

Scenario Design and Roadmap for Reducing Greenhouse Gas Emissions in Vietnam's Metallurgy Industry

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Abstract: *This study assesses greenhouse gas (GHG) emissions and potential mitigation pathways for Viet Nam's metallurgical industry, covering both ferrous and non-ferrous sectors. Emissions were estimated for the period 2015–2019 following the 2006 IPCC Guidelines, using national industrial statistics, enterprise energy reports, and detailed surveys conducted at major production facilities such as the Southern Steel Plant and Thai Nguyen Iron and Steel Joint Stock Company. Two scenarios were projected for 2025 and 2030: a Baseline Scenario, assuming continuation of current practices, and a Mitigation Scenario, which integrates technical and managerial measures including energy efficiency improvements, adoption of electric arc furnaces (EAF), waste heat recovery, fuel switching, deployment of innovative technologies (H₂-DRI, CCUS), and increased recycling of secondary metals. Results indicate that ferrous metallurgy accounts for over 90% of sectoral emissions, dominated by BF–BOF processes, while non-ferrous metallurgy especially aluminum production is experiencing rapid growth, with emissions projected to exceed 8 million tCO₂e by 2030. The proposed measures could reduce industry emissions by 20–35% by 2030 relative to the baseline. Based on these findings, a preliminary framework for Measurement, Reporting, and Verification (MRV) is suggested to enhance transparency and support integration of the metallurgical sector into Viet Nam's national climate strategies and emerging carbon market mechanisms..*

Keywords: *metallurgical industry; GHG inventory; emission scenarios*

1. Introduction

Climate change has emerged as one of the most pressing global challenges of the 21st century, requiring countries to take decisive actions to reduce greenhouse gas (GHG) emissions. Among the industrial sectors, heavy industries, particularly metallurgy, are recognized as some of the largest contributors to global CO₂ emissions, accounting for a substantial share of industrial greenhouse gases (Zhang, Jiao, Zhang, & Guo, 2021). International studies have highlighted that to achieve global climate targets, the metallurgical sector must undergo fundamental transformations. These include adopting advanced low-carbon technologies, integrating renewable energy, developing carbon capture, utilization, and storage (CCUS) solutions, and fostering circular economy models through recycling and reuse of raw materials (Saxena et al., 2024). Such measures are not only environmental imperatives but also necessary for maintaining competitiveness and ensuring the long-term sustainability of the industry. To achieve the target of net zero emissions by mid-century, the global metallurgical industry needs to reduce emissions by at least 50% by 2050 compared to today (Weaver, Zickfeld, Montenegro, & Eby, 2007). According to reports from the International Energy Agency (IEA) and the Intergovernmental Panel on Climate Change (IPCC), key solutions include: (i) improving energy efficiency and optimizing operations; (ii) increasing the use of scrap steel combined with electric arc furnace (EAF) technology; (iii) applying direct reduced iron (DRI) technology combined with hydrogen and renewable electricity; (iv) deploying carbon capture, utilization and storage (CCUS) systems for difficult-to-mitigate processes; and (v) promoting a circular economy through recycling and reuse of metals (Bishop & Economy, 2015; Okuh et al., 2024). Besides, many companies and countries have tested pilot projects such as hydrogen-powered iron production (H₂-DRI) in Europe (Truong, 2023), CCUS in steelmaking in China (Yang et al., 2022), or the construction of net-zero roadmaps by the world's leading metallurgical corporations (Bistline, 2021). However, the implementation of these solutions faces many challenges due to high investment costs, clean energy infrastructure requirements, technological limitations, and carbon market risks (Truong, 2023).

