Aluminium Sector Historical Greenhouse Gas Emissions Trends Over the Last Two Decades

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Abstract

Primary aluminium production is an energy-intensive process with the aluminium sector being responsible for approximately 2 % of all global greenhouse gas (GHG) emissions. This paper explores nearly two decades worth of IAI aluminium greenhouse gas data, from 2005 to 2018, utilising data collected directly from the industry. The data covers all production worldwide by implementing informed estimates from reporting plants and conservative assumptions from non-reporters. Here we present annual primary aluminium and global aluminium sector emissions, in tonnes CO_2 equivalent, accounting for all emissions sources and processes. The data is presented at unit process and emissions type level, enabling granular analysis of GHG trends. While fossil fuel generated electricity has increased over the years (51 % in 2005 to 71 % in 2018), the GHG emissions intensity of electrolysis has remained relatively stable. This has been possible mainly due to energy efficiency gains over this period, with total electricity required per tonne of primary aluminium decreasing from 15 080 kWh in 2005 to 14 221 kWh in 2018. Moreover, the evolution of the power mix utilised in the electrolysis process across 8 different regions is considered, along with implications of how different electricity generation sources influence the overall aluminium industry's greenhouse gas emissions. Non-CO_2 greenhouse gases in the primary aluminium production process have been declining consistently, from 1.6 to 1.1 tonnes CO_2e per tonne primary aluminium in 2018, highlighting the industry's efforts to reduce perfluorocarbon emissions. Emissions from thermal energy, ancillary materials and transport emissions have also shown a consistent decline.

Keywords: Aluminium greenhouse gas emissions, GHG, aluminium sector emissions, primary aluminium emissions, electrolysis energy mix.

1. Introduction and Background

Aluminium production begins with the mining of bauxite ore, which contains 30-54 % aluminium oxide (Al_2O_3, hereafter alumina), the rest being a mixture of iron oxides, silica and titanium oxide [1]. Alumina is extracted and purified in the Bayer Process, requiring energy in the form of heat and steam, as well as ancillary materials such as sodium hydroxide. After being calcined, the alumina is shipped in dry bulk to an aluminium smelter. Significant amounts of electricity are then required to break the strong oxygen bonds of alumina in the smelting process. The smelting of aluminium currently takes the form of a reduction-oxidation reaction between the raw material, alumina, and carbon anodes, in which three electrons are provided to each aluminium ion to reduce it to its metal form, while the carbon atoms of the anodes are oxidised to form carbon dioxide, as characterised in the following reaction:

$$2Al_2O_3 + 3C \rightarrow 4Al + 3CO_2 \tag{1}$$

In addition to alumina, the electrolysis process requires a variety of inputs including electricity, carbon anodes and other ancillary products. All of these come with a carbon footprint. Electricity-related emissions dominate the 75 % of sectoral emissions that smelting represents [2]. Electricity-related emissions can vary significantly across the industry, depending on the power mix used by smelters. Historically, the aluminium smelting power mix was dominated by electricity generated using hydropower. However, over the past 20 years, the overall power mix of the sector has shifted with greater amounts of coal and natural gas and is now dominated by coal-powered electricity [2] driven by the growth of production in India and China.

Aluminium is infinitely recyclable. Recycling aluminium requires up to 95 % less energy than production from ore [2], as it only requires melting the aluminium scrap, eliminating CO_2 that is associated with the smelting process. As such, increasing the global recycling efficiency rates for end-of-life products will be essential to further decrease the overall carbon footprint of aluminium.

The International Aluminium Institute (IAI) has recently explored the ways forward for decarbonising the aluminium industry, setting out three broad pathways to 2050. These include electricity decarbonisation, direct emissions reduction, and recycling & resource efficiency [2]. In contrast, this paper analyses the aluminium industry's historical trends, looking back at previous historical moments and changes that have influenced the industry's greenhouse gas emissions, and presents the most recent analysis of the industry's baseline emissions. Nearly two decades worth of aluminium GHG data, from 2005 to 2018, is presented at unit process and emissions type level making this is one of the most comprehensive GHG datasets of any material. This paper also considers the historical changes to the regional energy mix and how that has impacted the emissions intensity in those regions.

