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Original Article

Techno-Economic Analysis of Electric Arc Furnace Technology as a Pathway towards Indonesia Low-Emission Steel Production

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Abstract: *The European Union (EU) launched the European Green Deal, which led to the implementation of the Carbon Border Adjustment Mechanism (CBAM). Steel is subject to an additional carbon tax based on EU-CBAM. Indonesia also planned to impose a carbon tax on steel, but the tariff is low. There are 3 (three) major steelmaking production routes: Blast Furnace-Basic Oxygen Furnace (BF-BOF), gas-based Direct Reduced Iron-Electric Arc Furnace (DRI-EAF), and scrap-based Electric Arc Furnace (EAF). This research provides a technological review for PT Giga Steel facilities regarding their specific consumption of input materials, fuel, Energy, CO2 emissions, and the cost competitiveness for steel production routes. Furthermore, it will examine the impact of Indonesia's carbon tax and the EU-CBAM on the transition to low-carbon steel production. According to the analysis, the BF-BOF route has the lowest production cost but the highest CO2 emissions. The EAF route has the lowest CO2 emissions, but its production cost is 20.91% higher than that of the BF-BOF route. Given the current Indonesian carbon tax, the BF-BOF route remains the most competitive production route. When the carbon tax tariff exceeds 67 USD/-CO2, EAF will be more competitive. For export markets to the EU with a carbon price >80 USD/t-CO2, the scrap-based EAF route will become the preferred option.*

Keywords: *BF-BOF, CBAM, CO2 Emissions, EAF, and Cost Competitiveness.*

I. INTRODUCTION

The Paris agreement aims to strengthen global efforts to address climate change by maintaining the increase in global average temperature below 2 C above pre-industrial levels and limiting the temperature increase to 1.5 C above pre-industrial levels [1]. To achieve this goal, the European Union (EU) launched the European Green Deal to reduce emissions and become carbon-neutral by 20 [2]. As part of the European Green Deal, the European Commission adopted a regulation to support the EU's carbon-neutral target, the Carbon Border Adjustment Mechanism (CBAM) [3].

CBAM is a climate policy to create a level playing field for the carbon costs of imported products into the EU compared to those of internal EU production. The purpose of CBAM is to reduce the risk of carbon leakage, which occurs when products are produced in countries with less ambitious decarbonisation policies [4]. CBAM is imposed on 6 (six) types of goods: cement, electricity, fertiliser, iron and steel, aluminium, and Hydrogen [5]. After the Paris Agreement, the global steel industry has shifted toward green steel production. Many countries are investing more in emissions-reduction technologies for their steel industries[6]. Starting in 2026, EU-CBAM will be fully implemented and will impose financial consequences on iron and steel products exported to the EU. CBAM will have major economic impacts on the iron and steel industries [7].

Indonesia also ratified the Paris Agreement through Law No. 16 of 2016. As a follow-up to this law, Indonesia submitted a Nationally Determined Contribution (NDC) to the UNFCCC in 2016, with targets of reducing emissions by 29% (unconditional) and 41% (conditional). This target was enhanced in 2022 with Enhanced NDC into 31.89% (unconditional) and 43.2% (conditional) [8]. The Indonesian Government is taking bold steps to promote a low-carbon transition by implementing a carbon tax to reduce carbon emissions. To regulate the implementation of the carbon tax, the Indonesian Government issued Law number 7 of 2021 concerning Harmonisation of Tax Regulations [9]. This regulation states that the carbon tax will be imposed on the purchase of goods containing carbon or activities that produce carbon emissions.

Indonesia's steel industry will be the most affected sector due to the EU-CBAM and the implementation of the carbon tax. The steel industry is energy-intensive and emits a significant amount of Greenhouse Gases (GHG). The steel industry is responsible for around 7% of Global CO2 emissions [10]. Indonesian steel producers exported more than 900 kton of steel to the EU, valued at more than 600 million USD in 2023. Indonesian steel producers must take major steps to transform their production processes to reduce emissions. The high coal dependencies in the current steel production route, long-lived capital assets and the sector's exposure to international trade make the transition toward low-emission steel production challenging [11].

This study was conducted at PT Giga Steel Indonesia (PT GSI), which possesses various steel production routes and is one of the biggest steel producers in Indonesia. PT GSI has a significant portion of exports. In 2023-2024, around 70% of the company's production was for the domestic market, and 30% were for export. Around 22% of the total production was exported to the EU. Despite having DRI-EAF facilities with lower CO2 emission intensity, PT GSI is currently operating only BF-BOF technology to produce steel. The EU-CBAM implementation in 2026 will have a significant impact on PT GSI's export competitiveness.

The purpose of this study is to identify the impacts of Indonesia's carbon tax and CBAM Regulation on the competitiveness of steel produced via three (3) production routes: BF-BOF, DRI-EAF, and scrap-based EAF. A techno-economic analysis using Total Cost of Steel (TCOS) will be used to assess the feasibility of reactivating EAF facilities at PT GSI. The research questions that need to be answered are:

- How much is the production cost and CO2 emissions of steel produced through BF-BOF, DRI-EAF, and scrap-based EAF?
- How big is the impact of Indonesia's carbon tax on the TCOS of those three steel production routes for the domestic market?
- How big is the impact of EU-CBAM on the TCOS of those three steel production routes for the Indonesian steel export market?

After obtaining those three answers, the transition strategy for PT GSI regarding steel production routes can be developed.

II. LITERATURE REVIEW

This section will provide more details on CBAM, how to calculate CO2 emissions, and how to verify the calculation. The current condition of Indonesia's carbon tax will be reviewed. The technological aspects of the steel production routes will be explained, including their principles and the CO2 emissions generated by each route.

A) Embedded emission calculation for CBAM

To ensure a smooth implementation, the European Commission has granted a Transitional Period (01 October 2023 to 31 December 2025) before CBAM is fully implemented in January 2026. During this transitional period, CBAM goods importers are required to report a set of data, including the emissions embedded in their goods, without paying a financial adjustment for those emissions. From 2026, the definitive period of the CBAM will apply. Importers will have to pay CBAM certificates, which they purchase at the average price of EU-ETS allowances, for every CBAM good imported into the EU.

