UNIVERSITAS GADJAH MADA
PUSAT STUDI ENERGI

GUIDELINE
FOR INDUSTRY DECARBONIZATION

Prepared for : Iron and Steel Industry

2024

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FOREWORD

The global industrial landscape is undergoing a profound transformation, driven by the urgent need to reduce greenhouse gas emissions and align with international sustainability commitments. It is in this context that we are pleased to present the "Guideline for Industry Decarbonization: Prepared for Iron and Steel Industry," a document that provides comprehensive technical strategies to guide Indonesia's iron and steel sector through this transition.

This guideline has been meticulously developed to address the specific challenges and opportunities associated with decarbonizing one of Indonesia's most critical industrial sectors. The iron and steel industry, characterized by its energy-intensive processes and reliance on carbon-heavy inputs, has been identified as a key area for intervention. This document offers insights into technologies and economic frameworks necessary to achieve significant emissions reductions while maintaining operational efficiency and market competitiveness.

The recommendations presented herein are grounded in a rigorous analysis of current practices, emerging technologies, and global best practices. Topics covered include energy efficiency improvements, the integration of renewable energy, reduction gas injection technologies, and the adoption of low-carbon production methods such as Direct Reduced Iron (DRI) and Electric Arc Furnace (EAF). Each section provides actionable steps, supported by case studies and quantitative assessments, to enable stakeholders to implement these strategies effectively.

Furthermore, this guideline highlights the economic implications of transitioning to low-carbon technologies, including capital requirements and the long-term cost benefits of sustainability-driven operations. It also underscores the critical role of policy support and regulatory frameworks in accelerating the adoption of decarbonization measures within the sector.This publication is the result of collaborative efforts involving industry experts, academic researchers, and policymakers. It is designed to serve as both a strategic tool for decision-making and a technical reference for practitioners seeking to adopt best practices in industrial decarbonization.

As Indonesia strives to meet its emissions reduction targets and remain competitive in global markets, this guideline will serve as a pivotal resource. We encourage all stakeholders to engage with the recommendations outlined in this document and to commit to a shared vision of a sustainable and resilient industrial future.

Thank you,

Prof. Sarjiya
Director
Pusat Studi Energi (PSE, Center for Energy Research)
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1. Objective

The growing international consensus on climate change mitigation, such as the Paris Agreement, has led to the implementation of robust environmental policies worldwide. This global shift is driven by the pressing need to address the adverse impacts of climate change, reduce dependency on fossil fuels, and ensure long-term energy security. Countries are increasingly adopting measures to limit greenhouse gas emissions and promote renewable energy sources. This global push towards sustainable energy also represents a monumental shift in the way societies produce and consume energy. These changes in market agents' behavior, in the end, create a competitive global market for sustainable products.

Indonesia is among the nations that have pledged to transition toward sustainable energy. The Indonesian government has set ambitious targets for renewable energy utilization, aiming for 23% of the energy mix to come from renewable sources by 2025 and 31% by 2050. This commitment aligns with Indonesia's broader goals of reducing carbon emissions by 29-41% by 2030 and achieving net-zero emissions by 2060. The transition to renewable energy is not only crucial for meeting these targets but also for fostering economic growth, creating jobs, and improving energy access for the population. Furthermore, the shift towards renewables can

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enhance energy independence, reduce reliance on imported fossil fuels, and promote energy equity across different regions in Indonesia.

To achieve these energy transition objectives, the Indonesian government must prioritize the energy transition within the industrial sector, which is a significant contributor to the country's greenhouse gas emissions, accounting for over 60% of the national total. This heavy reliance on fossil fuels not only exacerbates environmental degradation but also exposes the sector to the volatility of global fuel prices. Such volatility can have profound economic repercussions, affecting the cost of production and the competitiveness of Indonesian exports in the international market. One of the hard-to-abate industries is the steel sector, which accounts for up to 17% of the total industrial sector emissions (in 2022).

The urgency of decarbonization for the Indonesian steel industry is not only driven by the country's energy transition commitment but also by the immediate impact of policies like the EU's Carbon Border Adjustment Mechanism (CBAM) and the broader global trend towards sustainability. As a major steel-producing nation with comparatively lenient environmental regulations relative to the EU, the consequences of the CBAM policy, which adjust the prices of goods entering the EU market according to their carbon content, could diminish the competitiveness of Indonesian steel products. On the other hand, since the global shift towards sustainability is reshaping market access and preferences, failure to decarbonize the steel industry could not only diminish its standing in the EU but also in other markets that might adopt similar measures to CBAM, further isolating Indonesia's steel product from key global value chains. Thus, the move towards decarbonization is not merely about compliance but also about leveraging opportunities. For the steel industry, which is traditionally energy-intensive and high in carbon emissions, the transition to greener methods can also mitigate future risks associated with carbon pricing mechanisms and environmental regulations and standards, such as

2. Why Should It be Green?

There are several reasons that can motivate industries to transition, from both a global and domestic market perspective. The implementation of carbon tax policies has become widespread in many countries, driving companies to reduce their emissions. From a national perspective, governments are also starting to adopt policies aimed at preventing carbon leakage from import activities. One such policy is the Carbon Border Adjustment Mechanism (CBAM).

The application of carbon taxes or of CBAM in export destination countries can reduce the competitiveness of the steel industry if it fails to decarbonize its industrial processes. Conversely, industries that decarbonize or transition to renewable energy sources will open up new opportunities, especially in international markets where the demand for low-carbon steel is increasing.

Steel is a fundamental industry, with its output utilized by many other sectors. Therefore, internationally mandated emission reduction targets across various sectors will drive demand for low-carbon steel. According to estimates from several market research institutions, the market value for low-carbon steel is expected to grow at a compound annual growth rate (CAGR) of 120% by 2032[1]. BloombergNEF and other research organizations highlight that the transportation sector will account for much of this increased demand, as the premium for low-carbon steel represents a relatively small percentage of total production costs[2].

Another driving factor is the actions taken by several global steel producers. According to the Green Steel Tracker[3], many international steel companies have already set targets to achieve carbon neutrality. Specifically, three companies aim to reach this goal before 2050, seventeen companies by 2050, and two companies by 2060. This indicates that international steel companies are already taking proactive steps toward decarbonizing their production processes. Domestic steel industries must also take immediate action toward decarbonization to avoid losing market share. Furthermore, as time progresses, the cost of producing green steel will decrease. BloombergNEF estimates that by 2050, the cost of green steel production could be 5% cheaper than conventional fossil fuel-based production (including carbon capture and storage or offsets)[4].

In terms of financing, funders—whether in the form of grants or soft loans—are increasingly focusing on decarbonization projects. Additionally, there is a growing tendency among investors

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[1] Precedence Research, "Green Steel Market Size, Share, and Trends 2024 to 2034", Accessed at https://www.precedenceresearch.com/green-steel-market, September 30th 2024

[2] BloombergNEF, "Green Steel Demand is Rising Faster than Production Can Ramp up", Accessed at https://about.bnef.com/blog/green-steel-demand-is-rising-faster-than-production-can-ramp-up/, September 30th,

[3] Leadership Group for Industry Transition. Green Steel Tracker. Accessed at https://www.industrytransition.org/green-steel-tracker/, September 30th, 2024.2024.

[4] BloombergNEF, loc.cit

to prioritize companies with strong Environmental, Social, and Governance (ESG) practices.

From a domestic perspective, the push for transition may come from the broader application of carbon policies in Indonesia, which will eventually extend beyond the power generation sector. If companies can successfully transition, their carbon tax burden may be reduced. Moreover, if carbon trading is implemented in Indonesia, it could serve as a potential revenue stream for companies that manage to reduce emissions, as they would be able to sell carbon credits.

3. Decarbonization Process

The iron and steel industry is a significant consumer of coal, accounting for around 7% of the global energy supply and producing most of the greenhouse gases that are responsible for 7-9% of global greenhouse gas emission[5]. In Indonesia itself, the iron and steel sector is responsible for 4.9% of the country's emissions, approximately 430 million tons of carbon dioxide annually[6.] To mitigate the emissions, decarbonization of the iron and steel industry is crucial. Decarbonization refers to an attempt to reduce the greenhouse gases emitted into the atmosphere, serving as the first step in transitioning to cleaner energy and more sustainable technologies.

3.1 The Current Situation of Iron and Steel Industry

Indonesia has the capacity for iron making and steelmaking of up to 9.590 ttpa and 14.275 ttpa respectively, using either Blast Furnace-Basic Oxide Furnace (BF-BOF) or Direct Reduced Iron-Electric Arc Furnace (DRI-EAF) methods, with around 86% and 64% of the ironmaking and steelmaking respectively still using the **BF-BOF** route . Reliance on **BF-BOF**[7], in which about 89% of the energy comes from coal[8], can lead to environmental issues. Therefore, there is still significant potential for greenhouse gas (GHG) mitigation in Indonesia's iron and steel industry, and the framework for analyzing the potentials is illustrated in . Hence, we have categorized various mitigation efforts based on energy efficiency, low-carbon fuels, renewable energy resources and low-emission technology.

[5] Kim et al., “Decarbonizing the Iron and Steel Industry: A Systematic Review of Sociotechnical Systems, Technological Innovations, and Policy Options”, https://www.sciencedirect.com/science/article/pii/S2214629622000706, September

[6] Institute for Essential Services Reform, “Iron and Steel Industry Needs a Comprehensive Roadmap to Decarbonise”, https://tanahair.net/iesr-iron-and-steel-industry-needs-a-comprehensive-roadmap-to-decarbonise/#:~:text=Jakarta%E2%80%94The%20Institute%20for%20Essential,tons%20of%20carbon%20dioxide%20annually, September 17th, 2024. 17th, 2024.

[7] Global Energy Monitor, “Pedal to the Metal 2023: It's Time to Shift Steel Decarbonization into High Gear”, https://globalenergymonitor.org/wp-content/uploads/2023/07/GEM_SteelPlants2023.pdf, October 8th, 2024.17th,

[8] World Steel Association, “Energy use in the Steel Industry”, https://worldsteel.org/wp-content/uploads/Fact-sheet-Energy-use-in-the-steel-industry.pdf, October 9th, 2024.17th, 2024.

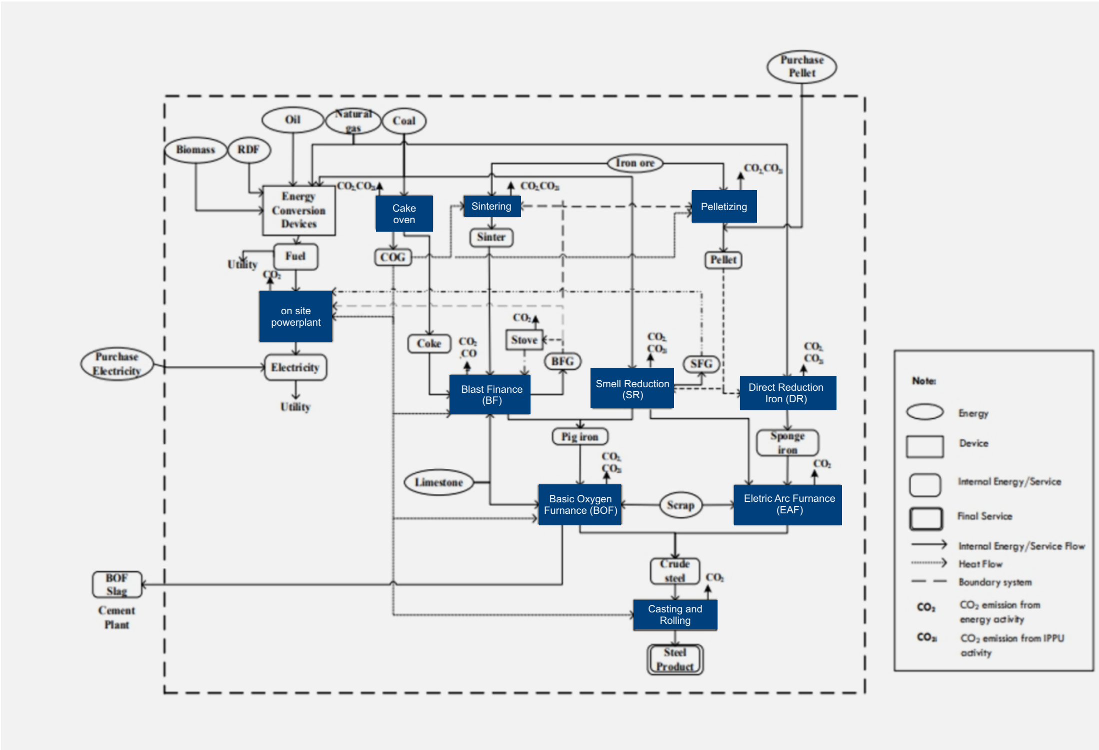

Figure 3-1. Indonesia's iron and steel model structure and emissions sources (2024)[9]

3.2 Decarbonization Options for Steel Industry

3.2.1 Energy Efficiency

As Indonesia is still dominated by the BF-BOF route, the figures for energy and emission intensity are significantly high, up to 22% and 15% higher than the global average for CO_2 emissions and energy intensity, respectively, as shown in the comparison in Figure 3-2 below.