2. Methodology

The dataset covers life cycle (cradle-to-gate) GHG emissions (as CO_2e) for the 2005–2018 period and is publicly accessible via International Aluminium Institute's website [3]. Aluminium GHG cradle-to-gate emissions comprise electricity, thermal energy, direct process, ancillary materials, transport, and non-CO_2 GHG emissions. This includes all sector generated emissions in its own facilities (primary and recycling), in addition to those embedded in the raw materials, ancillary materials and energy that the sector consumes. The data covers all production worldwide by using informed estimates for plants that report their data to IAI, and conservative assumptions for the sites that do not currently report their data to the IAI. Emissions types are summarised below:

- Direct process: direct, non-fuel combustion inputs and outputs (emissions) associated with primary aluminium production processes (bauxite mining, alumina production, anode/paste production, electrolysis, and casting).
- Thermal energy: material inputs and emissions associated with primary aluminium production thermal energy generation processes, including fuel extraction and preparation (e.g., coal from mine to boiler).
- Ancillary materials: all material and energy inputs and emission outputs associated with non-fuel input materials used in the production of primary aluminium (e.g., caustic soda, lime, aluminium fluoride, pitch & coke production).
- Electricity: all inputs and outputs associated with processes to generate and distribute the electricity directly used in primary aluminium production processes, including fuel extraction and preparation.
- Transport: inputs and outputs associated with the seaborne, road and rail transport of input materials.
- Non-CO_2: perfluorocarbon (PFC) emissions generated during operational disruption in the electrolytic cell due to anode effects.

2.1 Primary Aluminium

IAI has published three life cycle inventory (LCI) reports of the global primary aluminium industry for the reporting years 2005, 2010 and 2015. In the 2015 LCI report, total life cycle GHG emissions were modelled using GaBi Software (v8, 2018). For 2005 and 2010, the direct and electricity-related indirect emissions of reporting production were calculated using GHG Protocol tools. These two datasets are used as a reference to calculate the global average carbon footprint of one tonne of cast primary aluminium.

For the years with no LCI publication, data from the previous LCI report is used, updated with annually collected data from industry for smelting electricity, refining energy as well as PFC emissions data. These three datasets collectively constitute over 80 % of total global aluminium sector emissions.

Emissions from smelting power consumption are calculated using IAI power consumption data reported by power source and region [4]. The regional average electricity mix is not used for this calculation, rather the specific industry-consumed power in each region, as reported to IAI. There can be significant differences between the regional average (grid) electricity mix and the aluminium-industry specific electricity mix. To convert electricity data (kWh/tonne) for the years without an LCI report, national/regional electricity emission factors published by the International Energy Agency [5] - (CO_2) - and GaBi Database (CO_2e) are applied to the appropriate regional electricity mix.

Emissions from metallurgical alumina fuel consumption are calculated using IAI energy intensity and fuel mix data [6, 7]. To convert the energy data (MJ/tonne) to CO_2e emissions, global fuel emission factors published in the GaBi Database are used.

Since 2018, the dataset for alumina refining reflects a change in modelling assumptions for the process. This change in modelling assumptions impacts the overall non-CO_2 GHG as follows:
Aluminium sector (2018): non-CO_2 GHG, 0.7 t CO_2e → 0.4 t CO_2e
Primary aluminium (2018): non-CO_2 GHG, 1.1 t CO_2e → 0.6 t CO_2e

For the sake of more accurate historical trend analysis, this study will refer to 2018 data previous to the change of modelling assumptions. This is noted with an asterisk (*) on Figures 2 and 3.

2.2 Semi Fabrication and Recycling

Semi fabrication (i.e., production mix) production processes (without recycling of internal scrap) are equal to 0.3 tonnes CO_2e per tonne of semis.

For semis, the average of European Aluminium [8] and The Aluminum Association [9] published data is used, with the same per tonne CO_2e emissions assumed for all years. This is a weighted average across all semi-fabrication processes, though there is variability between each (e.g., rolling, extrusion, foil), as reported in the European Aluminium [8] and The Aluminum Association [9] publications.

New scrap = 0.5 tonnes CO_2e per tonne of recycled aluminium
Old scrap = 0.6 tonnes CO_2e per tonne of recycled aluminium
Internal scrap = 0.3 tonnes CO_2e per tonne of recycled aluminium

Recycling processes emissions data is taken from European Aluminium [8] and The Aluminum Association [9] and applied to the global recycling industry, with the same per tonne CO_2e emissions assumed for all years.