In the global context, many countries and regions have developed emission reduction policies and roadmaps for the steel industry. The European Union (EU) aims to be carbon neutral by 2050 (Perissi & Jones,

2022), implementing the Emissions Trading System (EU ETS) combined with the Carbon Border Adjustment Mechanism (CBAM) to limit carbon leakage (Bellora & Fontagné, 2023), and issuing an Action Plan for the Steel Industry to promote investment in electric arc furnace (EAF) (Stroud, Antonazzo, & Weinell, 2024), hydrogen direct reduction (H₂-DRI) and CCUS technologies [12]. In addition, China, the world's largest steel producer, has pledged to peak emissions by 2030 and become carbon neutral by 2060 (L.-L. Sun, Cui, & Ge, 2022). Its roadmap emphasizes rapidly increasing EAF rates, implementing H₂-DRI and CCUS pilot projects, and expanding the national carbon market to cover the steel industry (J. Sun et al.). Japan is also pursuing the goal of carbon neutrality by 2050, with close coordination between the Government and the Japan Steel Federation (JISF) through the Action Plan and Technology Roadmap, focusing on increasing the use of scrap, developing H₂-DRI, electrification, and applying transition finance to support businesses (Ohta, 2021). These experiences show that countries have chosen to synchronously combine many tools: from carbon markets, green financial mechanisms to technological innovation, in which EAF, H₂-DRI and CCUS are the main pillars. These are important suggestions for Vietnam to refer to in building an emission reduction roadmap for the metallurgical industry, especially preparing a transparent MRV framework, investment incentive mechanisms and low-carbon technology pilot projects, in order to both meet international commitments and improve the competitiveness of the steel industry in the context of globalization.

In Vietnam, the metallurgical industry has expanded rapidly over the past decade, driven by economic growth and rising demand for construction materials. This industry plays a pivotal role in the country's industrialization and modernization process. It provides essential materials such as steel, aluminum, copper, zinc, lead, and tin, which serve as critical inputs for construction, infrastructure development, manufacturing, and industrial production (Thy et al., 2020). Over the past decades, the rapid growth of the metallurgical industry has significantly contributed to socio-economic development. However, this growth has also led to rising energy consumption and GHG emissions. The ferrous metallurgy subsector (iron and steel production) is the dominant emitter, accounting for over 90% of total sectoral emissions, largely due to its reliance on coke and coal in blast furnaces and its high electricity consumption for smelting and processing (Truong, 2023). The challenge of reducing emissions in Vietnam's metallurgical industry has become increasingly urgent in light of the country's international commitments. At COP26 in 2021, the Government of Vietnam pledged to achieve net-zero emissions by 2050 (Binh, 2024). To operationalize this commitment, Vietnam has introduced a series of strategic policies and legal instruments, including the Nationally Determined Contribution (NDC), the National Climate Change Strategy, the Green Growth Strategy, the 2020 Law on Environmental Protection, and Decree No. 06/2022/ND-CP on GHG reduction and ozone layer protection. These policies have provided the legal framework and policy direction for various sectors, including metallurgy, to develop specific plans and pathways for emission reduction (Central Economic Committee, European Union, 2022).

Some scientists are researching a monitoring, reporting, and verification framework for GHG emissions in the metallurgical sector (Truong, Ha, Nghi, Anh, et al., 2020), determining the approaches for the GHG emission inventory and application for the metallurgy industry (Truong, Ha, Nghi, Hung, et al., 2020), studying the emissions and measures in greenhouse gas management for climate change mitigation in developing countries (Ho et al., 2022). Besides, (Tran et al., 2020) created a set of standards for setting priorities for GHG emission reduction initiatives in the metallurgical sector, (Pham, 2019) conducted measurement of greenhouse gas emissions from various techniques for treating municipal solid trash.

Although previous studies provide valuable insights, most of them focus on individual measures or general energy-saving practices, without presenting an integrated assessment that combines a comprehensive GHG inventory, future emission scenarios, and a full set of mitigation options for the metallurgical sector. In addition, there has been little quantitative analysis of cost-effectiveness tailored to Viet Nam's specific industrial context, and no dedicated proposal for a sectoral Measurement, Reporting, and Verification (MRV) framework. This study explicitly addresses these gaps by establishing a detailed GHG inventory for both ferrous and non-ferrous metallurgy in Viet Nam, developing baseline and mitigation scenarios up to 2030, assessing the abatement potential and cost-benefit of 23 mitigation measures, and proposing a preliminary MRV framework. By doing so, the research provides an integrated, evidence-based foundation to support the sector's contribution to Viet Nam's Net Zero commitment by 2050.