[9] Dewi et al., "Selecting Indonesia's Iron and Steel Industry Mitigation Pathways Based on AIM/End-Use Assessment", https://jrtpp i.id/index.php/jrtppi/article/download/181/131/1293, September 17th, 2024.

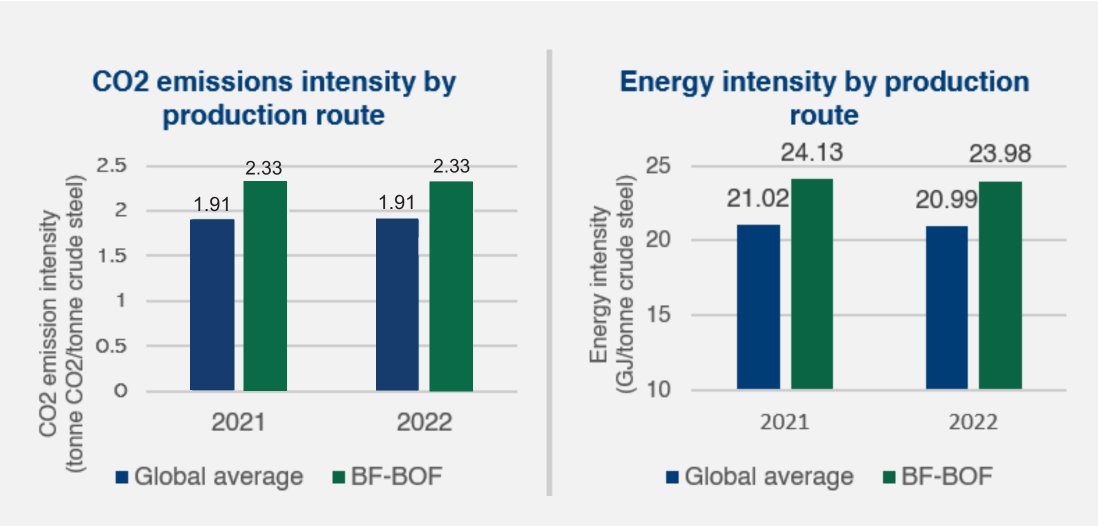

Figure 3-2. CO_2 emissions and energy intensity of global average VS BF-BOF[10] (processed by PSE UGM)

Based on the figure, there is potential to reduce the energy and carbon emissions intensity. Several stages are involved in steel production, including coking, sintering, pelleting, ironmaking, steelmaking, and rolling. Some of these processes can be optimized to increase production, reduce the carbon emission (CE), and improve energy efficiency (EE) and energy consumption (EC) in the process. Some of the options are outlined below:

a. Increasing Scrap Input Rate

Scrap metal is one of the materials that can be used as raw material in the ironmaking process, but its utilization is still lower compared to the other types of irons. In this context, there will be two scenarios: Business-As-Usual (BAU), where the share of energy and the equipment efficiency in 2030 and 2050 remains the same as in 2010 with no addition of scrap, while the other scenario is increasing the input rate of scrap by 20% (Scenario 1)[11]. The impact of Scenario 1 is expected to reduce up to 16.48% of carbon emissions and 13.39% of carbon emissions by 2050 from the energy and IPPU sectors, respectively, as shown in Figure 3-3

[10] World Steel Association, “Sustainability Indicators 2023 Report”, https://worldsteel.org/wp-content/uploads/Sustainability-indicators-report-2023.pdf, October 9th, 2024.
[11] Ibid, page 7.

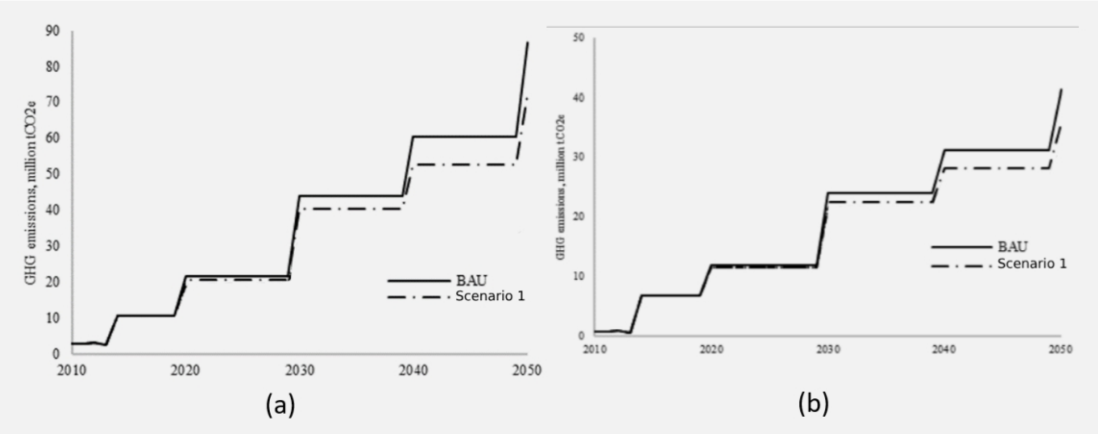

Figure 3-3. GHG emission forecast under different scenarios (a) Energy and (b) IPPU (2024)[12] (processed by PSE UGM).

b. Increasing the Ratio of Coal Injection to Blast Furnace (BF)

The primary fuel of the BF is typically coke, produced through the destructive distillation of coal in coke ovens, which removes all volatile elements from the coal. Even though coke has a high energy density, it is highly polluting when used in BF. One alternative is coal injection, which can reduce the consumption of coke in the process, thereby lowering both emissions and the input costs associated with the coke production. In addition, coal injection also improves the energy efficiency in the process[13]. These changes are illustrated below.

[12]Ibid, page 6.
[13]Na et al., “Optimization of Energy Efficiency, Energy Consumption and CO_2 Emission in Typical Iron and Steel ManufacturingProcess”, https://www.sciencedirect.com/science/article/pii/S036054422201725X/pdfft?md5=4c31faecd927f3c6aa772e21af0b6970&pid=1-s2.0-S036054422201725X-main.pdf, September 17th, 2024.

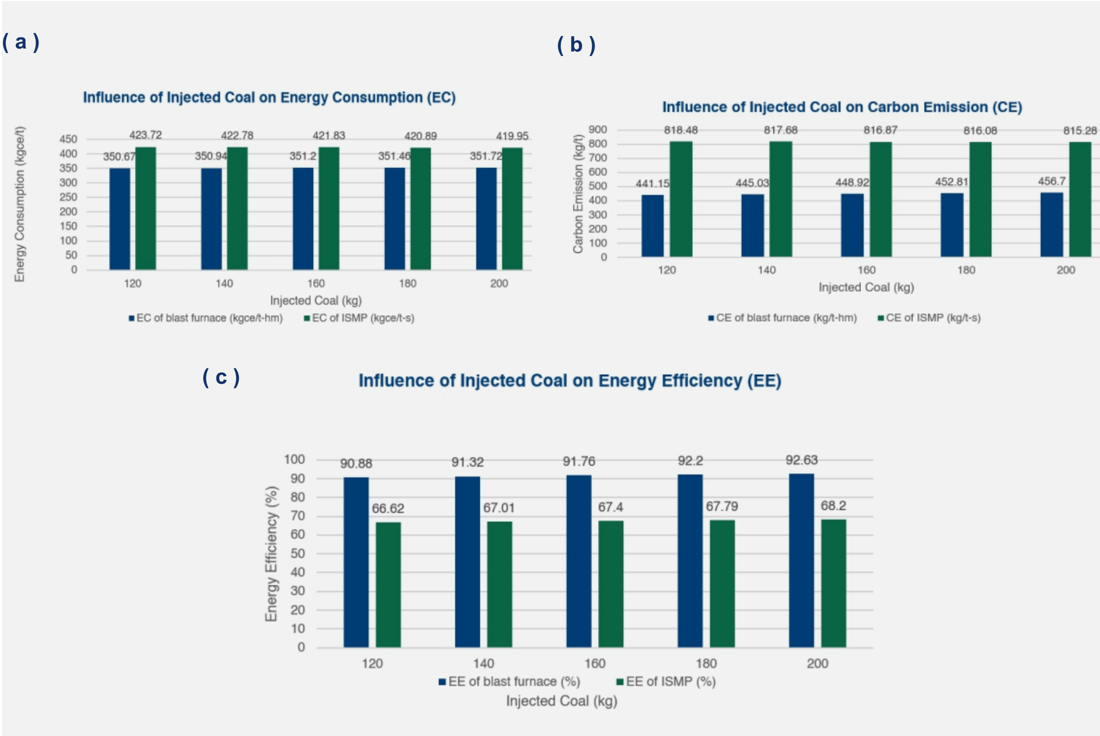

Figure 3-4. The Effects of Coal Injection on (a) Energy Consumption, (b) Carbon Emission, and (c) Energy Efficiency.[14]

[14]Na et al., "Optimization of Energy Efficiency, Energy Consumption and CO_2 Emission in Typical Iron and Steel Manufacturing Process", https://www.sciencedirect.com/science/article/pii/S036054422201725X/pdfft?md5=4c31faecd927f3c6aa772e21af0b6970&pid=1-s2.0-S036054422201725X-main.pdf, September 17th, 2024.

c. Reducing the Temperature Loss at the Iron-Steel Interface

The iron-steel interface, located between the connecting part of the blast furnace and the basic oxide furnace, tends to lose a large amount of energy. To prevent this loss, the "one tank to the end" technology can be implemented, which effectively reduces the temperature drop at the iron-steel interface[15]. The impact of the implemented technology is shown in Figure 3-5 below.

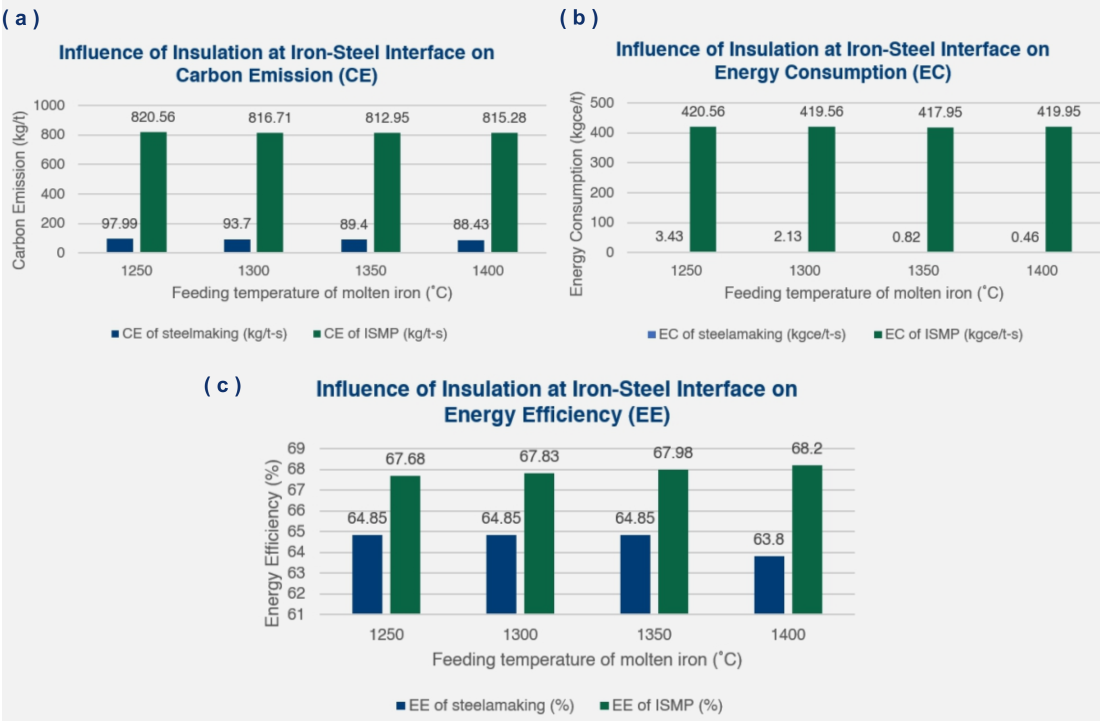

Figure 3-5. Influence of Insulation at Iron-Steel Interface on (a) Carbon Emission, (b) Energy Consumption, and (c) Energy Efficiency[16].

