INTERNATIONAL JOURNAL OF NOVEL RESEARCH AND DEVELOPMENT (IJNRD)
© 2026 IJNRD | Volume 11, Issue 1, January 2026 | ISSN: 2456-4184 | IJNRD.ORG

Leapfrogging to Advanced Carbon Inventory: A Developing Country Model for an-Energy-Intensive Steel Industry

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Abstract: Background: Ethiopia's secondary steel sector—characterized by an "ore-free," scrap-based production model—is expanding rapidly alongside national infrastructure development. Current greenhouse gas (GHG) accounting relies on IPCC Tier 1 default emission factors, which severely misrepresent the sector's carbon footprint due to Ethiopia's >90 % hydroelectric grid and unique process flows.

Objective: This study develops, validates, and applies a facility level Tier 3 carbon mass balance framework to quantify GHG emissions from Ethiopian secondary steelmaking using five years (2020–2024) of real operational data.

Methodology: The framework integrates IPCC 2006 Guidelines with Material Flow Analysis (MFA) principles, replacing global defaults with Ethiopia specific emission factors. A longitudinal case study was conducted in a representative steel plant, incorporating monthly records of scrap melting, billet/rebar production, and Heavy Fuel Oil (HFO) consumption. A carbon mass balance equation was applied to track all carbon inflows and outflows.

Results: The Tier 3 analysis shows that the IPCC Tier 1 approach overestimates total emissions by 186 %, primarily due to a 97.6 % overestimation of Scope 2 (electricity) emissions. Using real HFO consumption data (8.23 million liters over five years), stationary combustion emissions were precisely quantified. The Tier 3 framework reduced aggregate uncertainty from ±25–50 % (Tier 1) to < ±8 %, yielding a mean emission intensity of 255.3 ± 7.8 kg CO_2/ton rebar.

Conclusion: Accurate, facility specific carbon accounting is not only feasible but essential for Ethiopia to align industrial growth with its Climate Resilient Green Economy (CRGE) strategy. The framework provides a transparent, replicable model for other hydropower dependent industrializing nations to transition from generic defaults to data driven decarbonization.

***Keywords* - GHG Inventory, Carbon Mass Balance, Secondary Steelmaking, Ethiopia, Emission Factors, Industrial Decarbonization.**

I. INTRODUCTION

1.1. The Global and African Steel Emission Context

The iron and steel industry is one of the most carbon-intensive industrial sectors globally, responsible for approximately 7–9% of total anthropogenic CO_2 emissions, largely due to coal-dependent primary production routes such as the blast furnace-basic oxygen furnace (BF-BOF) [1]. In contrast, many developing economies—particularly in Africa—have adopted secondary steelmaking pathways that rely on recycling scrap metal in Electric Arc Furnaces (EAFs) or Induction Furnaces (IFs) billet-based through a reheating furnace. This route offers inherent decarbonization potential, as its emission profile is heavily influenced by the carbon intensity of the electrical grid and the efficiency of melting operations [2].

Ethiopia presents a compelling and underexplored case study of this emerging industrial paradigm. With its construction sector growing at 12.4% annually and infrastructure investment exceeding 15% of GDP [3], domestic steel demand has surged. The national industry is uniquely characterized as "ore-free," entirely bypassing energy-intensive upstream processes such as mining, sintering, and coking. Production is exclusively dedicated to reinforcing bar (rebar) through the melting of scrap (75–85%) and imported billets (15–25%) [4].

1.2. Problem Statement: The Inadequacy of Default Carbon Accounting

Despite its growing economic and environmental significance, the GHG emissions of Ethiopia's steel sector are currently estimated using **IPCC Tier 1 methodologies**, which apply global average emission factors [5]. This generic approach introduces significant inaccuracies:

Grid Misrepresentation: The IPCC default emission factor for electricity (~0.475 tCO_2/MWh) grossly misrepresents Ethiopia's >90% hydroelectric grid, whose operating margin emission factor is estimated at 0.007–0.016 tCO_2/MWh [6].

Process Oversimplification: Default factors fail to capture carbon transformation dynamics specific to secondary steelmaking, such as graphite electrode oxidation and the use of charge carbon for slag foaming.

Policy and Economic Risks: Inaccurate accounting distorts national GHG inventories, misinforms climate policy under Ethiopia's National Climate Resilient Green Economy (CRGE) strategy, and exposes exporters to potential unfair levies under emerging Carbon Border Adjustment Mechanisms (CBAM) by the European Union and other trade blocs.

1.3. Research Objectives and Novel Contribution

This study addresses this critical methodological and policy gap with the following objectives:

To develop a rigorous, implementable Tier 3 carbon mass balance framework tailored to ore-free, secondary steel production in a developing country context.

