displaces the use of primary material, was used to avoid co-product allocation in the case of aluminium scrap and dross recycled from casting and aluminium silicate recycled from spent pot linings. That is, the system boundaries were expanded to include the recycling of aluminium scrap, dross and aluminium silicate and the impacts of this alternative treatment of the relative outputs. Typically, an environmental credit is given for the avoided production of material and this is the case for this study as will be observed in Section 5.1 on results. This is of great importance for aluminium in LCA, that is crediting primary aluminium for recycled aluminium, since the energy consumption for the production of primary aluminium is much larger than that for recycling aluminium (Frees, 2008).

Assumptions expected and limitations

Primary Life Cycle Inventory data on bauxite mining, alumina refining and anode production, in addition to ancillary processes, such as the production of

- Lime
- Caustic soda
- Aluminium fluoride
- Petrol coke
- Coal tar pitch
- Electricity generation

were not available, hence these processes form the background system. The GaBi 6 Education database and EAA's LCI environmental datasets from 2010 (European Aluminium Association, 2013) provided LCI data for these processes.

Cut-off criteria

All material flows going into the aluminium processes over 1% of the total mass flow (in tonnes (t)) or higher than 1% of the total primary energy input (in megajoules (MJ)) are part of the system and modeled in order to calculate and model elementary flows. All material flows leaving the product system, accounting for more than 1% of the total mass flow, are part of the system. The cut-off rules do not apply to hazardous and toxic materials or flows believed to have potential significant environmental impact. This is due to their potential harmful effects to humans and the environment and therefore these materials were included in this study based on experience on their potential hazards to the environment.

These criteria, for including all flows larger than 1% in mass flow and 1% in total primary energy input have been adhered to with one exception. An output from anode production, referred to in the EAA report (European Aluminium Association, 2013) as 'other landfill waste, of which part is hazardous according to local legislation' amounting to 1.4 kg per tonne anode produced was excluded despite being listed as hazardous. The EAA was contacted in order to determine the type of waste and appropriate treatment. Since no response was received, the decision was made to exclude this particular output due to insufficient information for proper identification and its subsequent modelling.

The total mass and energy excluded was 0.64% and 0.0225% respectively, based on 1 metric tonne output and 22242 MJ consumed primary energy (renewable and non-renewable).

Data quality requirements

These requirements describe the characteristics of data necessary and important to understanding the reliability and proper interpretation of the study (Guinée, et al., 2002).

- **Time-related coverage:** the goal was to use as recent data as possible and available to ensure that the assessment be a relevant and realistic representation of the cradle-to-gate assessment of the production process of aluminium. Primary data from Norðurál was related to an annual average of 2012 and secondary data a maximum of ten years old (as far as possible). Some data in the GaBi database was older, but it was used as no other background data was available from the references listed. Similarity in temporal coverage allows for comparison with other up-to-date LCAs related to aluminium.
- **Geographical coverage:** the study was exclusively concerned with aluminium smelted and cast at Century aluminium's smelter, Norðurál, at Grundartangi, Iceland. The product, 22 kg pure aluminium ingots, is sold to two buyers: BHP Billiton and Glencore. The study included the transport of inputs from suppliers to Norðurál: pre-baked anodes from China, alumina from Texas, United States etc. Secondary data from EAA also satisfied requirements on geographical representativeness, covering the EU-27 and EFTA countries.
- **Technology coverage:** it was assumed that Norðurál used the best available technology for its processes as it strives for stable and safe operation of its plant for efficient performance in production and minimizing environmental impacts. It was assumed that secondary data from databases that were used for this assessment, were temporally and technologically comparable to that of primary data and within the temporal coverage already addressed.
- **Completeness:** the percentage of flow that was estimated and used for this assessment was 99% of total mass of the product (ISO, 2006a). Secondary data from the EAA's LCI environmental dataset from 2010 were statistically representative of the aluminium production process and relevant activities and processes.
- **Representativeness:** the aim was to construct a dataset that is geographically, temporally and technologically representative of and relevant to the processes being evaluated.
- **Consistency:** efforts were made to ensure that consistency of data used, to the extent required to meet the overall necessary accuracy, completeness and precision of the study and that the LCA methodology was applied uniformly to all contributing processes.
- **Uncertainties:** these are typically caused by model assumptions, data gaps or lack of accuracy; efforts were made to minimize any uncertainties. Precision, accuracy and completeness of LCI data have been assessed in Section 4.4 on data quality.

4.4.2 Life cycle inventory analysis

This second stage of LCA involved data collection and quantification of relevant inputs and outputs of the product system defined in the first stage and their aggregation to the defined functional unit (ISO, 2006a). This required the calculation of the consumption of resources and

generation of waste flows and emissions associated with the inputs and outputs of the product's life cycle, scaled to the assessed functional unit. Once data had been related to the reference flow of the functional unit, a model of the product system was constructed which represented all material and energy flows in addition to inputs and outputs from and to the natural environment (Rebitzer, et al., 2004).

4.4.2.1 Methodology and data collection procedure

Bauxite mining, alumina refining and anode production form the background system, as introduced in Section 4.4. Environmental datasets from the EAA (2013) and IAI (2013a) were used to model these stages in the cradle-to-gate life cycle of pure aluminium ingots produced at Norðurál. For comparison purposes and as part of the goal of this study, a model based solely on EAA data was constructed and assessed in GaBi as well.

The EAA's primary dataset for aluminium produced by smelters in Europe includes environmental aspects of processes and raw materials used to deliver 1 metric tonne of sawn primary ingots. Efforts were made by the EAA to develop a dataset composed mostly of elementary flows, that is material or energy directly drawn from the environment without prior treatment or material or energy released into the environment without treatment. The LCI dataset is produced from various industry surveys conducted during 2010 from which absolute figures for input and output data for the entire year of 2010 were gathered to calculate European averages for each production step. The EAA also used global average production data for processes occurring outside Europe. Data on bauxite mining, for example, is entirely provided by the IAI. Furthermore, the EAA dataset relies on background data for ancillary processes from GaBi database version 5.

For all production stages in the EAA constructed model, that is bauxite mining, alumina refining, anode production, electrolysis and casting, the following assumptions were applied:

- Outputs of water (fresh water and sea water) were summed and included in each respective model as one figure and treated with an average chemical reduction/oxidation process.
- An average water treatment (chemical reduction) process was created and used for all processes outside of Iceland. It represents an average waste water treatment plant using a chemical reduction/oxidation process, with iron chloride, calcium hydroxide and phosphoric acid as treating agents (Woodard, 2001).
- Inputs of water were assumed to be pretreated as this is general practice globally and typically water at industrial facilities either comes from the tap or is processed, unless otherwise specified. The GaBi process selected was RER: Tap water.

Some data from the EAA dataset have been excluded due to cutoff criteria, and other assumptions for specific production steps in the cradle-to-gate model are shown in Tables 3 and 4.

Table 3 Assumptions made and exclusions of data for EAA's cradle-to-gate constructed model

EAA model		Assumption		Exclusion		
Bauxite mining	Summary/description		Justification	Summary/description		Justification
	Thermal energy from combustion of diesel oil and heavy fuel oil were modelled rather than as fuel inputs to the process in GaBi.		IAI combustion emissions are global averages calculated from a survey with a response rate of less than 30%.	Emissions data for CO ₂ , methane and nitrous oxide excluded.		Thermal energy from combustion of diesel and heavy fuel oil have been modelled. Emissions data excluded to avoid double counting and to accurately represent preparation and combustion of fuels.
	Data for bauxite residue for external recycling and bauxite residue (solid waste) summed and modelled as solid waste.		Bauxite residue for external recycling is small in relation to the total of solid waste for the production of 1 tonne bauxite, counting for only 0.55%.	Diesel oil input excluded (1 MJ) excluded.		Cut-off criterion 1% total primary energy input.
Alumina refining	Thermal energy from combustion of natural gas and heavy fuel oil were modelled rather than as fuel inputs to the process of alumina refining in GaBi.		The EAA data on air emissions from alumina production are a combination of reported figures and LCI data from GaBi. Only restricted data on air emissions from fuel combustion were collected in EAA survey.	Emissions data for CO ₂ , SO ₂ and NO _x excluded.		Thermal energy from combustion of natural gas and heavy fuel oil has been modelled. Emissions data excluded to avoid double counting and to accurately represent preparation and combustion of fuels.
	Bauxite residue treated with 'Landfill of ferro metals' disposal treatment process in GaBi.		The process was the only one available in GaBi which treated hazardous materials such as iron oxides, a component of the residue.			
	Other source of fuel/electricity modelled as heavy fuel oil.		Information on what type of fuel the EAA refers to was not available. This is a conservative approach.	Input of imported green anodes excluded.		Cut-off criterion 1% total mass flow.
Anode production	Input of anode scrap is assumed to be waste anodes from electrolysis.		It is common practice to gather anode butt scrap for remelting into new carbon anodes.	Input steel for anodes excluded.		Cut-off criterion 1% total mass flow.
	Other source of fuel/electricity, diesel oil and heavy fuel oil summed up and modelled as thermal energy rather than as fuel inputs into the process. Natural gas modelled as thermal energy as well.		Only restricted data on air emissions due to fuel combustion are part of EAA's LCI, restricted to particulates, SO ₂ and NO _x .	Output steel, a byproduct for external recycling, excluded.		Cut-off criterion 1% total mass flow.
	Note: EAA data used are based on 1000 kg of production mix: 95% prebake and 5% Söderberg anodes.		Prebaked anodes are prebaked in separate anode plants while Söderberg anodes bake during the electrolytic process. In 2010, 95% of European primary aluminium was produced using prebake technology. Many plants have recently discontinued use of the technology (Hydro, 2009), (CBC News, 2013).	Output "other landfill waste" excluded, of which part is "hazardous according to local legislation."		No data on type of byproduct or what characteristic makes it hazardous. No data on waste treatment required.
	Carbon waste output treated with 'Landfill of ferro metals' disposal treatment process in GaBi.		This landfill process is the most conservative, its processes include landfill gas treatment, leachate treatment	Output "other externally recycled byproduct" excluded.		No data on this byproduct or the recycling treatment it requires.
(continued)						

(continued)

		and sludge treatment.		
Anode production (continued)	Other industrial waste' output treated with 'Landfill of ferro metals' disposal treatment process in GaBi.	This landfill process is the most conservative, its processes include landfill gas treatment, leachate treatment and sludge treatment.	Output CO ₂ emissions to air excluded.	To avoid double counting of CO ₂ emissions due to fuel combustion.
	Suspended solids output treated with 'Landfill of ferro metals' disposal treatment process.	This landfill process is the most conservative, its processes include landfill gas treatment, leachate treatment and sludge treatment.	Input refractory material excluded.	Cut-off criterion 1% total mass flow.
	Outputs refractory waste for external recycling and refractory waste for landfill were added and modelled together for disposal.		Outputs refractory waste and refractory material for landfill excluded.	Cut-off criterion 1% total mass flow.
	Emissions data from EAA for casting used.	Primary data not available.		
Electrolysis			Output SPL stored from normal operations excluded.	Cut-off criterion 1% total mass flow.
			Input refractory material excluded.	Cut-off criterion 1% total mass flow.
Casting	Input diesel modelled as tranport on site.	Diesel oil is normally used for internal transport (International Aluminium Institute, 2013a).	Other solid wastes for landfill excluded.	Cut-off criterion 1% total mass flow.
			Output filter dust for landfill excluded.	Cut-off criterion 1% total mass flow.
			Other source of fuel/electricity excluded.	Cut-off criterion 1% total primary energy input.
			Input alloy additives excluded.	Cut-off criterion 1% total mass flow.
			Refractory materials for landfill and recycling excluded.	Cut-off criterion 1% total mass flow.
Transport	Transport of bauxite from Australia to Europe: 5919 km by sea, 4 km by road, 56 km by rail.	Average distance according to EAA model (European Aluminium Association, 2013).		
	Transport of alumina within EU: 200 km by boat, 200 km by barge, 50 km by rail, 5 km by road.	Average distance according to EAA model (European Aluminium Association, 2013).		
	Transport of anodes was not included in the representation of the EAA model.	This was done in order to represent the EAA model as accurately as possible, and it excludes transport for anodes.		

