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Towards GHG Emissions Neutrality of Aluminium Slug Production: An Industrial Study

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The aluminium industry is one of the largest emitters of greenhouse gases (GHG) and accounts for approximately 1 % of global GHG emissions. A large portion of emissions are indirect emissions, due to the large GHG footprint of consumed electricity, while direct energy and process-related emissions are also significant. The aluminium is widely used in packaging, transportation, the building sector and for various other purposes. This study focuses on aluminium slugs, which are semi products made from aluminium alloys and are used as tubes and containers in the pharmaceutical, food and cosmetic industries. Since the aluminium industry is among the largest GHG emitters, a Life Cycle Assessment (LCA) was performed to evaluate the environmental impact of aluminium slug production. Environmental impact assessment was performed using OpenLCA software, the Ecoinvent 3.1 database and self-collected plant data. The study includes the environmental impact of anode production, electrolysis and slug production. The functional unit for the study is 1 t of aluminium slug at the company exit gate. Besides GHG emissions and the related GHG footprint associated with slug production, acidification potential and photochemical oxidation potential are further assessed. Various opportunities for GHG emission reduction are further investigated in accordance with the longer-term company strategy. If more aluminium scrap were used and carbon capture performed, the GHG footprint could be reduced by 65 % compared to the base case.

1. Introduction

Aluminium is the most abundant metal in the Earth's crust and the second most commonly used metal in the world. Because of its lightness, electrical conductivity and corrosion resistance, it is used in a variety of products, including vehicles, buildings, furniture, cans, electronic gadgets and many others (Freiría Gándara, 2013). The aluminium industry is among the highest energy intensive industries, with a consumption of around 4 % of the global electricity output (Tyabji and Nelson, 2012) and thus produces large amounts of greenhouse gas (GHG) emissions. Besides indirect electricity-related emissions, around 25 % of GHG emissions in the aluminium industry constitutes direct energy-related emissions, while around 20 % is process-related emission (Tyabji and Nelson, 2012). GHG emissions are thus generated in almost all the processes and stages of the aluminium industry. It is also expected that aluminium consumption and production will rise significantly over the next decades and, consequently, energy use and GHG emissions will also rise (Gautam et al., 2018). Life Cycle Assessment (LCA) of aluminium production is important in order to mitigate or reduce GHG emissions. Several emission mitigation strategies have been identified for reducing emissions along the aluminium supply chain, such as improvements to current technology, alternative technologies in aluminium production pathways, recycling and carbon trading (Gautam et al., 2018).

Numerous research studies have been carried out to assess the environmental impact of primary aluminium production in specific regions, such as in China (Gao et al., 2009), globally (Nunez and Jones, 2016) and at the country level (Paraskevas et al., 2016). Several studies have also been performed at the supply chain level related to specific aluminium products, such as extrusion ingots and foundry alloys (Al Hawari et al., 2014) and aluminium billets (Tan and Khoo, 2005), while to the best of the authors' knowledge, no studies have been performed related to aluminium slug production.

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In this study, the LCA was performed to evaluate the environmental impact of aluminium slug production using OpenLCA software (GreenDelta, 2018), the Ecoinvent 3.1 database (Ecoinvent, 2019) and self-collected plant data. The study was performed in accordance with the principles, requirements and guidelines in the ISO standards 14040 (ISO, 2006a) and 14044 (ISO, 2006b). The study focuses on GHG emissions associated with slug production, since these are significant for the company, which is included in the European Emission Trading Scheme (ETS). Other impact categories related to emissions into air, such as acidification potential (AP) and photochemical oxidation potential (PCOP), are further assessed. More importantly, different scenarios have been analysed for reduction in GHG emissions.