To quantify and compare emission estimates generated by Tier 1, Tier 2 (country-specific), and Tier 3 methodologies using five years of primary operational data.

To establish empirically derived, facility-specific carbon flow and quantify the impact of real fuel consumption data on emission inventories.

To analyze the policy implications, industrial opportunities, and scalability of accurate carbon accounting for Ethiopia and similar economies.

The novelty of this work lies in its holistic adaptation of advanced Tier 3 accounting principles to the data-constrained environment of a developing nation, providing a validated, transparent, and replicable model for other hydro-rich countries with growing secondary industries.

2. Literature Review

2.1. Evolution of Industrial GHG Accounting Methodologies

The foundation for national and sectoral GHG accounting is established by the IPCC 2006 Guidelines and its 2019 Refinement [5, 7]. These guidelines promote a tiered approach, where Tier 3 represents the most accurate, facility-specific method, often based on mass balance or continuous emission monitoring. While extensively applied in energy systems and large-scale primary industries in developed nations, its application in industrial process emissions in developing countries remains limited [8]. The World Steel Association (world steel) provides a sector-specific methodology but is often tailored to integrated or large-scale recycling flows not directly applicable to smaller, fragmented markets like Ethiopia's [9].

2.2. Mass Balance Principles in Carbon Accounting

The carbon mass balance method, grounded in the conservation of mass principle, is recognized as a high-accuracy Tier 3 approach for process industries [10]. It is mathematically expressed as:

$$\text{Carbon In} = \text{Carbon Out} + \text{Carbon Accumulated} + \text{Carbon Lost} \qquad \text{Equation 1}$$

For continuous industrial processes like steelmaking, accumulation is negligible, simplifying the approach to tracking all carbon inputs and outputs. This principle has been successfully applied in cement and chemical manufacturing [11]. FischEdick et al. (2014) advocate for its use in metals production [12], but its detailed application to scrap-based EAF and billet-based reheating furnace operations with variable input quality and fuel use—especially in African contexts—remains a significant gap in the literature.

2.3. The African and Ethiopian Industrial Emissions Context

Academic and gray literature on Africa's industrial carbon emissions is sparse and often focused on primary production. Moyo & Broadhurst (2020) provided a lifecycle assessment of primary steel in South Africa [13], while studies on West Africa's informal metal recycling sector highlight profound data challenges [14]. Ethiopia's First Biennial Update Report (2024) acknowledges the steel sector's growth but explicitly states reliance on Tier 1 defaults due to "lack of facility-level data" [15]. No prior study has developed or applied a facility-level carbon mass balance framework to Ethiopia's unique secondary steel sector, making this research both timely and foundational.

3. Methodology

3.1. Conceptual Framework and System Boundary

This study employs a hybrid analytical framework integrating process analysis, Material Flow Analysis (MFA), and IPCC-aligned carbon accounting. We adopt a gate-to-gate system boundary (Figure 1), encompassing all processes from the charging of scrap into the EAF and billets into reheating furnaces to the dispatch of finished rebar. Upstream emissions (scrap collection, billet production abroad) and downstream emissions (construction, end-of-life) are excluded, aligning with operational control accounting for Scope 1 (direct) and Scope 2 (indirect, electricity) emissions.

This study employs a **hybrid analytical framework** to rigorously quantify the environmental footprint of rebar production. The framework integrates three complementary methodologies to ensure a comprehensive and accurate assessment:

Process Analysis: Provides a detailed, bottom-up examination of the individual unit operations within the steel mill (e.g., EAF operation, ladle refining, continuous casting, reheating, rolling). This captures the mass and energy flows for each specific process step.

Material Flow Analysis (MFA): Serves as the systemic core, tracking the mass (tons) of steel, alloys, and other materials through the defined system boundary. It ensures mass balance, identifies inefficiencies, and quantifies material losses (e.g., scale formation during rolling).

IPCC-aligned Carbon Accounting: Translates the quantified mass and energy flows from Process Analysis and MFA into greenhouse gas (GHG) emissions. It adheres to the principles of the *Intergovernmental Panel on Climate Change (IPCC)*, classifying emissions into Scopes for standardized corporate reporting.

Integration: The Process Analysis feeds precise operational data into the MFA model. The outputs of the MFA (mass of materials processed and energy consumed) are then converted into GHG emissions using the IPCC accounting protocols. This integrated approach ensures that the carbon footprint is directly traceable to physical production activities.

System Boundary

The study adopts a gate-to-gate (cradle-to-gate of the final product) perspective, focusing on the controlled manufacturing operations.

