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Green Steel Production using Mass Balance Approach

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The study focuses on greenhouse gas (GHG) emissions in a midstream iron and steel industry that specializes in producing cold-rolled coils (CRC) as the main product. Data on GHG emissions were collected and analysed for Scope 1, 2 and 3. This study demonstrates the development of new framework called the mass balance approach (MBA) to quantify the percentage of green steel production. The MBA serves as a transitional solution for reducing emissions for the iron and steel industry until advanced decarbonisation technologies become widely feasible. Findings show that green steel accounted for 15.5 % of the total 143,959 MT produced in FY24 was achieved by employing solar photovoltaic (PV) and more efficient compressed air systems (CAS) as emission-reduction strategies. This highlights the applicability of MBA as a systematic framework for assessing green steel production and supporting progress toward climate neutrality.

1. Introduction

The iron and steel industry is crucial for infrastructure development and economic growth, as steel is widely used in manufacturing, construction, and defense sectors. Additionally, steel supports low-emission infrastructure, such as wind turbines, electric vehicles, bioenergy refineries, and green buildings (Oliveira et al., 2024). Over 70 % of world steel is produced in Asia nowadays, indicating the importance of the iron and steel industry in Asia as well as in Malaysia (World Steel Association, 2021). However, the steel sector remains one of the most challenging industries to decarbonize due to its high capital intensity, long asset lifespans, and reliance on carbon as a process input. In 2020, it accounted for 2.6 gigatonnes of CO_2 emissions, representing 7 % of global energy-related emissions (International Energy Agency, 2020). In response, the concept of green steel has gained momentum, emphasizing the adoption of cleaner energy sources and innovative production methods to meet the climate objectives set out in the Paris Agreement (Gerres et al., 2021). Technologies such as carbon capture and renewable hydrogen are being actively explored to reduce GHG emissions in steel production (Hieminga et al., 2023). The Carbon Border Adjustment Mechanism (CBAM) introduced by the European Union (EU) will also have a significant impact on international trade in iron and steel (Wang et al., 2023). Emission Trading Schemes (ETS) can further accelerate industrial decarbonisation, but their effectiveness relies on robust monitoring, reporting, and verification (MRV) systems to ensure that one tonne of carbon emitted or reduced at one facility is equivalent to a tonne emitted or reduced at another (Hashim et al., 2022). In Malaysia, the iron and steel industry faces significant decarbonization challenges, with GHG emission intensity projected to surpass 12 % of the nation's total emissions by 2030 (Oliveira et al., 2024). Despite this, the midstream steel industry currently produces no green steel, primarily due to high capital requirements and limited access to advanced green steel technologies (Lux Metal, 2024). Transitioning to green steel also presents cost barriers, as production costs are estimated to be 20–30 % higher than conventional methods (Muslemani et al., 2021). This study was undertaken to demonstrate the practicality of the MBA in producing green steel products. The study also aims to forecast the future green steel production needed to achieve a 3 % annual reduction in emission intensity and supports the New Industrial Master Plan 2030 (Ministry of Investment, Trade and Industry, 2023) and Malaysia's pathway toward climate neutrality by 2050.

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2. Methodology

This section discusses the methodology for the estimation of green steel production using the MBA which was adopted from Japan (JISF, 2023). The method is robust and can be applied to iron and steel industries worldwide, but in this study, it was implemented in a Malaysian iron and steel company. The process begins with the collection of activity data on GHG emissions, emission factors, GHG reduction measures, and production capacity. Subsequently, the GHG Protocol is applied to calculate both emissions and emission intensity. The final step involves determining the percentage of green steel production. The detailed steps will be discussed in the following section.

2.1 Data Collection

Data were collected from a midstream iron and steel industry with maximum output production capacity around 260,000 MT/year. The process comprises pickling, cold rolling, electrolytic cleaning, annealing, and final rolling (skin-passing, tension leveling, and oiling) as shown in Figure 1.