[15]Ibid,page 6.
[16] Na et al., "Optimization of Energy Efficiency, Energy Consumption and CO_2 Emission in Typical Iron and Steel Manufacturing Process", https://www.sciencedirect.com/science/article/pii/S036054422201725X/pdfft?md5=4c31faecd927f3c6aa772e21af0b6970&pid=1-s2.0-S036054422201725X-main.pdf, September 17th, 2024.

d. Reducing temperature Loss at the Casting-Rolling Interface

The casting-rolling interface is another intersection between continuous casting and hot rolling is another area where significant energy loss occurs. Reducing heat loss at this interface results in the improvement of the energy efficiency, energy consumption, and CO2 emission reduction[17]. The impact of this reduction is shown in Figure 3-6 below.

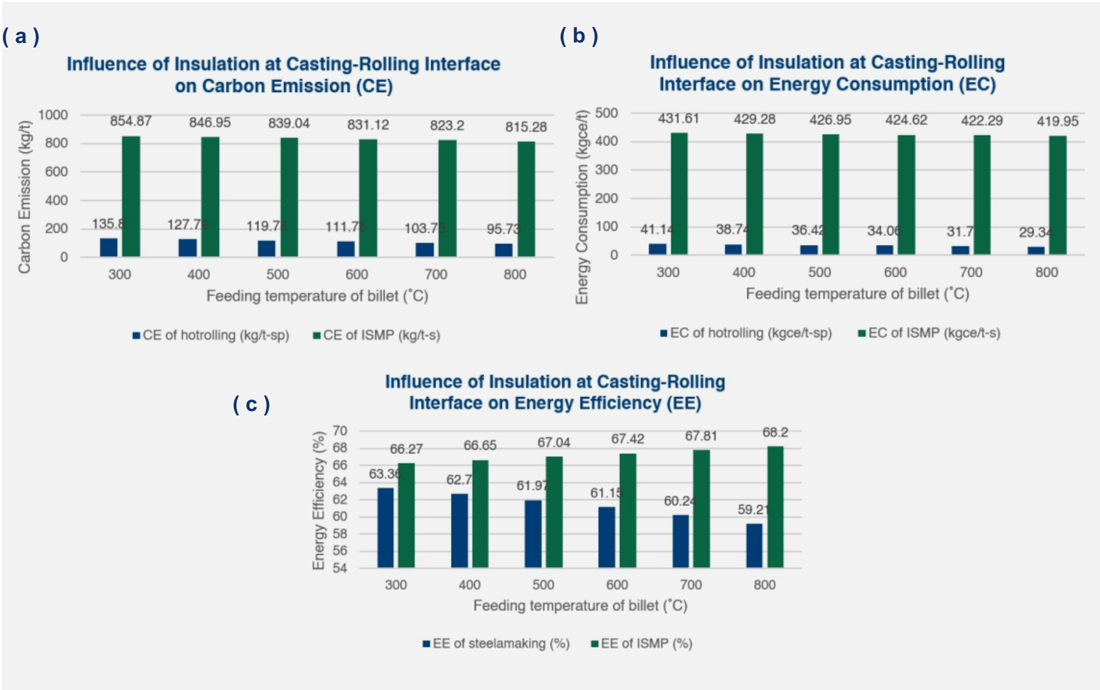

Figure 3-6. Influence of Insulation at Casting-Rolling Interface (a) Carbon Emission, (b) Energy Consumption, and (c) Energy Efficiency.[18]

Note: - kgce/t-s = kilogram of Coal Equivalent/ ton crude steel

- kgce/t-sp = kilogram of Coal Equivalent/ ton steel product

- kgce/t-hm = kilogram of Coal Equivalent/ ton hot metal

[17] Na et al., "Optimization of Energy Efficiency, Energy Consumption and CO_2 Emission in Typical Iron and Steel Manufacturing Process", https://www.sciencedirect.com/science/article/pii/S036054422201725X/pdfft?md5=4c31faecd927f3c6aa772e21af0b6970&pid=1-s2.0-S036054422201725X-main.pdf, September 17th, 2024.

[18] Na et al., "Optimization of Energy Efficiency, Energy Consumption and CO_2 Emission in Typical Iron and Steel Manufacturing Process", https://www.sciencedirect.com/science/article/pii/S036054422201725X/pdfft?md5=4c31faecd927f3c6aa772e21af0b6970&pid=1-s2.0-S036054422201725X-main.pdf, September 17th, 2024.

3.2.2 Renewable Energy Resources.

Renewable energy resources, energy derived from natural sources that are replenished at higher rate than they are consumed, can be another alternative in reducing the carbon footprint, such as electricity provided from solar, hydro, nuclear, wind or combination energy. Even though some of the electricity is not directly used in the plant, it can be utilized in some of the operations as the Figure 3-7 shown.

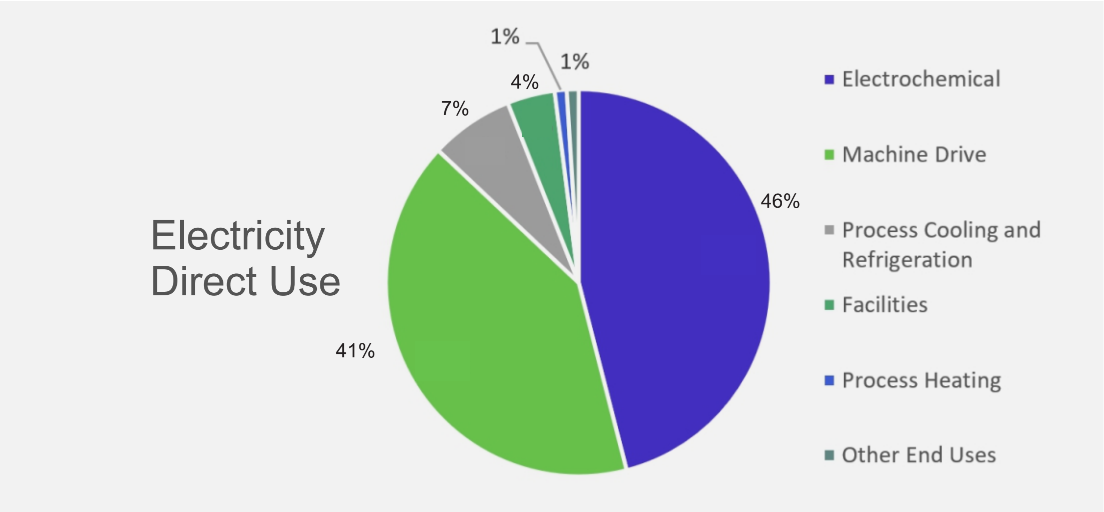

Figure 3-7. Electricity direct use in the Iron and Steel Industry (2012).[19]

[19] Office of Energy Efficiency & Renewable Energy, "U.S. Manufacturing Energy Use and Greenhouse Gas Emissions Analysis", https://www.energy.gov/sites/default/files/2013/11/f4/energy_use_and_loss_and_emissions_iron.pdf, September 17th, 2024.

Biomass can also be use in the process of manufacturing iron and steel, especially in the cokemaking, sintering, and ironmaking. With the energy mix of biomass, the emission can be reduced in the process. The process of using biomass in the cokemaking and ironmaking is illustrated in Figure 3-8 .

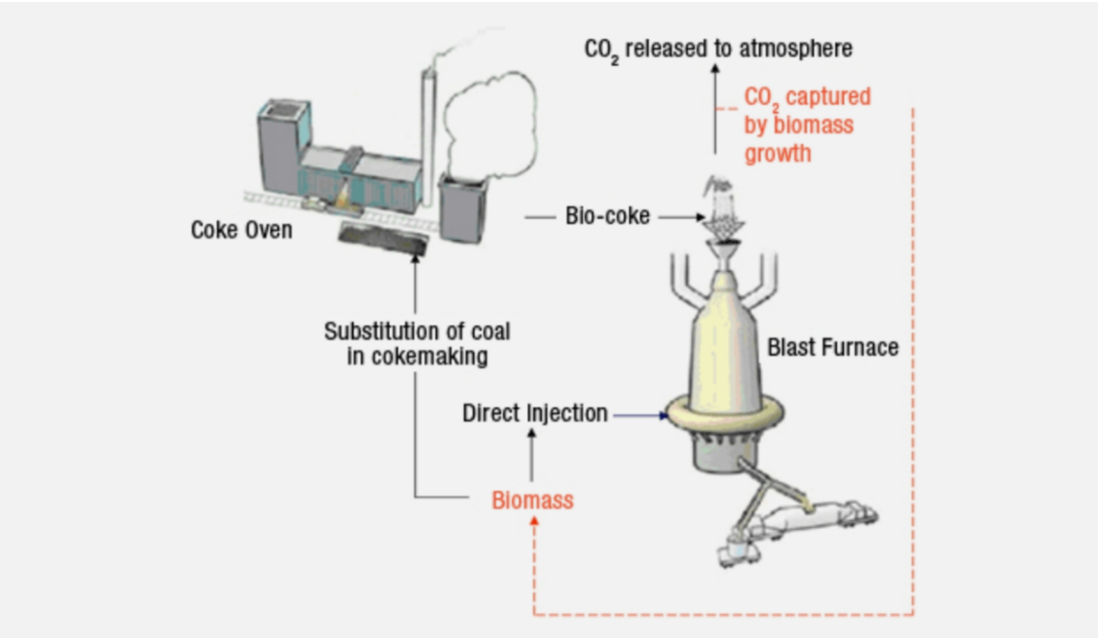

Figure 3-8. Illustration of Biomass Application in Cokemaking-Ironmaking System.[20]

Several types of biofuels, such as eucalyptus, switchgrass, biofuel, and charcoal, can be utilized, with charcoal showing the highest emission reduction, as detailed in Table 3.1. below.

Table 3.1. Comparison of CO2 Emission (/t Hot Metal)[21]

Injectant	Coal	Eucalyptus	Switchgrass	Bio-Oil	Charcoal
Coking coal (kg)	537	645	651	659	528
CO_2 Produced (t)	1.52	1.65	1.65	1.65	1.55
Biofuel Contribution (t)	0	0.22	0.21	0.19	0.38
GHG Emission (t)	1.52	1.43	1.44	1.46	1.16
Reduction (%)	-	6.2	5.4	4.1	23.5

[20] Wing et al., “Direct Injection of Biofuel in Blast Furnace Ironmaking”, https://www.cancarb.ca/pdfs/pubs/CCRA%20AISTech%202010_BF%20biofuel%20injection.pdf,

[21] Ibid, page 7

3.2.3 Reduction Gas Injection (Coke Oven Gas, Natural Gas, & Hydrogen)

Using the reduction gas injection, either coke oven gas (COG), natural gas, or hydrogen, can help the industries optimize fuel efficiency. Injecting the COG to the BF through the Tuyere can work as both fuel and reduction agent, potentially lowering the carbon emissions, lowering the energy consumption, and increasing the production[22]. However, before COG can be fully utilized, the gas needs to be cleaned in the Coke Battery Gas Treatment Plant to reduce as much naphthalene, ammonia, and sulfur as possible[23]. For this case, the composition of COG injected into the system is shown in , and the injection process is illustrated in Figure 3-9.

To achieve optimal conditions, the injection rate of COG can be maintained at around 36,000 Nm3/hour, reducing the traditional coke consumption to around 525.9 kg/t-hot metal. This approach potentially reduces carbon emissions by 30-40% as the hydrogen content in COG accelerates the reduction process in the BF, hence improving the productivity to approximately 2.5 t-hot metal/m3/day.[24]

Table 3.2. Composition of Injected COG.[25]

Composition of Injected COG Used					
Component	**Ch4**	**H2CO**	**CO**	**Co2**	**N2**
Volume Fraction (%)	31.81	50.53	7.59	7.80	2.25

[22] Li et alet al., “Numerical investigation of Coke Oven Gas (COG) Injection into an Ironmaking Blast Furnace (BF)”, https://www.sciencedirect.com/science/article/pii/S0360319922030506/pdfft?md5=c36c0a8919009e474b8c08c2939d0df2&pid=1-s2.0-S0360319922030506-main.pdf, October 31st, 2024.