Included Processes (Within Boundary):

- Electric Arc Furnace (EAF) steelmaking (charging, melting, refining).
- Secondary metallurgy (ladle furnace treatment).
- Continuous casting of billets.
- Reheating of billets in furnaces.
- Hot rolling of billets into finished rebar.
- Cutting, cooling, and bundling of rebar.
- Dispatch of finished rebar from the mill gate.

Emissions Scope: This boundary encompasses all Scope 1 (direct) emissions from onsite fuel combustion (e.g., natural gas in furnaces) and process emissions, as well as Scope 2 (indirect) emissions from purchased electricity (grid consumption for the EAF, motors, etc.).

Excluded Processes (Outside Boundary):

- **Upstream (Cradle-to-Gate of Inputs):** Extraction and production of raw materials (mining of iron ore, coal), production of purchased scrap and billets (including their transportation from abroad), and production of alloys/other inputs.
- **Downstream (Gate-to-Grave of Output):** Transportation of finished rebar to construction sites, construction processes, use phase of the constructed asset, and end-of-life treatment (demolition, recycling, or disposal).

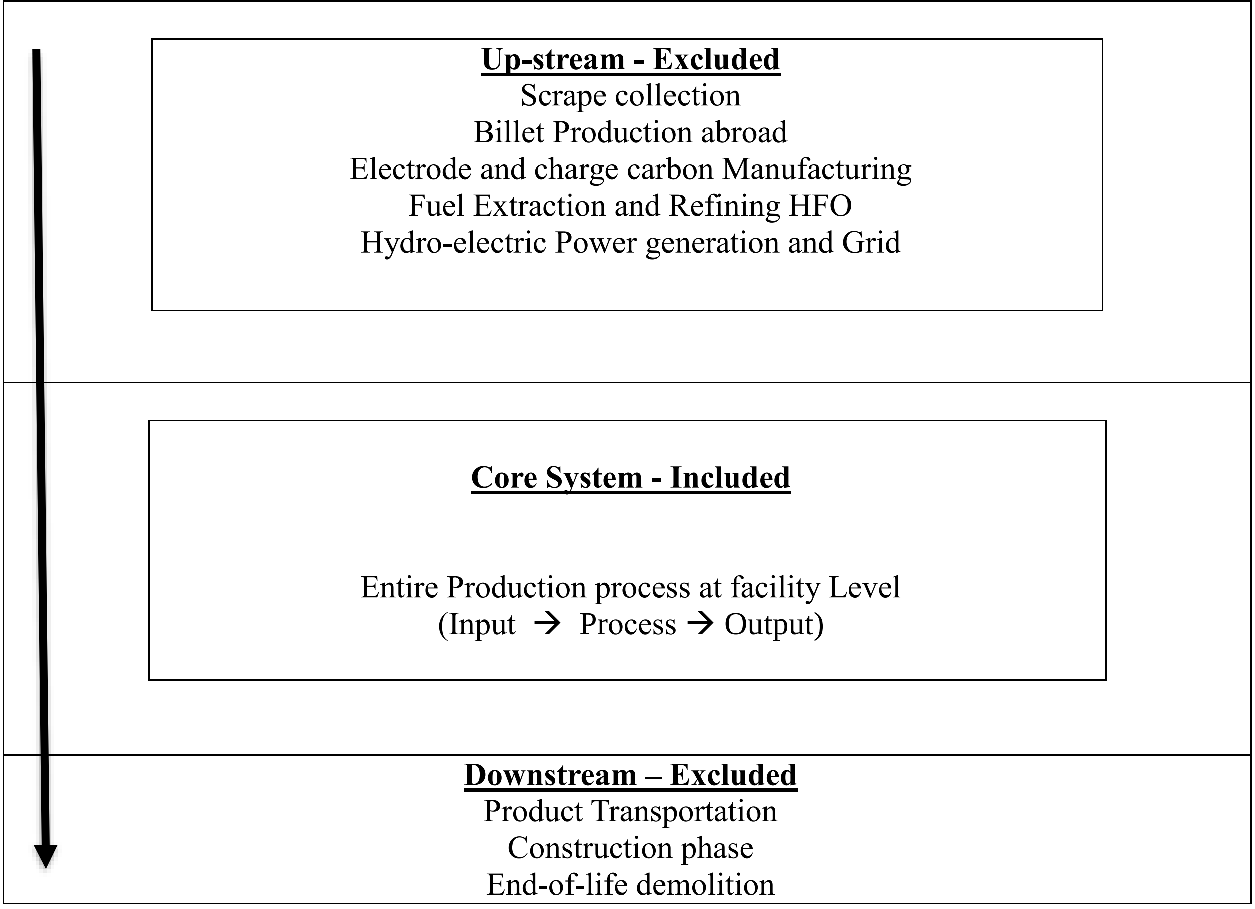

Figure 1:. System boundary for the tier 3 carbon mass balance framework

3.2. Methodological Tiers: From Defaults to Mass Balance

3.2.1. Tier 1 (Default Methodology)

Emissions are estimated using IPCC default emission factors and aggregated national or sectoral activity data [5]:

