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Environmental Impact Assessment of the Development of Primary Aluminium Industry in Indonesia based on MFA and LCA as a Baseline Study to Achieve Sustainable Industry

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Abstract. The primary aluminium industry in Indonesia is taken as an object study which its production process system was evaluated by the Material Flow Analysis (MFA) and Life Cycle Assessment (LCA) methods. Bauxite mine, alumina refinery, aluminium smelting and casting, the transportation modes and the power generation for supplying the electricity are the processes within the scope of study. The results show that 5.53 tonnes of washed bauxite ore are needed to produce 1.96 tonnes of alumina (64% material reduced) which require the energy in the form of $6.59x10^{-1}$ MWh of electricity and 7.21x10 litre of diesel fuel, and from 1.96 tonnes of alumina with the additional $6.21x10^{-1}$ tonnes of prebake anode, 1 tonne of aluminium ingot can be produced (the material reduce about 49%) which are processed by supporting of 1.57x10 MWh of electricity and 3.78x10 litre of diesel fuel as the energy source. The significant environmental impacts consist of tailings (1.22x10 m^3) to produce 1 tonne of washed bauxite ore, bauxide residue (1.54 tonnes) to produce 1 tonne of alumina, and gaseous emissions (SO_2 emission of 1.15x10 kg and Total Flouride of $2.33x10^{-4}$ kg) during primary aluminium production. While for CO_2 emissions accounted for 1.29x10 tonnes per 1 tonne of aluminium ingot production that is derived from the electricity usage (72.3%), technical process (13.8%), fuel combustion (10.5%), and transportation modes (3.40%). The outlook of CO_2 emission in 2025 due to the development of smelter to produce aluminium ingot product reach to $1.31x10^7$ tonnes (80% increasing compared to 2013's data).

Keywords: primary aluminium industry, material flow analysis, life cycle assessment, Indonesia, Carbon Dioxide (CO_2) emissions.

1. Introduction

As for case in Indonesia, the primary aluminium industry which produces alumina, molten aluminium metal and ingot through the Bayer process and Hall-Heroult process [1], becomes the developed principal sector which supports the national economic condition. Indonesia currently will face the development of primary aluminium industry chain as the advanced process to work with the large potential deposit of bauxite ore (contributes for around 15% of the world demand). The production of primary aluminium is a complex system involving a series of different processes, including bauxite mining, alumina production, an anode (carbon electrode) production, aluminium electrolysis and ingot casting [2]. Hence, these production chains lead to the large extent issues related to resources limited, energy intensive process, and environmental emissions such as atmospheric emissions, high level of carbon dioxide, red mud waste, and, etc [3]. Therefore, this study describes a MFA of 1 tonne of aluminium ingot product and a LCA of the primary aluminium production with particular emphasis on carbon dioxide (CO_2) emissions, as well as provides the future estimation of CO_2 emission based on the Roadmap Frame of Indonesia Aluminium Development.

2. Methodology

Material flow analysis (MFA) is a systematic method to assess the flows and stocks of material within a well-defined system and is used as an important tool particularly in environmental management application

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and industrial ecology to illustrate a better understanding of the material flow, to reveal the important processes during the material life cycle, and to control the industrial closed loop system (strategy development) [4]. Furthermore, material flow analysis of the product system is required for continuing assessment through the Life Cycle Assessment (LCA) method. Life Cycle Assessment is a systematic method for evaluating the environmental burdens associated with a product at all stages in their life cycle – from the extraction of resources, through the production of materials, product parts, and the product itself and the use of the product to the management after it is discarded (therefore, known as "from the cradle to the grave), by identifying and quantifying energy and materials consumed and wastes released to the environment [5].