Embedded emissions include direct emissions, indirect emissions, and emissions from precursors used in the production process. Direct emissions are those released from sources owned and controlled by the company. Direct emissions can be calculated based on the quantities of all fuels and relevant materials consumed, using their respective emission factors. Indirect emissions are those that occur during the production of materials or the energy used in production processes. A common example of this indirect emission is electricity generation. We need to monitor electricity consumption in production processes and multiply it by the relevant electricity emission factor 4]. Precursors are materials used in production processes (for example, burnt lime, pellets, ferroalloys, semi-finished products, etc.). These materials contain embedded emissions from their production. These emissions need to be accounted for in the embedded emissions calculation for Iron and Steel production. The general approach to embedded emission calculation is to multiply the consumption of the relevant material in the production process by its emission factor [12].

During the transitional period, verification is a voluntary measure that installation operators may choose to improve their data quality and prepare for the requirements of the definitive period. After the definitive period begins, the authorised CBAM declarant shall ensure that the total embedded emissions declared in the CBAM declaration submitted are verified by a verifier accredited in accordance with the verification principles [4]. Currently, there are no accredited CBAM verifiers in Indonesia. The Government or the private sector in Indonesia need to capture the opportunity to become an accredited CBAM verifier. This can also help CBAM Goods exporters from Indonesia obtain verification of their embedded emissions.

B) Carbon tax in Indonesia

The European Union (EU) has proposed imposing a Carbon Border Adjustment Mechanism (CBAM) on countries without a suitable carbon control policy. Indonesia, as a developing country with an emission level of 0.563 Gt in 2016, will be heavily affected by other countries' domestic carbon pricing and BTA policy implementation [13]. To achieve the Enhanced Nationally Determined Contribution (ENDC) target of a 31.89% reduction in emissions compared to the business-as-usual scenario, the Indonesian Government included a carbon tax in the Law on Harmonisation of Tax Regulation, set at IDR 30/kg of CO2 equivalent. However, the proposed carbon tariff is lower than the level recommended by the World Bank.

According to the Indonesian Ministry of Finance, the estimated cost of mitigating climate change in Indonesia is IDR 3,779 trillion. The Government's efforts to address those needs are through green bonds, green sukuk, and hybrid financing. However, the result is still insufficient and requires innovative financing, such as a carbon market, as an alternative source of funds [14]. Indonesia's carbon market maturity is lower than that of the European Union, South Korea, Japan, and China. Indonesia already has a carbon market, IDX Carbon, but its volume and participation remain very limited. Applying a carbon tax in Indonesia is not easy. This becomes the reason behind postponing its application until 2025 [15]. A carbon tax will be implemented first in the power sector in 2022, then gradually expanded to other sectors, such as transportation, buildings, and sector-based land, from 2025, depending on sector readiness [16]. As a potential sector for carbon tax implementation, the steel industry needs to be prepared for net-zero aspirations by conducting a carbon emission inventory and following regulatory changes.

C) BF-BOF route

In the BF-BOF steelmaking route, carbon contained in the coking coal not only acts as an energy input but also as a reducing agent to bind and remove oxygen from iron ore. This process in the Blast Furnace is the most CO2-intensive, accounting for over 50% of the final product's total CO2 emissions[10]. The BF-BOF route is most affected by high CO2 prices, given its CO2 emissions [17] [18]. A Blast Furnace Plant requires preprocessed inputs such as Sinter Ore from the Sinter Plant, Coke from the Coke Oven Plant, and Pellets from the Pelletizing Plant. Those preprocessing plants also emit CO2 from the combustion of fossil fuels to reach the high processing temperatures required. Blast Furnace Plant produces Hot Metal, which is later processed in Basic Oxygen Furnace (BOF). Around 10% of steel scrap and DRI can be added to the Basic Oxygen Furnace with Hot Metal to produce steel using Oxygen Blowing. Blast Furnace Plant, Basic Oxygen Furnace and Coke Oven Plant also generate by-product gas, which still contains calories and is later utilised as fuel in the by-product gas power plant. The crude steel produced in a Basic Oxygen Furnace is then cast into Slab steel and rolled in facilities such as a plate mill or a Hot Rolling Plant to produce Plate or Hot-Rolled Coil (HRC).

D) DRI-EAF route

Another process route, which uses direct reduction of iron ore with natural gas as the reducing agent, is called the Direct Reduced Iron (DRI) process. In these processes, iron ore is reduced to metallic iron using reformed gases containing CO and H_2. The direct-reduced iron is then generally used as feedstock for EAFs. The main type of technology commercialised is shaft furnace-type reactors developed by Midrex and HYL/Energiron. The shaft furnace uses reformed natural gas to reduce iron ore pellets. Due to the need for abundant, cheap natural gas, most shaft furnace DRI plants are built in countries with abundant natural gas [10]. The DRI-EAF route is chosen as an alternative to reduce environmental impact through carbon emissions [19] [20].

E) Scrap-based EAF route

Further carbon emission reductions can be achieved using the scrap-based EAF route, which has low direct emissions despite high electricity consumption 21]. These furnaces operate at elevated temperatures and rely on a high electric current as their main power source, creating an electric arc between electrodes to facilitate the melting of the metal. Scrap plays the main role in the EAF. Failure to select the correct scrap in the melting operation can cause the electrodes to break or the molten steel to fall. The overall energy intensities observed in the examined EAFs ranged from 510 kWh/t to 80 kWh/t [22].

F) Conceptual Framework

Three technology routes will be analysed in this study: BF-BOF, gas-based DRI-EAF, and scrap-based EAF. For each route, costs will be evaluated using Capex, Operating costs, Raw Material costs, and Energy costs. Capex of each route will be determined using the depreciation value of the facilities from the Annual Reports. The operation cost will also be determined from the Annual Reports.

Raw Material cost will be calculated from the consumption of raw material multiplied by its corresponding market prices. Similar to Raw Material cost, Energy cost will be calculated by multiplying energy consumption by its corresponding prices. CO_2 emissions for each route will be calculated in accordance with ISO 14404-1 and CBAM rules. The amounts of emissions from the respective routes will affect the additional cost due to the Carbon Tax or the requirement for a CBAM Certificate. From all of that data, the Levelized Costing Model using Total Cost of Steel (TCOS) will be determined. TCOS will provide a fair comparison between those three routes. Lastly, a techno-economic evaluation using TCOS and the steel margin will be conducted for EAF technology to develop a transition strategy for low-emission steel production in Indonesia.