2. Methodology

The methodology for estimating greenhouse gas (GHG) emissions in the Vietnamese metallurgical industry follows the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, combined with national statistics, enterprise reports, and plant-level surveys. The estimation is based on comparing

baseline and project emissions using the following formula:

$$ER = BE - PE \quad (1)$$

where ER is the emission reduction (tCO₂e), BE is the baseline emissions without mitigation measures, and PE is the project emissions after implementing mitigation measures.

System boundary, gases, and GWPs

The inventory covers direct process and fuel-combustion emissions (Scope 1) and indirect emissions from purchased electricity (Scope 2) for both ferrous and non-ferrous metallurgy. The gases considered are CO₂, CH₄, and N₂O, all converted into CO₂-equivalent using 100-year Global Warming Potentials (GWPs) from the IPCC AR5 (2013).

Emission factors and activity data

Fuel calorific values and oxidation factors are taken from the 2006 IPCC Guidelines. Process emission factors for steelmaking (BF–BOF, EAF) and aluminum electrolysis are based on IPCC defaults unless country-specific values are available. For electricity, the grid emission factor applied is 0.8154 tCO₂/MWh (MONRE, 2015 baseline). Activity data, fuel use, electricity consumption, and production output were collected from official industrial statistics, enterprise energy reports, and surveys at representative plants.

Scenario development and projections

Two main scenarios were developed: a Baseline scenario, assuming continuation of current technologies and practices, and a Mitigation scenario (with Low and High variants), incorporating efficiency improvements, waste-heat recovery, increased EAF deployment, clean fuel substitution, and breakthrough options such as H₂-DRI and CCUS. Emissions were projected for 2025 and 2030 under each scenario.

Cost–benefit analysis (CBA)

For mitigation options with sufficient data, a CBA was conducted to estimate the marginal abatement cost (USD/tCO₂e) and assess their economic feasibility. The analysis accounts for capital and operating costs, energy savings, and co-benefits such as reduced air pollutants.

Methodological framework

The overall process is illustrated in Figure 1, which summarizes the five steps: (i) GHG inventory, (ii) scenario development, (iii) emission projections, (iv) CBA of mitigation measures, and (v) formulation of a roadmap with policy implications. The dashed feedback arrow from CBA back to scenario development indicates that economic results inform the refinement and prioritization of scenarios.

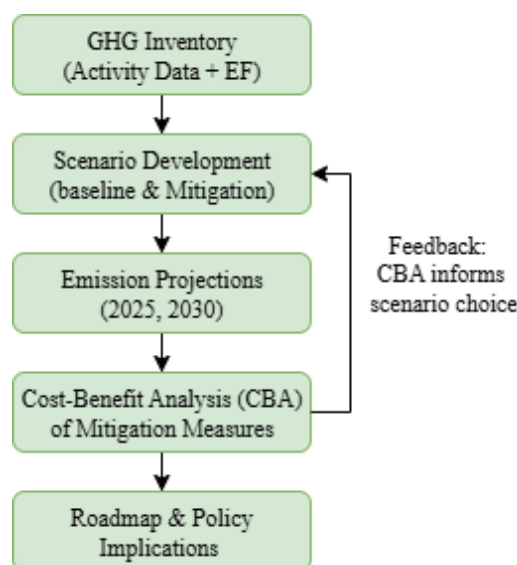


Fig. 1. Methodology Flowchart

In this way, the framework combines technical emission modeling with economic assessment. By integrating CBA feedback, the study ensures that the proposed pathways are not only technologically

feasible but also economically viable, providing a stronger basis for the emission reduction roadmap of Viet Nam's metallurgical industry

To enhance transparency, plant-level surveys were conducted using structured questionnaires and interviews with technical staff to collect data on production processes, energy consumption, and emission control practices. Reported figures from enterprises were cross-checked against national statistics and site observations to ensure consistency. Where data gaps or uncertainties existed, IPCC default values were compared with plant-specific information to improve reliability.

3. Results and discussion

3.1 Results of the emissions inventory

The results of the greenhouse gas emissions inventory for Vietnam's ferrous metallurgy industry are shown in Table 1.