This study focuses on the current situation and the future development situation of the primary aluminium industry in Indonesia. The major steps applied in this study are consisting as follows:

- Determine the scope of project which is covered the main processes (bauxite mine, alumina refinery and aluminium smelter, the power plant for supplying the electricity, and the transportation modes modes within the supply chain and the auxiliary material purchasing for the main process stages.
- Collecting data from the statistics released by the Statistical Yearbook of Indonesia as a major reference and the secondary data sources included published literature and public information reports.
- Calculating the data in certain defined system to establish the material flow model and the life cycle inventory to specify LCA.
- Environmental impact assessment of current development situation (emphasis on CO_2 emission).
- Calculating the outlook of CO_2 emission based on the development of primary aluminium in Indonesia until 2020.

Based on the scope of the LCA, the supply chain model is presented in Fig 1. The use of the final product by the end of user (consumers) and the product's end of life (recycling) are not included in the study.

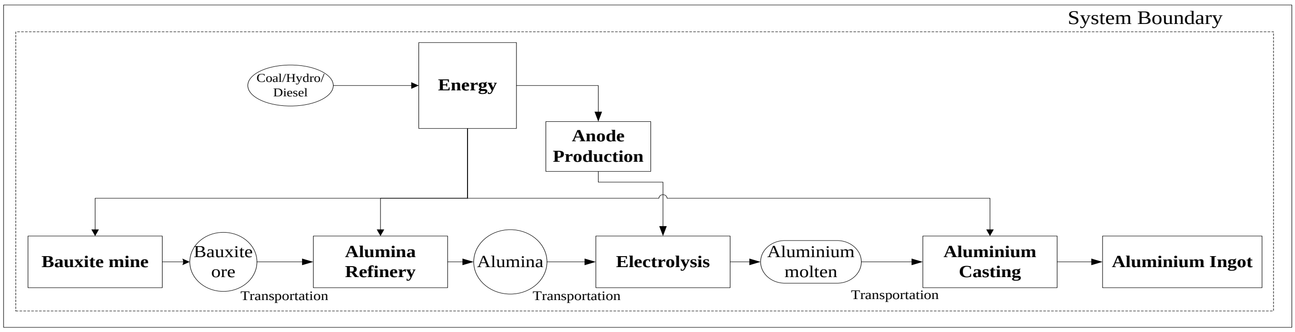

Fig. 1: Primary aluminium Production Process

3. Results

3.1. Material flow analysis (MFA) model

The material flow model for producing 1 tonne of aluminium ingot which presented in Fig.2, shows that 5.53 tonnes of washed bauxite ore are needed to produce 1.96 tonnes of alumina, and with the addition of $6.21x10^{-1}$ tonnes of prebake anode, the 1 tonne of aluminium ingot can be produced. Energy in the form of electricity and diesel fuel for produce 1 tonne of aluminium ingot within bauxite mining, alumina refinery, and aluminium smelter are $4.81x10^{-2}$ MWh and 2.71 litre; $6.59x10^{-1}$ Mwh and 7.21x10 litre; and 1.57x10 MWh and 3.78x10 litre, respectively.

3.2. Life cycle inventory

The LCI of the main materials and energy is presented in Table 1. The total emissions and waste released by the system are displayed in Table 2.

3.3. Future CO_2 emissions of primary aluminium industry

In 2025, the roadmap frame estimates the Indonesia's aluminium demand will reach to $1.44x10^6$ tonnes of aluminium, the alumina production will emerge to $1.80x10^6$ tonnes, the aluminium ingot production will advance to about $1.20x10^6$ tonnes (current situation production is $2.25x10^5$ tonnes), and the estimation of CO_2 emission production due to this development will increase to $1.31x10^7$ tonnes.