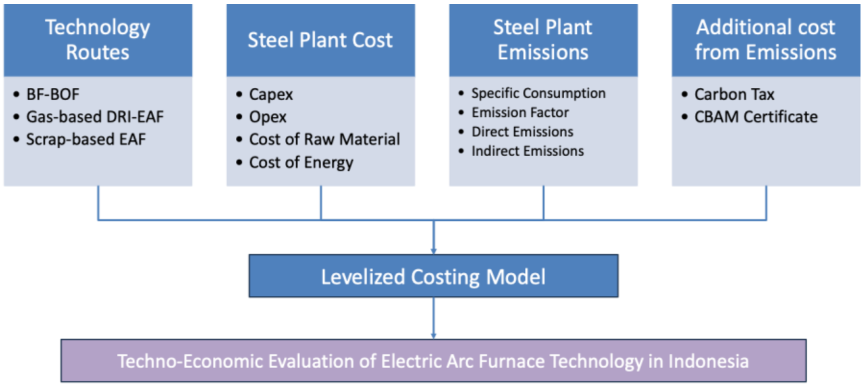

Figure 1. Conceptual Framework

G) *Research Design*

This study will use a quantitative method in data collection, calculation and analysis. In designing this research, start by defining the Research Question (a). Using the quantitative method, production data, Cost of Goods Sold (COGS), Operating Expenses, Raw Material consumption, and Energy consumption need to be collected through PT Giga Steel Indonesia data or Annual Reports. After gathering all necessary information, the production cost of steel for each steel production route can be calculated. The calculation result will be used to analyse which route has the most cost competitiveness. Second step is calculating the actual CO_2 emissions of steel produced through the BF-BOF route, gas-based DRI-EAF route, and scrap-based EAF route". More detailed types of raw materials and energy used in the production process will be needed for the carbon emission calculation. Raw materials consumption will be multiplied by each corresponding emission factor to get the emissions. Emission factor tier-3 will be used if available. If not, then the emission factor tiers 2 and 1 will be used. ISO 14404-1 will be used as the standard for emission calculation. These are internationally recognised methods used for greenhouse gas inventories.

Answering Research Question (b) needs Production cost and Carbon Emissions from Research Question (a). By multiplying the Indonesian Carbon Tax by carbon emissions, the additional cost of carbon emissions can be obtained. Using those numbers and adding the steel production cost, the domestic cost competitiveness of steel for each route can be calculated, and the impact of the Indonesian Carbon Tax can be analysed. The Research Question (c) needs products from Research Question (a). The carbon emissions of each steel production route will be multiplied by the value of the CBAM Certificate to get the additional cost due to carbon emissions. The CBAM Certificate will be charged based on the embedded carbon emissions of steel products imported into the EU. The impact of the CBAM Certificate on the cost competitiveness of exported steel products from each route can be analysed. After analysing the impact of Indonesia's Carbon Tax and EU-CBAM on the cost competitiveness of steel production routes, recommendations for the transition proportions of the steel production routes will be evaluated. The transition proportion refers to the proportion of steel produced through BF-BOF, gas-based DRI-EAF, or scrap-based EAF to fulfil domestic and export markets, using margin as the main parameter.

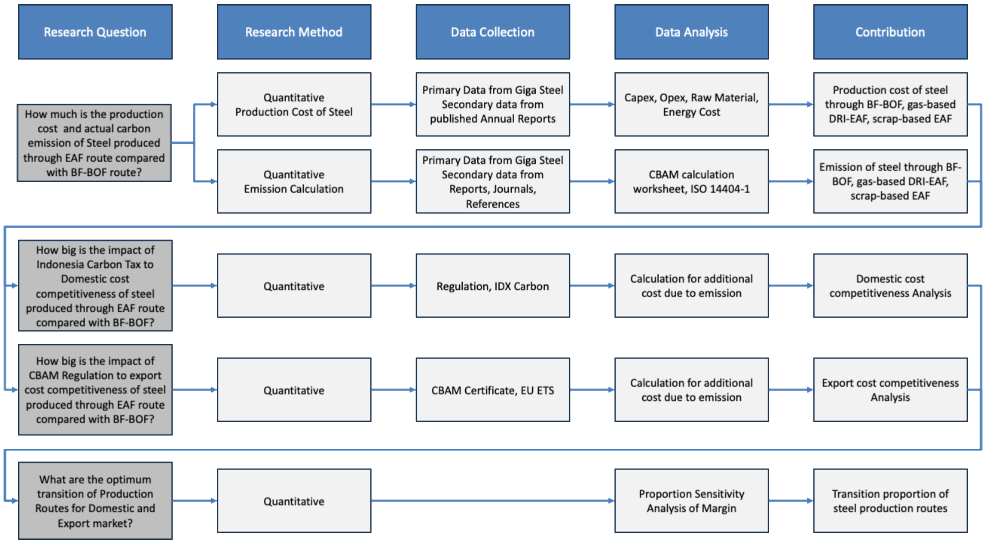

Figure 2. Research Design

H) Data Collection Method

This study will use two types of data: Primary Sources and Secondary Sources. Data from Primary Sources will be acquired from PT Giga Steel Indonesia for 5 years. Those data consist of, but are not limited to:

- Production (Ton)
- Iron Ore (Ton)
- Scrap (Ton)
- Coke (Ton)
- PCI Coal (Ton)
- Anthracite (Ton)
- Electricity (kWh)
- Natural Gas (MMBTU)
- Coke Oven Gas (Nm3)
- Blast Furnace Gas (Nm3)
- Converter Gas (Nm3)
- Burnt lime (ton)
- Lime stone (ton)

Emission factor data will be obtained from laboratory analysis of the corresponding material, if available. If not, the tier-2 emission factor from national data and the tier-1 emission factor from global average data will be used. The electricity emission factor for JAMALI PLN will be used and combined with the emission factor from PT GSI Power Plant. The electricity price will be based on the PLN price and the electricity price from PT GSI Power Plant. The PGN emission factor will be used for emissions from Natural Gas. Natural Gas price will consist of the HGBT price and the Normal PGN price, based on the HGBT allocation for PT GSI. Other material prices will be based on market prices obtained from reliable sources.