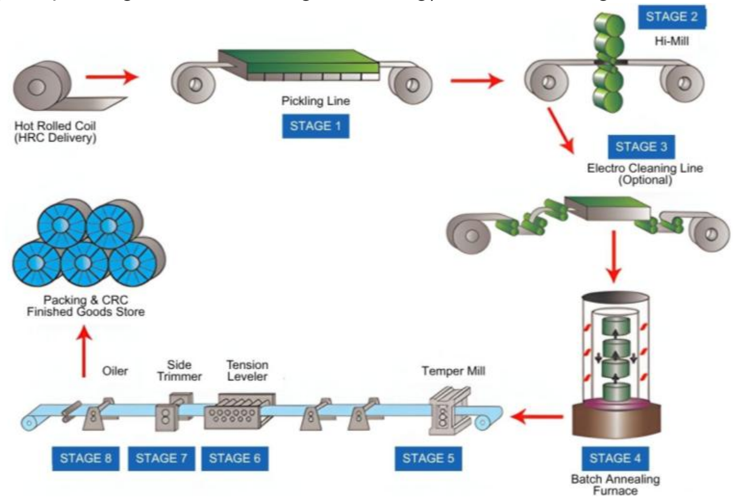

Figure 1: Defined Boundaries of the Research

The data collected includes production capacity of the main product (CRC) in ton, Scope 1 emissions which covers the natural gas, petrol, and diesel consumption, Scope 2 emission covers the electricity consumption, and Scope 3 emissions covers business travel and employee commuting. Scope 1 and Scope 2 activity data were collected from fuel and utility bills. For business travel, mileage was recorded through claims, and for employee commuting, the distance between the worker's home and the company, type of vehicles and fuels were recorded via a Google Form which was distributed by the top management to all workers in the company. The GHG emission factors used in the calculations were obtained from the GHG Protocol and are presented in Table 1. The Global Warming Potentials (GWPs) applied in this study were taken from the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC, 2013).

Table 1: Indicative emission factors for GHG emission sources

GHG Emission	Stage (S) (Refer Figure 1)	Source of Emission	Activity Data by Scope	Unit	Emission Factors ($MTCO_{2e}$/unit)	Reference
Scope 1	S1: Natural Gas in Furnace	Gas Fuel	Natural Gas	mmBtu	0.053115	US EPA (2025)
	S1: Forklifts	Liquid Fuel	Diesel	gallon	0.010223	US EPA (2025)
			Gasoline	Gallon	0.008812	US EPA (2025)
Scope 2	S1 to S8: Electricity Consumption for Equipments	Electricity		kWh	0.000585	MGTC (2018)
	-	Solar		kWh	0	-
Scope 3	Business Travel & commuting	Car	Diesel	km	0.172006	UK DESNZ (2025)
			Gasoline	km	0.180251	UK DESNZ (2025)

2.2 Green Steel Production using MBA

The MBA allocates verified greenhouse gas (GHG) emission reductions to specific steel products. The step-by-step procedure of MBA applied for this study was shown below.
Step 1. GHG emission calculations were performed using IPCC guidelines and GHG Protocol with the multiplication of activity data, emission factor (EF) and Global Warming Potential (GWPs) as shown in Eq(1).

$$Total\ Emission\ (MTCO_{2e}) = \sum_{n=1}^{n} Activity\ data\ x\ EF\ x\ GWP \tag{1}$$

Step 2. Calculate emission intensity (EI) of the steel products excludes the emission reduction due to installation of energy mitigation measures. EI can be calculated using Eq(2).

$$Emission\ Intensity\ (MTCO_{2e}/\mathrm{MT}) = Total\ Emissions\ (MTCO_{2e})/production\ (\mathrm{MT}) \tag{2}$$

Step 3: Identify emission reduction strategies and quantify the corresponding GHG emission reduction (ER). These strategies should be implemented within the organisation, involve additional costs, and demonstrate clear additionality. In this study, the adoption of solar PV and the installation of a more efficient CAS resulted in a total emission reduction. The emission reduction from solar energy can be calculated using Eq(3) while for CAS can be calculated using Eq(4).

$$ER\ by\ Solar\ PV\ (MTCO_{2e}) = Solar\ generation\ (kWh) x\ Electricity\ EF\ (MTCO_{2e}/kWh) \tag{3}$$

$$ER\ by\ Efficient\ CAS\ (MTCO_{2e}) = Electricity\ Reduction\ (kWh)\ x\ Electricity\ EF (MTCO_{2e}/kWh) \tag{4}$$

Step 4: The green steel production and percentage of green steel production were calculated by using Eq(5) and Eq(6).

$$Green\ Steel\ Production\ (MT) = \frac{Total\ Emission\ Reduction, ER\ (MTCO_{2e})}{Emission\ Intensity, EI\ (MTCO_{2e}/MT)} \tag{5}$$

$$\%\ Green\ Steel = \frac{Green\ Steel\ Production\ (MT)}{Total\ Finished\ Goods\ Production\ (MT)} x\ 100\ \% \tag{6}$$

ER refers to the reduction in emissions achieved through the implementation of green measures, such as solar power installation for electricity generation and the replacement of CAS with more efficient alternatives. EI, on the other hand, represents emission intensity, calculated as the total GHG emissions (converted into CO_2 equivalent) divided by the steel production output in metric tonnes (MT).

