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Environmental impact analysis of primary aluminium production at country level

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Abstract

Aim of this paper is to quantify and compare the environmental impact of primary aluminium production for the 29 major countries active in the primary aluminium value chain. The technology mix, electricity mix and heat mix vary a lot between countries. Different countries produce aluminium with different technologies, which can be translated into specific energy requirements and process efficiencies as well as different electricity inputs which is the main reason why the impact per unit mass is geographically dependent. The analysis illustrates this large difference among countries. A Life Cycle Assessment study was performed for comparison and comprehensive reasons based on two impact assessment methods; one at endpoint level and one using a midpoint indicator. Taking into account the production volumes for the year of 2012, the environmental impact caused by this sector is discussed. Moreover, a detailed view per country, analysing its specific dominant impact factors, is presented.

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Keywords: Life Cycle Assesment (LCA); primary alumium; global warming potential; China

1. Introduction

Environmental considerations need to be integrated with policy analysis. LCA is widely used in the aluminium industry [1-5] and provides a comprehensive methodology [6]. Previous work on LCA can be a valuable decision support tool, for example in aluminium recycling to identify the environmental burdens and benefits, of altering the raw materials in the recycling process [5]; or for comparing alternative solid state recycling routes with the remelting ones [7]; or for quantifying future emission pathways for the global aluminium cycle [2].

Primary aluminium production is one of the most energy intensive materials, requiring on average 66MJ of energy per kg in 2012, of which 80% as electricity in the Hall-Héroult process [8]. The Green House Gas (GHG) emissions associated with the 2007 global aluminium cycle account for 0.45 Gt CO2 eq., or approximately 1% of the global GHG emissions [9, 2]. Smelting and other primary-production-related processes (mining, refining and production of anodes for smelting) together are responsible for over 90% of the total emissions [2]. The energy consumed in any stage in the life cycle of the production chain has a significant effect on the associated inventory of emissions and environmental impacts because of large differences in power generation. The most important emission source is indirect emissions (65% of the total), predominately occurring from electricity production, followed by process emissions (18%) and fossil fuels (17%).

Thus, indirectly, the overall environmental impact of primary aluminium production, is highly geographically dependent on the energy mix used for power generation. Different regions/countries use different energy mixes for electricity production. Fossil-fuel-fired or nuclear-centralized steam generators; large-scale and small-scale hydroelectric power; and renewable options, such as geothermal, wind, and solar power, each have a unique set of properties that can significantly influence the results of the life cycle assessment. This paper aims to address this research question and provide a

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more detailed view of the sector's impact by analysing the identified major contributing countries. For this reason a detailed comparative LCA study was conducted.

2. Life cycle inventory (LCI), data sources and impact assessment method

2.1 LCI and impact assessment method

For the LCA, the latest update of the EcoInvent database v3.0 [10] was used as principal data source to model the primary aluminium production chain. Compared with the previous version of EcoInvent v2.2, which is more than 10 years old, the 3.0 version is much more accurate for process details that are crucial to this analysis: e.g. centralized electricity production efficiencies, aluminium related process emissions, etc.

The ReCiPe method [11] was selected for the Life Cycle Impact Assessment (LCIA). Following this method the damage assessment was performed in two steps: the modelling of the actual environmental damage for different impact categories and the normalization and weighting [11]. The endpoint approach was chosen since at that level all the environmental burdens of the 18 midpoint categories are further converted into a single measure (Pts) which facilitates comparison. The hierarchist perspective and the Worldwide average weighting set (Worldwide ReCiPe H/A) were selected for this purpose.

The main critic against the use of the Endpoint level is the fact that the weighing is relatively subjective. The Endpoint method thus carries extra uncertainty compared to the absolute values of the Midpoint damage categories. However the analysis was conducted systematically using the same weighing system so that the results can be compared with each other in order to evaluate their relative importance. Moreover, the widely accepted midpoint indicator of Global Warming Potential (GWP) calculated based on the IPCC 2007 GWP 100a method was used to compute long term CO_2 equivalent emissions. This method converts all emissions to 100 year CO_2 equivalents. The calculations were performed using the Simapro© software version 7.3.

2.2 Data sources and uncertainties

All production data (bauxite mining, alumina refining and primary aluminium smelting) have been retrieved from the USGS databases [12, 13]. Its data is highly reliable, complete and country specific. A total selection of 29 different countries was withheld, some active in all three stages of aluminium production and some only on one or two. In total, the selected countries represent 87% of total global bauxite production, 98% of alumina refining and 92% of primary aluminium smelting.