Secondary Sources data will be acquired from Annual Reports, Scientific and reputable Journals, Studies and Reports from reputable organisations, and other reliable references. Capex and operational cost data will be collected from the Annual Reports of Giga Steel and other Steel companies, based on the production route. Specific consumption of unavailable materials will be sourced from scientific journals, reports from reputable organisations, and other reliable sources. The Indonesian Carbon Tax will follow the latest regulation, and the Indonesian Carbon price is set according to IDX Carbon. The CBAM Certificate will be based on the EU ETS Carbon price.

I) Data Analysis Method

Techno-economic analysis will be used as the method of analysis in this study. Technical analysis consists of evaluating the performance of the steel production route and the specific consumption of raw materials, auxiliary materials, fuel, energy, and utilities. Those specific consumption data will be used to calculate the carbon emissions generated by each steel production route and will become an important factor in the analysis. The economic analysis will focus on the cost of production for each steel production route. It will cover Capital expenditure, Operational expenditure, Raw Material Cost and Energy Cost. The Total Cost of Steel (TCOS) will be used to directly compare the costs of steel production across three different routes. TCOS will calculate the average cost of steel production plus additional costs related to its CO_2 emissions.

The production cost of each steel production route will be increased by an additional cost for carbon emissions. Indonesia's Carbon Tax will serve as a variable to illustrate the level of Carbon Tax that can encourage the use of low-carbon technology in steel production. The total cost of steel for each technology will be calculated, varying with the Indonesian Carbon Tax tariff to show the sensitivity to increasing or decreasing the tariff. The proportion of the steel production route with the best competitiveness in the domestic market and the proportion of the steel production route with the best competitiveness in the export market will be simulated to determine the possible transition proportion. HRC market price will vary with the proportion of steel production routes to calculate the margin between the Total Cost of Steel and the HRC market price.

III. RESULTS AND DISCUSSION

There are 5 (five) steps used to analyse the cost competitiveness between the BF-BOF route, the DRI-EAF route, and the scrap-based EAF route. The first step is to calculate the specific consumption of raw materials, fuel/energy, and utilities per ton of product (Slab and HRC). The specific consumptions will be used to calculate the steel production cost in step 2. There will also be additions for OPEX and CAPEX to arrive at the total production cost. In step 3, CO_2 emissions of those 3 (three routes are calculated by multiplying the specific consumption of each carbon-containing material by its emission factor. Step 4 is to calculate the additional cost from carbon emissions. After determining the emissions for each steel production route, the additional cost can be calculated based on the estimated carbon price in the domestic or export market. Step 5 is to do the sensitivity analysis and comparison between those 3 (three steel production routes.

A) Specific consumption of steel production routes

BF-BOF, DRI-EAF and scrap-based EAF technology have different processes and therefore have different specific consumption for raw materials and energy. The BF-BOF route primarily uses coal as the main reductant and energy source. The DRI-EAF route primarily uses Natural Gas as the reductant, while EAF facilities use electricity as their main energy source. The data used to calculate the specific emissions for the BF-BOF route are the actual production and consumption data of PT GSI over a 5-year consecutive period. The raw materials, energy, fuel and utilities material-specific consumption data are shown in Table 1.

The data used to calculate the specific emissions for the DRI-EAF route are divided into 2 parts. The first part is for Direct Reduction Plant-specific consumption, and the Second part is for Slab Steel Plant-specific consumption. The raw material, energy and utilities specific consumption data of PT GSI's Direct Reduction Plant, and raw material specific consumption data of PT GSI's Slab Steel Plant are shown in Table 1.

Table 1: Specific Consumption of Raw Materials, Fuel, Energy and Utilities

Material	Unit	Specific Consumption				
		BF-BOF (Unit/t-Slab)	DR Plant (Unit/t-DRI)	DRI-EAF (Unit/t-Slab)	Scrap EAF (Unit/t-Slab)	Hot Rolling (Unit/t-HRC)
Iron Ore	Ton	1.32	-	-	-	-
Pellet	Ton	0.27	1.55	-	-	-
DRI	Ton	-	-	0.96	-	-
Scrap	Ton	0.21	-	0.29	1.14	-
Slab	Ton	-	-	-	-	1.04
Coking Coal	Ton	0.49	-	-	-	-
Anthracite	Ton	0.04	-	-	-	-
PCI	Ton	0.15	-	-	-	-
Limestone	Ton	0.17	-	0.02	0.02	-
Burnt lime	Ton	0.07	-	0.06	0.06	-
Ferroalloys	Ton	0.01	-	0.01	0.01	-
Electrodes	Ton	-	-	0.00	0.00	-
Electricity	kWh	264.13	80.33	838.09	576.00	127.62
Natural Gas	MMBTU	0.02	13.51	0.85	-	1.89
Natural Gas	Nm^3	0.69	386.86	24.23	-	53.99
Water	m^3	1.88	2.66	2.28	2.28	0.94
Oxygen	Nm^3	95.15	15.52	32.42	32.42	-
Nitrogen	Nm^3	83.20	39.71	10.12	10.12	-
Argon	Nm^3	2.01	-	1.57	1.57	-

The scrap-based EAF route has the same specific consumption as the DRI-EAF route. The difference is the raw material used in the process. Instead of using DRI as ferrous material input, the scrap-based EAF route uses scrap as its main ferrous material input. Based on the Best Available Techniques (BAT) Reference Document for Ferrous Metals Processing Industry issued by the Joint Research Centre, the European Commission's science and knowledge service, EAF consumes 1039 – 1232 kg scrap and 404-748 kWh electricity per ton of liquid steel. In this research, a median number of 1135 kg of scrap and 576 kWh of electricity per ton of slab is used as the specific consumption for the scrap-based EAF route.