[23] World Steel Association, “ArcelorMittal: CO2 Reduction by Means of Coke Oven Gas Co-Injection in Blast Furnace”, https://worldsteel.org/case-studies/environment/arcelormittal-co2-reduction-by-means-of-coke-oven-gas-co-injection-in-blast-furnace/, October 31st, 2024.

[24] Li et al., “Numerical Investigation of Coke Oven Gas (COG) Injection into an Ironmaking Blast Furnace (BF)”, https://www.sciencedirect.com/science/article/pii/S0360319922030506/pdf ft?md5=c36c0a8919009e474b8c08c2939d0df2&pid=1-s2.0-S0360319922030506-main.pdf, October 31st, 2024.

[25] Li et al., “Numerical Investigation of Coke Oven Gas (COG) Injection into an Ironmaking Blast Furnace (BF)”, https://www.sciencedirect.com/science/article/pii/S0360319922030506/pdf ft?md5=c36c0a8919009e474b8c08c2939d0df2&pid=1-s2.0-S0360319922030506-main.pdf, October 31st, 2024.

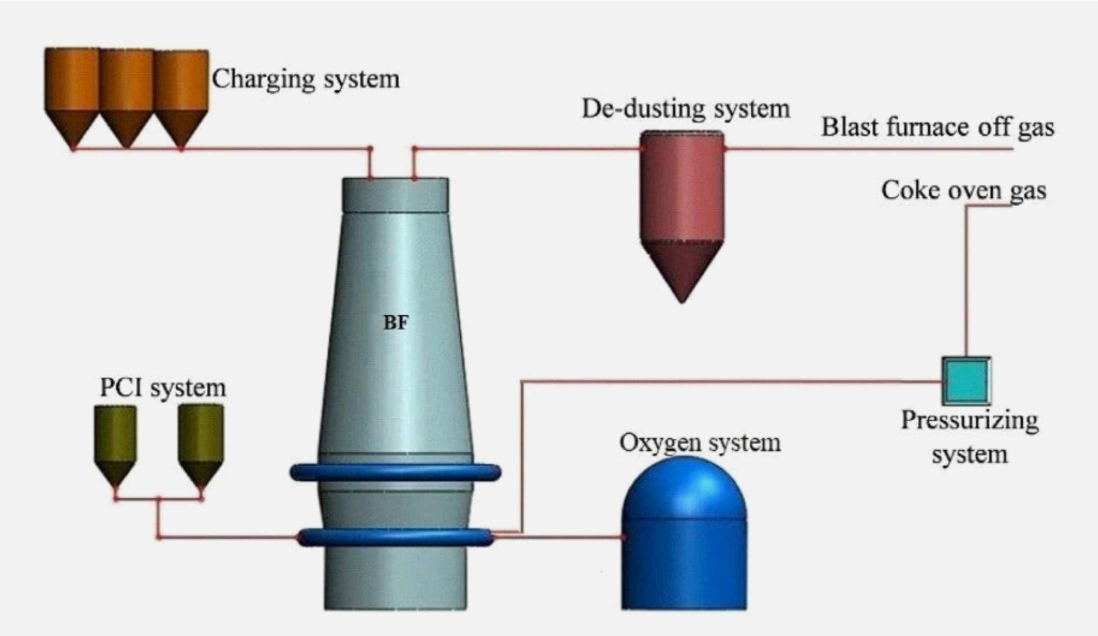

Figure 3-9. Schematic Illustration of Blast Furnace Production with Coke Oven Gas (COG) Injection.[26]

Another gas option is the natural gas, which injected into the blast furnace through the tuyere, impacting the reduction of coke and fuel usage, hence reducing the carbon emissions emitted by the overall process. The injection of natural gas itself poses a challenge, as it can cause a temperature drop in the furnace's high-temperature zone, as illustrated in . This effect, known as the "cold at bottom and hot at top", risks inadequate temperatures at the furnace's lower area, and potentially leading to poor slag-iron separation, inefficient combustion, and possible damage to the furnace. Thus, it is necessary to maintain sufficient heat in the high-temperature zone to avoid over-cooling of the furnace hearth; in this case, the allowable temperature drop is up to 80% of the case without natural gas injection[27].

[26] Li et alet al., "Numerical investigation of Coke Oven Gas (COG) Injection into an Ironmaking Blast Furnace (BF)", https://www.sciencedirect.com/science/article/pii/S0360319922030506/pdfft?md5=c36c0a8919009e474b8c08c2939d0df2&pid=1-s2.0-S0360319922030506-main.pdf, October 31st, 2024.

[27] Wang et al., "Numerical Analysis of Natural Gas Injection in Shougang Jingtang Blast Furnace", https://www.mdpi.com/2075-4701/12/12/2107, October 31st, 2024.

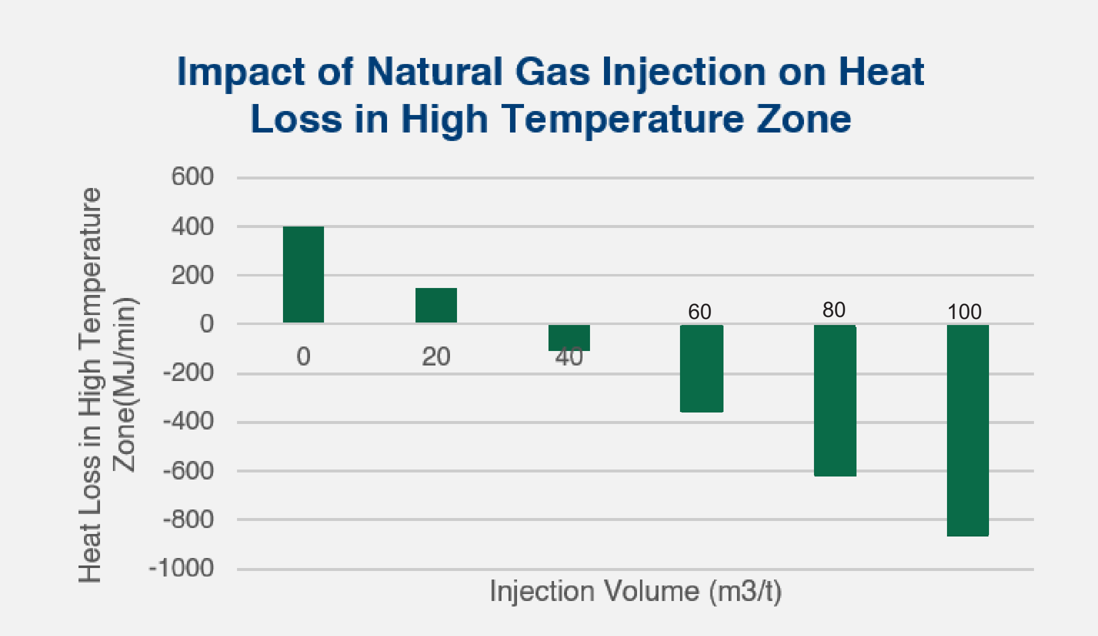

Figure 3-10. Effect of Natural Gas Injection on Heat Loss at High-Temperature Zone[28].

Natural gas has the potential to reduce the coal ratio uses in the blast furnace. When the heat loss is consistent with the base case, the acceptable natural gas injection rates are 17.3, 34.6, 52, 69.3 m3/t for every 20 kg/t coal injection reduction. While the acceptable temperature drop cases are 23.7, 41, 58.3, 75.7 m3/t per coal injection reduction. Details can be found in Table 3.3.

Table 3.3. Volume and Composition of Bosh Gas Under Different Acceptable Quantities of Natural Gas..[29]

Conditions	Coal Ratio (kg/t)	Gas Injection Volume (m3/t)	Bosh Gas Volume (m3/t)	CO (%)	H2 (%)	CO + H2 (%)
Base Case	153	0	1144.4	41.5	7.5	49
Base – 100	133	17.3	1167.1	40.4	9.6	50
	113	34.6	1189.7	39.6	11.2	50.8
	93	52	1212.4	38.8	12.8	51.6

[28] Wang et al., "Numerical Analysis of Natural Gas Injection in Shougang Jingtang Blast Furnace", https://www.mdpi.com/2075-4701/12/12/2107, October 31st, 2024.

[29] Wang et al., "Numerical Analysis of Natural Gas Injection in Shougang Jingtang Blast Furnace", https://www.mdpi.com/2075-4701/12/12/2107, October 31st, 2024.

Conditions	Coal Ratio (kg/t)	Gas Injection Volume (m3/t)	Bosh Gas Volume (m3/t)	CO (%)	H2 (%)	CO + H2 (%)
	73	69.3	1235.1	38.0	14.6	52.5
Base-80	133	23.7	1179.6	40.1	10.4	50.5
	113	41.0	1202.2	39.3	11.9	51.2
	93	58.3	1225.0	38.4	13.4	51.9
	73	75.7	1247.6	37.6	14.9	52.5

Furthermore, as shown , the CO concentration gradually decreases while the H2 concentration gradually increases with higher levels of total natural gas injection. Because of the gradual increase in hydrogen gas as the natural gas increases, the reduction process in the blast furnace is accelerated, which allows the fuel consumption of the blast furnace to be reduced. Details can be seen in Figure 3-11 .

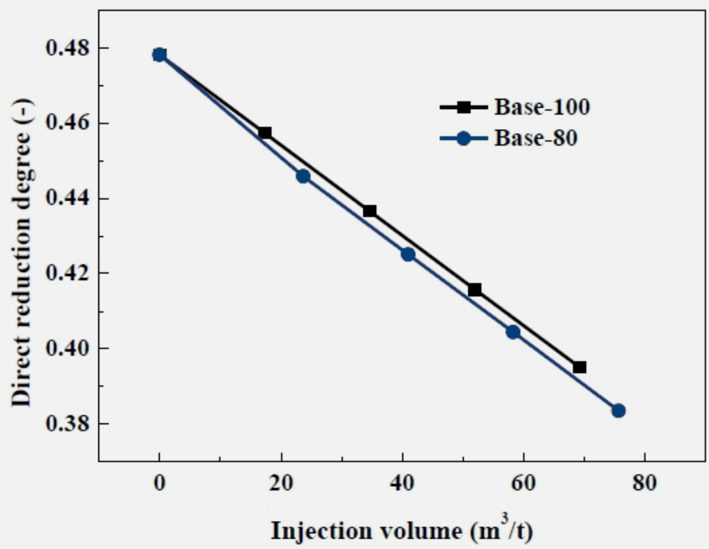

Figure 3-11. Direct Reduction Degrees in the Blast Furnace Under Different Suitable Gas Injection Volumes[30].

[30] Wang et al., “Numerical Analysis of Natural Gas Injection in Shougang Jingtang Blast Furnace”, https://www.mdpi.com/2075-4701/12/12/2107, October 31st, 2024.

Hydrogen injection in the ironmaking process, particularly in the blast furnace (BF), can serve as an alternative reducing agent to partially replace coke, which will have an impact in reducing the CO_2 emissions and in improving the efficiency of reducing iron oxides to molten iron. Hydrogen injection through the tuyere, as illustrated in , has been tested in several developed countries, such as Japan and Germany, as part of efforts to reduce reliance on coke and lower carbon dioxide emissions in steelmaking processes. Replacing carbon with hydrogen in the BF process can significantly decrease CO_2 emissions by up to 20-40%, depending on the extent of hydrogen substitution[31].