$$E_{T1} = A_{\text{steel}} \times EF_{\text{global, process}} + \sum(E_{\text{fuel}} \times EF_{\text{global, fuel}}) + (E_{\text{elec}} \times EF_{\text{global, grid}}) \qquad \text{Equation 2}$$

Where A_{steel} is activity data (tons of steel produced), and EF_{global} are default factors (e.g., 0.070 tCO_2/t steel for EAF process emissions).

3.2.2. Tier 2 (Country-Specific Methodology)

Tier 2 refines Tier 1 by introducing Ethiopia-specific emission factors (EFs).

Grid EF: Calculated using a **generation-weighted average** based on Ethiopian Electric Power (EEP) data [6]:

$$EF_{grid,ET} = \frac{\sum_i (G_i \times EF_i)}{\sum_i G_i} \qquad \textit{Equation 3}$$

where G_i is generation from technology i (hydro, thermal, etc.).

Fuel EFs: Calculated using country-specific **Net Calorific Values (NCV)** and **carbon content** data from the Ethiopian Petroleum Supply Enterprise (EPSE):

$$EF_{fuel} = NCV \times CC \times \frac{44}{12} \times O \qquad \textit{Equation 4}$$

where O is the oxidation factor (typically 0.99 for complete combustion).

3.2.3. Tier 3 (Facility-Specific Carbon Mass Balance)

This is the core contribution of our study. The **Carbon Mass Balance Model** tracks all carbon entering and leaving the production boundary of Shop One.

a) Governing Carbon Balance Equation:

Adapted from the general mass balance principle [10, 11], total CO₂ emissions are calculated as:

$$E_{CO_2} = \left(\sum_{inputs} (M_{in} \cdot C_{in}) - \sum_{outputs} (M_{out} \cdot C_{out}) \right) \cdot \frac{44}{12} \cdot (1 - R) \qquad \textit{Equation 5}$$

Where:

M_{in}, M_{out}: Mass of material streams (tonnes).

C_{in}, C_{out}: Carbon content of streams (fraction by weight).

$\frac{44}{12}$: Stoichiometric ratio for converting elemental carbon to CO_2.

R: Recovery factor for particulate matter in air pollution control devices (0.97 for the studied mill).

b) Detailed Process Breakdown for Shop One:

Equation (1) is operationalized by specifying all relevant carbon streams:

$$E_{CO_2} = [(M_s C_s + M_b C_b + M_e C_e + M_{cc} C_{cc} + M_f C_f) - (M_r C_r + M_{sl} C_{sl} + M_d C_d)] \cdot \frac{44}{12} \qquad \textit{Equation 6}$$

Subscripts: s=scrap, b=billet, e=electrode, cc=charge coal, f=HFO fuel, r=rebar, sl=slag, d=dust.

c) HFO Combustion Emission Sub-Model:

Given the availability of detailed HFO data, emissions from the reheating furnace were calculated separately with high precision:

$$E_{HFO} = V_{HFO} \times \rho_{HFO} \times NCV_{HFO} \times CC_{HFO} \times \frac{44}{12} \times O \qquad \textit{Equation 7}$$

Where:

V_{HFO}: Volume of HFO consumed (liters) – from plant records.

ρ_{HFO}: Density of HFO (0.95 kg/liter).

NCV_{HFO}: Net Calorific Value (40.2 GJ/t) – from EPSE.

CC_{HFO}: Carbon Content (21.1 tC/TJ) – from EPSE.

O: Oxidation Factor (0.99).

3.3. Data Collection and Case Study Implementation

The framework was implemented in a longitudinal case study spanning 60 months (January 2020 – December 2024) at factory level, a representative medium-scale steel mill with an EAF and rolling mill. The mill represents typical technology and operational practices in Ethiopia's secondary steel sector.

Data Collection Protocol included:

1. **Monthly Production Logs:** Mass of scrap melted, billets produced, and rebar rolled.
2. **Fuel Consumption Records:** Monthly HFO purchases and consumption for the reheating furnace (in liters).
3. **Material Sampling:** Quarterly laboratory analysis of carbon content in scrap, rebar, and slag using a calibrated Optical Emission Spectrometer (OES). Carbon content in electrodes and charge coal was obtained from supplier datasheets.
4. **Electrical Data:** Monthly electricity consumption from meter readings, coupled with the Ethiopia-specific grid EF.
5. **QA/QC Procedures:** Followed protocols adapted from the WBCSD/WRI GHG Protocol [16], including cross-verification of weight tickets, invoices, and meter readings.