3. Results and Discussion

3.1 GHG Emission

GHG emissions analysis across financial years (FY) FY19 to FY24 reveals evolving patterns in direct (Scope 1), indirect energy-related (Scope 2), and supply chain-related (Scope 3) emissions, alongside shifts in production output.

Table 2: Output Production Capacity, GHG Emission for Scope 1, Scope 2, Scope 3 and Emission Intensity Without ER Initiatives

Financial Year	Output Production Capacity (MT)	Scope 1 GHG Emission ($MTCO_{2e}$)	Scope 2 GHG Emission ($MTCO_{2e}$)	Scope 3 GHG Emission ($MTCO_{2e}$)	Total GHG Emission ($MTCO_{2e}$)	Emission Intensity ($MTCO_{2e}$/MT)
FY 19	150,385	7,666	14,315	133	22,115	0.147
FY 20	156,120	7,675	13,738	139	21,551	0.138
FY 21	180,535	7,691	14,289	167	22,148	0.123
FY 22	120,770	7,428	12,018	154	19,600	0.162
FY 23	77,438	5,192	10,773	162	16,127	0.208
FY 24	143,958	9,759	16,530	170	26,459	0.184

This study focuses on the FY2019–FY2024 period, as activity data outside this range were not available from the company. Based on Table 2, Scope 1 emissions remained relatively stable from FY19 to FY21 before declining in FY22–FY23, likely due to a decrease in output production capacity. The Scope 1 emissions in FY24 increased significantly due to an additional furnace being installed within the plant, leading to higher natural gas consumption. A similar pattern was observed for Scope 2 emissions which indicated a strong correlation between Scope 1 and Scope 2 emissions with output production capacity. Scope 3 emissions are smaller compared to Scope 1 and 2 as it only considered business travel and employee commuting. The emission intensity trend steadily decreased until FY21, then increased to its peak in FY23. The significant rise in emission intensity was mainly due to reduced production output caused by lower market demand for steel (Mycron Steel Berhad, 2024), before bouncing back in FY24.

3.2 Green Steel Production

Table 3 highlights the emission reductions achieved through the installation of solar power and a more efficient CAS, which lowered electricity consumption under Scope 2. The emission reductions from solar installation increased significantly from FY21 to FY22 due to increase of solar PV installation in the plant. The CAS emission reductions increased from FY23 to FY24 because the installation of CAS was carried out at the mid of FY23. These reductions in Scope 2 emissions contributed to lower total GHG emissions and emission intensity, as shown in Table 4. Figure 2 illustrates the trends in total GHG emissions and emission intensity from FY19 to FY24. Based on the results, Scope 2 emissions continue to dominate the company's total emissions despite the installation of solar PV and the efficient CAS.

Table 3: Emission Reduction (ER) Initiatives from the Installation of Solar PV and CAS

Financial Year	Solar Installation ($MTCO_{2e}$)	Compressed Air System ($MTCO_{2e}$)
FY 21	453.47	-
FY 22	1,485.12	-
FY 23	1,355.99	1,760.00
FY 24	1,567.91	2,540.00

Table 4: Output Production Capacity, GHG Emission for Scope 1, Scope 2, Scope 3 and Emission Intensity With ER Initiatives

Financial Year	Output Production Capacity (MT)	Scope 1 GHG Emission ($MTCO_{2e}$)	Scope 2 GHG Emission ($MTCO_{2e}$)	Scope 3 GHG Emission ($MTCO_{2e}$)	Total GHG Emission ($MTCO_{2e}$)	Emission Intensity ($MTCO_{2e}$/MT)
FY 19	150,385	7,666	14,315	133	22,115	0.147
FY 20	156,120	7,675	13,738	139	21,551	0.138
FY 21	180,535	7,691	13,836	167	21,695	0.120
FY 22	120,770	7,428	10,533	154	18,115	0.150
FY 23	77,438	5,192	7,657	162	13,011	0.168
FY 24	143,958	9,759	12,422	170	22,351	0.155

Figure 3 illustrates the trajectory of finished goods and estimated green steel production from FY19 to FY24. No green steel production was recorded in FY19 and FY20 due to the absence of ER initiatives in the preceding years, as green steel output is calculated based on prior-year emission savings. In FY21, the introduction of Solar PV in March 2021 marked the beginning of the organisation's green transformation, resulting in 2.09 % green steel production. This momentum continued in FY22, with enhanced solar energy utilization driving green steel output to 7.58 %. FY23 shows the highest green steel production % due to increased emissions reduction efforts (solar PV and CAS) and lower overall GHG emissions due to lower output production capacity. By FY24, the figure shows potential of 15.5 % green steel production, reflecting a deeper commitment to GHG reduction in the company. The graph also underscores the role of the MBA in aligning production with market demand for low-carbon products during a transitional phase where GHG reduction technologies are still maturing.