2. Life Cycle Assessment of Aluminium Slug Production

The supply chain of aluminium slug production consists of various steps, which start with bauxite extraction and end with disposal or recycling. As a system boundary, only processes within the gates of the company are considered, which are anode production (carbon plant), electrolysis (reduction plant) and slug production (cast house with processing), as shown in Figure 1. Consumption of electricity and other utilities, transportation, upstream processes such as bauxite mining and alumina production, and downstream processing, use and recycling of products are excluded from the study, since the company does not have much influence over these. Figure 1 shows a simplified entry-gate-to-exit-gate LCA model for aluminium slug production. The functional unit for this study is 1 t of aluminium slug at the exit gate. Three environmental indicators, Global Warming Potential (GWP) or GHG footprint, AP and PCOP, are assessed in the study.

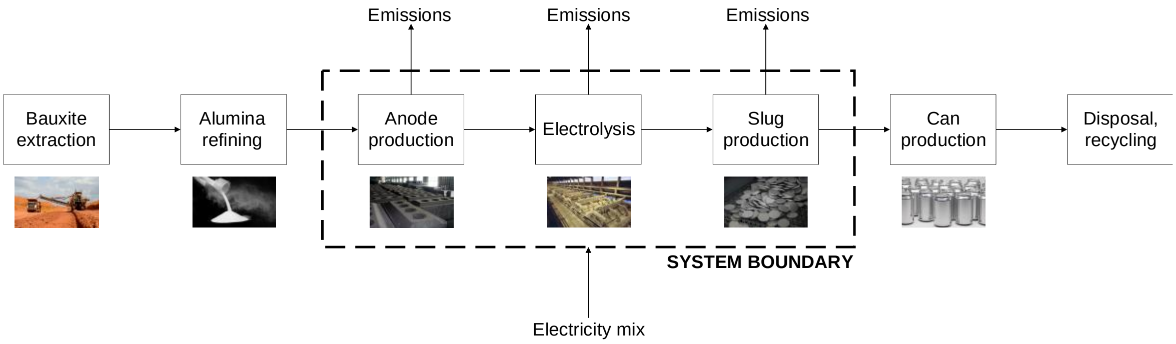

Figure 1: A simplified LCA model for aluminium slug production

2.1 Anode production (carbon plant)

Two different smelting technologies for aluminium production - Søderberg and prebake - are in operation today. Anode production, which occurs in a carbon plant and is the first step in slug production at the company location, is the main difference between aluminium smelting technologies. Prebake technology is far more commonly used than Søderberg technology. The carbon plant consists of a green mill, a plant and anode rodding. Petroleum coke and pitch are the two main raw materials for anode production and are mixed with anode residue to form green anodes. Pitch acts as a binder for the other materials. The green anodes are then baked in furnaces at high temperatures to form a solid block of carbon. The last stage in the carbon plant is anode rodding, where anodes are fused to molten steel and iron, through which an electrical current, needed for electrolysis, is passed. Anodes are then transported to the electrolytic cells. The theoretical consumption of anodes during aluminium production is 334 kg anodes/t Al (R&D Carbon, 2014). Waste gases containing benzene, dust, NO_x, HF, total organic carbon (TOC), polycyclic aromatic hydrocarbons (PAHs), SO_2 and CO_2 are emitted from the carbon plant (Kuenen et al., 2016).

2.2 Electrolysis (reduction plant)

Molten aluminium is produced by the electrolytic reduction process called the Hall-Héroult process and named after two chemists who simultaneously invented the process. Alumina or aluminium oxide, Al_2O_3, is used as the raw material for production of aluminium. Al_2O_3 has a high melting point, around 2,000 °C. Al_2O_3 is dissolved in the molten electrolyte consisting of cryolite, Na_3AlF_6, and aluminium fluoride, AlF_3, which lowers the melting point to below 1,000 °C. Carbon anodes are immersed in the solution carrying a powerful direct current, which is passed through the cell to the cathode. Consequently, the chemical bond between aluminium and O_2 in Al_2O_3 is broken. At the anode, solid carbon is oxidized to CO_2, while at the cathode, aluminium ions are reduced to aluminium. During the electrolysis process, anodes are consumed by O_2 and periodically replaced. Molten aluminium accumulates at the bottom of the electrolytic cell at the cathode (Mathisen et al., 2014). The main emissions from the electrolysis process are CO_2 emissions. Total amounts of CO_2 emissions are estimated to be 1.5 t CO_2/t produced primary aluminium. Other pollutants are CO, HF, AlF_3, Na_3AlF_6, SO_2, perfluorocarbons (PFC) and dust. CF_4 and C_2F_6, two PFCs, are formed as a result of anode effects from carbon in the anode and fluorine in the cryolite (Kuenen et al., 2016). Emissions from the electrolysis are collected and treated in dry scrubbers with a counter-current flow of Al_2O_3 (Kuenen et al., 2016).