The output product of steelmaking routes such as BF-BOF, DRI-EAF, and scrap-based EAF is in the form of a slab. But the products commonly traded internationally are in Hot Rolled Coil (HRC) form. This is the downstream product of the slab that is being processed in the Hot Strip Mill. In this research, HRC will be used as the finished product traded domestically and internationally. The data used to calculate the specific emission of the Hot Strip Mill are the actual consumption data from PT GSI over a 3-year consecutive period. Table 1 also shows HRC raw materials, energy, fuels, and utilities-specific consumption data.

B) Production cost of steel production routes

Specific consumption of Raw Materials, Energy and Utilities will be used to calculate the Production Cost of steel for each route. Unit price for each item used in the calculation is listed in Table 2.

Table 2: Price of raw materials, fuel, Energy, and utilities

Material	Unit	Price	Reference
Iron Ore	USD/Ton	101.75	Fastmarket Steel Market Tracker Feb 2026
Pellet	USD/Ton	127.97	Fastmarket Weekly 27 February – 06 March 2026
Scrap	USD/Ton	345.67	Fastmarket Steel Market Tracker Feb 2026
Coking Coal	USD/Ton	195.51	Fastmarket Weekly 27 February – 06 March 2026
Anthracite	USD/Ton	123.48	Fastmarket Weekly 27 February – 06 March 2026
PCI	USD/Ton	123.48	Fastmarket Weekly 27 February – 06 March 2026
Limestone	USD/Ton	37.86	Internal data
Burnt lime	USD/Ton	75.72	Internal data
Ferroalloy	USD/Ton	1902.41	Internal data
Refractories	USD/Ton	1298.48	Internal data

Electrode	USD/Ton	14,131.70	Internal data
Electricity (for BF-BOF)	USD/kWh	0.05	Composite between PLN and Internal Generation
Electricity	USD/kWh	0.06	PLN
Natural Gas	USD/MMBTU	7.50	PGN HGBT price
Water	USD/m^3	0.77	Local Provider price
Oxygen	USD/Nm^3	0.07	Local Provider price
Nitrogen	USD/Nm^3	0.06	Local Provider price
Argon	USD/Nm^3	0.65	Local Provider price

There are 2 (two) steps of the calculation that will be done. First is the production cost until the slab is a semi-finished product. And then continue with production cost until Hot Rolled Coil (HRC) as the finished product. Slab production route is differentiated into 3 (three) routes mentioned before. HRC production is the same for the 3 (three routes using slab as raw material and being processed at the Hot Rolling Plant.

Production cost calculation formula of HRC through BF-BOF routes is as follows:

$$\text{C-Slab}_{\text{BF-BOF}} = \sum P_{\text{slab}} * S_{\text{slab}} \quad (1)$$

$$\text{C-HRC}_{\text{BF-BOF}} = (\text{C-Slab}_{\text{BF-BOF}} * S_{\text{HRC}}) + \sum P_{\text{HRC}} * S_{\text{HRC}} \quad (2)$$

Where, $\text{C-Slab}_{\text{BF-BOF}}$ is the production cost of slab from the BF-BOF route, P_{slab} is the price of each material to produce Slab, S_{slab} is the specific consumption of each material to produce Slab, $\text{C-HRC}_{\text{BF-BOF}}$ is the production cost of HRC from BF-BOF slab, P_{HRC} is the price of each material to produce HRC, and S_{HRC} is the specific consumption to produce HRC. From the calculation, slab production cost using the BF-BOF route is 442.38 USD/t-Slab. HRC production cost from BF-BOF Slabs is 490.21 USD/t-HRC.

Production cost calculation formula of HRC through DRI-EAF routes is as follows:

$$\text{C-DRI}_{\text{DRI-EAF}} = \sum P_{\text{DRI}} * S_{\text{DRI}} \quad (3)$$

$$\text{C-Slab}_{\text{DRI-EAF}} = (\text{C-DRI}_{\text{DRI-EAF}} * S_{\text{slab}}) + \sum P_{\text{slab}} * S_{\text{slab}} \quad (4)$$

$$\text{C-HRC}_{\text{DRI-EAF}} = (\text{C-Slab}_{\text{DRI-EAF}} * S_{\text{HRC}}) + \sum P_{\text{HRC}} * S_{\text{HRC}} \quad (5)$$

Where, $\text{C-DRI}_{\text{DRI-EAF}}$ is the production cost of DRI from the DRI-EAF route, $\text{C-Slab}_{\text{DRI-EAF}}$ is the production cost of slab from the DRI-EAF route, and $\text{C-HRC}_{\text{DRI-EAF}}$ is the production cost of HRC from DRI-EAF slab. DRI production cost is 314.56 USD/t-DRI. Slab production cost using the DRI-EAF route is 564.69 USD/t-Slab. HRC production cost from DRI-EAF Slabs is 618.90 USD/t-HRC.

Production cost calculation formula of HRC through scrap-based EAF routes is as follows:

$$\text{C-Slab}_{\text{EAF}} = \sum P_{\text{slab}} * S_{\text{slab}} \quad (6)$$

$$\text{C-HRC}_{\text{EAF}} = (\text{C-Slab}_{\text{EAF}} * S_{\text{HRC}}) + \sum P_{\text{HRC}} * S_{\text{HRC}} \quad (7)$$

Where, $\text{C-Slab}_{\text{EAF}}$ is the production cost of slab from the scrap-based EAF route, and $\text{C-HRC}_{\text{EAF}}$ is the production cost of HRC from scrap-based EAF slab. Slab production cost using the scrap-based EAF route is 541.46 USD/t-Slab. HRC production cost from DRI-EAF Slabs is 594.78 USD/t-HRC.

C) CO_2 emissions of steel production routes

CO_2 Emissions in this study use ISO 14404-1, the International Standard for calculating carbon dioxide emission intensity from iron and steel production. The specific consumption of each emission source material will be multiplied by its corresponding emission factor. The emission factors used in the calculation are listed in Table 3.