Tab. 1. Total GHG emissions of the ferrous metallurgy industry

Year	2015	2016	2017	2018	2019
Emissions from BF - BOF (million tons)	5.83	8.87	14.56	28.13	33.43
Emissions from EAF (million tonnes)	2.64	3.50	4.84	4.87	5.17
Total emissions (million tonnes CO ₂ equivalent)	8.48	12.37	19.40	33.00	38.60

The results of the greenhouse gas emissions inventory for the Vietnamese metallurgical industry in the period 2015–2019 show a clear increasing trend, especially in the iron and steel sub-sector. According to Table 1, emissions from BF–BOF technology rose from 5.83 to 33.43 million tCO₂e between 2015 and 2019, while emissions from EAF rose from 2.64 to 5.17 million tCO₂e. This confirms that BF–BOF dominates total emissions, while EAF has a lower emission intensity due to scrap-based production.

At the production facility level, emissions also differ significantly. According to Table 2, the total emissions of the Southern Steel Plant ranged from 399.28 thousand tCO₂e (2015) to 440.74 thousand tCO₂e (2018), then decreased to 416.63 thousand tCO₂e (2019); of which emissions from electricity consumption accounted for a large proportion. For Thai Nguyen Iron and Steel Joint Stock Company (TISCO), Table 2 shows that the total emissions were 565.82 thousand tCO₂e (2015), 581.88 thousand tCO₂e (2016), 487.25 thousand tCO₂e (2017), 663.14 thousand tCO₂e (2018), and 598.57 thousand tCO₂e (2019), respectively. At the same time, the emission factor decreased from 1.60 tCO₂e/tonne of product (2015) to 0.84 tCO₂e/tonne of product (2019), reflecting an improvement in production efficiency despite a significant increase in output.

Tab. 2. Results of a detailed inventory of total GHG emissions at the production facility level

Production facility	Result	2015	2016	2017	2018	2019
Southern Steel Factory	Total emissions	399.28	414.98	412.22	440.74	416.63
	Emission factor	0.71	0.71	0.71	0.68	0.67
Thai Nguyen Iron and Steel Joint Stock Company	Total emissions	565.82	581.88	487.25	663.14	598.57
	Emission factor	1.60	1.45	1.07	1.02	0.84

For non-ferrous metallurgy, current emissions are small relative to ferrous metallurgy but are forecast to grow rapidly, especially in aluminum production, which could reach 8.42 million tCO₂e by 2030. According to Table 3, total emissions from the aluminum industry increased from 1231.94 thousand tCO₂e in 2015 to 2929.25 thousand tCO₂e in 2019. Emissions are forecast to reach 4761.20 thousand tCO₂e in 2025 and 8421.26 thousand tCO₂e in 2030, including emissions from the production process and energy consumption in aluminum electrolysis. Thus, aluminum is a sub-sector with a rapid growth rate in emissions and needs special attention in the medium- and long-term emission reduction roadmap.

Tab. 3. Forecast of GHG emissions of the aluminum manufacturing industry (thousand tons of CO₂ equivalent)

Emission source	2015	2016	2017	2018	2019	2025	2030
Aluminum metal production process	0.00	0.00	0.00	0.00	0.00	240.00	720.00
Energy consumption for alumina production	1231.94	1401.93	2435.21	2803.60	2929.25	2931.17	2931.17
Energy consumption for aluminum metal production	0.00	0.00	0.00	0.00	0.00	1590.03	4770.09
Total	1231.94	1401.93	2435.21	2803.60	2929.25	4761.20	8421.26

From the data on the GHG emission reduction roadmap of the ferrous and non-ferrous metallurgical industries, the emission reduction roadmap of the entire metallurgical industry in the period 2021 - 2030 is calculated as shown in Table 4 and Figure 2. Integrating the whole industry, Table 4 shows that annual emission reductions compared with the baseline increase from 13.04 million tCO₂e in 2021 to 19.92 million tCO₂e in 2030. This trend shows that without intervention, the industry's emissions will continue to increase rapidly, putting great pressure on the national emission reduction target and the commitment to achieve net zero emissions by 2050.