2.3 Slug production (cast house with processing)

At the cast house, the molten aluminium is converted into solid slugs. The main processes in the slug production plant are casting, production of the narrow strip, hot and cold rolling, stamping, annealing, surface treatment and packaging. In the casting phase, the molten aluminium is first alloyed with scrap and other materials in the furnace. The next step involves the production of a narrow strip with different widths. Since the slug production is a continuous process, the narrow strip is fed directly into the rolling mills for hot and cold rolling. Mechanical properties are improved by rolling. The thickness of the metal is reduced and is tailored to the customer's request. The round shape of the slug is formed at the stamping stage by power pressing the narrow strip. Mechanical properties of the material are improved with heat treatment, known as annealing, at a temperature above the recrystallization point. By means of surface treatment, the roughness of the slug surface is increased, which allows the optimum application of coatings for a more constant material flow during reverse extrusion. Sandblasting, vibration and drumming are the three most common surface treatment techniques. The last stage of the production is packaging of slugs. A flue gas containing dust, NOx, TOC and CO_2, is emitted from the cast house (Talum, 2019).

2.4 Life Cycle Inventory

For the three processes (system boundary of the study) as shown in Figure 1, LCA analysis (ISO, 2006a) is performed. In the life cycle inventory phase (ISO 2006b), the main resources of raw materials and wastes are identified. Inventory flows in the study include inputs of raw materials, water and energy and releases into the air. Data used in the base study are self-collected plant data. The main inventory data for the carbon plant (anode production), the reduction plant (electrolysis) and the cast house (slug production) are summarised in Table 1.

Table 1: Life cycle inventory for slug production (per 1 t of aluminium slug)

Flows	Amount	Unit	Flows	Amount	Unit
SUM OF INPUTS			SUM OF OUTPUTS		
Al_2O_3	1.277	t	Al	0.670	t
AlF_3	0.011	t	Aluminium slugs	1.000	t
			Anode	0.270	t
Aluminium scrap	0.740	t	Benzene	5.640	g
Carbon residue	0.043	t	CO_2	1.385	t
Compressed air	346.771	m^3	CO	0.062	t
Electricity	9.446	MWh	Dust	262.552	g
Natural gas	161.485	m^3	C_2F_6	1.889	g
Petrol coke	0.186	t	HF	10.578	g
Pitch	0.037	t	NO_x	464.555	g
Thermal energy	0.027	GJ	PAHs	0.012	g
Water	0.227	m^3			
			SO_2	26.226	g
			CF_4	15.618	g
			TOC	76.913	g
			Water	0.227	t

3. Results

Environmental impact assessment was performed using OpenLCA software, where the three process steps of aluminium slug production were treated separately. The values of different environmental impact categories for each stage of aluminium slug production are summarised in Table 2.

Table 2: Impact category indicator results (per 1 t of aluminium slug)

Unit	GWP (kg CO_2eq/t)	AP (kg SO_2eq/t)	PCOP (kg ethylene eq/t)
Carbon plant	108.4	0.044	0.002
Reduction plant	1,250.8	0.007	1.675
Cast house with processing	287.0	0.214	0.000
Total	1,646.2	0.265	1.677