The electricity mix of all 29 countries was retrieved from the International Energy Agency's (IEA) energy statistics [14]. Not all different electricity production sources have been withheld. Only hydropower, coal and gas, nuclear, fuel oil, geothermal, solar, wind and biofuels/waste were considered in this study. The coverage ranges between 92% (Brazil) and 100%, which was considered representative enough. The electricity mix taken into account in this analysis is based on the average national electricity production, because no specific data are available at a country level for the real consumed electricity mix (as aluminium plants sometimes also generate their own electricity). Electricity produced by the primary aluminium smelters is thus not taken into account in this study, but 100% grid dependency is assumed.

An important assumption is that electricity is not traded between countries. M. Koch and J. Harnisch in their study [15] show that important differences in CO_2 emissions related to primary aluminium smelting can occur based on the definition of this boundary. National networks, e.g. in Europe, are highly integrated with neighbouring countries, making the tracking of the exact energy mix very hard and complex. Within the scope of this study, 100% national grid dependency was opted for.

Total smelting process electricity densities are based on the average of the region each country belongs to, as given by the IAI website statistics [8]. No detailed data are available for every individual country. The heat mix used for this analysis is also based on the regional average provided by the IAI [8], due to lack of data. This is a rough approximation, but two reasons can be put forward to support this assumption. First of all, alumina refining represents only about a quarter of the total impact, it is hence much less determining than aluminium smelting. A second reason is that only a small number of countries per region is actively involved in alumina refining. Additionally, in many regions, the biggest share of production is taken up by only one or two countries (only Europe being an exception). These weigh heavy in the regional average, and therefore are represented relatively well by it.

Table 1: Data sources used for the impact analysis.

Data type	Source	Year	Source
Primary aluminium production per country	USGS	2012	[13]
Alumina production	USGS	2012	[12]
Bauxite production	USGS	2012	[12]
Heat mix	IAI	2012	[8]
Electricity mix	IEA	2012	[14]
Smelting energy intensity	IAI	2012	[8]

3. Methodology and model

The model used to analyze the environmental impact of primary aluminium production consists of several layers of flows, sub-processes and materials. Figure 1 is a simplified illustration of the structure of the process network implemented for this analysis. Many hundreds of other flows and processes are included in the total analysis, and the variables that were actively used or altered in the different simulations are shown in red color. These are: i) heat energy mix, ii) electricity energy mix and iii) energy density (in kWh/kg) for example in the smelting and refining process. Alumina and bauxite inputs are given in kg while electricity and heat inputs in kWh.

Regarding alumina, the process is divided into two sub-processes: the production of aluminium hydroxide and the production of alumina. The required energy for alumina refining is provided by heat generation, of which a part can be electricity (at medium voltage). Generally speaking the electricity is not used to generate heat, but is required for auxiliary processes of the refining plant. Aluminium hydroxide is produced from bauxite ore, which was taken equal for all countries throughout the study.

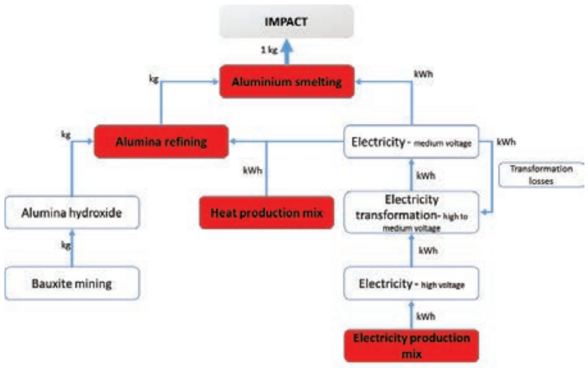

Figure 1: Process network used to calculate the environmental impact of primary aluminium production. The red boxes mark the country dependent variables.

Important conversion ratios, like the mass of bauxite required for the production of 1kg of alumina and the mass of alumina required for 1kg of primary aluminium, are fixed for every country, respectively 1.53kg/kg and 1.935kg/kg (according to global data in EcoInvent v3.0 [10]). This assumption is valid as most plants in the world operate with the same basic technology, mainly the energy requirements differ. Additionally, the fact that some bauxite and alumina is being used for other products than primary aluminium is not taken into account. According to the USGS [16] about 10% of all mined bauxite and 10% of alumina is used for other processes (chemicals, cement, abrasives etc).

The last step of the simulations regards the computation of the impact, which is based on the production of one final kilogram of primary aluminium. In the analysis methods where the three process steps are separately treated, impact results are obtained by only considering the upstream elements of the given flow scheme up to the point where the impact is assessed.

For instance, the impact of alumina refining is computed for 1kg of refined product, taking into consideration the heat mix and bauxite production, but not the smelting process. Similarly, the impact of bauxite production is computed for only 1kg of ore, leaving out all other branches.