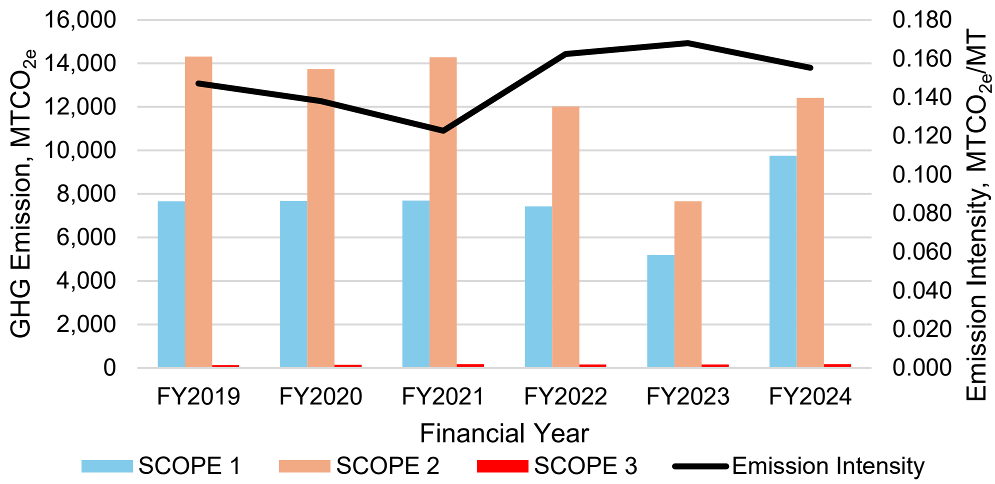

Figure 2: Total GHG Emission by Scope and Emission Intensity With ER Initiatives

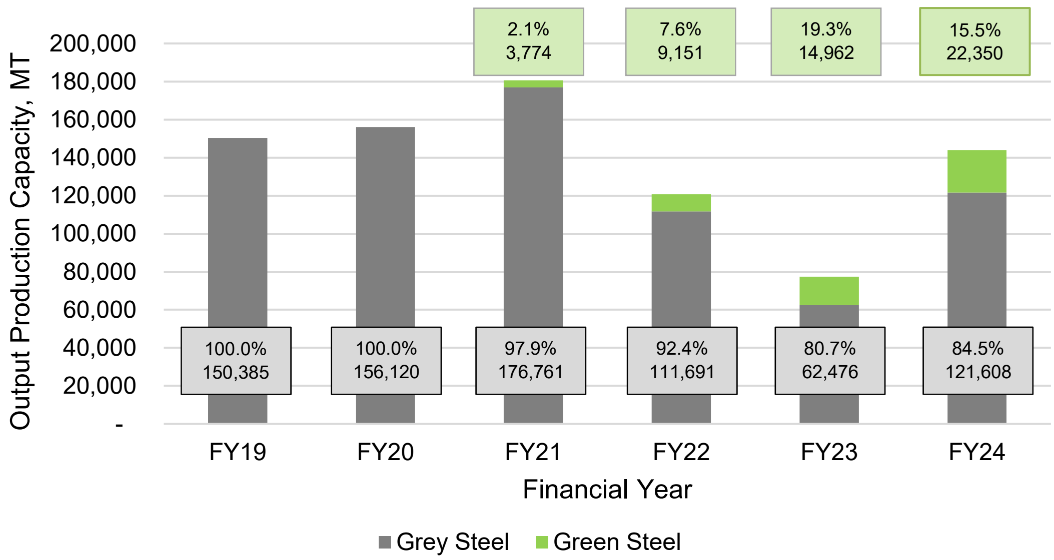

Figure 3: Finished Good and Green Steel Production

4. Conclusions

This study demonstrates the use of the MBA to estimate green steel production in the midstream iron and steel sector. Integration of Solar PV systems and a more efficient CAS increased green steel output to 15.5% in FY24. As the industry targets carbon neutrality by 2050, the MBA provides a practical framework for tracking progress and quantifying green steel production. The findings emphasize scaling up GHG reduction measures to meet emission intensity goals and promote sustainable growth, outlining a clear pathway for the steel industry toward climate neutrality.

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