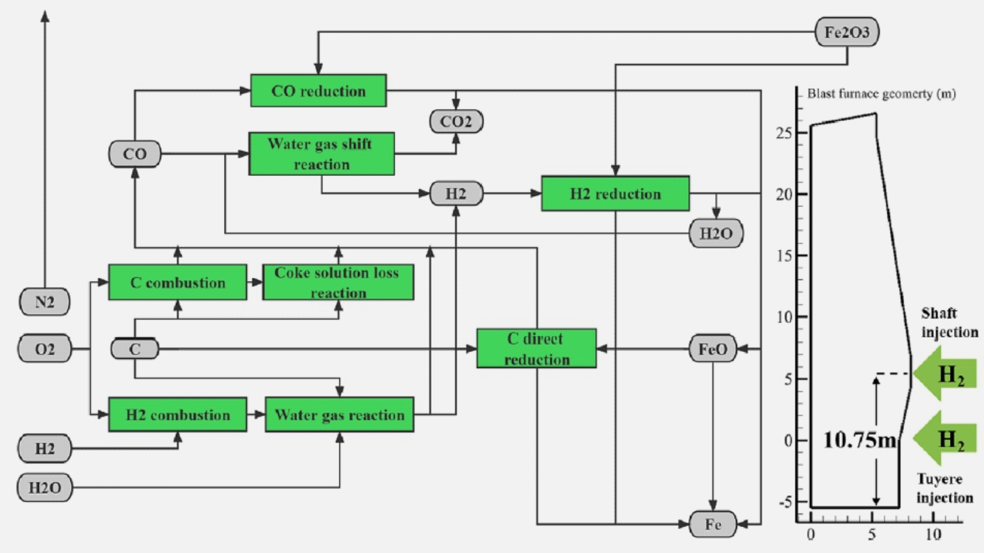

Figure 3-12. Hydrogen Injection through the Tuyere and the Chemical Reaction in a BF (2023).[32]

The reduction process can be accelerated by the hydrogen-enriched gas since it occurs at lower temperatures, thereby enhancing the gasification rate. The optimal hydrogen injection ratio between the tuyere and shaft is 40% and 60%, respectively, since it has the lowest coke rate at 258.5 kg-C/t-HM and the highest coke replacement ratio at 4.1kg-C/kg-H2, whose comparison can be seen in Figure 3-13 .

[31] Lan et al., "Effect of H2 on Blast Furnace Ironmaking: A Review", https://www.mdpi.com/2075-4701/12/11/1864, September 17th, 2024.

[32] Zhao et al., "CFD Study of Hydrogen Co-injection through Tuyere and Shaft of an Ironmaking Blast Furnace", https://www.sciencedirect.com/science/article/pii/S0016236123012541/pdfft?md5=93a9db88df75efbc7ff9f89b4fa5a54b&pid=1-s2.0-S0016236123012541-main.pdf, September 30th, 2024.

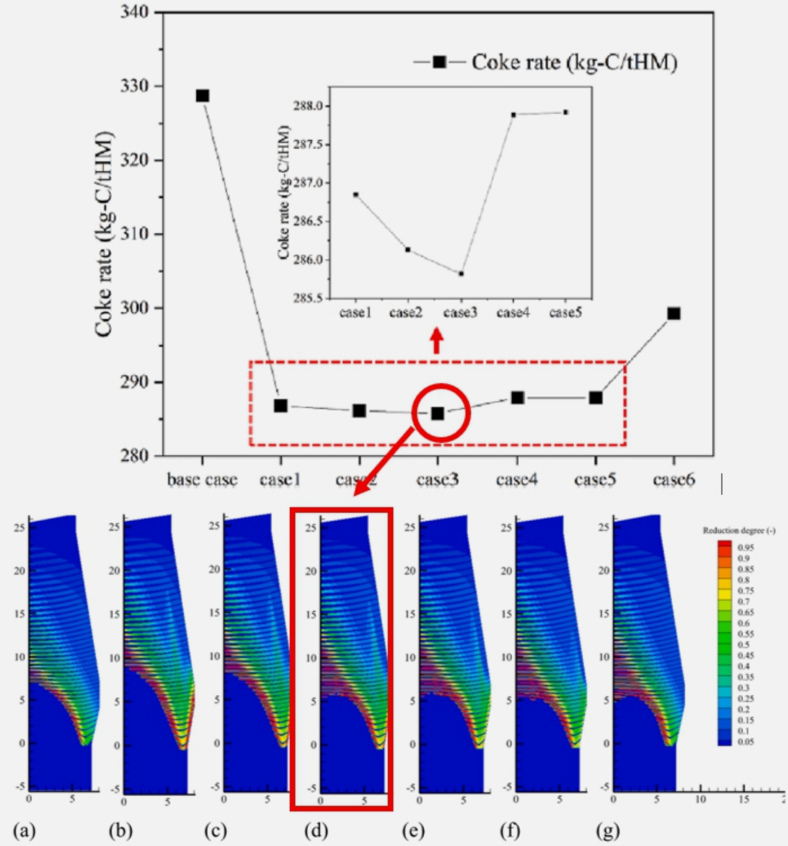

Figure 3-13. Coke Rate Variation and Reduction Degree Distribution of 7 Hydrogen Co-Injection Cases (2023) [33]

For more detailed case, it is presented below:

Table 3.4. Impact of Hydrogen Injection Ratio to Tuyere and Shaft (Processed by PSE UGM).[34]

Case	Tuyere Injection (%)	Shaft Injection (%)	Coke Rate (kg-C/t-HM)	Reduction Degree	Key Observations
a	0	0	~330	Low	No H_2 injection; highest coke consumption, minimal reduction.
b	0	0	< 290	Moderate	All H_2 injected through the shaft; significant coke reduction.

[33] Ibid, page 11.
[34] Ibid, page 11.

Case	Tuyere Injection (%)	Shaft Injection (%)	Coke Rate (kg-C/t-HM)	Reduction Degree	Key Observations
c	20	80	~287	High	Optimal balance between tuyeretuyere and shaft injection; best efficiency in reduction and coke consumption.
d	40	60	~285.8	High	Higher tuyere injection maintains efficiency but slightly higher coke consumption than case c.
e	60	40	~288	Moderate	Balanced but slightly less efficient in reducing coke consumption compared to cases c and d.
f	80	20	~290	Moderate	Majority of H_2 injected through ttuyere; lower reduction efficiency in upper furnace zones.
g	100	0	> 290	Low	All H_2 injected through tuyere; less efficient reduction, increased coke consumption.

3.2.4 Low-Carbon Technologies.

Direct Reduction Iron – Electric Arc Furnace (DRI-EAF)

In the long term, switching from the high-emission technology to the low-emission technology will be the main goal of the decarbonization process. Using low emission technologies, such as Direct Reduction Iron and Electric Arc Furnace (DRI-EAF), can significantly reduce carbon emission emitted from conventional Blast Furnace and Basic Oxide Furnace (BF-BOF). In general, based on the use of coal in BF-BOF compared to natural gas in DRI-EAF, the DRI-EAF technology emits 40-60% less CO2 than BF-BOF (depending on plant location and source of power generation)[35]. The overall process for both BF-BOF and DRI-EAF is shown in the and , respectively. Moreover, increasing scrap input and switching to low-emission technology (Scenario 2) can make a significant difference, as illustrated in Figure 3-14 .

[35] Steel Times International, “Emissions for BF-BOF vs DR-EAF”, https://www.proquest.com/openview/f473b22b3c99ea9d1700a6eae52cd2f9/1?cbl=1056347&pq-origsite=gscholar&parentSessionId=wZ0trSWg64SGXSrBP54sf1Ncfyg8tdsmJQaZLkxKyx8%3D, September 17th,

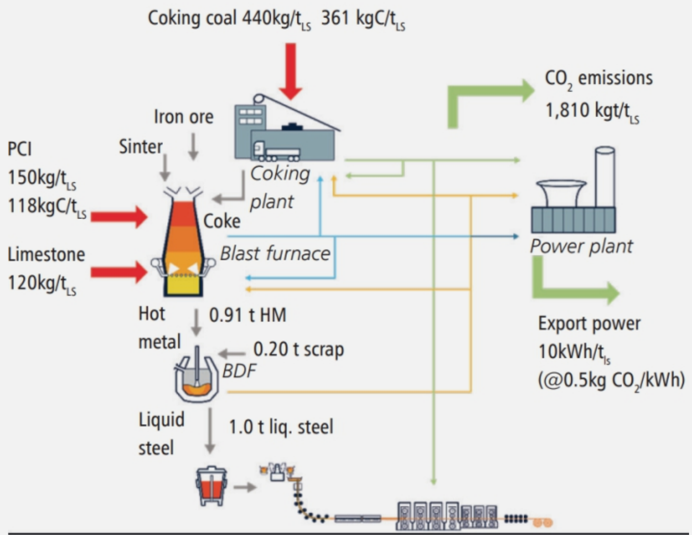

Figure 3-14. BF-BOF Route for HRC Production: Energy/CO2 Emissions Scheme (2020).[36]

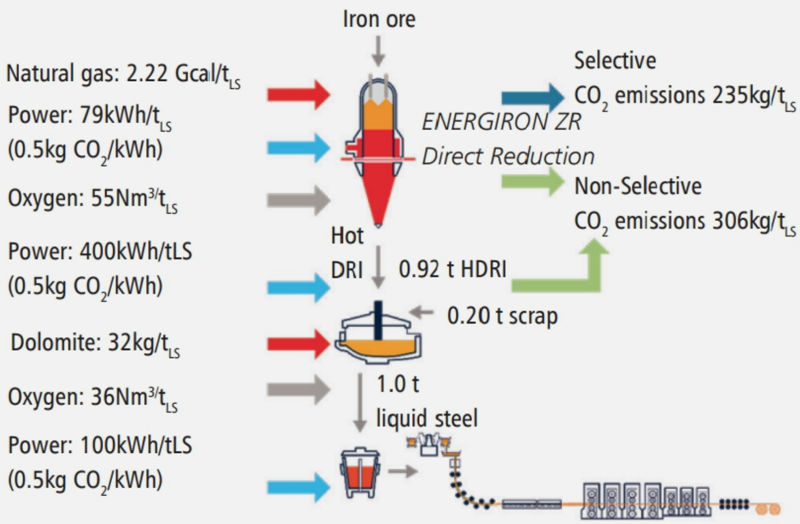

Figure 3-15. DRI-EAF Route for HRC Production: Energy/CO2 Emissions Scheme (2020).[37]

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[36] Ibid, page 15.
[37] Ibid, page 10..

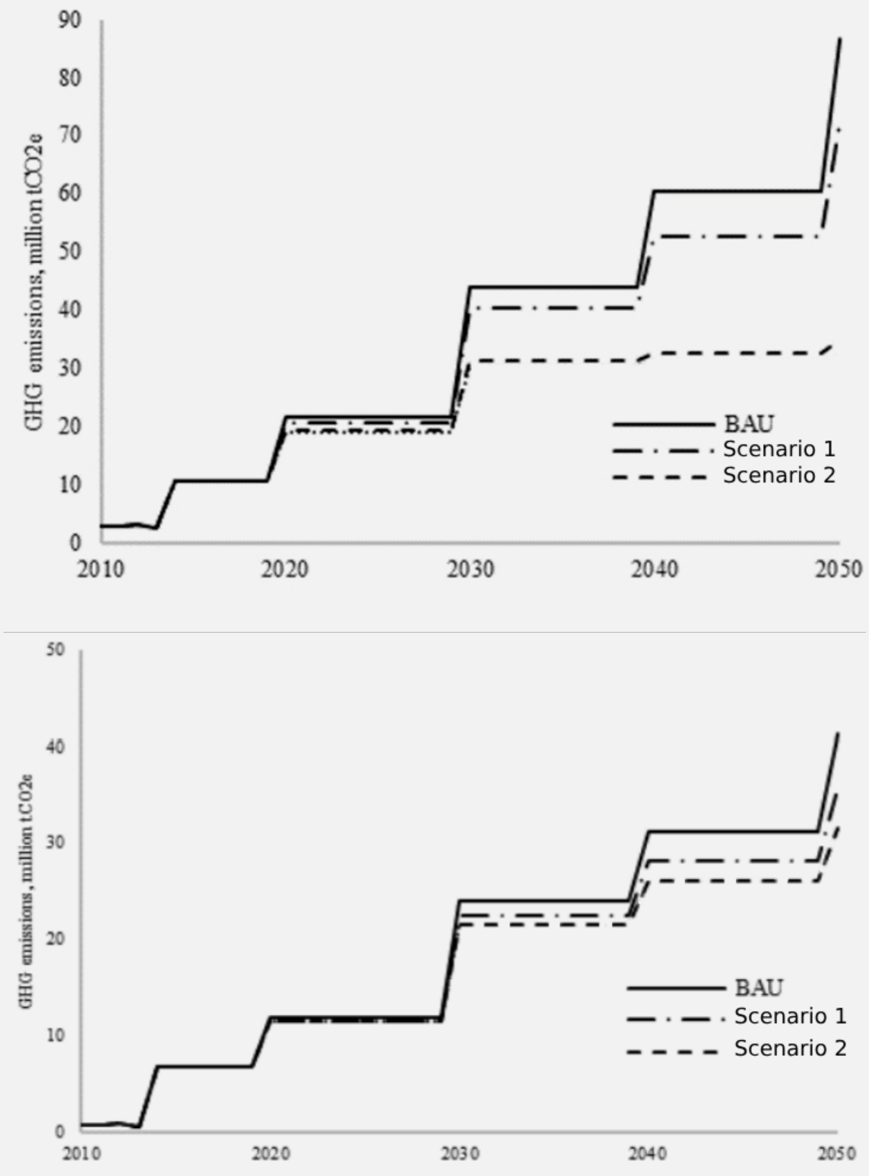


Figure 3-16. GHG Eemission fForecast under Different Scenarios from (a) Energy, (b) IPPU (2024)[38] (Processed by PSE UGM).