Tab. 4. Roadmap for greenhouse gas emission reduction of the entire metallurgical industry (million tonnes of CO₂ equivalent)

Year	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Ferrous metallurgy	12.63	13.25	13.87	14.49	15.11	15.96	16.80	17.65	18.50	19.35
Non-ferrous metallurgy	0.41	0.45	0.48	0.53	0.56	0.56	0.57	0.57	0.57	0.57
Total	13.04	13.70	14.35	15.02	15.67	16.52	17.38	18.22	19.07	19.92

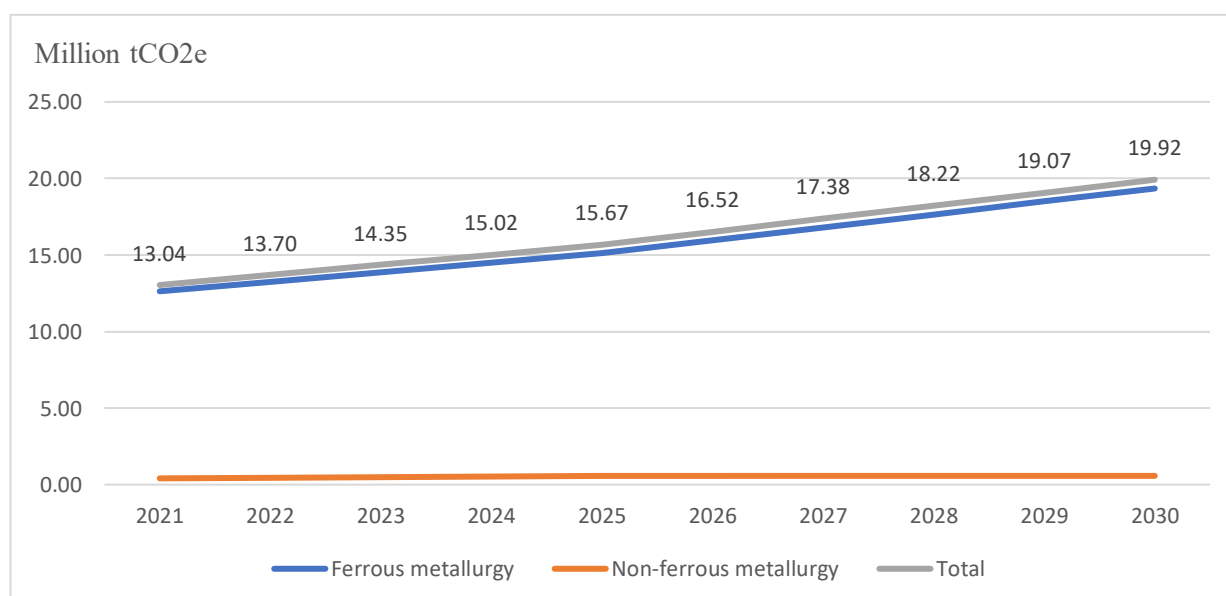


Fig. 2. Emissions reduction roadmap for the entire metallurgical industry

These results confirm that BF–BOF steelmaking is the dominant source of emissions, while EAF technology shows significantly lower emission intensity (Table 1 and Table 2). Facility level data further illustrate how production efficiency improvements can reduce emission factors, as observed at TISCO,

where the emission factor declined from 1.60 to 0.84 tCO₂e/tonne of product between 2015 and 2019. Although current emissions from non-ferrous metallurgy remain modest, aluminum production is projected to reach approximately 8.42 million tCO₂e by 2030 (Table 3), underscoring its growing importance in the sector's mitigation roadmap. Inventory results were cross validated against national statistics and enterprise self-reports, with IPCC default values applied where plant-level data were incomplete. Nonetheless, uncertainties remain, particularly regarding self-reported energy use and the limited scope of facility-level surveys (mainly at Southern Steel Plant and TISCO). Future studies should expand the survey coverage and include formal uncertainty analysis to further strengthen the reliability of results.

3.2. Emission reduction scenarios and roadmaps

Based on the results of emission inventory and analysis of technology and management solutions, the study has developed a number of greenhouse gas (GHG) emission reduction scenarios for Vietnam's metallurgical industry by 2030.