2.3 Production Data

Historical primary production data is from the IAI dataset [10]. Primary aluminium as defined in the IAI statistics is liquid aluminium tapped from electrolytic cells or pots during the electrolytic reduction of metallurgical alumina (aluminium oxide). It thus excludes alloying and scrap additions in cast metal production. While this data does not fully represent a primary ingot (i.e., excluding alloying elements and metal losses), this data is used as proxy for primary aluminium ingot production.

Recycling data is based on the IAI Material Flow Model [11].

3. Results and Discussion

3.1 Total Sector Emissions

Since 2005, aluminium production has grown strongly in response to growing global demand. The growth in production has resulted in the sector's emissions increasing from 585 Mt CO_2e in 2005 to 1095 Mt CO_2e in 2018 (Figure 1). To put the industry's emissions into perspective, 1095 Mt CO_2e (2018) is equivalent to approximately 2 % of all global anthropogenic emissions. The only year-on-year reduction in annual primary aluminium production can be observed in 2009 – a result of the closure of multiple smelters during the global financial crisis, causing global annual production to decrease by 2.3 Mt. This resulted in a commensurate reduction in emissions for that period by 55 Mt CO_2e from 2008 levels. Bradtke et al. [12] suggest that due to the global financial crisis events in 2009, primary aluminium consumption outside China dropped by 17 %, whereas Chinese consumption increased by 15 %.

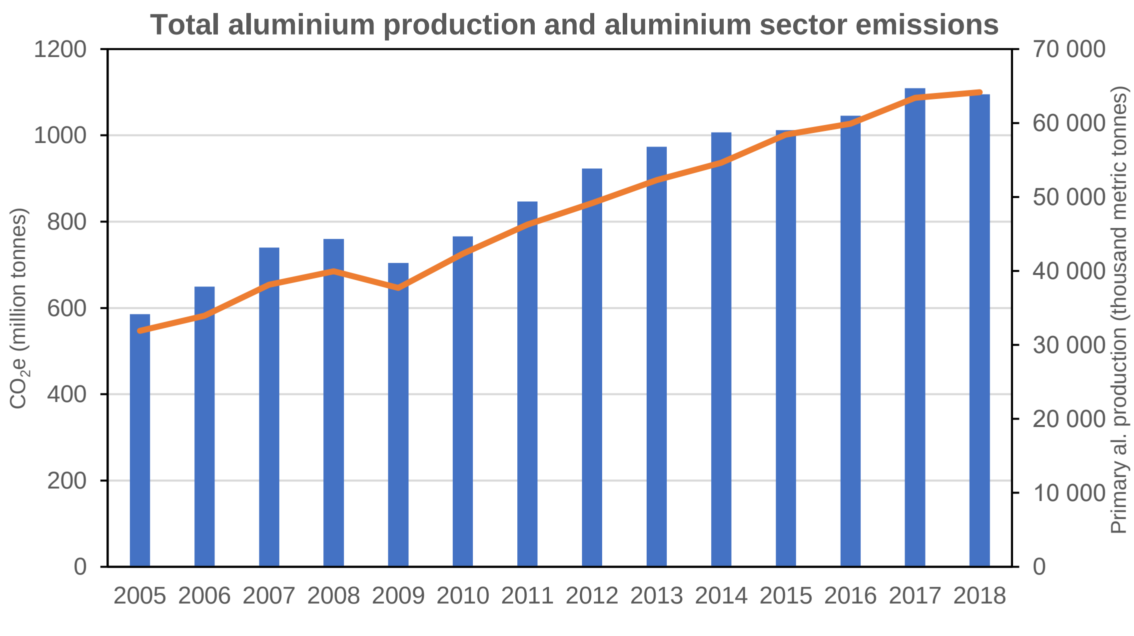

Figure 1. 2005–2018 time series of aluminium sector global emissions, in million tonnes CO_2e. The secondary axis (line graph) shows global annual primary aluminium production in thousand metric tonnes.

3.2 The Influence of Emissions from Electricity

The energy intensive nature of primary aluminium production means that the emissions related to electricity consumed during the smelting process are the most significant for the sector, accounting for 64.5 % of emissions from primary aluminium in 2018 (Figure 2). The overall emissions intensity for primary aluminium has remained stable between 16.5 t and 18.5 t CO_2e. Although the proportion of fossil fuel generated electricity used in primary aluminium production has gradually increased, from 51 % in 2005 to 71 % in 2018 (Figure 2), the emissions associated with electricity have remained relatively stable. This can be explained by an offset from efficiency gains over the same time period. Total electricity required per tonne of ingot has decreased from 15 080 kWh in 2005 to 14 221 kWh in 2018 [6], allowing the electricity emissions to remain stable despite the increase in use of electricity from fossil fuels.