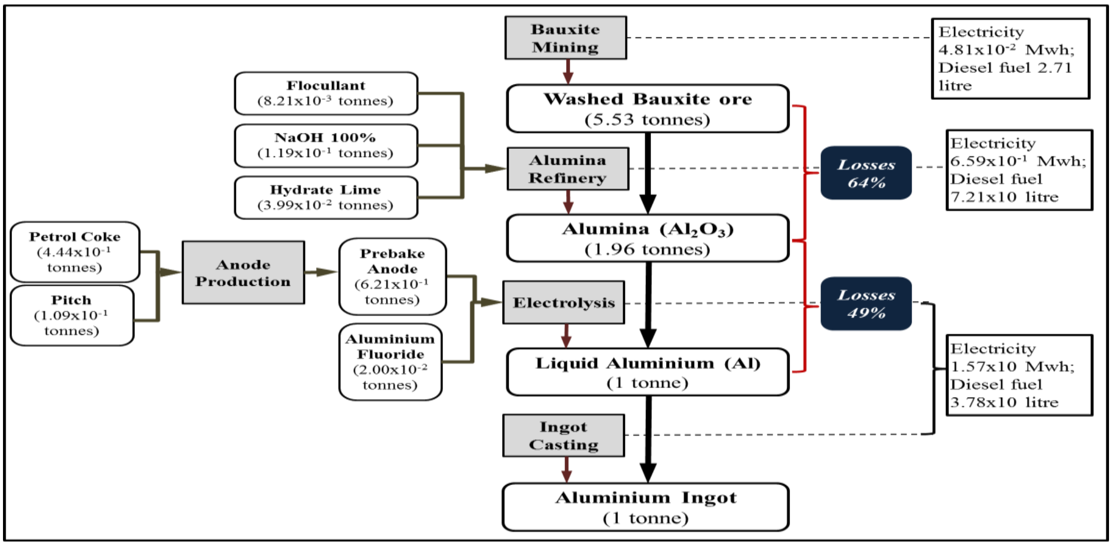

Fig 2: Material Flow Diagram for 1 tonne of aluminium ingot production in Indonesia

Table 1 Material Inputs and Energy Consumed for 1 tonne of product

Reference Flow	Unit	Bauxite *1 t bauxite*	Alumina *1 t alumina*	Aluminium *1 t ingots*
Material Inputs				
Bauxite	kg/t		$2.83x10^3$	
Caustic soda	kg/t		6.11x10	
Hydrate lime	kg/t		2.05x10	
Flocullant	kg/t		4.20	
Petrol Coke	kg/t			$4.44x10^2$
Coal Tar Pitch	kg/t			$1.09x10^2$
Aluminium Fluoride	kg/t			2.00x10
Alumina	kg/t			$1.96x10^3$
Anodes	kg/t			$6.21x10^2$
Flux	kg/t		1.00	
Water	m3/t	8.90	3.87	8.05
Energy Inputs				
Coal	kg/t		$2.58x10^2$	
Diesel Oil	kg/t	$4.10x10^{-1}$	3.08x10	3.16x10
Gasoline	kg/t			1.99
Total Thermal Energy	***MJ/t***	***1.47x10***	***$7.04x10^3$***	***$1.20x10^3$***
Electricity	kWh/t	8.71	$3.36x10^2$	$1.57x10^4$
Total Energy	***MJ/t***	***4.60x10***	***$8.26x10^3$***	***$5.79x10^4$***

4. Discussions

4.1. Life cycle assessment

The type and quantity of materials used in alumina production process are washed bauxite ore (97%), caustic soda (2.1%), flocculant (0.1%), and hydrate lime (0.7%) and supported by the energy in the form of electricity, coal, and diesel oil. While for producing the aluminium ingot from the alumina product, the main type and quantity of materials which are consisting of alumina (75%), aluminium fluoride (1%) and prebake anode (24%) are processed through the electrolysis process which require high consumption of energy (generated from hydropower and diesel oil). Using the current technology and process, the estimation of process efficiency for alumina production from bauxite ore and for aluminium ingot from alumina are 36% and 51% respectively. During the whole primary aluminium production process, the quantity of materials will decrease gradually as emissions in the form of tailings, bauxite residue, and other emissions.