3.2.1. Baseline scenario

Table 5 summarizes the greenhouse gas emissions of the entire metallurgical industry in Vietnam in the period 2015–2019 and forecasts for 2025 and 2030 according to the baseline scenario (Truong, 2023). The results show a continuous increase in emissions, from 9.90 million tCO₂e in 2015 to 41.77 million tCO₂e in 2019, and are expected to reach 69.24 million tCO₂e in 2025 and 97.25 million tCO₂e in 2030 from 9.90 million tCO₂e in 2015 to 41.77 million tCO₂e in 2019, and are expected to reach 69.24 million tCO₂e in 2025 and 97.25 million tCO₂e in 2030. This is an important input data for developing and comparing emission reduction scenarios in section 3.2, especially for the baseline scenario.

Tab. 5. GHG emissions from Vietnam's metallurgical industry to 2030 (thousand tons of CO₂ equivalent)

Activities	2015	2016	2017	2018	2019	2025	2030
Ferrous metallurgy	8475.4 9	12370.7 3	19403.1 1	32997.5 7	38603.1 9	63670.0 0	88015.0 0
Non-ferrous metallurgy	1420.8 6	1602.62	2636.13	3029.91	3167.94	5567.23	9237.40
- Copper smelting	58.91	60.56	59.96	61.36	65.08	247.30	247.30
- Aluminum smelting	8.70	1401.93	2435.21	2803.60	2929.25	4761.20	8421.26
- Lead training	18.05	26.71	26.71	26.71	26.71	45.79	45.79
- Zinc smelting	101.20	102.86	103.82	129.43	138.10	502.34	508.38
- Tin smelting	10.76	10.56	10.43	8.80	8.80	10.60	14.67
Total	9896.35	13973.35	22039.24	36027.48	41771.13	69237.23	97252.40

The baseline scenario assumes that Vietnam's metallurgical industry continues to expand production as planned, maintaining existing technology without applying additional emission reduction measures. According to (Truong, 2023), the industry's total greenhouse gas emissions are expected to increase from 69,237 thousand tCO₂e in 2025 to 97,252 thousand tCO₂e in 2030. Of which, the aluminum industry has a rapid growth rate, with forecast emissions of 4,761.20 thousand tCO₂e in 2025 and 8,421.26 thousand tCO₂e in 2030. The baseline scenario reflects a sharp increase in emissions without intervention, making the metallurgical industry one of Vietnam's largest emitters. The baseline scenario does not bring about emission reduction benefits because it maintains current technology and production scale. On the contrary, emissions increase sharply (from 69.24 million tCO₂e in 2025 to 97.25 million tCO₂e in 2030) (Truong, 2023), putting great pressure on the national target of emission reduction. The only effectiveness of this scenario lies in ensuring production growth and meeting domestic demand for steel and aluminum, but it entails environmental risks and increasingly high carbon costs when Vietnam participates in the carbon market

3.2.2 Low emission scenario

The low emission reduction scenario is built on the basis of partial implementation of emission reduction solutions, prioritizing short-term, low-cost, and easy-to-implement measures. The main solutions include: improving energy efficiency in production, optimizing operations, recovering waste heat, increasing the use of scrap steel in EAF technology, and partially applying alternative fuels (natural gas, biomass).

According to Table 4, the emission reduction will reach about 13.04 million tCO_{2e} in 2021 and gradually increase to 15–16 million tCO_{2e} in 2025, reaching 19.92 million tCO_{2e} in 2030. With this scenario, the remaining emissions in 2030 will be about 77.33 million tCO_{2e}, 20% lower than the baseline scenario, thereby showing clear effectiveness when applying energy-saving measures and improving basic technology. The low emission reduction scenario brings dual benefits of both reducing emissions and saving energy and operating costs. Measures such as heat recovery, operational optimization, and partial replacement of clean fuels will help reduce 19.92 million tCO_{2e} in 2030 (Table 4), equivalent to 20% compared to the Baseline. This would help the metallurgical industry avoid a large amount of emissions, while improving energy efficiency, reducing dependence on imported coking coal and reducing production costs in the long term. This scenario is feasible because much of the technology is already commercially available and does not require large investments.