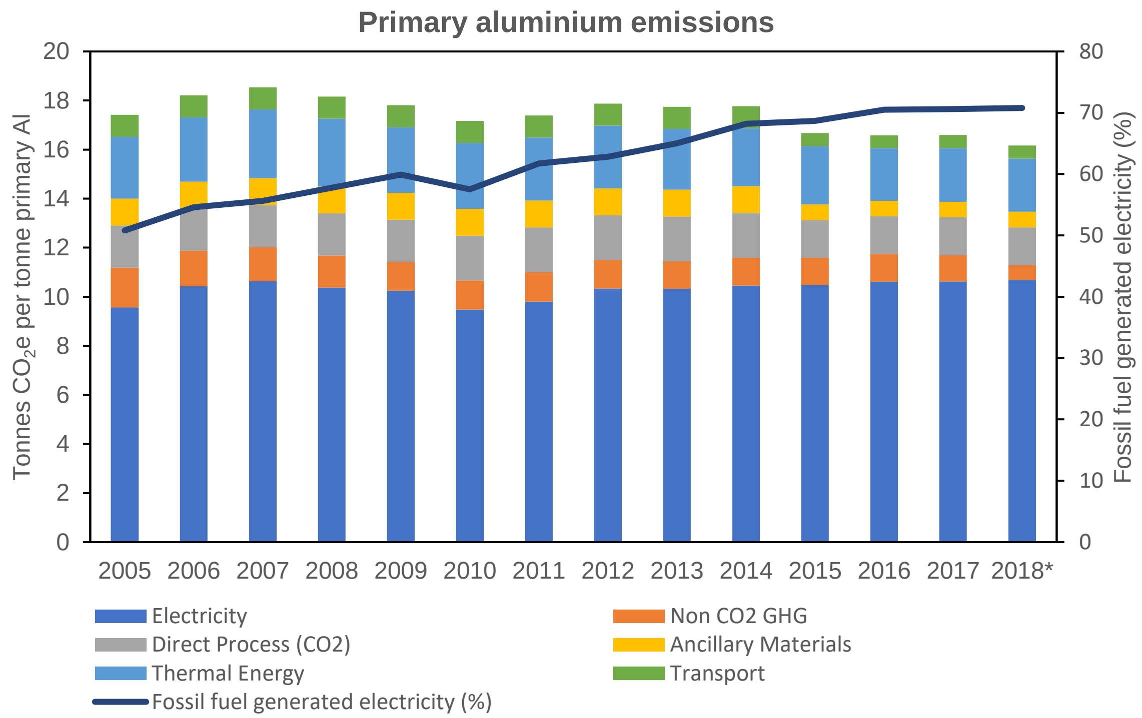

Figure 2. 2005–2018 time series of primary aluminium greenhouse gas emissions, in tonnes CO_2e per tonne primary aluminium. The secondary axis (right) shows the percentage of fossil fuel generated electricity globally each year.
***2018 data reflects a change in modelling assumptions for non-CO_2 GHG which is described in the Methodology section.**

Figure 3 shows the changes to the energy mix by region over the the 2006–2019 period while Figure 4 shows the GHG emissions from electricity consumption in the smelting process in those regions during the same time period. Changes to the emissions intensity can be observed in parallel to changes to the energy mix; for example, Asia (ex. China) shifted from 31 % coal power in 2011 to 91 % in 2012. As a result, their emissions intensity from electricity use rose from 10.5 to 16.6 t CO_2e per tonne primary aluminium. In contrast, the Gulf Cooperation Council (GCC), based on 100 % natural gas, have maintained a 6.1 t CO_2e emissions intensity over the 2011–2019 period. Regions with the highest proportion of hydropower energy, e.g., Europe (incl. Russia) and South America have smelting electricity GHG emissions intensities of between 2 t and 3 t CO_2e. While China has maintained a power mix of 90 % coal power and 10 % hydropower over the 2006–2019 period, its emissions intensity has been slowly decreasing – from 16.9 t CO_2e to 12.8 t CO_2e. This decline could be attributed to the emergence of cleaner coal technologies in China, in addition to overall increases in efficiency through retrofitting and relocation of smelting capacity. According to IEA [13], the average age of coal-fired power stations in China is less than 13 years. This, paired with significant new large-scale aluminium smelting capacity in China with new self-generated coal-fired power enables highly efficient production.