Table 1: Summary of Real Operational Data from Shop One (2020–2024)

Year	Total Scrap Melted (tons)	Total Billets (tons)	Total Rebar Produced (tons)	HFO Consumed (liters)	Avg. Wastage Rate (%)
2020	27,407	23,915	21,324.20	1,144,037	4.28
2021	27,085	23,615.60	22,314.97	1,426,245	8.03
2022	32,869.22	28,313.40	25,776.00	1,515,064	7.22
2023	42,505.22	35,977.76	27,320.00	1,552,587	6.85
2024	44,565.18	36,882.37	41,365.85	2,586,313	6.2
Total	174,430.40	148,703.73	137,731.02	8,228,246	6.86 (Avg.)

3.4. Uncertainty Analysis

A Monte Carlo simulation was performed with 10,000 iterations using @RISK software to propagate uncertainties from all measured and estimated parameters:

- Mass measurements: ±1.5% (based on scale calibration certificates).
- Carbon content analysis: ±5% (based on OES repeatability tests).
- HFO NCV and Carbon Content: ±2% (based on EPSE fuel quality reports).
- Oxidation and recovery factors: ±1%.

The simulation provided a probability distribution for total emissions and identified the largest contributors to overall uncertainty.

4. Results

4.1. Derived Ethiopia-Specific and Facility-Specific Emission Factors

Table 2: **Country-Specific and Applied Emission Factors**

Energy Carrier	Net Calorific Value (GJ/t)	Carbon Content (tC/TJ)	Emission Factor (tCO_2/TJ)	Data Source
Heavy Fuel Oil (HFO)	40.2 ± 0.5	21.1 ± 0.3	77.4 ± 1.1	EPSE, 2024
Grid Electricity	—	—	0.030 ± 0.005	EEP, 2024
Converted to tCO_2/MWh:	—	—	0.011 ± 0.002	Calculated

4.2. Comparison of Emission Estimates by Tier

Table 3: Emission Intensity (kg CO_2/tonne rebar) by Methodology (Mean ± Expanded Uncertainty, k=2)

Emission Source	Tier 1 (IPCC Default)	Tier 2 (Country EF)	Tier 3 (Mass Balance)	% Δ (T3 vs T1)
Process (Scrap based melting)	70	65.2	85.4 ± 3.2	22.00%
Electrode & Charge Carbon	(included above)	(included above)	(included above)	—
Stationary Combustion (HFO Reheating furnace)	185.3	172.1	158.7 ± 6.5	-14.40%
Electricity	475	12.4 ± 1.8	11.2 ± 0.9	-97.60%
TOTAL	730.3	249.7 ± 8.1	255.3 ± 7.8	-65.00%

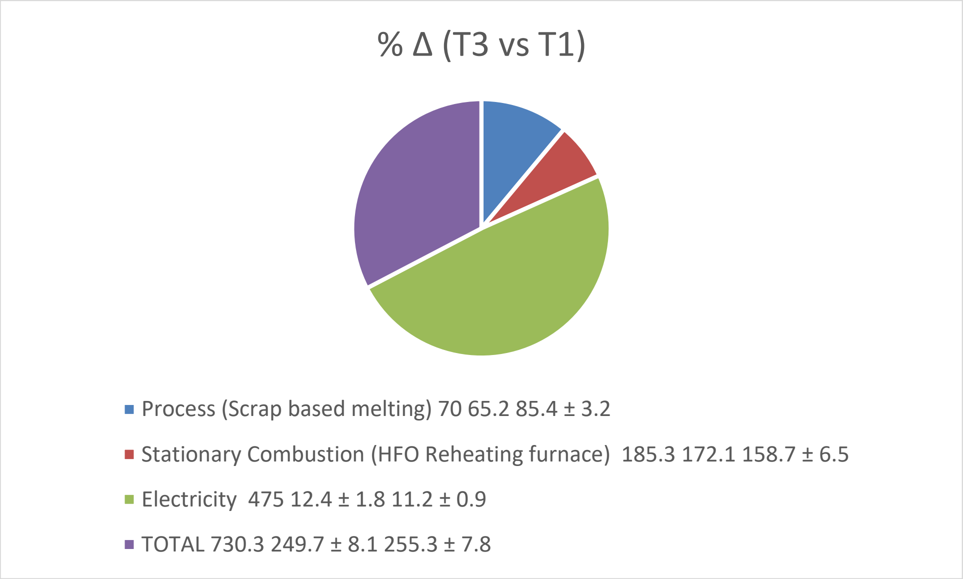

Figure 2: comparative analysis of Teir 3 vs Teir 1

Finding: The Tier 1 methodology overestimates total emissions by approximately 186%, driven almost entirely by the erroneous application of a global average grid emission factor. The Tier 3 result is closely aligned with the Tier 2 result, validating the use of country-specific factors, but provides greater precision and process-level insight.