Secondary data from EAA was used for to model the background system processes associated with Norðurál. Therefore, the assumptions made for the EAA model for these processes listed in Table 3 are also valid for the Norðurál model.

In the following specific cases, data from Norðurál was used:

- Electrolysis data consisted of material inputs, emissions to air, outputs: SPL, anode residue, emissions to seawater due to SPL
- Casting: inputs included liquid aluminium, aluminium scrap, propane, electricity consumption

For other data, the EAA environmental dataset supplied the missing information necessary to accurately model the foreground processes at Norðurál. The assumptions made for modelling Norðurál processes are listed in Table 4.

Table 4 Assumptions made for Norðurál's cradle-to-gate model

Norðurál model	Assumption	
	Summary/description	Justification
Bauxite mining	Electricity grid for Cyprus was used to represent Jamaica in GaBi.	Jamaica's energy mix is 91% oil (Ministry of Energy and Mining, 2010) while Cyprus's is 98% oil, it is the country with energy mix closest to Jamaica.
	Thermal energy from combustion of diesel oil and heavy fuel oil were modelled (JM/CY) rather than as fuel inputs to the process in GaBi.	IAI combustion emissions are global averages calculated from a survey with a response rate of less than 30%, whilst the geographical scope here is Jamaica.
	Process steam from natural gas' process for EU-27 in GaBi was used as input for wastewater treatment in Cyprus bauxite mining.	No such process available for Jamaica or Cyprus.
Alumina refining	Data on origin of alumina for 2013 used.	Data for 2012 not available.
Anode production	Secondary data from EAA used to model anode production in China.	Primary data not available.
	Note: all waste and water treatment processes are according to practice in EU-27.	No data available on waste treatment of anode production plant in China.
Electrolysis	Figure for input cathode carbon is from 2011.	No data available for 2012 on this input.
	Spent pot lining waste is modeled as emissions of CN ⁻ and F to sea water.	The company deposits SPL to seashore landfills and includes emissions of cyanide and fluoride to seawater.
Casting	Water assumed treated despite incomplete information. Process chosen which includes mechanical, biological and chemical treatment steps for the waste water (including precipitation and neutralisation), and treatment steps for the sludge (thickening, dewatering, incineration) to take a conservative approach.	Norðurál must comply with regulations before of disposal of water to freshwater or seawater.
Transport	Average transport distance of bauxite 54 km to shipping point or local refinery.	Data from Fourth sustainable bauxite mining report (International Aluminium Institute, 2008).
	Transport of bauxite from Port of Kingston to Port of Corpus Christi 3202 km by sea, container ship.	
	Transport of alumina from Port of Corpus Christi to Grundartangi 9628 km by sea, container ship.	
	Transport of anodes: 5 km by road, 372 km by rail within China and 21729 km by sea from Qinzhou Port to Grundartangi, container ship.	

Bauxite mining

Environmental data on the extraction of bauxite from EAA's 2010 LCI dataset have been used for the purposes of this study. This was included in the average European cradle-to-gate model and as part of the secondary data for Norðurál's model. The data were compiled by the IAI and have been published as part of EAA LCI data and IAI's own global LCI report. The data are based on a worldwide IAI survey, covering the extraction and preparation of 1 tonne of bauxite

ready for delivery to the alumina plant (European Aluminium Association, 2013). The operations associated with the process of bauxite mining include:

- Removal of overburden on the mining site
- Extraction of bauxite ore
- Washing, screening or drying of ore
- Treatment of mining residues and waste
- Restoration activities on site such as topsoil replacement

In its LCI report (2013a), the IAI encouraged LCA practitioners to show caution when using data from the report on air emissions from fuel combustion, particulates, SO₂ and NO_x emissions, in order to avoid double counting of emissions from fuel combustion. Emissions data for methane, nitrous oxide and CO₂ were calculated from fuel combustion by the IAI and were not part of its survey. The only emissions data the IAI collected which were reported by its members were those for particulates. Furthermore, the IAI model only documented energy consumption figures and direct CO₂ emissions. Indirect emissions data, from electricity, transport and ancillary processes, were not included.

For the purposes of this study, the decision was made to exclude IAI data related to combustion of fuels and model them as background processes. In this way, environmental burdens created by product flows associated with fuel and its consumption are included and appropriately accounted for in the life cycle of aluminium. This is a conservative estimate since the datasets for processes of energy production in GaBi are more extensive and incorporate more background industry data than single, specific energy flows for fossil fuels. Thus, modelling the combustion of fuels it is likely to overestimate the environmental impact. Refer to Table 5 for LCI datasets of Norðurál and EAA models, respectively.

EAA members import bauxite from Australia, Guinea and Brazil. Efforts were made to obtain information on the proportion of bauxite imports from each of these countries to EU but with no success. Since Australia was the greatest bauxite producer in 2012 (Minerals Council of Australia, 2012), the country was selected as the location of the bauxite mining and processing part of the life cycle. The largest impacts related to bauxite mining, as it is shown further in the results, are linked to the energy supply for waste water treatment, with steam and electricity providing the largest contribution. Therefore, in terms of impacts, geographical scope does not make a significant difference.

Alumina refining

Input and output data related to the production of alumina was modelled as part of the secondary data and taken from EAA's LCI environmental dataset from 2010 (European Aluminium Association, 2013). This applies to the EAA model created as well as the Norðurál model.

The activities included within the process of alumina refining which were taken into account for the purposes of this study are (European Aluminium Association, 2013):

- Bauxite crushing, digestion and processing of materials

- Precipitation of alumina and calcination
- Treatment of emissions to air, water and soil

The process output is smelter grade alumina ready for transport to the primary aluminium smelter.

As was the case regarding air emissions from fuel combustion related to bauxite mining, collected data from EAA members on emissions only included SO₂ and NO_x, while CO₂ emissions were estimated from fuel combustion. These data were complemented by other emissions to air from LCI data in the GaBi software (reference year 2008) associated with fuel extraction, preparation and combustion. In order to accurately portray the environmental burden of fuel combustion, air emissions of NO_x, SO₂ and CO₂ have been excluded, as in the process of bauxite mining, and the background processes for the production of thermal energy from heavy fuel oil and natural gas have been modeled separately. For specific figures on input and output data associated with the Norðurál and EAA model, refer to Table 5.

Anode production

At the end of 2013, it became clear that primary data for the production of anodes from Norðurál's supplier, Baise Haohai Carbon Co., Ltd., would not be available in time for use in this LCA study. Therefore, data from EAA's LCI environmental dataset (European Aluminium Association, 2013) were used. These data represent and cover the following processes for anode production:

- Recovery of spent anode butts
- Forming and baking of anode blocks and briquettes
- Addition of steel bars to anode butts
- Treatment of gaseous, liquid and solid emissions

The input and output data are average European figures related to the production of 5% mixed paste and 95% pre-baked anode.

The scale of CO₂ emissions was determined to be greater in proportion to the other constituents NO_x and SO₂. Moreover, the EAA estimates CO₂ emissions using CO₂ intensity conversion factors for fuel combustion and, in order to avoid double counting, CO₂ emissions were excluded from the dataset for the purposes of this study. Emissions were therefore modelled by including thermal energy production from related fuels (heavy fuel oil and natural gas), see specific figures for input and output data in Table 5.

The EAA integrates transport data only for bauxite, alumina and primary ingots into its LCI datasets. In order to emulate the life cycle of aluminium produced in the EU as closely as possible and ensure an accurate representation of EAA data, the transport of anodes was not included in the EAA model of this LCA study. Transport for Norðurál model according to Table 5.

Electrolysis

The EAA environmental dataset represents the following activities related to aluminium electrolysis:

- Preparation of process materials
- Process control activities associated with heat, bath and melt
- Treatment of gaseous, liquid and solid emissions

The input and output data correspond to the production of 1000.9 kg of molten aluminium by the Hall-Héroult process using a production mix of 95% pre-bake and 5% Söderberg anodes, ready for transport to the casthouse. It should be noted that the amount of molten metal is higher than the functional unit of 1 tonne in order to account for aluminium scrap.

The method of system expansion was used to account for the recycling of spent pot linings. The waste from one product system, here SPL from electrolysis, is used as raw material for another product system, in this case the same process, electrolysis. Thus when modelled, environmental loads of raw materials that are substituted by recycled waste or byproducts are subtracted from those of the system which generates the waste. Their potential for environmental impact are, in effect, negative when it comes to results.

Data on inputs and outputs for electrolysis at Norðurál are, for the most part, public information from the firm's Green Accounting Report (2012). Some data, provided directly from Norðurál, have been altered slightly in this report for confidentiality purposes. The data for air emissions from electrolysis were confirmed by internal documents prepared by the Environment Agency of Iceland. Data on production from potrooms and casthouse were also confirmed by an internal document.

It should be noted that the electricity consumption at Norðurál is 4.5% lower than that of the average European smelter. This issue was addressed and discussed at length and the validity of data confirmed by Norðurál. The difference may be explained by better technology and/or state of the art equipment which in turn contributes to more efficient production and better current efficiency (Steinsen, 2014b).