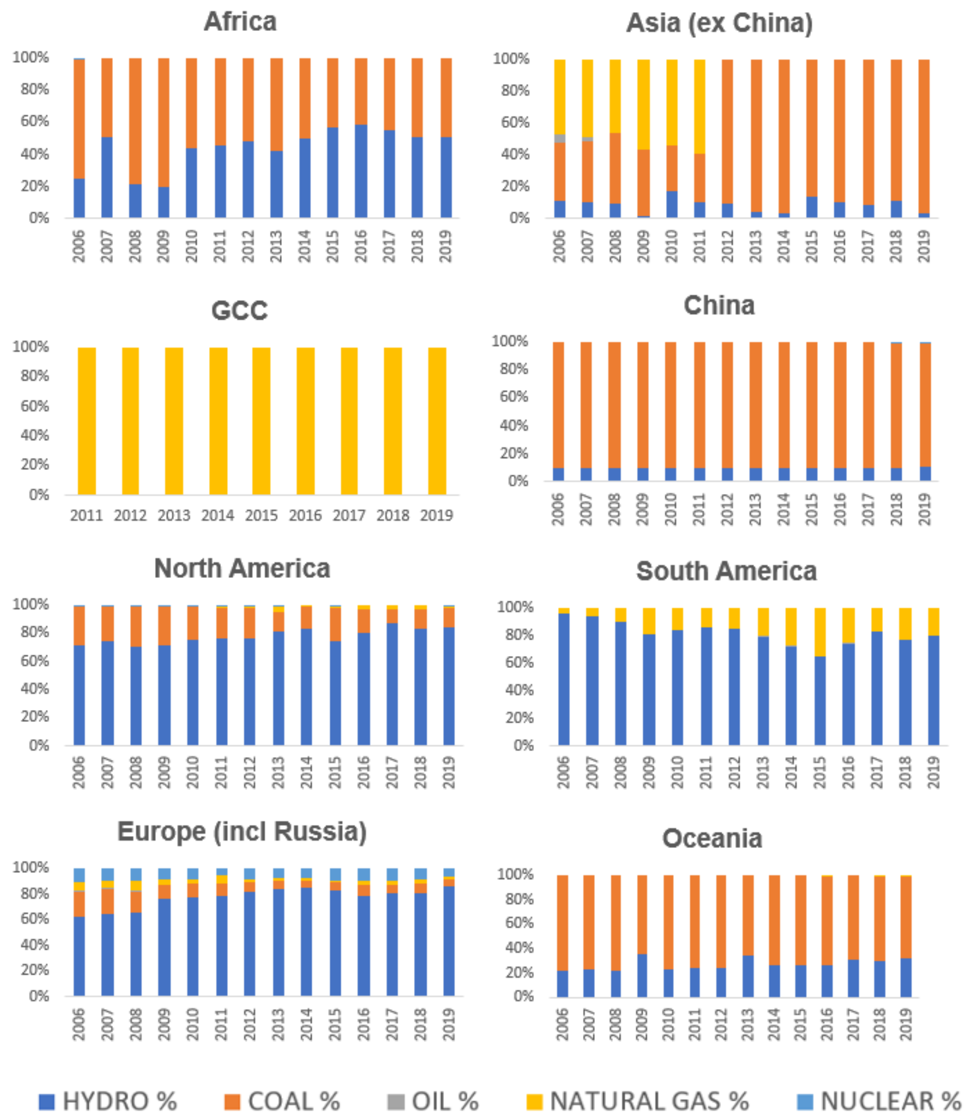

Figure 3. 2006-2019 regional evolution of the energy mix utilised in the electrolysis process.