4.2. Tailings

Beneficiation process is required as the only significant processing in bauxite mining [6]. One the beneficiation applied in most bauxite mining in Indonesia is washing process after the ore was extracted. The waste water from the washing process known as tailings which is normally treated in a settling pond and recycled for continual reuse. Around 1.22x10 m^3 is discharged for producing 1 tonne of washed bauxite ore and approximately 75% of it could be recycled to the washing plant.

Table 2 Atmospheric Emissions, CO_2 Emission and Wastes for 1 tonne of product

Emissions and Wastes	Unit	Bauxite Mining *1 t bauxite*	Alumina Production *1 t alumina*	Aluminium Smelter *1 t ingots*
Air Emissions				
Sulfur Dioxide	kg/t	$3.34x10^{-8}$	2.98	5.62
Carbon Monoxide	kg/t	$5.65x10^{-6}$	$1.58x10^{-6}$	$3.13x10^{-2}$
Nitrous Oxides (as NO_2)	kg/t	$4.88x10^{-8}$	1.20	4.10
Hidrocarbon	kg/t	$2.56x10^{-1}$	$9.19x10^{-8}$	$8.67x10^{-6}$
Particulates (dust)	kg/t	$1.82x10^{-7}$	$4.89x10^{-8}$	$8.13x10^{-1}$
Fly ash	kg/t		$2.43x10^{-1}$	
Gaseous Flour (as F)	kg/t			$2.33x10^{-4}$
Hydrochloride (as HCl)	kg/t			$7.85x10^{-5}$
Water Emissions				
Tailings	m3/t	1.22x10		
Oil & grease	kg/t	$1.88x10^{-7}$	$3.69x10^{-6}$	$3.08x10^{-2}$
Suspended solid	kg/t	$6.35x10^{-6}$	$1.83x10^{-3}$	
Hg	g/t	$4.71x10^{-7}$	$9.23x10^{-6}$	
Flouride (F)	kg/t			$3.59x10^{-2}$
Solid Wastes				
Bauxite Residue	kg/t		$1.54x10^{3}$	
Bottom ash	kg/t		$8.11x10^{-2}$	
Filter dust bag	kg/t			9.91
Carbon dust	kg/t			6.67
Dust of alumina	kg/t			3.24
Spent lining	kg/t			2.89x10
Used cathode	kg/t			9.78
Dross Al	kg/t			9.00
Solidified bath	kg/t			$4.41x10^{2}$
Collector bar, iron used	kg/t			1.11x10
CO_2 Emission	kg/t	8.45	$8.78x10^{2}$	$1.11x10^{4}$