Casting

The electricity consumption reported for casting at Norðurál is 60.89 kWh/tonne Al (equivalent to 219.2 MJ/tonne Al), which amounts to approximately 62% of the electricity consumption of an average European smelter according to the EAA (European Aluminium Association, 2013). However, the average smelter in the EAA dataset also consumes heavy fuel oil, natural gas and diesel oil as part of the casting process, bringing the average total energy consumption to 1936 MJ, with thermal energy accounting for 1585 MJ (see Table 5 for EAA LCI data). Due to this discrepancy in energy consumption, the decision was made to include additional energy from fuels, by the amount of 982.7 MJ of thermal energy from heavy fuel oil. This, together with the electricity consumption, corresponds to 62% of EAA total thermal energy data. Furthermore, the energy was assumed to be heavy fuel oil, since only data on thermal energy use associated with propane at Norðurál was available and another aluminium casthouse in Iceland uses fuel oil for

heating furnaces (Rio Tinto Alcan, 2012). Finally, as was the case for some EAA members, no emissions data for casting was available from Norðurál, thus emissions data for casting from the EAA dataset was used for the Norðurál model in the same proportion as the thermal energy for casting, 62%. Output data from Norðurál consisted of that for cast metal.

The EAA environmental dataset for casting represents average data for a generic aluminium ingot and covers ingots for rolling, extrusion and remelting. The dataset includes:

- Pre-treatment of metal, such as cleaning and alloying
- Treatment of molten material and casting activities
- Sawing of cast ingots
- Recovery and handling of process scrap
- Treatment of gaseous, liquid and solid emissions

The inputs and outputs are associated with the production of 1 tonne of sawn aluminium ingot at the casthouse.

For the EAA production system, the methodology of system expansion was applied to resolve the modelling issue of external recycling of dross and aluminium scrap from casting. Dross at Norðurál is recycled internally and thus treated as a net input and not modelled.

The EAA notes that European averages of air emissions from casting are not significant due to their occasional inclusion with electrolysis emissions data. In fact, some members disclose no specific figures for the casthouse. The EAA also notes that fuel consumption for casting is higher at the European level than the global average, due to a higher proportion of solid aluminium to the process. It is important to bear this in mind when assessing the environmental impact of the casting process of aluminium production.

The study is a cradle-to-gate LCA, thus it ends at the factory gate, with the final product of pure aluminium ingots ready for transport.

Table 5 presents LCI data used for modelling Norðurál production processes (in blue) and for the average European model, using EAA data (in black). Observe that the figures in parentheses represent those of data for emissions and fuels that have been modelled as thermal energy from the associated fuels.

Table 5 LCI data for Norðurál and EAA models, Norðurál (blue) and secondary/EAA (/black) data

Norðurál/EAA required for 1000 kg cast Al output	kg	bauxite mining	alumina refining	anode production	electrolysis	casting
		4341/3246	1928/1442	421/407	1001/751	1000/1000
INPUTS		per tonne output				
raw materials						
bauxite	kg	1062	2251			
caustic soda (NaOH)	kg		53			
calcined lime (CaO)	kg		42			
petrol coke	kg			717		
pitch	kg			152		
recycled butts	kg			204		
alumina	kg				1927/1920	
anode / paste	kg				421/542	
aluminum fluoride	kg				16/16	
cathode carbon	kg				6/7	
steel (for cathodes)	kg				3/4	
sodium carbonate	kg				1	
liquid aluminum from electrolysis	kg					1001/751
aluminium ingot	kg					142
aluminum scrap	kg					4/102
fresh water	m ³	0.50	4	6	17	5/8
sea water	m ³	0.66			28/49	
Fuels and electricity						
diesel oil	MJ	(0.28 kg)				
heavy fuel oil	MJ	(0.1706 kg)	(5822)	(536)		983/186
natural gas	MJ		(4299)	(2225)		1349
propane	MJ					28
steam	MJ		249			
electricity	kWh	0.92	181	108	14196/14880	61/98
OUTPUTS						
air emissions	kg					
particulates	kg	0.17	0.14	0.25	0.84	0.04
CO ₂	kg	(2)	(834)	(199)	1516/1574	113
NO _x (as NO ₂)	kg	(0.00001)	(1)	0.45	0.44	0.21
SO ₂	kg		(3)	0.77	12/7.4	0.15
mercury	g		0.06			
gaseous fluoride	kg			0.01	0.34	
particulate fluoride	kg			0.02	0.41/0.18	
CO	kg				72	
Total PAH	kg			0.06	0.60/0.01	
BaP	g			0.06	4.7E-03	
CF ₄ (tetrafluoromethane)	kg				/2.6E-02	
C ₂ F ₆ (hexafluoroethane)	kg				0.01/0.04	
HCl	kg				1.1E-03	
					4.0E-03	0.02
Water emissions - wastewater						
sum of water	m ³	0.71	3	3	64	9
oil/grease	kg		0.10			
suspended solids	kg		0.23	0.14		0.34
mercury	g		1.3E-04			
PAH	g			0.96		
fluoride	kg				0.02/0.35	

(continued)

cyanide	kg			1.0E-04/ 1.0E-04
Solid waste for landfilling				
mine solid waste	kg	0.06	675	
other solid waste	kg		48	4
carbon waste	kg			10
scrubber sludges	kg			0.60
Solid waste for ext recycling	kg			
anode residue	kg			0.09
spent pot lining	kg			6/9
dross	kg			18
filter dust	kg			1
scrap (sold commercially)	kg			3
Transport				
sea transport	km	3202/5919	9629/200	21729
road transport	km	4	5	5
rail transport	km	56	50	372
barge transport	km		200	

4.4.2.2 Data quality assessment

Data quality requirements

It is important that data quality is in accordance with the requirements of the study's goal and scope. This is essential to the reliability of the study and achievement of the intended application. The quality of the LCI data for modelling the life cycle stages at Norðurál have been assessed according to ISO 14044 (ISO, 2006b) and the data quality requirements set in the scope of the LCA study in chapter 5.1.3.4.

Table 6 Data quality assessment for Norðurál

Temporal representativeness	Primary data from Norðurál is related to the same reference year, 2012, with the exception of cathode carbon, the data for which are from 2011 since 2012 data was not available. This is the most recent data available. Secondary data from GaBi databases varies in age, ranging from year 1998 to 2015.
Geographical representativeness	Secondary data from the EAA are not geographically specific, but rather European averages calculated from EAA survey data. The geographical scope of EAA LCI includes EU27 and EFTA countries (Norway, Switzerland and Iceland). The data for the inputs and outputs of electrolysis at Norðurál are very representative of the facility's production process in Iceland. However, the processes for auxiliary inputs in GaBi are representative of European and country averages since the GaBi Education database is quite limited.
Technological representativeness	The production processes from GaBi are representative of average European production processes and elementary flows.
Completeness	Every effort was made to ensure that the models for Norðurál and the EAA accurately represented the production processes and associated environmental burdens. A rather conservative approach with respect to emissions to air and waste treatment was selected. The total percentage of

	flows excluded due to cutoff criteria was 0.64% for mass and 0.0225% for energy (see Tables 3 and 4 for details).
Consistency/reliability	With regard to EAA data, critical reviewer Klöpffer asserts that the user can be sure that the dataset is the best possible for aluminium in Europe (European Aluminium Association, 2013). As for Norðurál's data, a large part of which comes from the company's official Green Accounting Report it is legally obligated to publish. One may infer that the data are accurate and reliable.

Care has been taken to include all emissions, from combustion as well as auxiliary production processes. Combustion of fuels was modelled separately in some cases, taking a more conservative approach and in order to ensure that emissions were not double counted in processes and combustion.

4.4.3 Life cycle impact assessment

The aim of this phase is to evaluate the amount and significance of potential environmental impacts, arising from the set of results of the previous phase of inventory analysis (ISO, 2006a). The elements of this phase are: selection of impact categories, classification, characterization and normalization (optional).

4.4.3.1 Selection of impact categories

The selection of impact categories depends on the environmental effects and issues of the assessed product system and should be justified and reflect the goal and scope of the LCA. In order to facilitate collection, assignment and characterization modelling of LCI results, necessary components of life cycle inventory analysis (LCIA), for each category, are (ISO, 2006b):

- identification of category endpoints
- for category endpoints, the definition of category indicator
- identification of appropriate LCI result for each impact category
- identification of characterization model and characterization factors

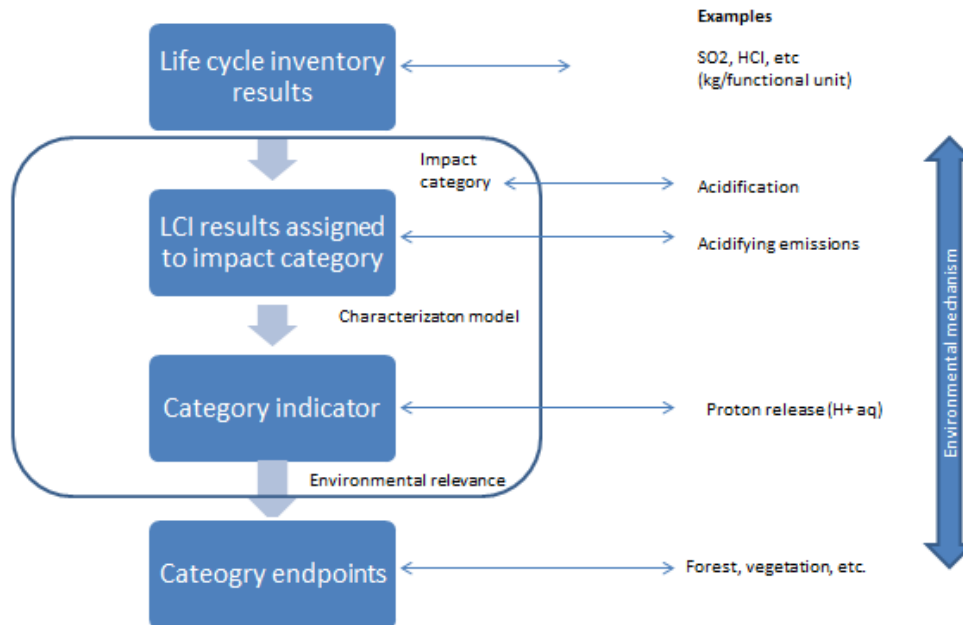


Figure 7 Characterization models and category indicators (Figure adapted from (ISO, 2006b))

Figure 7 depicts the approach of selecting category indicators where characterization models reflect the environmental mechanism. They describe the relationship between the LCI results, category indicators and, in some cases, category endpoint(s).

4.4.3.2 Classification

A list of relevant impact categories and category indicators is defined and associated with the inventory data; this is termed classification. Various environmental impacts and emissions are associated with each stage of aluminium production, from ore extraction to casting.

Acidification potential (AP) relates to the release of acidic gases or acidic emissions, which have the potential to react with moisture in air, soil or water. Acid depositions can alter the pH of natural ecosystems and the man-made environment. Main acidifying agents are SO₂, NO_x and ammonia, their main sources being agriculture and fossil fuel combustion. Acidification potential is based on the contributions of SO₂, NO_x, HCl, NH₃, HF and their potential to form H⁺ ions; it is expressed in kg SO₂ equivalents and its scale can be local and regional.