4. Results

4.1 Environmental impact per kg of produced aluminium

Figure 2 presents the environmental impact per kg (functional unit) of produced liquid primary aluminium per country expressed in Pts/kg. The impact share of bauxite mining, alumina refining and primary aluminium smelting is also presented as well as the GWP per kg of primary aluminium expressed in CO_2eq.

For the refining part, it is obvious that the impact is quite similar for countries belonging to the same region, which is a result of the assumption related to the heat mix. However, small differences exist, because of the difference in electricity mix which accounts for a small fraction of the heat mix. Countries with coal and oil-rich mixes and high process energy density, rank at the top, while those with relatively lower densities and cleaner mixes emit less.

For aluminium smelting, regional dependency (as the total smelting electricity density is a regional factor) is quasi eliminated. Countries with high fossil fuel shares in their mixes visibly rank higher than those with cleaner technologies, like nuclear, solar, wind and hydropower. Countries like Mozambique, Iceland and Norway have a unit impact up to 4 times smaller than Guinea, South Africa and Kazakhstan.

The observed specific CO_2eq. emissions relate very well to the nature of the heat and electricity mix of each country As a matter of fact, not all countries are equally active in all three sectors, so this graph can be misleading if misinterpreted: it displays the theoretical emissions if the country would engage in aluminium related activities.

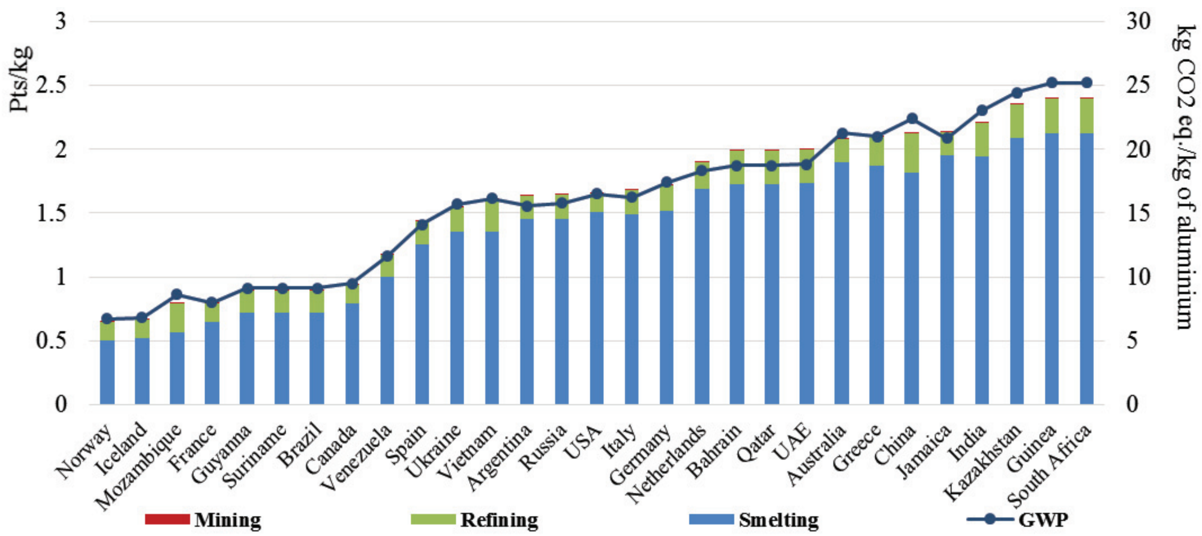

Figure 2: Overall environmental impact per kg (Pts/kg) and GWP (kg of CO_2 eq/kg aluminium) of produced primary liquid aluminium per country.

On a unit level, not China but South Africa is the most polluting country (because of a 92% share of coal in its electricity mix). China ranks fifth on the specific impact ladder, but of the four preceding ones, only South Africa and India contribute to primary aluminium smelting (together only 6% of the global production). As the smelting activity is most critical, it can hence be concluded that China still ranks among the most impacting countries on a unit basis.

4.2 Production volumes (2012) and sector environmental impact

Figure 3 presents the total primary aluminium production per country for 2012. It also contains the overall impact for this year per country expressed in billions of Pts. The difference between the production output rank and the environmental impact contribution rank per country is visible in Figure 3. The graph puts forward China as the world's dominating polluter in this sector; representing 54% for the total impact. It is no surprise that 9 of the top 10 primary aluminium producing countries are among the top 10 most impacting countries. They represent a total of 82% of global primary aluminium production and account for 91% of global impact. These statistics show how paramount the smelting process is. The one country that is missing from that top 10 is Norway. It ranks 9th as a primary aluminium producer, but only 16th for its impact. The explanation is simple: hydropower (96% of its electricity mix). Only Mozambique has a higher share (99%), but produces only half the primary aluminium Norway does, hence its much lower total impact. Italy has no actual impact. It was included in the analysis as it used to play a role in the alumina refining sector until 2009. By 2012 it had completely stopped all its aluminium related activities.