3.1 Global warming potential (GHG footprint)

The GHG footprint, also called the carbon footprint or GWP, is the most widely accepted environmental indicator and measures the amount of energy absorbed by greenhouse gases, relative to the emission of CO_2. It is calculated in CO_2eq. Gases that have an impact on GWP are CO_2, CO, CH_4, N_2O, chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), hydrochlorofluorocarbons (HCFCs), PFC and SF_6 (Čuček et al., 2015). Direct GHG emissions from slug production are estimated to be 1,646.2 kg CO_2eq/t of slugs, as can be seen from Table 2. The reduction plant has the highest impact on the GWP and represents 76 % of GWP. The main sources of GWP are CO_2 emissions from anode combustion. Gases that are released from slug production and have an influence on GWP are CO_2, CO, CF_4 and C_2F_6. CO has a GWP value relative to CO_2 of 1.9, while CF_4 and C_2F_6 have higher values: for CF_4, the GWP value is estimated to be 7,390 kg CO_2eq/kg, and for C_2F_6, it is estimated to be 12,200 kg CO_2eq/kg (IPCC, 2014).

3.2 Acidification potential

AP is the ability of gases to form H^+ ions and is calculated in SO_2eq. Acidifying substances are HCl, HF, NO_x, SO_2, H_2S, NH_4 and NH_3 (Čuček et al., 2015). Because of emission of NO_2, the cast house is the major contributor to AP and represents 81 % of AP. Total AP is estimated to be 0.265 kg SO_2eq/t of slugs.

3.3 Photochemical oxidation potential

PCOP is caused by the reaction of emissions and sunlight and is calculated in ethylene eq. PCOP occurs in the presence of NO_x and volatile organic compounds (VOCs) such as ethane, ethylene, benzene, acetone and formaldehyde (Čuček et al., 2015). PCOP is estimated to be 1.677 kg ethylene eq/t of slugs. As can be seen from Table 1, the carbon plant has a minor influence on PCOP, while the cast house has no influence on PCOP. The majority of PCOP is due to the reduction plant.

4. Towards GHG Emissions Neutrality

The scenario analysis related to GHG emission reduction is further performed, since reduction in GWP is important for the company, which is included in the ETS. Multiple scenarios, such as use of aluminium scrap instead of electrolysis aluminium, implementation of carbon capture and a mix of both, are investigated for the reduction of environmental impact in accordance with the company's long-term strategy.

In accordance with company strategy, it is assumed that the consumption of electrolysis aluminium will reduce from 0.67 t to 0.42 t per t of aluminium slug, while the consumption of aluminium scrap will increase. Although the amount of electrolysis aluminium is reduced, the use of secondary or aluminium scrap alone is not technically possible. The use of aluminium scrap material has benefits for the environment and reduces energy consumption by 95 % in comparison with primary aluminium production, while producing only 5 % of GHG emissions (Capuzzi and Timelli, 2018). In the entry-gate-to-exit-gate model, GHG emissions from aluminium scrap are assumed to be zero.

Carbon capture is another promising strategy for reduction of CO_2 emissions. During post-combustion capture, CO_2 could be separated from other flue gases by absorption. Monoethanolamine (MEA) is the most commonly used chemical for the absorption process. However, deployment of such carbon capture comes with safety, health and environmental concerns (Badr et al., 2017). Nevertheless, the amines are mainly recycled during the process, while small amounts can degrade or be emitted into the air. The emitted substances are unstable in nature and can degrade to dangerous, toxic substances (Shao and Stangeland, 2009). Other emissions from electrolysis remain the same as in the base when carbon capture is not employed. A CO_2 capture rate of 90 % was assumed in the study.

The results of various GHG emission mitigating scenarios are shown in Figure 2. The functional unit for this study is 1 t of aluminium slug at the exit gate.