Abiotic resource depletion potential (ADP) estimates the consumption of abiotic resources, such as extraction of metals, scarce minerals and fossil fuels. An abiotic depletion factor is determined based on the remaining global resource reserves and their rates of extraction. The results are expressed in kg antimony (Sb) equivalents for mineral resources, and in megajoules (MJ) for fossil fuel resources.

Eutrophication potential (EP) is a reflection of the amount of nutrients leached to the aquatic, air and soil environment. Nitrates and phosphates are essential for life but increased

concentrations of nutrients in the aquatic environment can cause excessive growth of algae, reducing the oxygen levels within or being translated to water bodies and damaging ecosystems on a local scale. Overfertilization of soil is related to increased growth of biomass and results in a change in species composition within the soil habitat. The results are expressed in kg phosphate (PO_4^{3-}) equivalents.

Global warming potential (GWP) is the sum of the emissions of CO_2 and other greenhouse gases (N_2O , CH_4 and VOCs) into the atmosphere. Predicting the cumulative effects of these gases on the global climate, the GWP is expressed in kg CO_2 equivalents and span a time horizon of 100 years.

Ozone depletion potential (ODP) indicates the potential of emissions of chlorofluorohydrocarbons (CFCs) and chlorinated hydrocarbons (HCs) for depleting the ozone layer. The release of these substances contributes to the depletion of the stratospheric ozone layer and increased ultraviolet radiation to the earth's surface. The ODP is expressed in kg CFC-11 (or R11) equivalents and its potential effects are felt globally.

Photochemical ozone creation potential (POCP) is an indicator of the ability of VOCs to contribute to photochemical ozone formation for a local effect. Ground level ozone, which effects flora and fauna, is produced by photochemical oxidation, a reaction between NO_x and VOCs exposed to UV radiation. It is expressed in kg ethylene (C_2H_4) equivalents.

Primary energy demand from renewable and non-renewable resources refers to energy resources directly drawn from the hydrosphere, atmosphere, geosphere or energy source without any conversion or transformation process, including renewable and non-renewable resources. Renewable energy includes solar power, wind power, hydroelectricity, biomass and biofuels while non-renewable energy consists of finite resources such as coal, crude oil, natural gas and uranium. Primary energy demand is expressed in megajoules (MJ).

4.4.3.3 Characterization

Characterization involves the quantification of indicator results and conversion of inventory data to common reference units using characterization factors.

Once LCI results have been assigned to impact categories, characterization factors are applied to the relevant quantities, converting the results to reference units (see Equation (6)). For example, for the impact category Global Warming Potential, the LCI results would give an amount of a greenhouse gas per functional unit. Relative to its contribution to its contribution to the category, each greenhouse gas has an assigned global warming potential (GWP_{100}) characterization factor, which converts the LCI results to the reference unit, kilograms of CO_2 equivalents per functional unit (ISO, 2006b).

The impact of each category is calculated as

$$\text{Impact} = \sum_i E_i * CF_i \quad (6)$$

Where

- i is the substance contributing to the calculated impact category
- E_i is the emission of substance i [kg/functional unit]
- CF_i is the characterization factor of substance i

Methane's characterization factor, for example, is 25, indicating that the gas contributes 25 times more than CO_2 to global warming potential within a 100 year timeframe (PE International, 2010). Converted results for each impact category are aggregated and the outcome is a numerical category indicator result.

4.4.3.4 Normalization and weighting

Normalization refers to the calculation of the magnitude of the results from the characterization step relative a common reference value or information. The indicator result is transformed by dividing it by a reference value providing a result, for example, for a given geographical area or on a per capita basis, like the average environmental impact of an American citizen in a year. This is done in order to better understand the magnitude and significance of each indicator result (ISO, 2006b).

Weighting attaches a value to each of the normalized indicator results producing a value based on the importance, or weight, of each impact. Weighting steps are based on value-choices; since individuals and societies have difference preferences, it is possible that different parties would produce different weighting results based on the same indicator results (ISO, 2006b). The normalized and weighted LCIA results can subsequently be summed up across all impact categories (Guinée, et al., 2002).

Both normalization and weighting are optional steps in LCIA according to ISO14044: 2006.

5. Life cycle interpretation

In the final phase of LCA the findings from inventory analysis and impact assessment are evaluated and checked for conformity with the goal and scope definition. Significant issues are identified and results are evaluated with respect to completeness, sensitivity and consistency (ISO, 2006b). The interpretation phase draws overall conclusions, explains limitations and provides recommendations and mitigation measures for the intended audience, consistent with the goal and scope of the study (ISO, 2006a).

5.1 Results and discussion

GaBi Education software version 6.0 was used to perform a numerical analysis of the cradle-to-gate life cycle of aluminium, for two separate models: one based on average data (EAA & IAI), the other based on Norðurál data for electrolysis and casting (i.e. the foreground system) and EAA data for bauxite mining, alumina refining and anode production (i.e. the background system). Both models in GaBi (Figure 8) cover all five life cycle stages from cradle-to-gate's primary aluminium:

1. Bauxite mining
2. Alumina refining
3. Anode production
4. Electrolysis and,
5. Casting.

In addition, the transport of bauxite, alumina and carbon anodes were included when relevant.

The impact categories covered in Section 4.4 according to the goal and scope of the study, have each been addressed.

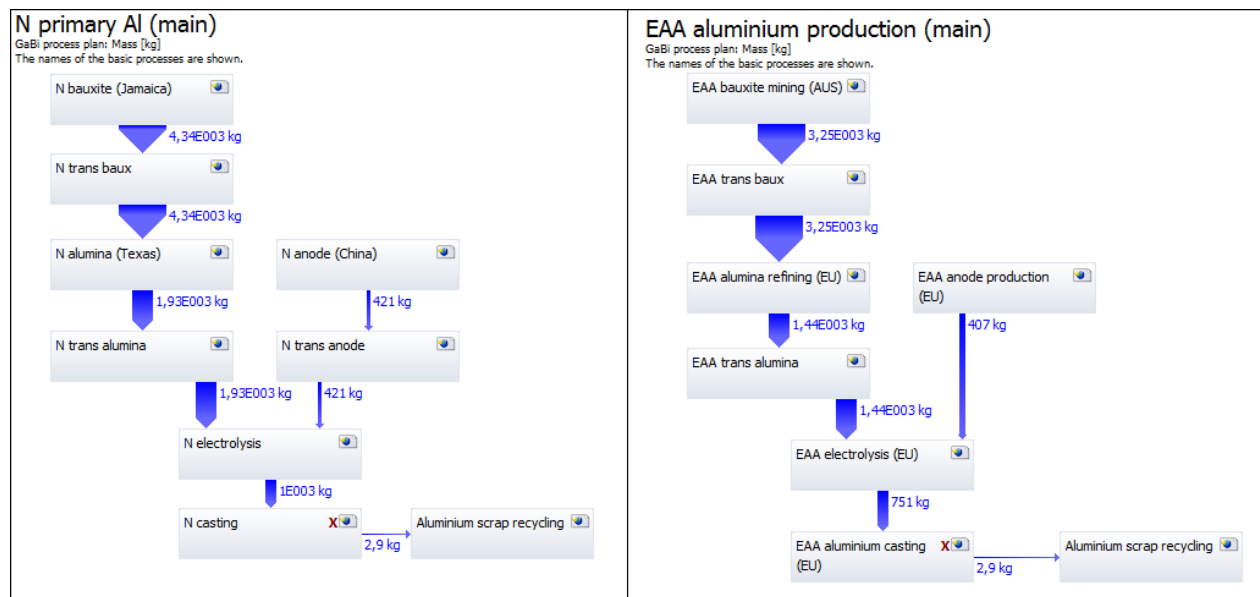


Figure 8 Norðurál and EAA models in GaBi

The results for each impact category are presented in Table 7. They are given in their respective units per tonne cast aluminium, both for the Norðurál model and the EAA model for comparison. The ratio for Norðurál and EAA results in red indicates the instances in which Norðurál aluminium has a greater potential environmental impact than EAA aluminium.

Table 7 Results of impact assessment for Norðurál and EAA models

	GWP kg CO ₂ eq	AP kg SO ₂ eq	EP kg PO ₄ ³⁻ eq	ODP kg R11 eq	POCP kg C ₂ H ₄ eq	ADPf MJ	ADPe kg Sb eq	PED MJ
Norðurál	5560	80	5.36	3.25E-05	4.98	56731	4.08E-03	166060
EAA	9503	47	7.99	4.01E-04	3.15	105416	2.02E-03	154011
Norðurál/EAA ratio	0.59	1.72	0.67	0.08	1.58	0.54	2.02	1.08

Captions: GWP = Global Warming Potential, AP = Acidification Potential, EP = Eutrophication Potential, ODP = Ozone layer Depletion Potential, POCP = Photochemical Ozone Creation Potential, ADPf = Abiotic Depletion Potential of fossil fuels, ADPe = Abiotic Depletion Potential of elements, PED = Primary Energy Demand (renewable & non-renewable)

5.1.1 Global warming potential (GWP)

For the Norðurál production process from cradle-to-gate, the total GWP is 5560 kg CO₂ equivalents (eq) per tonne of aluminium ingot cast at Norðurál, as defined by the system boundaries of the scope of the study. The relative contributions of production stages for the Norðurál model are presented in blue the chart of Figure 9. Alumina refining contributes almost half, or 45.2% and electrolysis 33.8%; these stages constitute the environmental hot spots for GWP at Norðurál. For alumina refining, this is due to the thermal energy supply from heavy fuel oil (1170 kg CO₂ eq) and from natural gas (631 kg CO₂ eq). The Norðurál electrolysis process contributes with 1610 kg CO₂ eq, while the Icelandic electricity grid mix of 70% hydropower and 30% geothermal energy only accounts for 253 kg CO₂ eq per tonne cast aluminium. Anode production accounts for 6%, specifically the thermal energy supply from heavy fuel oil and natural gas, and the heavy fuel oil consumption of the stage for transport of alumina contributes 4.8% to the total GWP for Norðurál.

Note the negative numbers in Figure 9 for the process of aluminium scrap recycling, which represent an environmental credit. For Norðurál and EAA production of one metric tonne of primary aluminium, the recycling of aluminium scrap from casting, which was modelled with system expansion (see Subsection 4.4.2.), represents a potential reduction of 23.5 kg CO₂ eq emissions. Hence, environmental credits appear as negative values since they must be subtracted from the overall environmental burden.