Table 3: Emission factor of raw materials, fuel, energy, and utilities

Material	Unit	Emission Factor	Reference
Pellet	t-CO_2/Ton	0.137000	ISO 14404-1
Scrap	t-CO_2/Ton	0.036000	IPCC 2019
Coking Coal	t-CO_2/Ton	3.059000	ISO 14404-1
Anthracite	t-CO_2/Ton	2.784000	ISO 14404-1
PCI	t-CO_2/Ton	2.955000	ISO 14404-1
Limestone	t-CO_2/Ton	0.440000	ISO 14404-1
Burnt lime	t-CO_2/Ton	0.950000	ISO 14404-1
Electrodes	t-CO_2/Ton	3.666667	IPCC 2019
Electricity (for BF-BOF)	t-CO_2/kWh	0.658778	Composite between PLN and Internal Generation
Electricity	t-CO_2/kWh	0.870000	PLN Jamali Emission Factor
Natural Gas	t-CO_2/Nm^3	0.201400	ISO 14404-1

Oxygen	$t\text{-}CO_2/Nm^3$	0.000355	ISO 14404-1
Nitrogen	$t\text{-}CO_2/Nm^3$	0.000103	ISO 14404-1
Argon	$t\text{-}CO_2/Nm^3$	0.000103	ISO 14404-1
COG	$t\text{-}CO_2/Nm^3$	0.000952	ISO 14404-1
BFG	$t\text{-}CO_2/Nm^3$	0.000185	ISO 14404-1
LDG	$t\text{-}CO_2/Nm^3$	0.000470	ISO 14404-1
Coal Tar	$t\text{-}CO_2/Ton$	3.389000	ISO 14404-1
Light Oil	$t\text{-}CO_2/Ton$	3.382000	ISO 14404-1

Similar to production cost calculations, 2 (two steps of the CO_2 emission calculation will be done. First, the CO2 emissions calculation is until the slab is a semi-finished product. And then continue with the CO_2 emissions calculation until Hot Rolled Coil (HRC) as the finished product. From the calculation, the CO_2 emissions of the slab using the BF-BOF route are 2.189 t-CO_2/t-Slab. CO_2 emissions of HRC from BF-BOF Slabs are 2.466 t-CO_2/t-HRC. CO_2 emissions of DRI are 1.071 t-CO_2/t-DRI. CO_2 emissions of slab using the DRI-EAF route are 1.905 t-CO_2/t-Slab. CO2 emissions of HRC from DRI-EAF Slabs are 2.198 t-CO_2/t-HRC. CO_2 emissions of slab using scrap-based EAF route are 0.684 t-CO_2/t-Slab. CO_2 emissions of HRC from scrap-based EAF Slabs are 0.904 t-CO_2/t-HRC.

D) *Additional cost from the CO2 emissions of the steel production route*

CO_2 emissions from steel products can result in additional costs due to Carbon Tax or other Environmental protection regulations, such as the Carbon Border Adjustment Mechanism (CBAM) in the European Union. The formula for the total cost of HRC can be derived from the production cost and CO_2 emissions as follows:

$$TCOS_{BF\text{-}BOF} = 491.93 + 2.466\ X \quad (8)$$

$$TCOS_{DRI\text{-}EAF} = 618.90 + 2.198\ X \quad (9)$$

$$TCOS_{EAF} = 594.78 + 0.930\ X \quad (10)$$

Where, $TCOS_{BF\text{-}BOF}$ is the total cost of HRC production plus additional carbon cost from the BF-BOF route. $TCOS_{DRI\text{-}EAF}$ is the total cost of HRC production plus additional carbon cost from the DRI-EAF route. $TCOS_{EAF}$ is the total cost of HRC production plus additional carbon cost from the scrap-based EAF route. And X is the Carbon price per ton of CO_2.

E) *Indonesia's carbon tax impacts on the domestic steel market*

The carbon tax in Indonesia is stipulated in Law number 7 of 2021. According to Article 13 of the law, the minimum carbon tax tariff is 30 IDR/kgCO_2. This is equal to 2 USD/tCO_2. Using this number, the impact of Indonesia's carbon tax on steel production routes is shown in Table 26. When the BF-BOF route uses regular electricity, the impact of additional CO_2 cost is 4.93 USD/t_{HRC} (1.0%). The impact for the DRI-EAF route is 4.40 USD/t_{HRC} (0.7%). Another case is scrap-based EAF, which experienced the impact of 1.86 USD/t_{HRC} (0.3%). When the company uses REC for its electricity supply, the additional CO_2 impact decreases slightly to 4.68 USD/tHRC (0.9%) for the BF-BOF route, 2.52 USD/tHRC (0.4%) for the DRI-EAF route, and 0.60 USD/t_{HRC} (0.1%) for the scrap-based EAF route.

Due to Indonesia's low carbon tax rate, the impact of additional CO_2 emissions is not significant. In this condition, the BF-BOF route remains the most competitive, with a total steel production cost of 496.98 USD/t_{HRC}. DRI-EAF and scrap-based EAF total production costs (623.67 USD/t_{HRC} and 596.89 USD/t_{HRC}) are more expensive compared to the BF-BOF route. With a low carbon tax tariff, the incentive and motivation for steel companies to transition to lower-carbon-emission technology are also less attractive.

F) *EU-CBAM impacts on the export steel market*

When EU-CBAM takes effect in 2026, steel products exported to the European Union will incur an additional cost due to the CBAM Certificate. The importers need to purchase a CBAM Certificate based on the CO_2 emissions of the imported steel. Recently, the EU carbon price was approximately 70 EUR/tCO_2, or about 80 USD/tCO_2. At this level of carbon price, the additional carbon cost significantly increased the total cost of steel production. The carbon price in the European Union is shown in Table 27. For the BF-BOF route, the additional carbon cost is 197.28 USD/tHRC (28.6%) with regular electricity and 187.19 USD/tHRC (27.5%) with REC. The DRI-EAF route also experienced an impact of 175.87 USD/t_{HRC} (22.1%) for regular electricity and 100.88 USD/t_{HRC} (14.0%) when using REC. The lowest impact was experienced by scrap-based EAF with 74.44 USD/t_{HRC} (11.1%) for regular electricity and even lower with REC at 23.94 USD/t_{HRC} (3.9%).

Total steel production costs, with high carbon prices in the European Union, shift the cost competitiveness of steel production routes. Scrap-based EAF is becoming the most competitive route, with a total production cost of 620.23 USD/tHRC, compared to the BF-BOF and DRI-EAF routes at 679.49 USD/tHRC and 722.03 USD/tHRC, respectively. A high carbon price tariff will encourage companies to transition to lower-emission technologies.