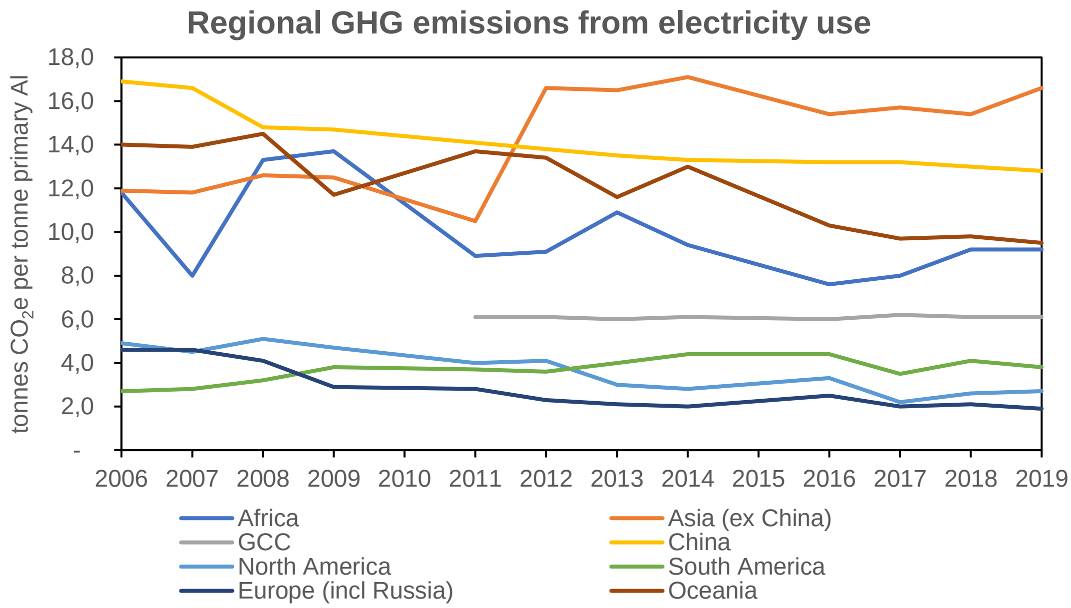

Figure 4. 2006–2019 time series of regional greenhouse gas emissions from electricity use in electrolysis, in tonnes CO_2e per tonne primary aluminium.

3.3 Other Emissions

Non-CO_2 greenhouse gas emissions from the primary aluminium production process have been declining consistently, from 1.6 t CO_2e (per tonne primary aluminium) in 2005 to 1.1 t CO_2e in 2018, highlighting the industry's efforts to reduce PFC emissions, which are the primary source of the non-CO_2 GHG emissions. Reducing PFC emissions has been an industry focus since the early 1990s; IAI [14] has released a good practice guidance on measuring PFCs, offering practical information to support smelters in conducting PFC measurements for different objectives, including process improvement, benchmarking and GHG inventory reporting.

Thermal energy related emissions have also shown a consistent decline: 2.5 to 2.2 t CO_2e per tonne primary aluminium. The majority of thermal energy related emissions are associated with the alumina refining process. Between 2005 and 2018, the global energy intensity of alumina refining decreased by 2 774 MJ per tonne of alumina [15]. The mix of energy for alumina refining also changed during this time period, from 32 % coal, 27 % oil, 30% gas and 9 % electricity to 56 % coal, 8 % oil, 27 % gas and 7 % electricity [7].

Ancillary materials and transport emissions have also shown a consistent decline from 1.1 to 0.6 t CO_2e, and 0.9 to 0.5 t CO_2e from 2005 to 2018, respectively. The reasons behind these reductions could be related to changes in the production process for ancillary materials or reductions in the transport distances for input raw materials over time.

3.4 Overall Sector Emissions Intensity

The emissions associated with primary aluminium production have a significant influence on the overall emissions intensity for the aluminium sector, accounting for 95 % of emissions (Figure 5). Aluminium sector emissions intensity from 2005 to 2018 has been fairly stable between 11 t CO_2e per tonne semis and 13 t CO_2e per tonne semis (Figure 6). The only period when the overall sector emissions per tonne of semis exceeded 13 t CO_2e was 2007 and 2008 when recycled production as a share of total semis production dropped below 31.4 % (Figure 6). This decrease in recycled production contributes to the slight uptick in emissions per tonne semis for 2007 and 2008 where a greater share of primary aluminium influences the overall emissions intensity for the sector.