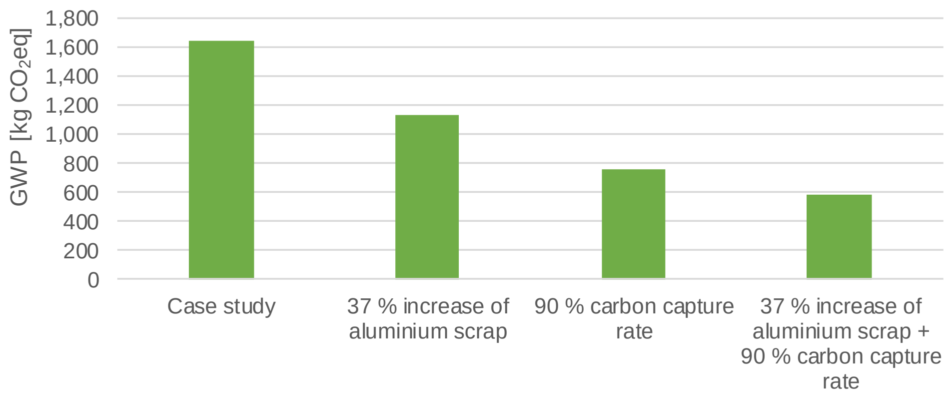

Figure 2: Greenhouse gas footprint of different scenarios for aluminium slug production

It can be seen from Figure 2 that having a higher share of aluminium scrap in the raw material instead of electrolysis aluminium, and implementation of carbon capture technology can significantly reduce the GHG footprint. The use of more aluminium scrap reduces the GHG footprint by 31 %, while carbon capture reduces the GHG footprint by 44 %. If both strategies are implemented, the GHG footprint is reduced by 65 % compared to the base case (current emissions). Use of secondary aluminium and carbon capture are thus promising technologies for reducing GHG.

In addition to these scenarios for reducing GHG emissions, there are certain other opportunities under research, such as the use of non-carbon (inert) anodes instead of conventional anodes (Kvande and Drabløs, 2014), the use of ionic liquids with low melting points to reduce energy consumption in aluminium production (Poilimenou et al., 2014) and others.

By expanding the scope of the study from cradle to gate, the consumption of electricity and other utilities, upstream processes such as bauxite mining and alumina production could be included in the analysis. Production of primary aluminium is one of the most energy intensive industrial processes and consequently, a significant source of GHG emissions. Thus, changing energy source(s) for electricity production towards more renewable sources has major potential for reducing GHG emissions.

5. Conclusions

The environmental impact of aluminium slug production was studied using the LCA approach. Three environmental indicators were taken into consideration: GWP or GHG footprint, AP and PCOP. Results have shown that electrolysis is the main contributor to the GHG footprint of aluminium slug production. The GHG footprint could be significantly reduced (up to 65 %) by implementation of the proposed scenarios, the combined use of more aluminium scrap and carbon capture. In order to further reduce GHG emissions, companies should adopt additional sustainable improvements. In the future work, possible implementation of those additional options will be investigated, together with expanding the current scope (gate-to-gate) to the whole supply chain without use and disposal (cradle to gate), including energy supply, transportation and usage of inert anodes. Besides emissions into the air, future research will analyse emissions and effluents into water and soil. Furthermore, economic and social analysis will be undertaken, together with multi-objective optimisation in order to obtain more sustainable solutions for energy intensive production industries such as the aluminium industry.

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References

Al Hawari A., Khader M., El Hasan W., Alijla M., Manawi A., Benamour A. A., 2014, Life Cycle Assessment (LCA) of Al Production Process, International Journal of Environmental and Ecological Engineering, 8 (4), 704-710.

Badr S., Frutiger J., Hungerbuehler K., Papadokonstantakis S., 2017, A framework for the environmental, health and safety hazard assessment for amine-based post combustion CO2 capture, International Journal of Greenhouse Gas Control, 56, 202-220.

Capuzzi S, Timelli G., 2018, Preparation and Melting of Scrap in Aluminum Recycling: A Review, Metals, 8 (4), 249, 1-24.

Čuček L., Klemeš J.J., Kravanja Z., 2015, Chapter 5 - Overview of environmental footprints, Chapter In: J.J. Klemeš (Ed.), Assessing and Measuring Environmental Impact and Sustainability, Butterworth-Heinemann, Oxford, UK, 131-193.