[38] Ibid, page 6.

Other than using DRI-EAF, much a cleaner technology is using option is the Scrap-EAF. Without the reduction process provided by DRI, using scrap as the raw material in the melting process in the EAF can reduce more carbon emissions emitted and the energy consumption in the process. We can see tThe comparison is shown in Table 3.5.

Table 3.5. Steelmaking Process: Carbon Emissions and Energy Consumption.[39]

Technology Process	Direct CO2 (t)/ Crude Steel (t)	Direct and Indirect* CO2/ ton of Crude Steel	Energy Consumption (GJ/t)		Share of Global Steel Production (%)
			International Energy	World Steel**	
BF-BOF	1.2	2.2	21.4	22.7	73.2
DRI-EAF	1	1.4	17.1	21.8	4.8
Scrap-EAF	0.04	0.3	2.1	5.2	21.5

Note:

* Indirect emissions are indirect GHG emission from the generation of purchased energy consumed by company

** The IEA states all energy intensities in final energy terms, whereas World Steel accounts for electricity

Consumption in primary energy terms, using a conversion factor of 9.8 GJ of fuel per MWh of electricity (equivalent to a 37% conversion efficiency) makes processes consuming electricity to appear more energy-intensive under the World Steel analytical boundary relative to the IEA boundary.

The technology itself is quite mature, especially scrap-EAF with green power, which is already commercially available. Meanwhile, the other technologies are still in development, as shown in below:

[39] Institute for Energy Economics and Financial Analysis, "Fact Sheet: The facts about Steelmaking - Steelmakers Seeking Green Steel", https://ieefa.org/sites/default/files/2022-06/steel-fact-sheet.pdf, September 17th, 2024.

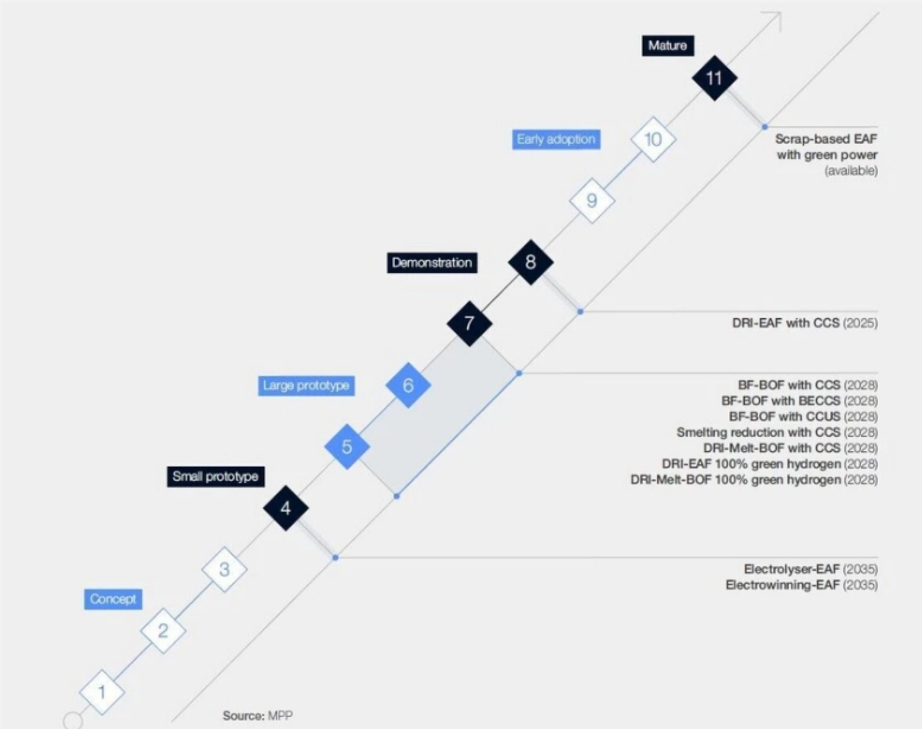


Figure 3-17. DRI-EAF Route for HRC Production: Energy/CO2 Emissions Scheme (2020).[40]

Molten Oxide Electrolysis (MOE)

Another technology, Molten Oxide Electrolysis (MOE) for the ironmaking, which could can utilize the renewable electricity to convert all iron ore grades to high-quality liquid metal. This direct approach eliminates several steps in the steelmaking process and does not require coke production, iron ore sintering, and pelletizing, blast furnace reduction, or basic oxygen furnace refinement, as the cell heats at 1600C, whichwhere the electrons split the bonds in the iron ore, producing the pure liquid metal. Molten Oxide Electrolysis MOE is also much more energy-efficientcy, with requiring 4 MWh of electricity/ per ton of crude steel, while compared to an Integrated Steel Mill, which have need requires 5.5 MWh of coal/ per ton crude steel of coal, which saving 27.27% of energy in the process.[41] As the main fuel will only utilize electricity, the MOE-EAF can could potentially reduce the emissions by up to 100%, depending on the electricity sources., but However, this also poises posesed as the drawback to MOE since the reliance on electricity of the technologyis nearly 100% , and which made making it difficult

[40] World Economic Forum, "Net-Zero Industry Tracker 2023", https://www.weforum.org/publications/net-zero-industry-tracker-2023/in-full/steel-industry-net-zero-tracker/, September 17th, 2024.

[41] Boston Metal, "Steel production through electrolysis: impacts for electricity consumption", https://iea.blob.core.windows.net/assets/imports/events/288/S5.4_20191010BostonMetalIEADecarbonization2019.pdf, October 31st 2024.

challenging to be implemented in several places.[42] While the advantages given are various MOE offers many benefits, the technology is still under development, with thea Technology Readiness Level (TRL) of 2 in year 2020, improving expected to reach TRL 3-4 in the year by 2030, and achievinge the TRL 9 at by 2050.[43]

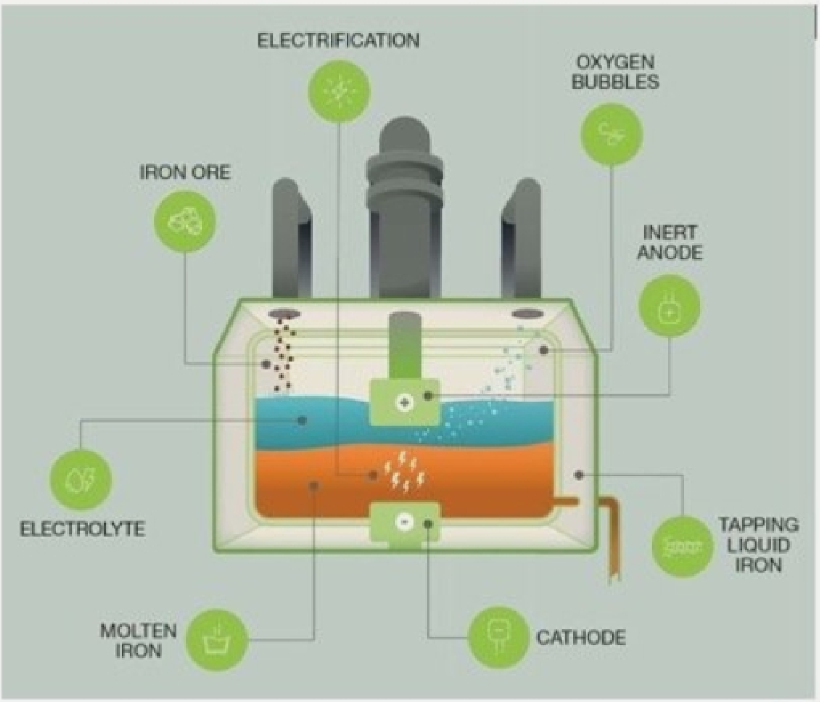
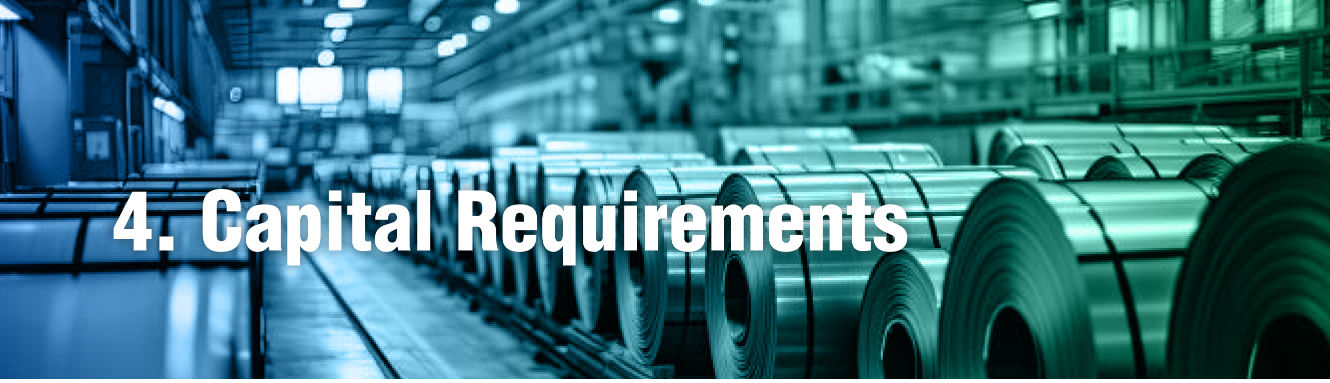


Figure 3-18. Molten Oxide Electrolysis Configuration.[44]

[42] Carbon Commentary, "Decarbonizing steel: hydrogen or metal oxide electrolysis?", https://www.carboncommentary.com/blog/2023/1/31/decarbonising-steel-hydrogen-or-metal-oxide-electrolysis, October 31st, 2024.

[43] Green Steel for Europe, "Technology Assessment and Road mapping", https://www.estep.eu/assets/Projects/GreenSteel4Europe/GreenSteel_Publication/EXEC_Sum/Technology-Assessment-and-Roadmapping.pdf, October 31st, 2024.

[44] Boston Metal, "Decarbonizing steelmaking for a net-zero future", https://www.bostonmetal.com/green-steel-solution/, October 31st, 2024.



4. Capital Requirements

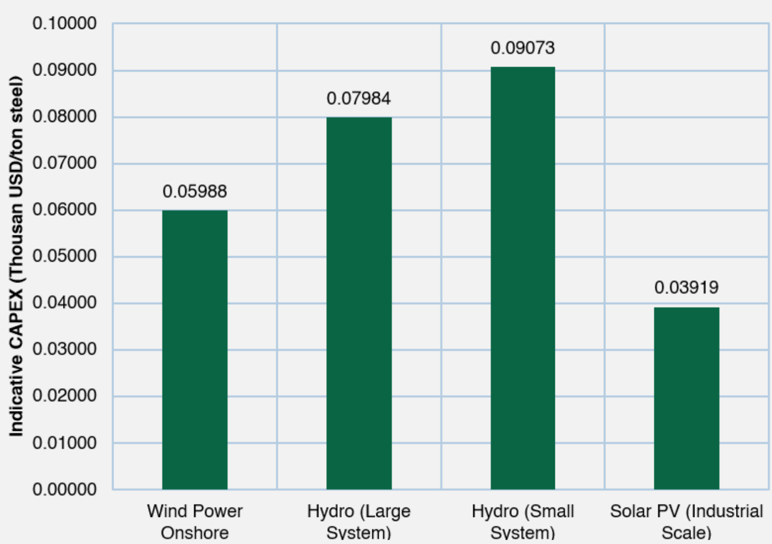
Based on the analysis of decarbonization options outlined in the previous subsection, an assessment was conducted to examine each option's potential impacts or implications for the firm.