3.2.3. High emission reduction scenario

The high emission reduction scenario assumes the synchronous and comprehensive deployment of advanced technological solutions, including measures in the low scenario along with low emission and carbon neutral technologies. Specifically, the steel industry is gradually shifting to direct hydrogen reduction technology (H₂-DRI), increasing the use of renewable energy, and combining the application of carbon capture and storage (CCUS) technology at BF–BOF facilities. With this scenario, emission reductions can exceed 30% by 2030 compared with the baseline, resulting in remaining emissions of about 65–70 million tCO_{2e} by 2030 (Truong, 2023). This is an ambitious scenario, but consistent with Vietnam's commitment to carbon neutrality by 2050 if there is international technological, financial and policy support. The high emission reduction scenario achieves a 30–35% reduction by 2030 compared to the baseline, corresponding to 65–70 million tCO_{2e} of residual emissions. The main benefit is to promote the metallurgical industry to switch to green technology (H₂-DRI, CCUS, renewable energy), helping Vietnam move closer to its goal of net zero emissions by 2050. In addition, this scenario also enhances international competitiveness, as “green” steel and aluminum products have a great advantage in the context of the EU and developed markets applying the Carbon Border Adjustment Mechanism (CBAM). However, socio-economic efficiency can only be achieved if there is strong support from policies, investment, and technology transfer.

Table 6 presents a comparison between greenhouse gas emission scenarios of Vietnam's metallurgical industry to 2030, including the baseline scenario, low emission reduction scenario, and high emission reduction scenario (data taken from Tables 4 and 5).

Tab. 6. Comparison of greenhouse gas emission scenarios of Vietnam's metallurgical industry to 2030 (Unit: million tCO₂)

Year	Baseline	Mitigation – Low	Mitigation – High	Cut Rate vs Baseline
2025	69.24	53.57 (= 69.24 – 15.67)	49.85–51.93 (2025 High)	Low: 22.63% High: 25–28%
2030	97.25	77.33 (= 97.25 – 19.92)	63.21–68.08 (2030 High)	Low: 20.48% High: 30–35%

Baseline: Projected emissions without reduction measures, maintaining current technology.

Mitigation – Low: Apply energy saving measures, heat recovery, increase EAF ratio, partially replace clean fuel

Mitigation – High: Synchronously deploy advanced technologies such as H₂-DRI, CCUS, renewable energy; estimated emissions reduction is deeper than Baseline by about 30–35% by 2030.

Overall, the scenario analysis highlights clear opportunities for emission reduction. The Low Mitigation scenario shows that near-term measures such as energy efficiency improvements and expansion of scrap-based EAF can deliver reductions of about 20% by 2030 relative to the Baseline. The High Mitigation scenario emphasizes the transformative role of breakthrough technologies (H₂-DRI, CCUS, renewable energy integration), achieving reductions of 30–35% (Table 6). These findings provide quantitative evidence that Viet Nam's metallurgical industry can align with national climate targets if a phased strategy is adopted. However, the effectiveness of these pathways will depend on supportive policy incentives, access to green financing, and improved data transparency to reduce uncertainties in long-term projections.

3.3. Emissions reduction roadmap

Short-term (2025):

- Focus on energy-saving measures and operational optimization across production, such as furnaces, heating equipment, and exhaust gas treatment systems.
- Recover waste heat from the smelting and casting processes for reuse in production or to provide energy to auxiliary areas, reducing primary energy consumption
- Pilot application of Electric Arc Furnace (EAF) technology at a number of large steel mills to evaluate the effectiveness of reducing emissions, energy consumption and operating costs before scaling up.
- Conduct human resource training, raise awareness of energy management, economical operation and equipment maintenance to reduce energy loss

Medium term (2030):

- Expand EAF technology in key steel mills, integrate process optimization and automation to enhance efficiency and reduce CO₂ emissions.
- Promote the recycling of steel and non-ferrous metals from scrap, reduce the need to produce steel from iron ore, thereby significantly reducing the amount of CO₂ generated.
- Expand the use of clean fuels such as natural gas, biomass, and other alternative energy sources, gradually replacing traditional fossil fuels.
- Implement carbon credit mechanisms and an MRV (Monitoring, Reporting, Verification) system across the industry to build a transparent emissions database, support management, and enable participation in domestic and international carbon markets.