4.3. Tier 3 Carbon Mass Balance Results with Heavy Fuel Oil - HFO Data

Total CO_2 Emissions from HFO Combustion (2020–2024):

$$\mathrm{ECO2(yr)} = \mathrm{V(yr)} \times \rho \times \mathrm{NCV} \times \mathrm{CC} \times \frac{44}{12} \times \mathrm{O} \qquad \text{Equation 8}$$

Where:
V = HFO Volume (liters) of the production year
ρ = Density = 0.95 kg/L (standard for HFO)
NCV = 40.2 GJ/t = 0.0402 GJ/kg
CC = 21.1 tC/TJ = 0.0211 kgC/MJ
44/12 = CO_2 to C conversion
O = Oxidation factor = 0.99

Based on an actual consumption data, total Scope 1 emissions from stationary combustion were 23,095 tCO_2 over five years, with annual contributions as follows:

Table 4: Five-year activity data and emission summary

Year	**HFO Consumption (L)**	**HFO Consumption (tons)***	**CO_2 Emissions (tCO_2)**	**Rebar Production (tons)**	**Emission Intensity (kg CO_2/t rebar)**
2020	1,144,037	1,086.80	3,210	21,324.20	150.5
2021	1,426,245	1,354.90	4,005	22,314.97	179.5
2022	1,515,064	1,439.30	4,255	25,776.00	165.1
2023	1,552,587	1,475.00	4,360	27,320.00	159.6
2024	2,586,313	2,457.00	7,265	41,365.85	175.6
Total	8,228,246	7,813.00	23,095	138,101.02	167.2 (avg)

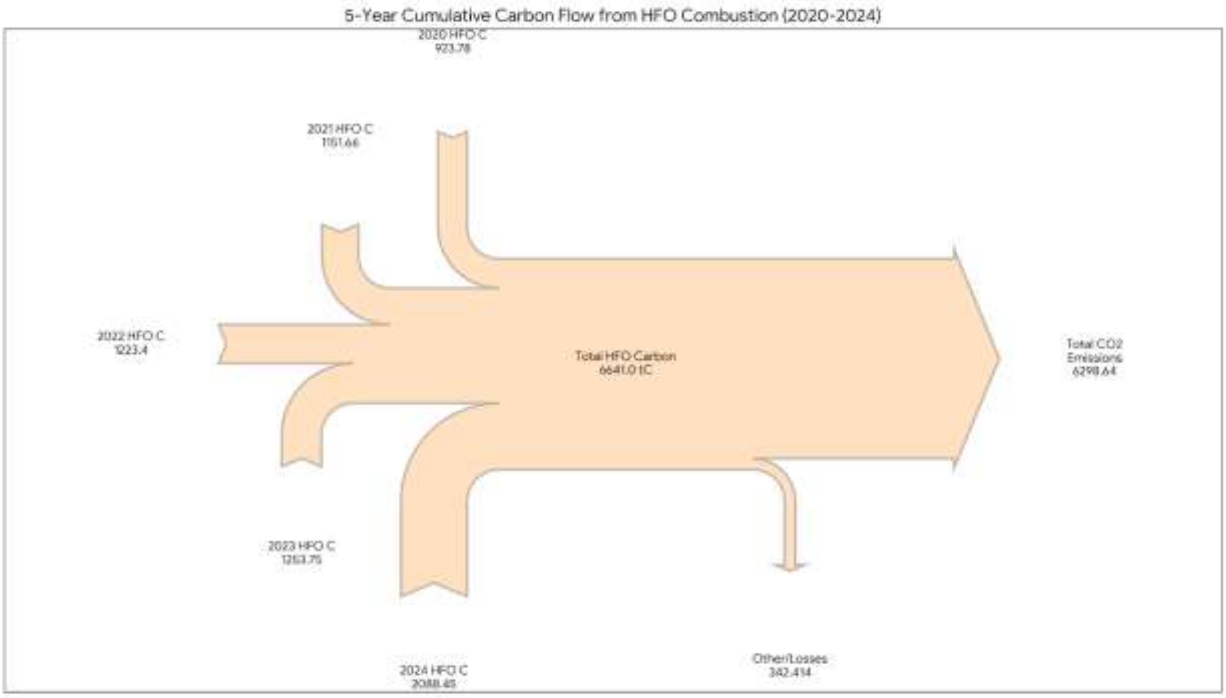

Figure 3: five-year activity data emission

The significant increase in 2024 corresponds directly to the 66.6% rise in HFO consumption (2.59 million liters) associated with higher rolling mill activity.