Table 4.1. Decarbonization Option and Its Impact for Firm

No	Decarbonization Option	Implication for Firm	Cost
1	Increasing scrap input rate	Increasing the scrap input by 20%	No additional capex or modifications to existing production technology
2	Increasing the ratio of Coal Injection to Blast Furnace (BF)	Increasing coal injection, no improvement needed	No additional capex or modifications to existing production technology
3	Reduce the temperature loss at the iron-steel interface	Using insulation, new investment	
4	Reduce the temperature loss at the casting-rolling interface	Using insulation, new investment	
5	Renewable energy resources	New investment for captive power Buying REC to ensure the electricity purchased are generated from RE	New investment, further explanation are provided below
6	Hydrogen injection	Change technologies to BF-BOF H2	New investment, further explanation are provided below
7	Low-carbon Technologies	Change technologies to: · DRI-EAF · BAT BF-BOF H2 · EAF · Molten Oxide Electrolysis-EAF	New investment, further explanation are provided below

Our analysis suggests that increasing the scrap input ratio in the BOF process is feasible up to 20%. This increase does not require new capital expenditure or equipment modifications. However, it should be noted that scrap input is currently more expensive than iron ore input. Scrap prices in Italy, Germany, Turkey, the USA, and China are consistently above USD 350/ton[45]. On the other hand, iron ore prices remain significantly lower, averaging between USD 103 and USD 107/ton[46].

Switching to renewable energy source has two implications for firms. First, firms can purchase Renewable Energy Certificates (RECs) to ensure that their electricity supply is sourced from renewable energy. However, a limitation of this option lies in REC availability and compatibility with international policies, such as CBAM; based on prior analysis, RECs cannot be utilized for CBAM compliance. Second, companies may opt to build captive renewable power generation facilities. While this option supports direct renewable energy use, it involves higher costs. Indicative capital expenditures (CAPEX) per ton of steel produced for this approach are presented as follows.

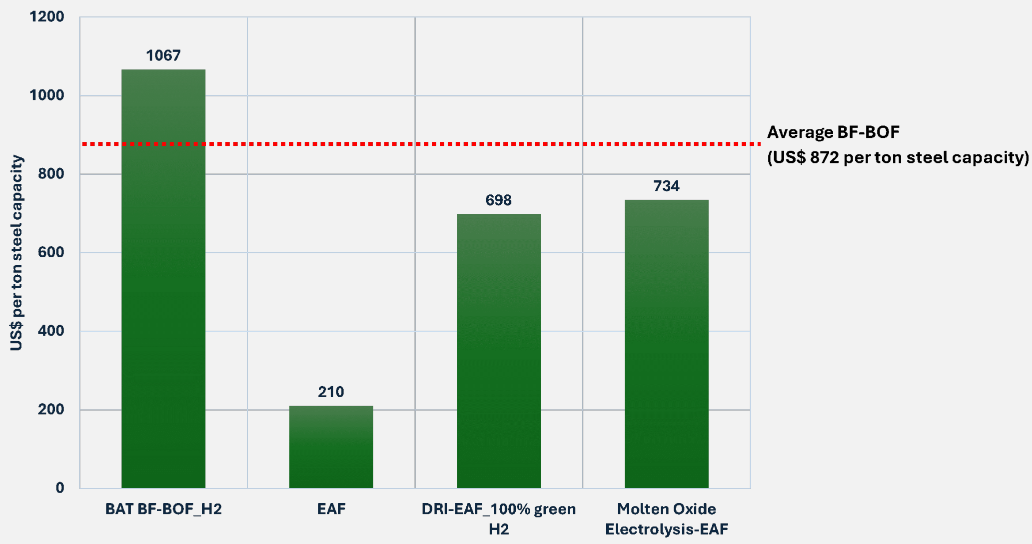


Graph 1 Indicative Capital Expenditure for Developing Captive Power.[47]

[45] GMK Center (2024). Global Scrap Prices Stabilized in Early July. https://gmk.center/en/news/global-scrap-prices-stabilized-in-early-july/ Accessed on October 31th, 2024

[46] GMK Center (2024). Iron re prices fell by 6-7% during July. https://gmk.center/en/news/iron-ore-prices-fell-by-6-7-during-july/ Accessed on October 31th 2024

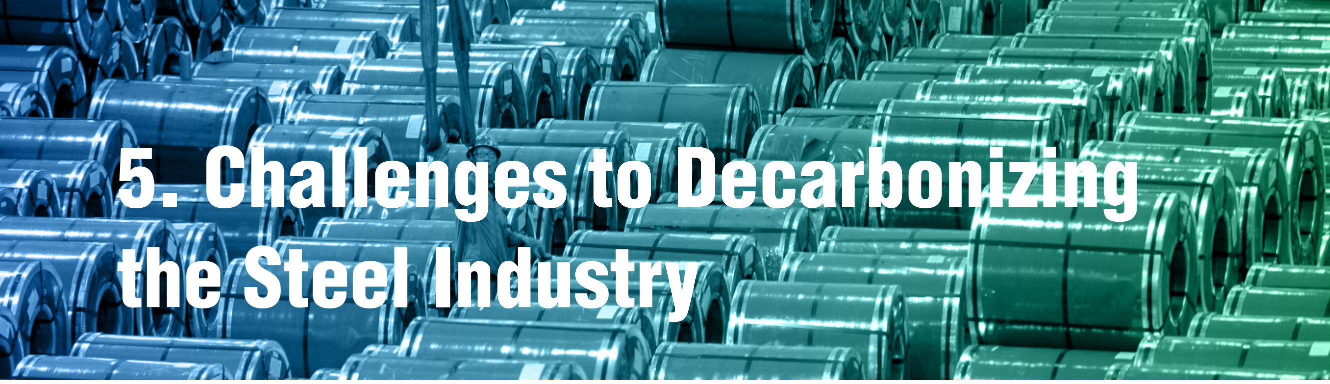
[47] MEMR (2024), Technology Data for the Indonesian Power Sector



Graph 2 Capital expenditure of steel production technology in 2025[48]

The graph above illustrates the investment expenditures associated with for decarbonization alternatives that incorporate involving a technology shift.switching. Capital expenditure in this case refers to the entire cost of new construction, not the development cost of existing technologies. The lLow-carbon technology, excluding the BAT BF-BOF with hydrogen, exhibits a lower investment cost than the average BF-BOF investment cost of US$USD 872 per ton of steel capacity. In facilities utilizing BF-BOF technology, ttuyere modification incurs a capital expenditure of US$USD 195 per ton of steel capacity. Investment in Electric Arc Furnace (EAF) technology to replace Basic Oxygen Furnace (BOF) costs US$USD 210 per ton of steel capacity. Furthermore, if steel producers decide to replace BOF technology with DRI technology that utilizes hydrogen, it will necessitate an additional investment of US$USD 488 per ton of steel capacity. In addition to the DRI option, the ironmaking process may also utilize MOE technology. This alternative necessitates a higher investment cost than the DRI option, which is US$USD 524 per ton of steel capacity. By evaluating the necessary investment expenses and the technology readiness level, steel enterprises can identify the decarbonization phases that align optimally with their specific circumstances.

[48] Mission Possible Partnership (2022), Making net-zero steel possible: an industry-backed, 1.5°C-aligned energy strategy.



5. Challenges to Decarbonizing the Steel Industry

This guide focuses primarily on the technological obstacles encountered by businesses in their decarbonization initiatives, in contrast to the typical guide that addresses issues affecting all stakeholders. By emphasizing critical aspects of technology and investment requirements, steel producers can formulate more precise and cost-effective strategies for reducing their carbon footprint. There are several challenges that are generally encountered by steel producers in Indonesia.

First, the average age of steelmaking technology currently used in Indonesia is still relatively young. Over 50% of steelmaking technology in Indonesia is under 20 years old, with approximately 40% of production capacity being around 11 years old.[49] On the other hand, the technological age of BOF technology, which is predominant in Indonesia, can extend up to 60 years.[51] Studies investigating the potential for emission reductions in the steel industry indicates that conventional energy-efficiency strategies can only collectively mitigate approximately 25–40% of the average CO2 emissions per ton of crude steel produced.[52] [53] [54] [55] The decarbonization of the steel industry requires retrofitting of existing equipment or the potential complete reconstruction of facilities, which presents a financial risk resulting from the mismatch between investment returns and the investment associated with Basic Oxygen Furnace (BOF) technology. In the short term, young high-emission-intensive assets, such as BF-BOF, that have not yet attained their first investment cycle may not be able to undergo deep plant transformations.

Second, the initial investment required to transition to low-carbon technology is substantial. Decarbonization must be cost-effective for large-scale implementation without impairing production performance. However, the lack of established business models and limited practical

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[49] OECD (2024), "Steelmaking capacity by economy", OECD Statistics on Measuring Globalization (database), https://doi.org/10.1787/2ae1e9c7-en (accessed on July 5th, 2024).

[50] OECD (2023), The Heterogeneity of Steel Decarbonization Pathways, https://www.oecd.org/publications/the-heterogeneity-of-steel-decarbonisation-pathways-fab00709-en.htm (accessed on July 18th, 2024).

[51] Li, Y and Zhu, L (2014). "Cost of energy saving and CO2 emissions reduction in China's iron and steel sector". Applied Energy, 130, 603-616.

[52] Morrow III, W. R., Hasanbeigi, A., Sathaye, J., & Xu, T. (2014). "Assessment of energy efficiency improvement and CO2 emission reduction potentials in India's cement and iron & steel industries". Journal of Cleaner Production, 65, 131-141.

[53] He, K., & Wang, L. (2017). "A review of energy use and energy-efficient technologies for the iron and steel industry". Renewable and Sustainable Energy Reviews, 70, 1022-1039.

[54] An, R., Yu, B., Li, R., & Wei, Y. M. (2018). "Potential of energy savings and CO2 emission reduction in China's iron and steel industry". Applied energy, 226, 862-880.

experience hinder the commercial viability of these promising emission reduction technologies.[55][56] The process of scaling up various steel decarbonization technologies, many of which remain at the pilot stage, requires progression to commercial production, which entails a complex and costly process. A promising technology with the potential to substantially reduce emissions is hydrogen-based direct reduction. However, this technology has not yet become commercially viable. Industry incentives, government action, and coordination among multiple stakeholders are essential to promoting the widespread adoption of low-carbon technologies.

Third, renewable energy remains in the developmental phase. One of the steel decarbonizing technologies with a high energy requirement is electric arc furnaces (EAFs).[57] Hydrogen, another fuel alternative for industry decarbonization, requires significant electricity for its production process. Therefore, to further reduce the carbon footprint, companies must optimize the utilization of renewable energy sources. Indonesia possesses many natural resources, many of which can be utilized for renewable energy. However, the current contribution of renewable energy is notably low. In 2023, the share of new and renewable energy in the energy mix was only 13.29%.[58] The limited usage of new and renewable energy prevents low-carbon electricity generation from achieving economies of scale, resulting in the cost of renewable electricity remaining comparatively higher than those of fossil fuel sources. Industrial decarbonization will not be optimal if the emission factor for electricity on the grid remains high. Companies have an additional alternative: captive power. However, this involves a substantial initial investment.

Fourth, despite being a crucial raw material for the steel sector to meet its carbon neutrality targets, scrap availability remains limited. The extended lifespan of steel products leads to a shortage of scrap in developing nations like Indonesia, where industrialization has not been as longstanding as in developed countries. The absence of regulations during collecting and sorting of metal scrap may further exacerbate the scarcity. Therefore, it is crucial for the industry to preserve its ability to manufacture steel through two production routes during the transition phase: (1) the primary route, which utilizes iron ore as raw materials, and (2) the secondary route, which utilizes scrap as raw materials for production.

Fifth, in BF-BOF steel making, each batch processed in the basic oxygen furnace, which converts carbon-rich pig iron into crude steel, typically containing about 15% of scrap. Scrap is used as a source of iron and a cooling agent while absorbing excess heat from the exothermic decarbonization reaction. To lower greenhouse gas emissions, scrap is occasionally added directly to BF to supply iron units. Due to the unique chemistry and temperature management required during the oxygen blowing, BOFs can incorporate a higher proportion of scrap compared to blast furnaces, which are limited to about 20% or less. However, the amount of scrap used in BOF remains constrained compared to the EAF, which can operate entirely on scrap. In the steelmaking of EAF, up to 100% scrap can be melted using electrical energy to produce new steel products.

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[55] Kapetaki, Z., & Scowcroft, J. (2017). “Overview of carbon capture and storage (CCS) demonstration project business models: risks and enablers on the two sides of the Atlantic”. Energy Procedia, 114, 6623-6630.