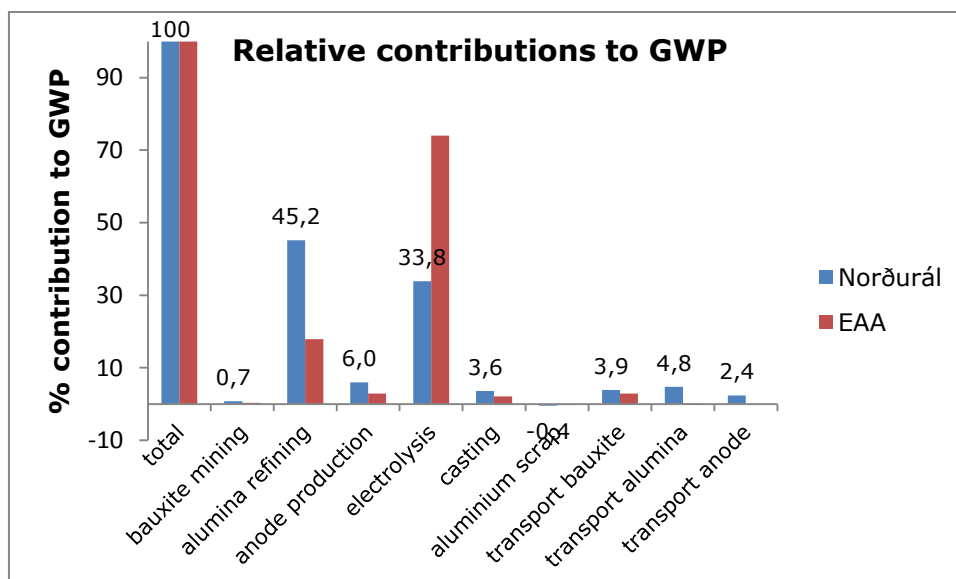


Figure 9 Relative contributions to GWP (100 years) of production stages of Norðurál and EAA cradle-to-gate models

The production of one tonne cast aluminium according to the EAA model, on the other hand, has a GWP of 9503 kg CO₂ eq, more than 1.7 times the GWP for the production of the same amount produced at Norðurál. Electrolysis is the major contributor, the environmental hot spot for GWP according at EAA, with 74% of the total GWP (EAA is represented by red bars in Figure 9), for which the EU-27 electricity grid mix is mostly responsible, causing emissions of 5172 kg CO₂ eq from CO₂ alone and the total greenhouse gases reaching 5972 kg CO₂ eq. Alumina refining accounts for 17.9% of the total GWP of EAA production, where thermal energy from heavy fuel oil contributes 778 kg CO₂ eq and thermal energy from natural gas contributes 449 kg CO₂ eq. The smallest contributor of 0.1% to the EAA model is represented by the transport of alumina.

The EU-27 electricity grid mix, as modelled in the GaBi database (PE International, 2013), represents the average for the region where nuclear takes a 28% share, lignite coal represents 11%, hard coal 16% and natural gas 23%. This applies to the generation of electricity in the EU-27 countries and, for the purposes of this study, an average European aluminium smelter. Bearing this in mind, and examining the red bars in the chart in Figure 9, these are consistent with the expectation that the GWP is greater for production processes consuming more fossil fuels than one based on renewable energy.

5.1.2 Acidification potential (AP)

The total AP per tonne aluminium produced at Norðurál model is 80 kg SO₂ equivalents while the EAA has an AP of 47 kg SO₂ eq. Electrolysis is the greatest contributor to AP at Norðurál, with 47.2 kg SO₂ eq (58.9%) of the total (blue bars of Figure 10). It is Iceland's electricity grid mix of hydro and geothermal power which is the environmental hot spot for acidification. The emissions of hydrogen sulphide (H₂S) from geothermal energy generation present a possible reason for the large difference in AP between Norðurál primary aluminium and EAA. H₂S emissions due to Iceland's electricity grid mix, accounts for 31.9 kg SO₂ eq of the total according to the results of the assessment.

An AP of 11.1 kg SO₂ eq results from alumina refining, more specifically from thermal energy supply from heavy fuel oil, and the transport of alumina contributes 10% of the total AP for one metric tonne of Norðurál cast aluminium ingots, equivalent to 8.04 kg SO₂ eq, owing to the combustion of heavy fuel oil. The transport of bauxite from Jamaica to Texas has a share of 7.6% and, as is the case for the transport of alumina, it is mostly the combustion of heavy fuel oil which produces the contribution to AP.

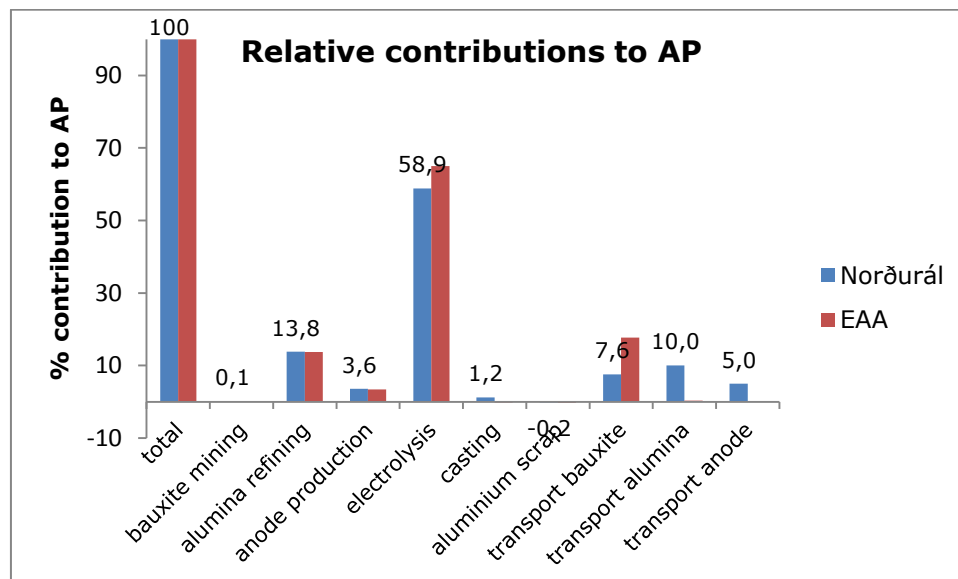


Figure 10 Relative contributions to AP of production stages of Norðurál and EAA cradle-to-gate models

For the one metric tonne of EAA cast aluminium ingots, the total AP is 46.7 kg SO₂ eq (Table 7), 70% less than the Norðurál product system. Electrolysis is, as well, the hot spot with 65% of the total (red bars in Figure 10), 60% of which are associated with the EU-27 electricity grid mix, and emitted as SO₂. Again it is evident that the combustion of heavy fuel oil is a large contributor to this impact category. For EAA cast aluminium ingots, it responsible for close to all of the contribution of transport of bauxite (17.7%) and 80% of the contribution of alumina refining (13.8%) to the total. The production stage that is the smallest contributor to both models is bauxite mining, accounting for 0.13% for Norðurál and 0.18% for EAA.

Aluminium scrap recycling contributes an environmental credit of -0.129 kg SO₂ eq to AP at Norðurál. For primary aluminium production at EAA, two output materials from casting are recycled, namely dross and aluminium scrap and both create an environmental credit for AP: -0,097 kg SO₂ eq and -0.129 kg SO₂ eq respectively.

The large difference in AP between the product systems at Norðurál and EAA may reasonably be attributed to definitions and assumptions for geothermal energy in the GaBi database which assume a greater potential acidification effect than is the case. This presents an interesting challenge to further explore the accuracy of assumptions for geothermal energy in LCA. In fact, currently, research on H₂S is ongoing at the University of Iceland (Ólafsdóttir, 2014) with the objective to map the distribution of H₂S once it is emitted and determine which environmental factors affect its fate and distribution. The issue is further addressed in Section 5.2 Discussion.

5.1.3 Eutrophication potential (EP)

The total EP of primary aluminium produced by Norðurál is 5.36 kg PO₄³⁻ eq (Table 7). It is emissions of NO_x to air that account for almost half. These emissions are split between the processes which consume the greatest amount of heavy fuel oil and natural gas: the transport of alumina (15.2%, 0.811 kg PO₄³⁻ eq), transport of bauxite (11.6%, 0.623 kg PO₄³⁻ eq), anode production (13.1%, 0.703 kg PO₄³⁻ eq) and the transport of anodes (7.6%, 0.396 kg PO₄³⁻ eq).

Alumina refining is, however, the environmental hot spot for EP, contributing to 2.14 kg PO₄³⁻ eq (39.9%), as presented in blue bars in Figure 11. Almost half of alumina refining's contribution is due to a wastewater treatment process, 0.97 kg PO₄³⁻ eq, specifically emissions of nitrogen and phosphorus to fresh water. Emissions of ammonia to soil associated with the landfilling and treatment of the large amount of bauxite residue add up to 0.5 kg PO₄³⁻ eq. Finally, 0.367 kg PO₄³⁻ eq are related to the thermal energy supply of heavy fuel oil for alumina refining.

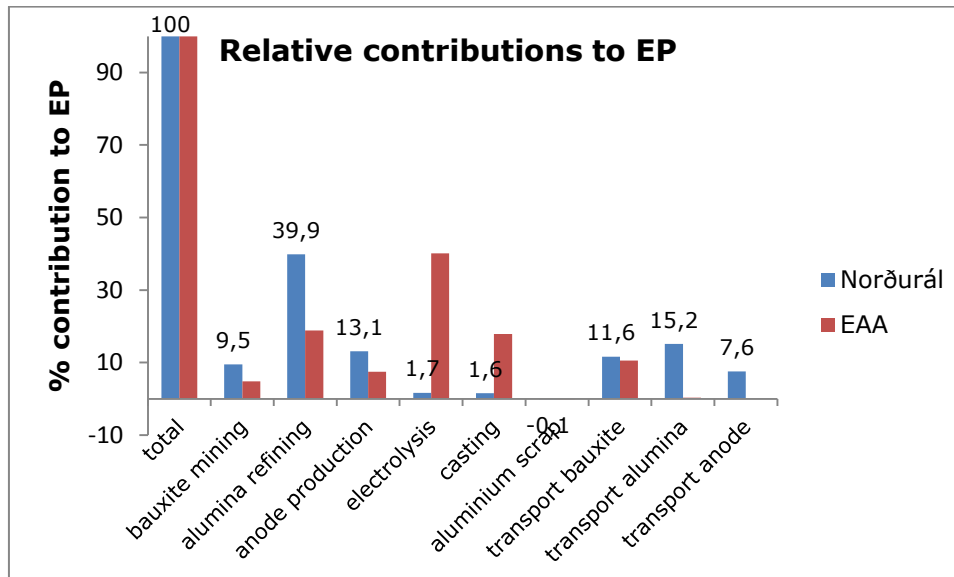


Figure 11 Relative contributions to EP of production stages of Norðurál and EAA cradle-to-gate models

Average primary aluminium in Europe, according to EAA, presents a total EP of 7.99 kg PO₄³⁻ eq. Electrolysis is the environmental hot spot (3.22 kg PO₄³⁻ eq), specifically nitrogen and nitrate emissions from waste water treatment. Anode production contributes 7.5%, two thirds of which is related to the production of coal tar pitch and heavy fuel oil combustion is responsible for the contribution of the transport of EAA bauxite, from Australia to Europe.