In total, after rescaling to 100% coverage, the primary aluminium industry produced 861Mtonnes of CO2eq emissions in 2012. The Chinese CO_2eq. emissions corresponded to the total national CO_2 emissions of France and Belgium combined.

5. Conclusions

The result of the 29 country study yields a global average of 18.4 tonnes of CO_2 equivalent emissions and 1.87 Pts per kg of primary aluminium production. In total, the aluminium industry was responsible for the emission of about 861Mtonnes of CO_2eq. in 2012, both directly and indirectly. China systematically appeared as being the most important player in all categories on all levels. It produced 40% of global alumina and 46% of global primary aluminium. Doing so, according to the final results, it accounted for 56% of total CO_2 equivalent emissions and 54% of global impact. It hence pollutes proportionally more than what it produces.

Refining energy densities are exceptionally high in China due to low domestic bauxite ore grades, but that should soon change as China's bauxite reserves are depleting rapidly and consequently it will have to rely even more on import. Despite being equipped with the most state-of-the-art and new smelting technology, its coal based electricity production causes it to pollute more than other countries.

If the aluminium industry is to reduce its impact on the planet, or stabilize it, it should start by focussing on China. An extra percentage point of efficiency or cleaner energy mix will have greater effects in China than anywhere else in the world. Not so much the aluminium production energy intensity, but rather the used energy mix seems to be the most determining factor. Countries with a clean mix have a specific smelting impact up to four times smaller compared to countries relying heavily on fossil fuels. It is however true that electricity production is usually not controlled by the aluminium producers, as they tap their electricity from national grids. They can however increase on-plant production and pay more attention to the nature of the heat generation at their refining plants.

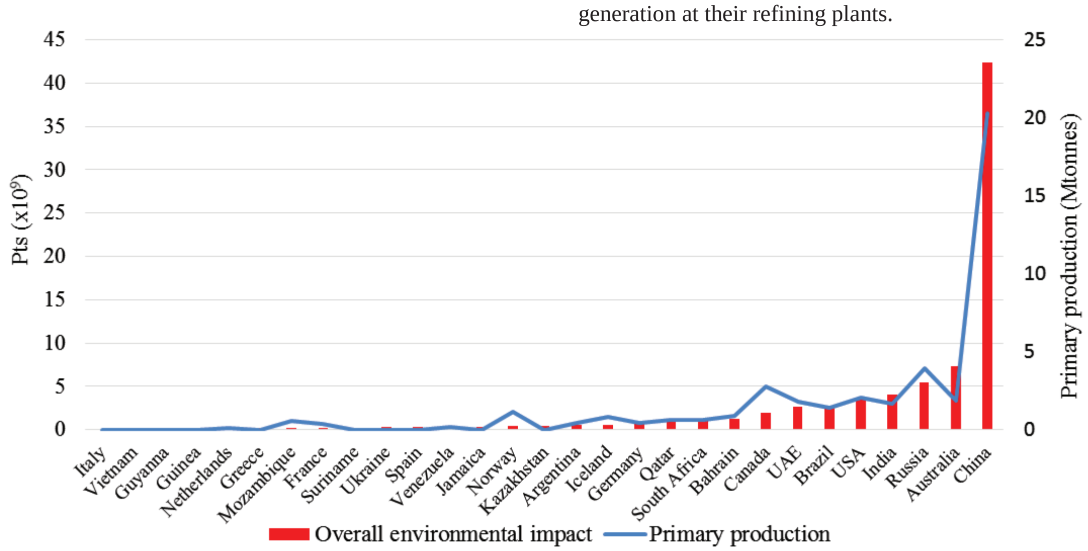

Figure 3: Production volumes (2012) and overall environmental impact per country-producer.

Over the last decades, environmental awareness has grown mainly in Western countries and Japan. This resulted in more stringent regulation but pushed aluminium producers into cheaper energy markets. Today, large volumes of bauxite ore and alumina are traded on a world scale. Parallel, industries are relocating to regions with lower energy costs (e.g. the migration from Europe and North America to the Middle East) and where demand is stronger (China's boom in the 21st century after it integrated the WTO). Unfortunately these regions are often burning tremendous amounts of fossil fuels in order to generate electricity. Today, there are signs that this awareness is burgeoning in the Chinese and Indian giants. Gradually de-carbonizing the energy production through 'cleaner sources' is crucial for the energy intensive material production industries and in particular for the primary aluminium industry in order to meet the carbon emission targets.

Acknowledgments

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