[56] Muslemani, H., Liang, X., Kaesehage, K., & Wilson, J. (2020). “Business models for carbon capture, utilization and storage technologies in the steel sector: a qualitative multi-method study”. Processes, 8(5), 576.

[57] Sukmak, P., Sukmak, G., De Silva, P., Horpibulsuk, S., Kassawat, S., & Suddeepong, A. (2023). “The potential of industrial waste: Electric arc furnace slag (EAF) as recycled road construction materials”. Construction and Building Materials, 368, 130393.

[58] Ministry of Energy and Mineral Resource Republic of Indonesia (2023). Handbook of Energy & Economic Statistics of Indonesia 2023.

6. Potential for Carbon Emissions Reduction

The industry's transition will be a great opportunity to reduce the emissions released to the atmosphere. Emission reduction by increasing the scrap input significantly reduces GHG by 16.48% and 13.39% in 2050 in the energy and IPPU sectors, respectively. Further reduction can be made by switching to more energy conservation technology, resulting in GHG reduction of up to 59.81% and 23.4% in the energy and IPPU sectors, respectively. Both of these results can be seen in 6-1.

Another attempt in the short-term, such as increasing coal injection and reducing heat loss, can help reduce the carbon emission up to 32.9% and energy consumption up to 21.9%. Not only that, it also improves the energy efficiency by 4.2% in the overall process.[59] Using biomass or biofuel has also shown great improvement, especially charcoal. Using charcoal can reduce the emissions produced by the coking and ironmaking process by up to 23.5%.

Using hydrogen injection can significantly reduce the emissions emitted in the production process. Hydrogen works as fuel and reductant in the BF, hence reducing the coke consumption and helping with the reduction process. Only water is produced as the reaction, thereby reducing the carbon emission emitted. Because of the potential of hydrogen as fuel and reductant, the overall carbon emission can be reduced from 20% to 40%, depending on the specific implementation of hydrogen injection.

Switching to low-emission technology such as DRI-EAF would further reduce the emission. While this process takes a long time, the impact itself will be great since it could reduce emissions from 40% to 60%, depending on plant location and the power source used for the process.[60] Combining the short-term transition strategy of increasing the amount of scrap input with low-emission technology forecasts the potential for GHG reduction, as shown in Figure 6-1 presented below.

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[59] Na et al., “Optimization of Energy Efficiency, Energy Consumption and CO2 Emission in Typical Iron and Steel Manufacturing Process”, https://www.sciencedirect.com/science/article/pii/S036054422201725X/pdfft?md5=4c31faecd927f3c6aa772e21af0b6970&pid=1-s2.0-S036054422201725X-main.pdf, September 17th, 2024.

[60] Ibid, page 20.

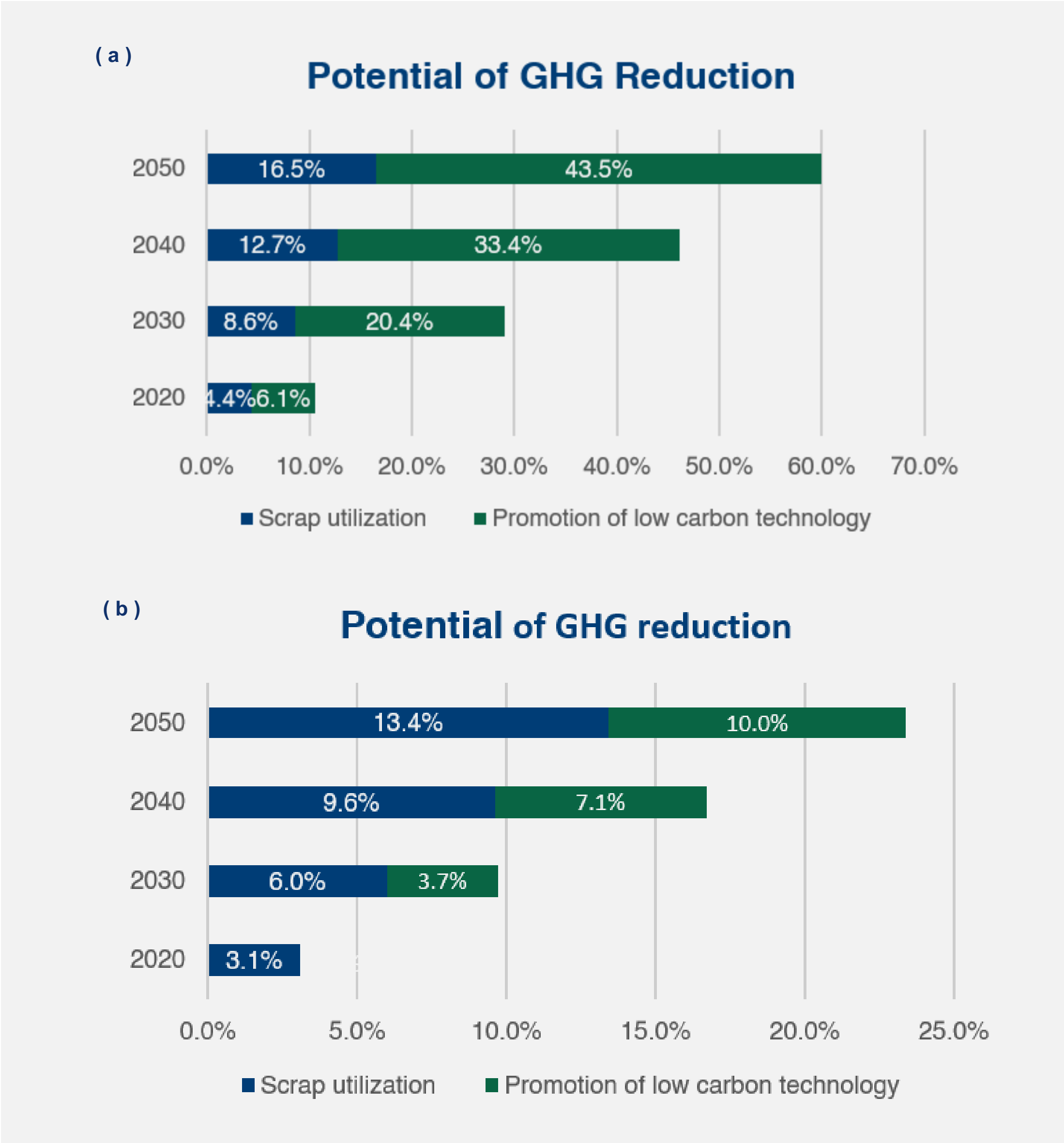

Figure 6-1 . Potential for GHG Emission Reduction under Different Scenarios: (a) Energy and (b) IPPU Activities in Indonesia's Iron and Steel Industry, 2020-2050 (2024)[61] (Processed by PSE UGM).

[61] Ibid, page 6.

The DRI reduction process can be removed in the overall process, thereby reducing the coke or fuel needed in the reduction process. To achieve this objective, the raw material for EAF, which in this case is scrap, must be available. With this approach, the emissions in the steelmaking process will be reduced to 0.3 tCO_2 per ton of crude steel produced, but it still depends on the power source used later on.

Promising ironmaking technology, Molten Oxide Electrolysis (MOE), can be used to melt all grades of iron ore to high-quality liquid metal without any pelletizing, sintering, or refinement. Moreover, nearly 100% of the process relies on electricity. Hence, the implementation of MOE with EAF can greatly decrease carbon emissions by potentially up to 100%, depending on the source of electricity .

7. Market Potential for Green Steel

Currently, the market for green steel is in the early stages of demand formation among companies. This demand formation is facilitated through various initiatives, such as the First Movers Coalition (FMC), SteelZero, the Mission Possible Partnership, and the Clean Energy Ministerial's Industrial Deep Decarbonization Initiative (IDDI). These initiatives aim to signal to steel producers that there is a demand for green steel. For instance, members of the FMC have pledged that at least 10% (by volume) of the steel purchased annually will originate from low-carbon sources, as defined by the FMC, by the year 2030. In addition to private sector initiatives, the IDDI encourages governmental initiatives to engage in green procurement of low-carbon materials, including steel.

From a projection standpoint, several research institutions have calculated the total growth of the green steel market. On the supply side, the global steel industry aims to produce 100 million metric tons of low-carbon steel annually by 2030[62]. On the demand side, the need for green or low-carbon steel will be significantly driven by global initiatives and offtake agreements with end users. At a global level, 44% of these offtake agreements originate from the transportation sector.[63] For example, companies such as Mercedes Benz have entered into agreements to purchase 50,000 tons of hydrogen-based green steel annually.

Estimates for the market size of green steel project an increase from USD 440.81 million in 2023 to USD 624.414 million by 2032, achieving a compound annual growth rate (CAGR) of 123.94% during this period.[64]Other research institutions have indicated a lower CAGR of 55.6% from 2024 to 2032, estimating a market size of USD 129.08 billion[65]. When comparing supply and demand, it is expected for there to be an excess in demand for green steel by 2030.[66]

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[62] BloombergNEF (2024). Industry Decarbonization Market Outlook 1H, 2024. https://about.bnef.com/blog/industry-decarbonization-market-outlook-1h-2024/ Accessed on October 29th, 2024.

[63] Ibid, page 4.

[64] Ibid, page 4.

[65] Fortune Business Insight (2024). Green Steel Market Size, Share, and Industry Analysis. https://www.fortunebusinessinsights.com/green-steel-market-108711 Accessed on October 29th, 2024.

[66] McKinsey&Company (2022). Green Steely Resolve. https://www.mckinsey.com/featured-insights/sustainable-inclusive-growth/charts/green-steely-resolve Accessed on October 29th, 2024.

8. Decarbonization Timeline

Based on the previous analysis, a decarbonization timeline for Indonesia's steel industry can be developed.

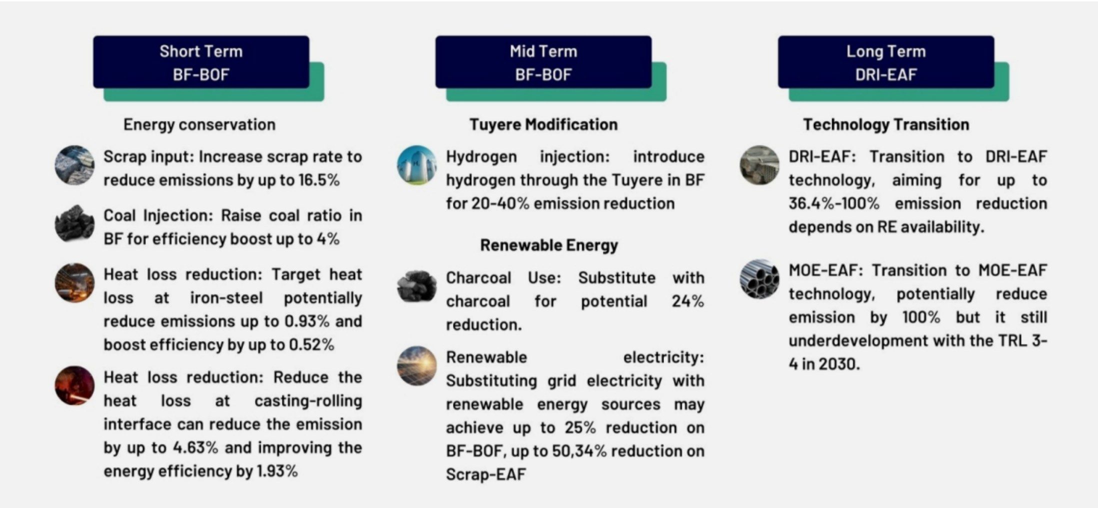

Figure 8-1. Decarbonization Time Frame for Indonesia's Steel Industry

Decarbonization options discussed are classified into three timeframes: short-term, medium-term, and long-term.

Short-term options involve measures requiring no significant changes or modifications to existing technologies. These decarbonization options include increasing the scrap input rate, increasing the ratio of coal injection, and reducing temperature loss.

Medium-term options include those that necessitate modifications to current technologies and additional CAPEX investments. These decarbonization options include transitioning to renewable energy sources for electricity and hydrogen injection through tuyere modification.

Finally, long-term options require substantial investment in new production equipment, meaning companies will need to replace existing production technologies with low-carbon technologies, such as EAF, BAT BF-BOF H2, DRI-EAF H2, and Molten Oxide Electrolysis.