G) Policy Implication

Figure 3 shows that if the carbon price is below 66 USD/t-CO2, the BF-BOF route remains more cost-competitive than the scrap-based EAF and DRI-EAF routes. Starting from a carbon price of 67 USD/t-CO_2, scrap-based EAF has the best cost competitiveness compared to other routes. The carbon price in Indonesia, as reported by IDXCarbon, is below 10 USD/t-CO_2. Despite this condition, HRC produced via the BF-BOF route still has better competitiveness than other routes for domestic transactions. The European Union has different conditions from Indonesia regarding carbon pricing. The recent carbon price in Europe is approximately 80 USD/t-CO_2. In this condition, HRC produced via scrap-based EAF has better cost competitiveness compared with the BF-BOF route. The scrap-based EAF route is suitable for export-oriented steel products, especially to Europe.

Based on Indonesia's Second Nationally Determined Contribution (Second NDC), a commitment to reduce emissions, the renewable energy mix target is 19%-23% in 2030, increasing to 36%-40% in 2040, and jumping to 70%-72% in 2060. With the increase of the renewable energy mix in Indonesia, we can expect a reduction of electricity-specific emissions. With lower electricity-specific emissions, the competitiveness of the EAF steel production route will be stronger. Nowadays, REC can be a solution to get electricity from renewable sources with zero emissions.

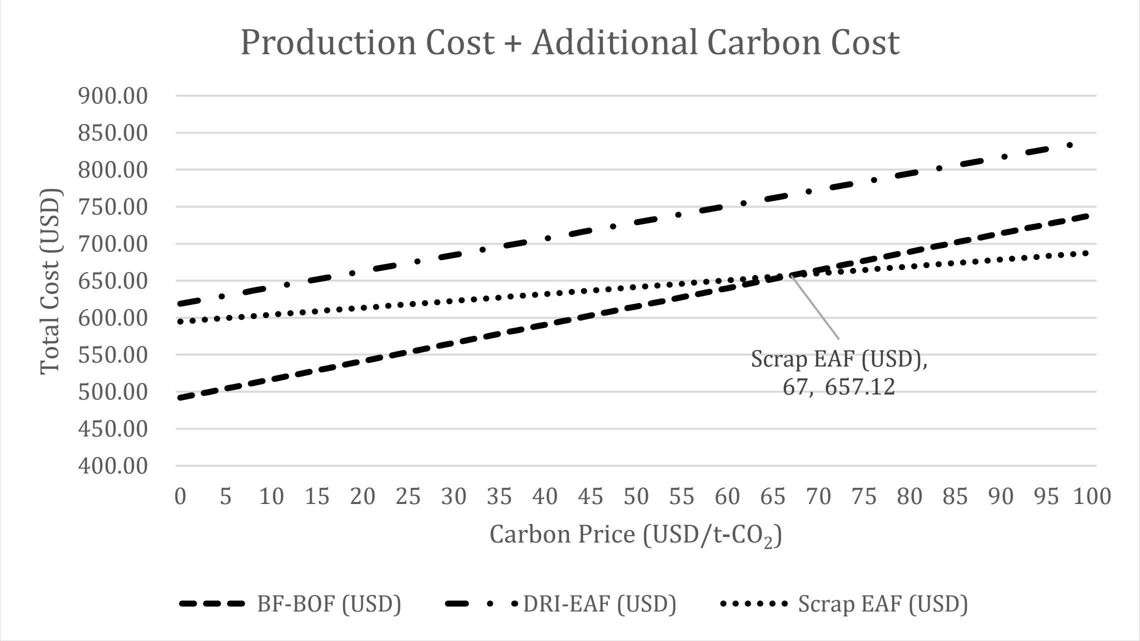

Figure 3. Total Cost of Steel Production Routes

H) Sensitivity analysis and proportion for steel production routes

Regardless of the carbon tax tariff issues, from the steel industry's perspective, Giga Steel needs to prepare for the possibility of a future change in carbon prices. A sensitivity simulation is being conducted to understand better what PT GSI needs to do based on the HRC market price. In the scenario, the BF-BOF route will produce steel for the domestic market with a carbon price of 2 USD/t-CO_2. The scrap-based EAF route will produce steel for the export market with a carbon price of 80 USD/t-CO_2. The production proportion of BF-BOF: Scrap-based EAF will be varied from 100:0 to 0:100. And the numbers shown in Table 4 are the margin between the Total Cost of Steel and HRC Market price in USD/t-HRC. The margin for each condition can be formulated as follows:

$$\text{Margin} = \text{Price} - \{(\%_{BF\text{-}BOF} * TCOS_{BF\text{-}BOF(ID)}) + (\%_{EAF} * TCOS_{EAF(EU)})\} \quad (11)$$

Where price is the HRC market price in USD/t-HRC, $\%_{BF\text{-}BOF}$ is production proportion from BF-BOF route, $TCOS_{BF\text{-}BOF(ID)}$ is the total cost of steel using Indonesia Carbon Tax (2 USD/t-CO_2), $\%_{EAF}$ is production proportion from EAF route, $TCOS_{EAF(EU)}$ is the total cost of steel using EU carbon price (80 USD/t-CO_2). When the HRC price is 500 USD/t, the BF-BOF route is the only option that can generate a margin for PT GSI. Production is 100% BF-BOF, serving only the domestic market. At a level of 540 USD/t-HRC, PT GSI has the opportunity to use a 75% BF-BOF route for the domestic market and a 25% scrap-based EAF route for export. PT GSI can use a 50:50 proportion at the HRC market price level of 590 USD/t-HRC. At 630 USD/t-HRC, the scrap-based EAF route could become more dominant than the BF-BOF route, with a 25% BF-BOF:75 % scrap-based EAF split. And at the minimum price level of 670 USD/t-HRC, the scrap-based EAF can fully replace the BF-BOF route.

From Table 4, we can see that the largest margin is generated when PT GSI uses 100% BF-BOF and supplies only the domestic market. This is because the low carbon price in Indonesia (2 USD/t-CO_2) will make the BF-BOF route pay less for its high CO_2 emissions. In this condition, transitioning to scrap-based EAF will reduce PT GSI's margin, but it will open the possibility of accessing the export market. Using the PT GSI February 2026 HRC export price of 550 USD/t-HRC, it is possible to use a 70% proportion of the BF-BOF route and a 30% proportion of the scrap-based EAF route.