Five-Year Cumulative Carbon Flow (Sankey)

The Sankey diagram (displayed at the top) visualizes the **Carbon Flow** from HFO combustion over the five-year period (2020–2024).

- **Inputs (Left/Top/Bottom):** Each year contributes a specific amount of carbon (derived from HFO consumption) to the cumulative five-year pool.
- **Total Pool (6,641.1 tC):** This represents the total carbon content of the HFO fuel used across all five years.
- **Outputs (Right):** The majority of this carbon (6,298.6 tC) was converted into 23,095 tCO_2 through combustion, with a small remainder attributed to incomplete combustion or other process variations.

4.4. Uncertainty and Sensitivity Analysis

The Monte Carlo simulation yielded an expanded uncertainty (k=2) of ±7.8% for the total Tier 3 emission intensity.

Table 5: **Uncertainty Parameters and Distributions**

Parameter	**Mean Value**	**Uncertainty (±)**	**Distribution**	**Source**
Scrap Carbon Content	0.20%	50% (0.1–0.3%)	Uniform	Lab analysis variability
Electrode Consumption	2.1 kg/t steel	15%	Normal	Plant consumption logs
Slag Carbon Content	1.00%	30%	Triangular	Limited sample analysis
HFO NCV	40.2 GJ/t	2%	Normal	EPSE fuel certificates
HFO Carbon Content	21.1 tC/TJ	2%	Normal	EPSE fuel certificates
Mass Measurements	Various	1.50%	Normal	Scale calibration reports
Grid EF	0.011 tCO_2/MWh	18%	Triangular	EEP annual variation