Ecoinvent, 2019, Ecoinvent 3.1, <www.ecoinvent.org/database/older-versions/ecoinvent-31/ecoinvent-31.html>, accessed 07.03.2019.

Freiría Gándara M.J., 2013, Aluminium: The metal of choice, Materials and Technology, 47 (3), 261-265.

Gao F., Nie Z. R., Wang Z. H., Li H. M., Gong X. Z., Zuo T. Y., 2009, Greenhouse gas emission and reduction potential of primary aluminium production in China, Science in China Series E: Technological Sciences, 52, 8, 2161-2166.

Gautam M., Pandey B., Agrawal M., 2018, Carbon Footprint of Aluminum Production: Emissions and Mitigation, Chapter In: S. S. Muthu (Ed.), Environmental Carbon Footprints: Industrial Case Studies, Butterworth-Heinemann, Oxford, UK, 197–228.

GreenDelta, 2018, openLCA, <www.openlca.org/>, accessed: 07.03.2019.

International Organization for Standardization, 2006a. ISO 14040:2006: Environmental management – Life cycle assessment – Principles and framework, Geneva, Switzerland.

International Organization for Standardization, 2006b. ISO 14044:2006: Environmental management – Life cycle assessment – Requirements and guidelines, Geneva, Switzerland.

IPCC, 2014, Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (Eds.)], IPCC, Geneva, Switzerland.

Kuenen J., Berdowski J., van der Most P., Mulder W., Bloos J.P., Pacyna J.M., Rentz O., Oertel D., Woodfield M., Pulles T., Appelman W., Dellaert S., 2016, EMEP/EEA air pollutant emission inventory guidebook, 2.C.3 Aluminium production, European Environment Agency, Copenhagen, Denmark <www.eea.europa.eu/publications/emep-eea-guidebook-2016/part-b-sectoral-guidance-chapters/2-industrial-processes/2-c-metal-production/2-c-3-aluminium-production-2016/view>, accessed 07.03.2019.

Kvande H., Drabløs P.A., 2014, The aluminum smelting process and innovative alternative technologies, Journal of Occupational and Environmental Medicine, 56 (Suppl. 5), 23-32.

Mathisen A., Sørensen H., Eldrup N., Skagestad R., Melaaen M., Müller G. I., 2014, Cost optimised CO2 capture from aluminium production, Energy Procedia, 51, 184–190.

Nunez P., Jones S., 2016, Cradle to gate: life cycle impact of primary aluminium production, International Journal of Life Cycle Assessment, 21, 1594-1604.

Paraskevas D., Kellens K., Van de Voorde A., Dewulf W., Duflou J. R., 2016, Environmental impact analysis of primary aluminium production at country level, Procedia CIRP, 40, 209-213.

Poulimenou N.I., Giannopoulou I., Panias D., 2014, Use of Ionic Liquids as Innovative Solvents in Primary Aluminum Production, Materials and Manufacturing, 30 (12), 1-5.

R&D Carbon, 2014, Prebaked Anodes for aluminium Electrolysis <rd-carbon.com/data/ documents/publications/general/Prebaked_Anodes_ Aluminium _Electrolysis_2014.pdf>, accessed 28.02.2019.

Shao R., Stangeland A., 2009, Amines Used in CO2 capture – Health and Environmental Impacts, The Bellona Foundation, Oslo, Norway <bellona.org/assets/sites/3/2015/06/fil_Bellona_report_September__2009_-_Amines_used_in_CO2_capture-1.pdf>, accessed: 07.03.2019.

Talum, 2019, Slugs, <talum.si/en/rondelice.html>, accessed 22.02.2019.

Tan R.B.H., Khoo H.H., 2005, An LCA study of a primary aluminum supply chain, Journal of Cleaner Production, 13, 607-618.

Tyabji N., Nelson W., 2012, Mitigating Emissions from aluminium: The GNCS Factsheets. Columbia Climate Centre, Earth Institute, Columbia University, <climate.columbia.edu/files/2012/04/GNCS-Aluminum-Factsheet.pdf>, accessed: 07.03.2019.