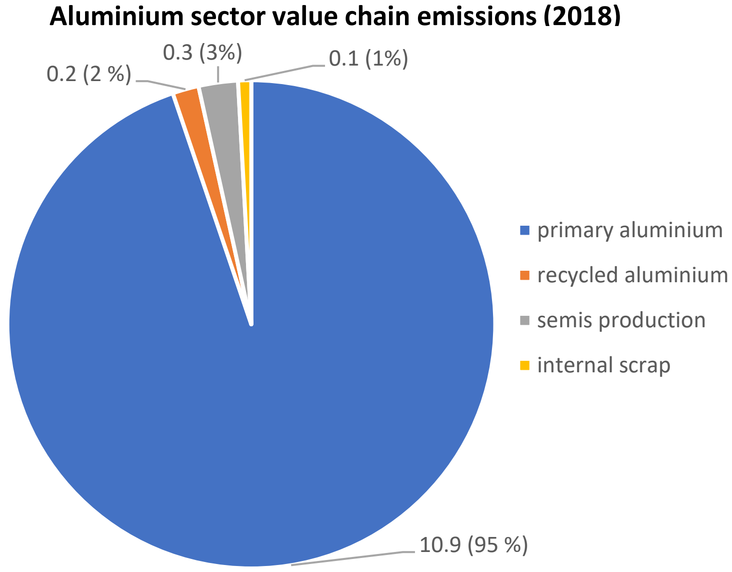

Figure 5. Global aluminium sector value chain emissions for 2018 (in t CO_2e per tonne semis).

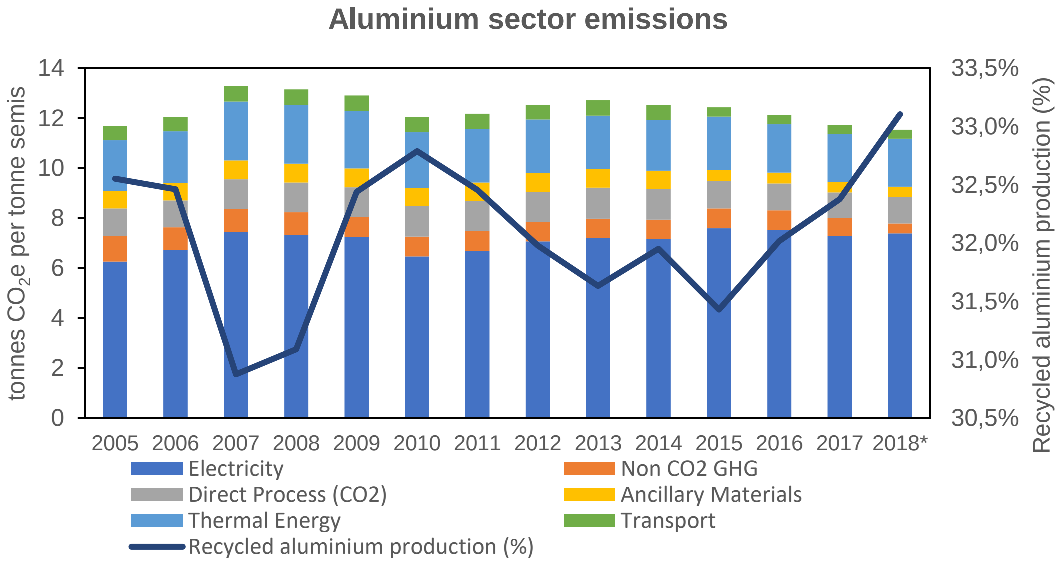

Figure 6. 2005–2018 time series of global aluminium sector greenhouse gas emissions, in tonnes CO_2e per tonne semis product. The secondary axis (right) shows the percentage of recycled aluminium production each year.
***2018 data reflects a change in modelling assumptions for non-CO_2 GHG which is described in the Methodology section.**

4. Conclusions

There are GHG emissions associated with every stage of aluminium production, from mining to end of life. The most significant emissions include those generated during electricity generation for the smelting process, combustion of fossil fuels during alumina refining, CO_2 emissions from carbon anode consumption during the electrolysis process, and PFCs generated in the electrolytic cell due to anode effects.

Primary aluminium production over the last two decades has grown consistently to meet growing demand. From 2005 to 2018, global aluminium production increased by 101 % and global aluminium sector emissions by 87 % as a result. Over this same time period, the emissions intensity per tonne of ingot and per tonne of semis has remained fairly stable at between 16.5 t and 18.5 t CO_2e (primary) and 11 t and 13 t CO_2e (semis) respectively.

The emissions intensity of primary aluminium production has a significant influence on the overall emissions intensity for the aluminium sector. Primary aluminum emissions intensities can vary significantly depending on the source of energy for electricity generation. The proportion of recycled aluminium production as a proportion of the overall production also plays a notable role in the emissions intensity for the sector.

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