It is important to note that alumina refining and casting for the average European smelter provide similar contributions to EP, 1.51 and 1.43 kg PO₄³⁻ eq respectively. While the EP of alumina refining (18.9%) is due to the generation of bauxite residue, its treatment and that of wastewater, the EP for casting is almost entirely caused by the treatment of wastewater and the production of phosphoric acid which is used as part of the casting process, which contributes 17.9% to EP. As observed in the assumptions listed in chapter 4.4.2.1, an average chemical reduction/oxidation process for treating waste water for all production stages was included in both product systems.

The transport of alumina for the average European primary aluminium production according to the EAA, has a very small EP, amounting to 0.3% of the total EP. This is due the small transportation distance within the EU relative to transport of other materials.

Comparing the results for EP for the two products, one metric tonne of Norðurál cast aluminium ingots and the same amount of EAA cast aluminium ingots, it is evident that, despite the different contributions to EP of the life cycle stages, two types of processes dominate the impact category, the supply of fossil fuels and wastewater treatment.

An environmental credit for aluminium scrap recycling at Norðurál and EAA amounts to a negative relative contribution, -0.1%, representing -0.00569 kg PO₄³⁻ eq per tonne primary aluminium produced.

5.1.4 Ozone depletion potential (ODP)

The total ODP of aluminium production by Norðurál is 3.25E-05 kg R11 eq (Table 7). As Figure 12 demonstrates, alumina refining and anode production make up the greatest contributions, with 35.7% and 46.9% respectively. Electricity generation and supply in Texas and wastewater treatment are the causes of ozone depletion due to alumina refining. The ODP of the wastewater treatment process is created by the production of iron chloride, a chemical constituent for treating wastewater. The production of coal tar pitch is responsible for 96% of the ODP of anode production, more specifically, R22, chlorodifluoromethane which is produced during the production of coal tar pitch at a coke plant. The 12% contribution of electrolysis to ODP is on account of the production of aluminum fluoride and cathode carbon while for bauxite mining (5.8%), wastewater treatment accounts for more than half the ODP. Casting accounts for 0.5% of the total ODP, the transport of alumina 0.3%, transport of anodes 0.002% and the transport of bauxite contributes 0.5%.

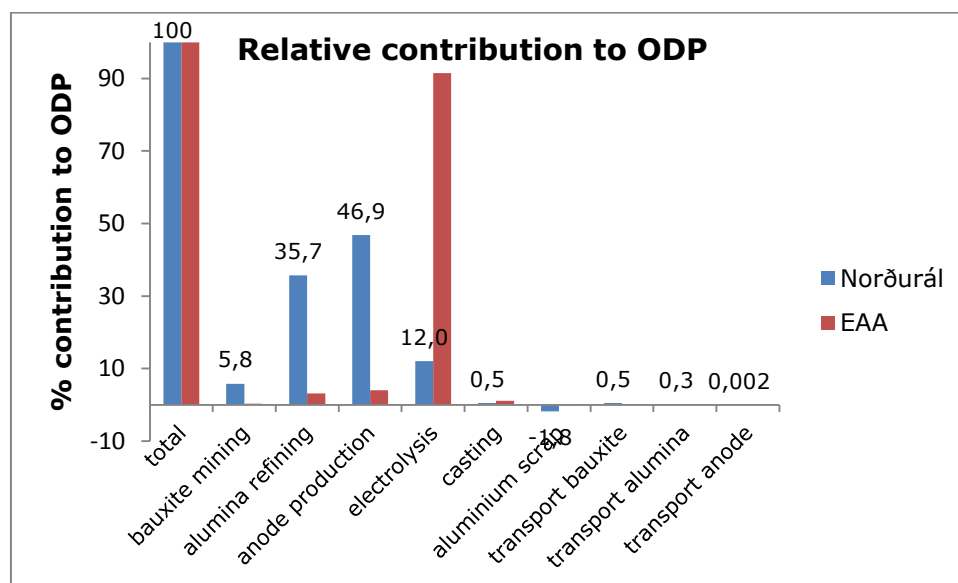


Figure 12 Relative contributions to ODP of production stages of Norðurál and EAA cradle-to-gate models

The total ODP for the average production of aluminium according to EAA is $4.0\text{E-}4$ kg R11 eq, an order of magnitude larger than at Norðurál. For the European average primary aluminium, electrolysis accounts for 91.5% of the emissions contributing to ODP, specifically the emission to air of R114 (dichlorotetrafluoroethane) from the EU-27 electricity generation. Anode production in the EU provides 4.1% to EAA ODP, due to the production of coal tar pitch. As the right side of Figure 12 demonstrates, since electrolysis dominates in the contribution to ODP for the EAA model, many of the other production stages are proportionally very small; transport of alumina provides 0.001%, transport of bauxite 0.0002% and bauxite mining 0.3%. Both models incur environmental credits due to aluminium scrap recycling.

Comparing the two product systems of Norðurál and EAA, the difference in ODP is only 8%. However, the ODP is created by production processes of auxiliary materials, not any specific life cycles stages of the product systems being studied.

5.1.5 Photochemical ozone creation potential (POCP)

The total POCP for primary aluminium production by Norðurál is $4.98 \text{ kg C}_2\text{H}_4 \text{ eq}$, of which electrolysis contributes about half (51.1%). The emissions constituents from the electrolysis stage at Norðurál contributing the most to POCP are CO and SO₂ from the electrolytic process itself. The other production stages contribute to POCP to a lesser extent; emissions from alumina refining (14.4%, $0.717 \text{ kg C}_2\text{H}_4 \text{ eq}$) are associated with the provision of thermal energy from heavy fuel oil, from anode production (11.9%, $0.592 \text{ kg C}_2\text{H}_4 \text{ eq}$) due to petrol coke and coal tar pitch production and, finally, emissions from the transport of alumina are related to the supply of heavy fuel oil (9.5%, $0.475 \text{ kg C}_2\text{H}_4 \text{ eq}$). The share of transport of bauxite from Jamaica to Texas is 7.3% and anode transport from China to Grundartange accounts for 4.7% of POCP for Norðurál primary aluminium.

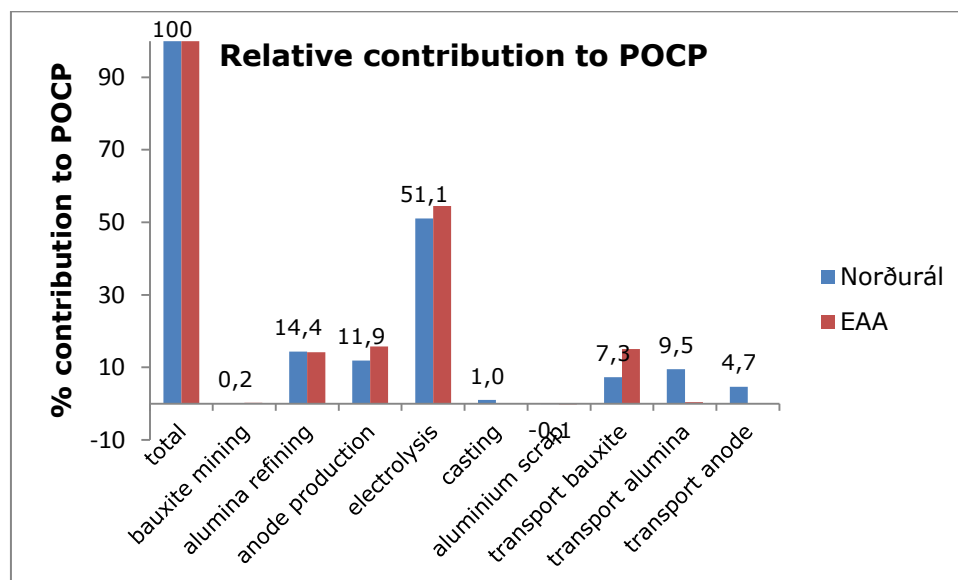


Figure 13 Relative contributions to POCP of production stages of Norðurál and EAA cradle-to-gate models

The POCP from average European primary aluminium according to EAA is different from that of Norðurál as Figure 13 shows. The total is 3.15 kg C₂H₄ eq, half of which is related to electrolysis while the rest is quite evenly distributed among three production stages: alumina refining, anode production and the transport of bauxite. The emissions contributing to POCP are associated with the supply of fossil fuels. In the case of alumina refining it is the provision of thermal energy from heavy fuel oil, for anode production it is from the emission of nonmethanous VOCs (NMVOCs) during the production of coal tar pitch and for the transport of bauxite POCP is due to NO_x and SO₂ emissions from the combustion of heavy fuel oil. The relative contribution of bauxite mining is the same for both primary aluminium product systems, accounting for 0.2%.

The difference in POCP between the two models can be explained by two important differences in emissions. First of all, emissions of CO are included in the LCI of Norðurál (71.7 kg per tonne cast Al) but CO listed in the EAA data inventory for electrolysis. Secondly, the SO₂ emitted per tonne cast at Norðurál is more than twice that of the average European model (12.13 kg versus 5.55 kg respectively). This could be due to a higher sulphur content in the carbon anodes used at Norðurál. SO₂ emissions due the EAA electrolysis account for almost half of the POCP, 1.42 kg C₂H₄ eq, to a great extent a result of the EU-27 electricity grid mix.

As seen previously, the recycling of aluminum scrap incurs an environmental credit, which is shown as a negative number in Figure 13.