Table 4: Margin Sensitivity of BF-BOF and scrap-based EAF production portion versus HRC market price

BF-BOF:EAF	HRC Market Price (USD/t-HRC)														
	490	500	510	530	540	550	580	590	600	620	630	640	660	670	680
100:0	(7)	3	13	33	43	53	83	93	103	123	133	143	163	173	183
95:5	(15)	(5)	5	25	35	45	75	85	95	115	125	135	155	165	175
90:10	(24)	(14)	(4)	16	26	36	66	76	86	106	116	126	146	156	166
85:15	(33)	(23)	(13)	7	17	27	57	67	77	97	107	117	137	147	157
80:20	(41)	(31)	(21)	(1)	9	19	49	59	69	89	99	109	129	139	149
75:25	(50)	(40)	(30)	(10)	0	10	40	50	60	80	90	100	120	130	140
70:30	(59)	(49)	(39)	(19)	(9)	1	31	41	51	71	81	91	111	121	131
65:35	(67)	(57)	(47)	(27)	(17)	(7)	23	33	43	63	73	83	103	113	123
60:40	(76)	(66)	(56)	(36)	(26)	(16)	14	24	34	54	64	74	94	104	114
55:45	(84)	(74)	(64)	(44)	(34)	(24)	6	16	26	46	56	66	86	96	106
50:50	(93)	(83)	(73)	(53)	(43)	(33)	(3)	7	17	37	47	57	77	87	97
45:55	(102)	(92)	(82)	(62)	(52)	(42)	(12)	(2)	8	28	38	48	68	78	88
40:60	(110)	(100)	(90)	(70)	(60)	(50)	(20)	(10)	(0)	20	30	40	60	70	80
35:65	(119)	(109)	(99)	(79)	(69)	(59)	(29)	(19)	(9)	11	21	31	51	61	71
30:70	(128)	(118)	(108)	(88)	(78)	(68)	(38)	(28)	(18)	2	12	22	42	52	62
25:75	(136)	(126)	(116)	(96)	(86)	(76)	(46)	(36)	(26)	(6)	4	14	34	44	54
20:80	(145)	(135)	(125)	(105)	(95)	(85)	(55)	(45)	(35)	(15)	(5)	5	25	35	45
15:85	(153)	(143)	(133)	(113)	(103)	(93)	(63)	(53)	(43)	(23)	(13)	(3)	17	27	37
10:90	(162)	(152)	(142)	(122)	(112)	(102)	(72)	(62)	(52)	(32)	(22)	(12)	8	18	28
5:95	(171)	(161)	(151)	(131)	(121)	(111)	(81)	(71)	(61)	(41)	(31)	(21)	(1)	9	19

0:100	(179)	(169)	(159)	(139)	(129)	(119)	(89)	(79)	(69)	(49)	(39)	(29)	(9)	1	11

IV. CONCLUSION

The purpose of this study is to conduct a techno-economic analysis of the Electric Arc Furnace technology to help achieve low-emission steel production. Technical analysis is done by acquiring specific consumption of raw materials, auxiliary materials, fuels, energy, and utilities for each steel production route. The production costs for each steel production route are also being calculated. From the analysis, there are answers to the research questions as follows:

1. The BF-BOF route has the lowest production cost at 491.93 USD/t-HRC. Scrap-based EAF is in the middle with 594.78 USD/t-HRC. Gas-based DRI-EAF has the highest production cost with 618.90 USD/t-HRC. Regarding CO_2 emissions, scrap-based EAFs have the lowest emissions at 0.930 t-CO_2/t-HRC. The BF-BOF route has the highest emission with 2.466 t-CO_2/t-HRC. In between, gas-based DRI-EAF emissions are 2.198 t-CO_2/t-HRC.
2. Due to the low carbon price in Indonesia (2 USD/t-CO_2), the impact of the Indonesian Carbon Tax is relatively low. For the BF-BOF route, which has the highest CO_2 emission, the impact is 4.93 USD/t-HRC (1.0% from TCOS). The impact for gas-based DRI-EAF is 4.40 USD/t-HRC (0.7% from TCOS). And even lower impact for scrap-based EAF with 1.86 USD/t-HRC (0.3% from TCOS).
3. Different levels of carbon price are enforced in the European Union with CBAM. With a carbon price of approximately 80 USD/t-CO_2, the impact on TCOS of the BF-BOF route is significant, amounting to 197.28 USD/t-HRC (28.6% of TCOS). Scrap-based EAF, which has the lowest emission, still suffers an additional cost of 74.44 USD/t-HRC (11.1% from TCOS). In between, gas-based DRI-EAF suffers an additional cost of 175.87 USD/t-HRC (22.1% from TCOS).

Based on the sensitivity analysis of HRC market price versus BF-BOF and scrap-based EAF proportions, when the HRC market price is 500 USD/t-HRC, PT GSI can only use the 100% BF-BOF route. Along with the increase in HRC market price, there is the possibility of increasing the proportion of scrap-based EAF to the point that, at a price level of 670 USD/t-HRC, PT GSI can use 100% scrap-based EAF.

The BF-BOF route has the lowest production cost but the highest CO_2 emissions. In a country with a low carbon price, the BF-BOF route will become the most competitive steel production route. Scrap-based EAF is a steel production route with the lowest CO_2 emissions. In areas with high carbon prices, such as the European Union, the scrap-based EAF route will be more competitive than the BF-BOF route. The use of REC as a renewable electricity source can further improve the competitiveness of the scrap-based EAF route.

With the current HRC market price at 550 USD/t-HRC, PT GSI can use a 70% BF-BOF and 30% scrap-based EAF mix from production to supply the domestic and export markets. This research is using Indonesian-based data, and PT GSI has already built facilities. Further research can be conducted using broader data and also in the condition for new investment in the facilities.

Interest Conflicts

The author declares that there is no conflict of interest concerning the publication of this paper. This study was conducted solely for the author's interest, and no financial or funding support from any organisation has influenced the result of this study.

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