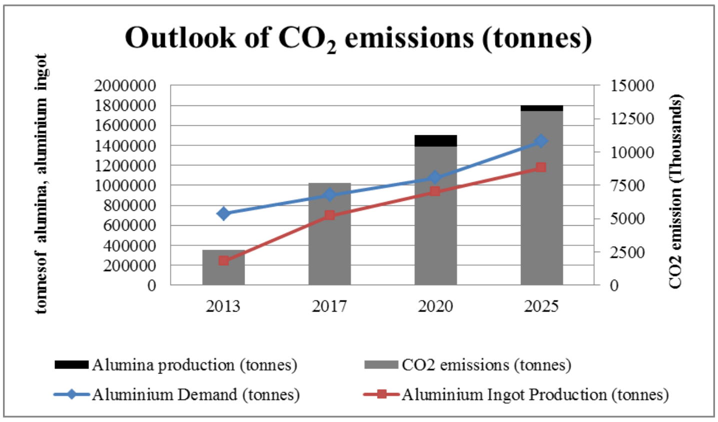

Fig. 3: Trendline CO_2 Emissions of Primary Aluminium Industry to 2025

4.3. Bauxite residue

High quality of bauxite ore contains the concentration of aluminium hydroxide averagely about 40-60% [1], the main impurities such as reactive silica with the value less than 4%, iron, titanium oxide, and loss on ignition (LOi: combined water) [7]. These impurities form insoluble oxides called bauxite residue which be produced through alumina production. The bauxite residue production will be depending on the characteristic of bauxite source and the process efficiency, however 1.54 tonnes of bauxite residue is produced per tonne of alumina. This amount is significant higher if compared with the data published by the IAI (1.35 tonnes) [6] and the EAA (0.68 tonnes) [8]. The disposal of bauxite residue is a major problem in alumina plant through the world due to the high cost and large area of land for building the dams as well as its high alkalinity which lead a problem to water, land, and air of the surrounding area [9]. For the future development, some efforts are should be made to reduce or utilize the bauxite residue in the form of improvement of red mud disposal practices, and utilization of red mud for building construction, micro-fertilizer and neutralizer of pesticides, production of cement, and etc [10].

4.4. Gaseous emissions

Almost all the process stages that involve in primary aluminium production including main processes, transportation and power supply generation release the gaseous emissions such as NOx, SO_2, Total Flouride, CO and CO_2 of which have particularly affected the natural environment around aluminium supply chain plants. This paper will focused only on *Sulfur Dioxide* (SO_2) and *Fluoride* (F). SO_2 is emitted from almost process production stages which related to the fossil fuel combustion (including steam production, calcinations, baking furnace, cast house) and in particular from anodes combustion in the smelters. The total SO_2 emissions for produce 1 tonne of aluminium ingot is 1.15x10 kg. *Flouride* is emitted in gaseous form from the cyrolite bath with the main component derived from aluminium fluoride. The fluoride gaseous is measured about 2.33×10^{-4} kg per tonne of aluminium ingot. This amount is quite low if compared to IAI data [6] which reports 5.72×10^{-1} kg of total fluoride per tonne of aluminium ingot. However, some lack of data for fluoride measurement of aluminium smelting in Indonesia is considered to be affected to the low fluoride emission. The GHG emissions contributed factor namely the *perfluorocarbons* (PFCs) consist of tetrafluoromethane (CF_4) and hexafluoroethane (C_2F_6) gases are not evaluated in this study due to no public data is available.

4.5. Carbon dioxide (CO_2) emissions

Carbon Dioxide (CO_2) emission is definitely emitted through all the primary aluminium supply chain processes including main processes, the transportation modes, and the power generation to produce electricity. Total CO_2 emissions to produce 1 tonne of aluminium ingot reach to 1.29x10 tonnes CO_2, of which 72.3% derived from electricity usage (washing plant, electrolysis process, operational plant); 10.5% derived from fuel combustion (heavy equipment usage, energy generation for power plant, calcinations, baking anode furnace, and casting plant); 13.8% from technical process itself such as anode consumption, and baking anode production; and 3.40% from transportation modes cover transportation product within the primary aluminium supply chain and purchasing auxilarry materials. In China, as the world's largest aluminium producer, the CO_2 emission accounted for 1.82x10 tonnes CO_2/tonne product, of which 72% was contributed by aluminium smelting process and 22% by alumina refinery [2]. While in Indonesia, as recorded by the Ministry of Energy and Mineral Source of Republic of Indonesia in 2010, the CO_2 emission was reached to 4.50×10^{8} tonnes which contributed mainly by sector of industry and power plant. Total CO_2 emission emitted by primary aluminium supply chain in Indonesia is 3.26×10^{6} tonnes and of which responsible for about 0.7% of the total CO_2 emission in Indonesia.

Based on roadmap frame of national aluminium development [11], Government of Indonesia plans to develop the primary aluminium industry as the major national industry and attempts to increase the supply of aluminium ingot and alumina product to meet the national demand. The development will in line with the increasing of CO_2 emissions resulted from the related industry. Assume that there is no change of the power plant technology types which used for both alumina refinery (coal-fired power plant) and smelter (hydropower plant) then it is estimated that CO_2 emissions will rise reach to 80%, in comparison with that in 2013.

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