5.1.6 Abiotic resource depletion potential (ADP)

5.1.6.1 ADP fossil fuels (ADP_f)

The total ADP for fossil fuels (ADP_f) from primary aluminium produced at Norðurál is 56731 MJ. The thermal energy supply to alumina refining accounts for nearly 56% of the total and is the environmental hot spot for this impact category. The transport stages of the Norðurál product system, requiring the combustion of fossil fuels, each contribute 4.6% (bauxite transport), 5.7% (alumina transport) and 3.1% (anode transport). Observing Figure 14 and Table 7, the differences in ADP_f for the Norðurál and EAA product systems are evident. Since the Icelandic electricity mix supplying the electrolysis process is 24.4% geothermal and 75.6% hydro (PE International, 2013), the process contributes only 1% to the model's overall consumption of fossil fuels. Alumina refining in Texas makes up approximately 56% and anode production in China accounts for 26% of ADP_f. Thus the production of aluminium in Iceland incurs less consumption of abiotic resources, namely fossil fuels than does EAA primary aluminium production

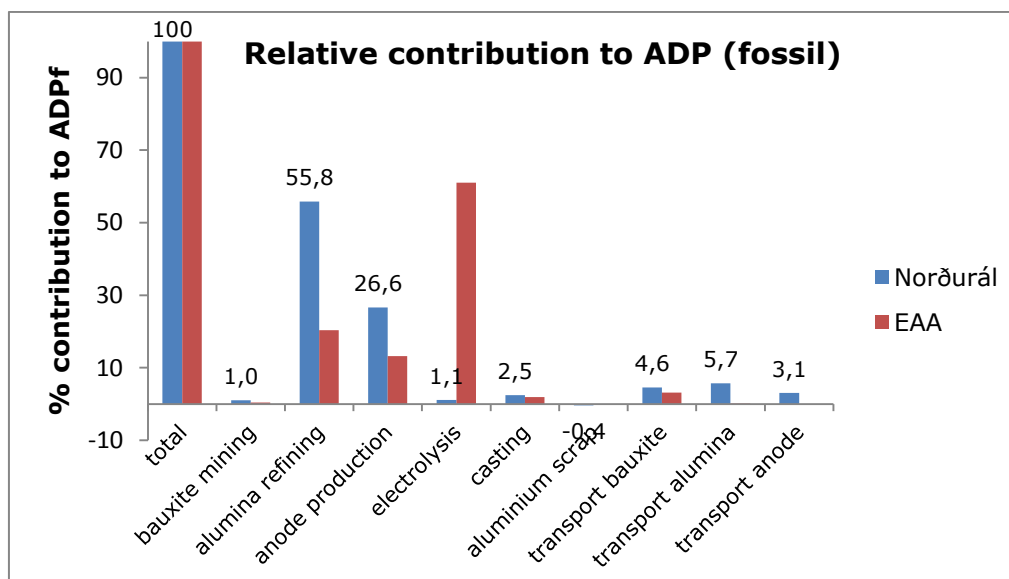


Figure 14 Relative contributions to ADP (fossil fuels) of production stages of Norðurál and EAA cradle-to-gate models

With regard to the average European primary aluminium according to EAA, the depletion of fossil fuels as abiotic resources is over 105000 MJ (see Table 7), and three times that of Norðurál. Very nearly 61% is contributed by the electrolysis stage, most of which is due to electricity generation to supply this process, with alumina refining and anode production accounting for just over 20% and 13% respectively. The smallest contributors to this category of environmental impacts are, as seen previously, bauxite mining, with 0.41% and the transport of alumina with 0.1% of ADPf.

A negative potential for ADPf due to aluminum scrap recycling for both Norðurál and EAA primary aluminium offsets the need to produce primary aluminum and thereby consume fossil fuel resources by a small amount, here -0.4% of ADPf for Norðurál and -0.2% for EAA:

5.1.6.1 ADP elements (ADPe)

For this impact category, the depletion of NaCl (rock salt) is the greatest contributor to the abiotic depletion potential of elements (ADPe) of both product systems, Norðurál and EAA. Caustic soda, which is an input for alumina refining, is produced through the electrolysis of rock salt, where 0.979 kg NaCl is required per kg caustic soda (British Geological Survey, 2006). Consumption of other elements contributing to ADPe is that of copper, chromium and lead used in electricity grid mixes and electronics.

The ADPe for the primary aluminium produced at Norðurál, the total is 0.004079 kg Sb eq where alumina refining and electrolysis contribute 51.34% and 45.15% respectively. Just over half is due to the depletion of rock salt as a resource – the use of caustic soda for alumina refining. The other half is due to the electricity grid mix of Iceland supplying electrolysis. Metals chromium (Cr) 18,6%, copper (Cu) 19,4% represent the resources most depleted due to electrolysis in Iceland, used in electrical systems and cables.

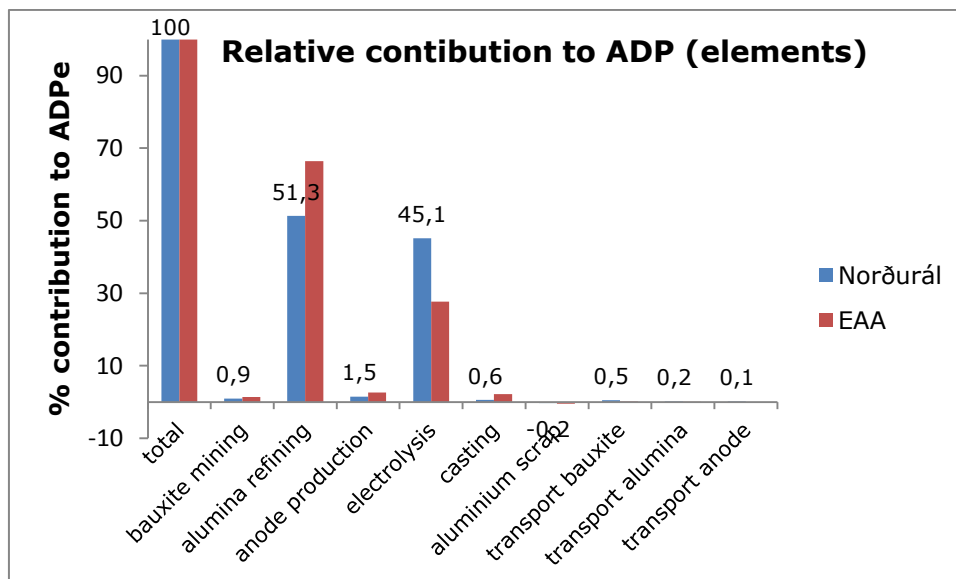


Figure 15 Relative contributions to ADP (elements) of production stages of Norðurál and EAA cradle-to-gate

The total ADP elements for the average European primary aluminium according to EAA is 0.002021 kg Sb eq, about half of the amount of aluminium production by Norðurál. Alumina refining accounts for over 66% due to the production of caustic soda and it is the resource of rock salt which is being depleted. Three quarters of the rest of ADPe is contributed by electrolysis, specifically the consumption of copper, 11.3%, gold, 9.9%, chromium, 6.6% and lead 4.9% for electronics.

As seen previously for ODP, the transport stages of the models are small contributors. For the European primary aluminium produced by the EAA, transport of alumina is 0.02% and the transport of bauxite is 0.2% and with regard to the Norðurál model, transport of alumina accounts for 0.2% of ADPe and the transport of anodes has a share of 0.1%.

The ADPe for Norðurál primary aluminium is twice that of the average European primary aluminium. This is due to the larger consumption of non-renewable elements such as copper, chromium, the EAA production process uses nearly four time less than does the Norðurál process. Electrolysis is a smaller contributor to the total ADPe for the EAA process in proportion to the contribution of electrolysis to Norðurál primary aluminium, with 27.7% and 45.1% respectively.

Aluminium scrap recycling offsets the ADPe by a small amount. This is reflected in the negative contribution to ADPe, -0.2% for Norðurál primary aluminium and -0.5% for EAA.

5.1.7 Primary energy demand of renewable and non-renewable resources (PED)

The total primary energy demand (PED), expressed in terms of the net calorific value, by Norðurál is 166059 MJ per tonne aluminium produced. As expected for PED, the most energy intensive production processes of this cradle-to-gate model, electrolysis and alumina refining,

account for 64.8% and 20.1% of the total PED respectively, while bauxite mining requires the least energy, 0.4% of the total PED. The geothermal and hydropower supply for electrolysis represent the renewable energy resources part of PED for Norðurál. The consumption of non-renewable energy resources is to a large extent made up of crude oil resources, 18.7% of PED (alumina refining and anode production) and natural gas resources, 11.4% of PED (80% due to alumina refining).

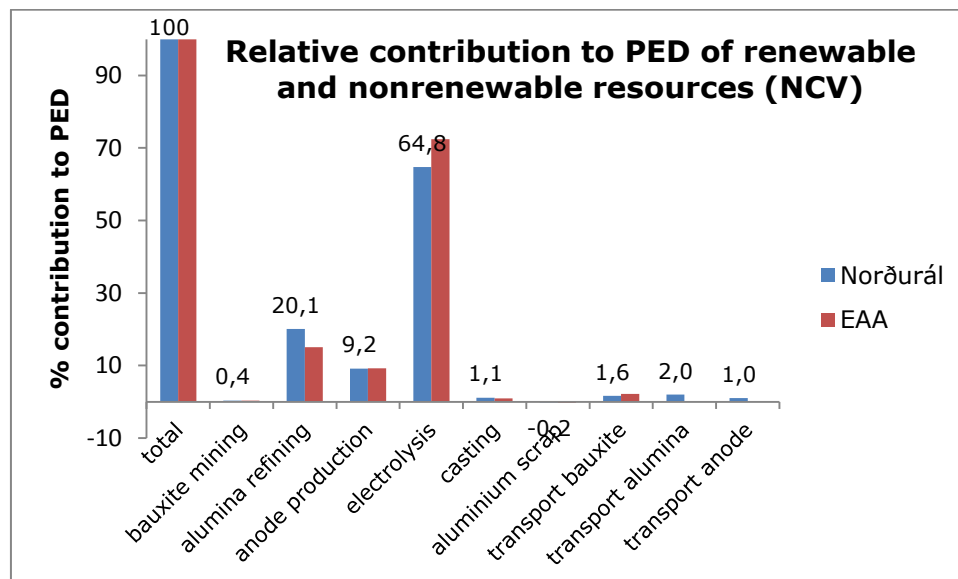


Figure 16 Relative contributions to PED of production stages of Norðurál and EAA cradle-to-gate

Electrolysis dominates for the average European smelter, as it does for the Norðurál model. The total PED is as seen in Table 7), where energy from non-renewable resources for energy generation for electrolysis accounts for just over 97500 MJ, 63.3% of PED. The renewable resources which are part of the EU-27 electricity grid mix account for 9.1%; these are hydropower (4.01%), wind power (2.49%) and solar energy (2.33%). Alumina refining ranks second in contribution to total PED for EAA primary aluminium, with 15.1%, and anode production has a PED of 9.3%. The least energy intensive processes of the EAA model are casting, accounting for 0.9% PED, and the transport of alumina is 0.1% of the total.

Observing the total PED for all the life cycle stages of EAA primary aluminium, the consumption of natural gas accounts for 26.6%, uranium is 22.5% (as part of the EU-27 grid mix), the share of crude oil is 17.1% and hard coal consumption is 15.8% of the total PED.

The difference of roughly 12000 MJ is mainly attributable to the larger energy consumption for alumina refining by Norðurál. This is due to the greater proportion of molten aluminium required as an input for casting (European Aluminium Association, 2013), hence a larger portion of alumina required per tonne aluminium relative to the EAA. Moreover, although transport stages do not account for a large proportion of environmental burden as Figures 9 to 16 have demonstrated, they do amount to close to 5% of the total PED for Norðurál and this contributes to the difference between models. Furthermore, the transport for EAA intermediate products has been on a smaller scale than for Norðurál.

5.2 Discussion

As primary aluminum production is an energy intensive process, the resources used for electricity generation and energy are significant contributors to the various environmental impact categories of this cradle-to-gate product system. The results of this study have shown that the electricity grid mix of Iceland, made up of renewable energy resources geothermal and hydro, has a potential to contribute less than the EU-27 grid mix to some impact categories, namely GWP, EP, ODP, and ADPf but accounts for a greater share to the categories of acidification, AP, and the depletion of abiotic elemental resources, ADPe. The difference in reported emissions for the two product systems with regard to CO and SO₂, explains the difference in POCP, where primary aluminium at Norðurál is higher (4.98 kg C₂H₄ eq) than EAA (3.15 kg C₂H₄ eq). The discrepancy in results regarding primary energy demand of renewable and non-renewable energy resources (PED) for the two product systems only amounts to 8%, which can be explained by the fact that transport modelled for EAA was minimal compared to that of Norðurál, hence the smaller overall contribution of transport to PED and most other impact categories for EAA.