Long-term (after 2030):

- Research and apply green hydrogen in the steelmaking process, gradually replacing coke and other fossil energy sources, towards a nearly zero-emission steelmaking process.
- Deploy CCUS (Carbon Capture, Utilization, and Storage) on an industrial scale to capture and treat CO₂ generated from furnaces and auxiliary processes.
- Integrate renewable energy sources (solar, wind, biomass) into the metallurgical production chain, reduce dependence on fossil energy and cut indirect emissions.
- Develop green supply chain management solutions, including transportation optimization, logistics emission reduction and promotion of environmentally friendly materials.
- The long-term goal is to achieve net zero emissions in line with the national climate commitment by 2050, while creating a competitive advantage in the context of the global metallurgical market increasingly focusing on ESG and carbon footprint.

3.4 Challenges and Opportunities

3.4.1 Challenges

High investment costs: Transitioning to low-carbon technologies such as EAF, CCUS, and green hydrogen requires significant upfront capital. For many steel mills, especially small and medium-sized enterprises, financial constraints may delay adoption.

Technology readiness: While EAF and clean fuel substitution are relatively mature, breakthrough solutions like large-scale CCUS and hydrogen-based steelmaking remain at pilot or early commercialization stages. Uncertainties in efficiency, scalability, and cost-effectiveness pose risks to long-term implementation.

Resource constraints: The success of circular economy strategies depends heavily on the availability and quality of scrap materials. Similarly, green hydrogen production relies on sufficient renewable energy capacity, which is still limited in many regions.

Policy and regulatory framework: Inconsistent or unclear climate policies, carbon pricing mechanisms, and incentives may undermine the industry's ability to plan and invest confidently. A lack of robust MRV systems could also limit access to carbon markets.

Workforce and skills gap: Adoption of advanced digital, automation, and green technologies requires a skilled workforce. Training programs must be expanded to address potential gaps in technical expertise.

3.4.2 Opportunities

Global competitiveness: By transitioning early to low-carbon production, the steel industry can gain a competitive edge in international markets where ESG performance and carbon footprint increasingly influence trade and investment decisions.

Access to carbon markets and green financing: Implementation of MRV systems and emission reduction projects allows industries to generate carbon credits, attracting investment and enabling participation in international carbon trading mechanisms.

Technological innovation: The roadmap creates opportunities for domestic research institutions, universities, and companies to collaborate in developing and localizing advanced technologies such as hydrogen-based processes, CCUS, and AI-driven optimization.

Energy security and diversification: Expanding renewable energy and alternative fuels reduces dependence on imported fossil fuels, improving resilience to global energy price fluctuations.

Sustainable development co-benefits: Emission reduction strategies not only mitigate climate change but also improve air quality, reduce health risks for surrounding communities, and promote sustainable industrial growth.

4. Conclusion

This study provided a comprehensive assessment of GHG emissions and mitigation pathways in Viet Nam's metallurgical industry. Using IPCC 2006 guidelines combined with enterprise reports and plant-level surveys, the analysis confirmed that ferrous metallurgy, particularly BF-BOF, is the dominant source, accounting for over 90% of emissions. Non-ferrous metallurgy, especially aluminum, is emerging as a rapidly growing emitter, projected to reach about 8.42 million tCO₂e by 2030. Scenario modeling showed that mitigation measures could reduce emissions by 20% under a low scenario and up to 30–35% under a high scenario relative to the baseline.

The study outlines a phased roadmap: in the short term (to 2025), priority should be given to low-cost efficiency improvements, waste-heat recovery, and pilot application of EAF technology; in the medium term (to 2030), scaling up EAF, promoting recycling, and adopting cleaner fuels are key; and in the long term, deep decarbonization will require breakthrough technologies such as H₂-DRI, CCUS, and integration of renewable energy sources.

Beyond technology, the findings emphasize the importance of enabling frameworks. A robust MRV system is necessary to ensure transparency and support participation in carbon markets. Policy measures should include targeted tax incentives for low-carbon equipment, pilot and demonstration programs to reduce technology risk, and green financing mechanisms to mobilize investment. With coordinated policies, strengthened MRV, and international cooperation for technology transfer and funding, Viet Nam's metallurgical industry can substantially reduce emissions while maintaining competitiveness and contributing to the national Net Zero commitment by 2050.

Acknowledgment

This work was financially supported by the Science and Technology Program for Addressing Climate Change, Natural Resources, and Environmental Management for the period 2016-2020, under Program Code BDKH/16-20

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