In review done by Liu and Müller (2012) presented a range of greenhouse gas emissions intensity of 5.92-41.10 kg CO₂ per kg output for primary aluminium ingot production limited to smelters in Europe, North America and Australia. The production of primary aluminium at Norðurál results in a GWP lower than the lowest score in Liu and Müller, a score which was estimated for a state-of-the-art smelter due to open in Greenland in 2014. Despite using electricity generated from hydro and geothermal power, Norðurál incurs significant environmental burdens. In fact, the Icelandic electricity grid mix presents an environmental hot spot when it comes to AP. However, it is important to bear in mind that the EAA LCI data is average data with coverage for alumina refining, anode production, electrolysis and casting processes reaching between 84 and 93% of the EU-27 countries and participating EFTA countries (Norway, Iceland and Switzerland). Furthermore, it is probable that the assumptions behind the GaBi process representing the Icelandic electricity grid mix do not accurately portray the emission and significance of SO₂ and H₂S, that is, that the AP for Norðurál is exaggerated.

The process in GaBi software representing the Icelandic electricity grid mix, a combination of 24.4% geothermal and 75.6% hydro (PE International, 2013) assumes an emission per kWh of 0.014 kg H₂S, 1.5E-06 kg SO₂ and 0.177 kg CO₂. This process is based on average data for reference years 2008-2013 from various literature which may not accurately reflect conditions in geothermal plants in Iceland. One Icelandic study found that the generation of electricity at Fljótsdalsstöð hydropower plant amounted to 2.6 g CO₂ eq per kWh (EFLA Verkfræðistofa, 2011). Ármannsson (2003), for example, demonstrates a range of values for CO₂ and SO₂ emissions from three Icelandic geothermal power plants, 10-152 g CO₂/kWh and 2-23 g S as SO₂/kWh for total production. Marta Rós Karlsdóttir, one of the supervisors of this study, is currently doing research on the division of H₂S into SO₂ from a particular geothermal power plant located near Reykjavík.

Contributions of the various energy carriers

Heavy fuel oil and natural gas were the main fossil fuels used in modelling energy supply for alumina refining, anode production and casting for the aluminium production process according

to both models, Norðurál and the EAA. Diesel fuel was modelled to a much lesser extent and in practice it is mainly used for on-site transport by road (EAA, 2013, IAI, 2013a).

A quarter to a half of GWP is attributable to the supply of heavy fuel oil for the background processes bauxite mining, alumina refining and anode production, which were modelled using secondary data from EAA for both models, 30% of the AP (not including the share of heavy fuel oil in the EU-27 electricity grid mix) and 30% of POCP. Natural gas, on the other hand, is responsible for less than 10% of GWP, less than 1% of AP, and 3% of POCP. The consumption of heavy fuel oil and natural gas contributes to the depletion of abiotic resources (ADPf) and primary energy demand of renewable and non-renewable resources, as the titles of the impact categories indicate.

The EU-27 grid, which is electricity provider in the case of all production stages for the EAA model aside from bauxite mining contributes to all impact categories but to a varying degree. It is a major factor in GWP, AP, ODP and POCP with 60%, just over 50%, over 90% and less than 50% respectively.

Finally, the Icelandic electricity grid mix has environmental burdens quite different from those of the supply of fossil fuels and the European grid. Recall from Table 5 that electrolysis at Norðurál requires 14196 kWh per tonne aluminium cast and 61 kWh for casting per tonne cast aluminium. While the Icelandic electricity grid mix contributes less than 1% to GWP, it does account for, in this model 40% of the total AP for the Norðurál model, as has been discussed previously. The grid mix also accounts for nearly 100% to ADPe, where the consumption of chromium and copper associated with electrolysis make up close to half of the total ADPe for the entire Norðurál model.

Effect of wastewater treatment processes on results for EP

The wastewater treatment process which was created to model the treatment of wastewater outputs is one which covers both chemical reduction and oxidation. The inputs to the process for treating waste water include hydrated lime ($\text{Ca}(\text{OH})_2$), phosphoric acid (H_3PO_4) and iron(III)chloride (FeCl_3). Recall that the recovery of metals from wastewater can be accomplished by precipitation using phosphate, and ferric chloride is commonly used for the removal of arsenic and sulfides. Lime is used as a precipitating agent for fluorides, heavy metals and phosphorus and also for raising the pH of waste (Woodard, 2001).

The wastewater treatment process created in GaBi was used for all outputs of water from all production stages in both models with the exception of the foreground system of the Norðurál model, electrolysis and casting, since information on wastewater treatment at Norðurál was limited and Iceland's regulation on water treatment differs from that of the EU.

The production stages of the background system, namely bauxite mining, alumina refining and anode production, clearly dominate in EP for the Norðurál model. For each of these the wastewater treatment process contributes, by itself, 9%, 18% and 3% of the total EP for Norðurál, for each background stage respectively. The foreground processes register with less than 2% contributions to EP. The same is true for the EAA model, where the wastewater treatment process

dominates as a contributor to EP, in correlation to the amount of water to be treated. For the EAA model, bauxite mining is 5%, alumina refining 9%, anode production 2%, electrolysis 24% and casting 18% of the total EP. Due to time constraints, it was not possible to alter the GaBi models and use other treatment process for water. However, this would prove an interesting further study.

Effects of adding energy consumption to Norðurál casting process

Thermal energy from heavy fuel oil by the amount of 982 MJ was added to the Norðurál casting process (see Subsection 4.4.2 on casting). This meant increasing the energy input by more than a degree of magnitude. The results made it evident that the process of casting accounts for between 0.5 and 3.5% of most impact categories, for the models of Norðurál and the average European aluminium smelter. Other LCA studies for primary aluminium have shown similar results (Liu & Müller, 2012). Removing the input of thermal energy from heavy fuel oil further reduces the impact of casting to 0.3-2% for all impact categories but does not eliminate the environmental effects of the process of casting altogether. Thus the decision to add the input of thermal energy to casting at Norðurál has not affected to any significant detriment the calculated results for environmental impacts associated with Norðurál casting.

6. Final remarks

Comparing the two models for primary aluminium production assessed in this study, it is difficult to give an absolute answer as to whether production at Norðurál is definitively less unfavorable to the environment than at an average European smelter. In some respects and according to the goal and scope of this life cycle assessment, Norðurál aluminium incurs less potential environmental impacts, as has been touched upon in the discussion. This is most significantly with regard to the potential for global warming which has been the focus of many LCAs of metal production. Moreover, this category presented the greatest advantage of the Icelandic electricity grid mix over that of the EU.

There are some measures Norðurál could implement in order to further improve its environmental performance. Reducing transport distances, as it has done by acquiring an anode production facility in the Netherlands, could prove beneficial with regard to various environmental effects. This has implications for all impact categories but especially though to GWP, AP, EP, POCP and ADPf. In order to reduce its potential contribution to acidification, a localized or regional impact, purchasing anodes with a lower sulphur content would lessen the relative emissions of SO₂ from electrolysis. This would also reduce the contribution to POCP.

6.1 Potential improvements and further work

It should be mentioned that, strictly speaking, the study undertaken here is not a full LCA since there is no full LCI of a product or service taking into account activities which occur after the product leaves the production facility gate. However, doing so would call for modelling all uses of aluminium products, an impossible task.

Had time not been a constraint for this study, various different approaches and analyses regarding data and data collection would have been interesting to pursue. Although all of the major constituents of material inputs were included in this study it would be advisable to put efforts into creating a more complete dataset of primary data for aluminium smelting in Iceland, modelling all relevant production processes rather than using GaBi processes. The study did not, for example, cover country-specific production process for inputs such as aluminium fluoride, cathode carbon and steel (for cathodes of electrolysis cells). Due to time constraints, limited GaBi database access and other factors, this was not possible.

Carrying out a more comprehensive and detailed cradle-to-gate LCA study would prove an interesting and important assessment serving the interests of Norðurál. A more detailed LCA would allow the company to assess more accurately and fully the environmental burdens of each input material and help determine measures to reduce them. A more extensive study of aluminium production in Iceland would also benefit other large scale, energy intensive industry in the country, which have not been introduced to LCA. This would further prove to be a valuable contribution to the field of LCA and environmental management in Iceland.

Performing an LCA using data from Norðurál's new anode production plant in the Netherlands would be a straightforward task which would bring important and relevant information to

Norðurál and Century Aluminum's management. Given the scope of this study, it has shown that transport accounts for between 1 and 10% of the various environmental burdens associated with aluminium production.

Unfortunately, and again due to time constraints, a sensitivity analysis was not possible. Suggestions for parameters to consider include transport, wastewater treatment, aluminium scrap, and energy supply for casting. Performing such an analysis based on the assumptions made for the study would have proven useful and would make for interesting further work.

Finally, it was brought to the author's attention during the defense of the thesis that though GaBi Education software models the Icelandic electricity grid mix as 70% hydropower and 30% geothermal energy which indeed corresponds to national data (National Energy Agency, 2012), this may not necessarily be the case for Norðurál but rather the other way around. Certainly, the electricity Norðurál is from the following:

- HS Orka, which supplies Norðurál with electricity generated at Svartsengi and Reykjanesvirkjun geothermal power plants. Svartsengi provides Norðurál with 27.8 of its 75 MW to Norðurál and most of the generation of Reykjanesvirkjun is sold to Norðurál
- Landsvirkjun generates its electricity through hydropower
- Orkuveita Reykjavíkur generates electricity via Nesjavellir (120 MW) and Hellisheiði (303 MW) geothermal power plants and two small hydropower plants (12 MW total) (Orkuveita Reykjavíkur, 2014)

Taking these figures into account in addition to new information directly from Norðurál it has come to light that the energy mix at Norðurál is in fact 35% hydropower from Landsvirkjun and 65% geothermal from HS Orka and Orkuveita Reykjavíkur. This is an issue of some importance, since CO₂ and especially SO₂ are emitted in significantly greater quantities due to electricity generation from hydropower compared to that of geothermal power, as has been touched upon in the discussion of Section 5.2. This has implications for all impact categories, but especially GWP, EP, ODP and AP where the electrolysis is dominant among the production stages of the cradle-to-gate models. AP is the impact category which is most sensitive to the assumption made in GaBi, since SO₂ emissions due to electrolysis, the process with the greatest energy requirement, were seen to be significant even with the division being geothermal 30% and hydro 70% . However, research into this issue must also be the subject of future work and further contributions to the growing field of LCA in Iceland.

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