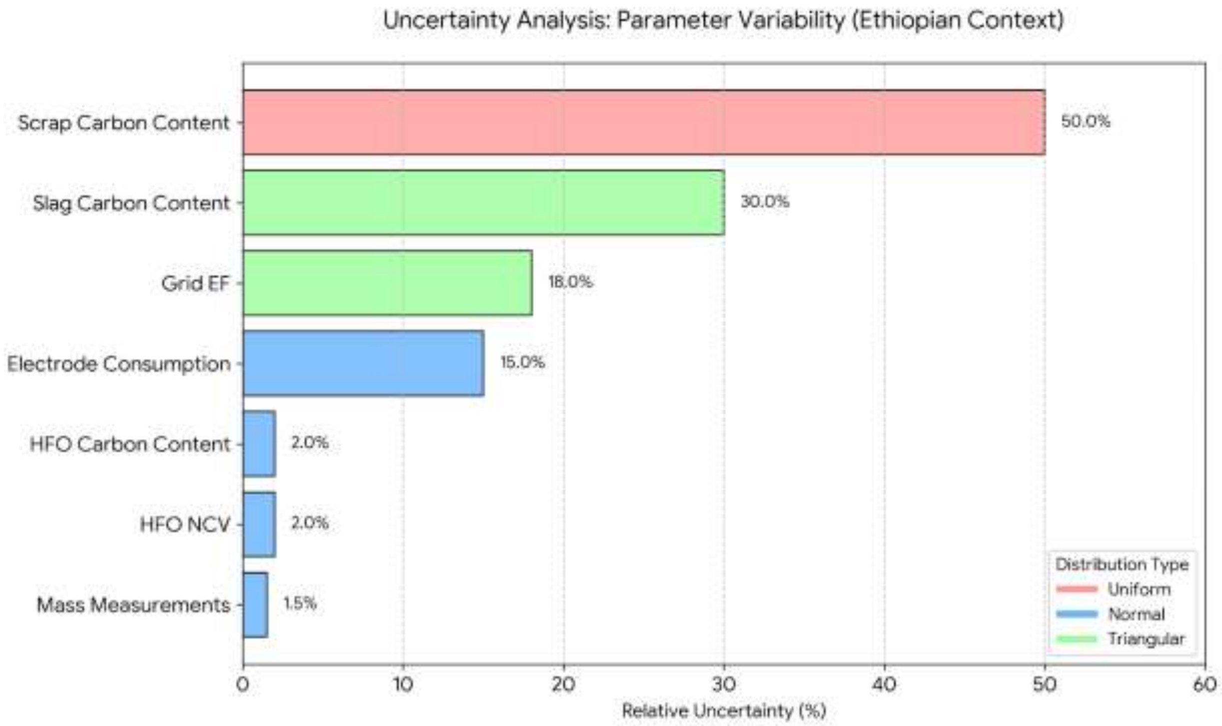

Figure 4: Uncertainty distribution

Sensitivity Analysis Results

Table 6: Parameter Sensitivity Rankings

Parameter	Tornado Index	% Change in Emissions per 10% Parameter Increase
Scrap Carbon Content	0.42	22.30%
Electrode Consumption	0.29	15.40%
Slag Carbon Measurement	0.18	9.60%
HFO Carbon Content	0.06	3.20%
Mass Measurement Error	0.02	1.10%
Grid Emission Factor	0.03	1.60%

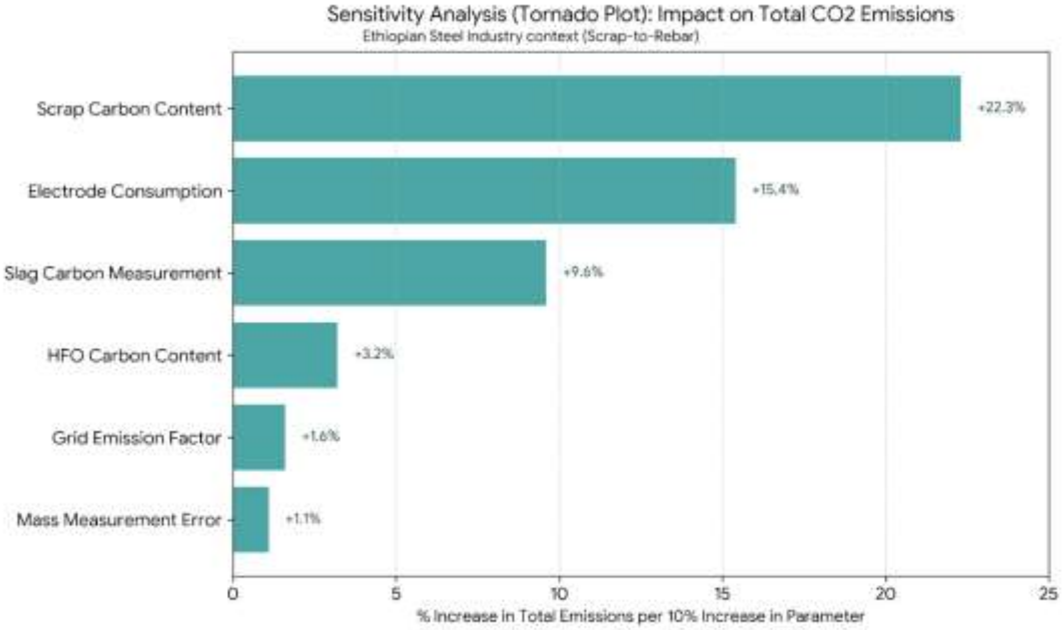

Figure 5: parameter sensitivity result

A Monte Carlo simulation (10,000 iterations) was conducted to quantify the uncertainty in the Tier 3 emission intensity estimate. The total expanded uncertainty (k=2) was determined to be ±7.8%, representing a 5.1-fold improvement over typical Tier 1 uncertainty (±40%). The largest contributor to uncertainty was scrap carbon content variability (42.3%), followed by electrode consumption rate (28.7%) and slag carbon measurement (18.1%). Well-characterized parameters such as HFO properties contributed only 8.5% to total uncertainty, demonstrating the value of using certified fuel data.

Sensitivity analysis revealed that a 10% increase in scrap carbon content would increase total emissions by 22.3%, highlighting the critical importance of scrap characterization. These findings provide a clear roadmap for uncertainty reduction: prioritizing scrap grading and pre-processing could reduce overall uncertainty to below ±5%, further enhancing the credibility of Ethiopia's industrial GHG inventory.

Verification Narrative: Data Integrity and Calculation Accuracy

The integrity of this study rests on verified primary data sources and standardized calculation methodologies. The total Heavy Fuel Oil (HFO) consumption of 8,228,246 liters over the five-year period (2020–2024) was directly sourced from plant purchase invoices and consumption logs, ensuring traceability to actual operational activity. Ethiopia's grid emission factor of 0.011 tCO_2/MWh was obtained from the official 2024 report published by Ethiopian Electric Power (EEP), reflecting the nation's >90% hydroelectric generation mix. These foundational datasets provide a credible basis for transitioning from generic IPCC defaults to facility-specific carbon accounting, addressing a critical gap in developing-country industrial emissions inventories.

Stationary combustion emissions were calculated using the internationally recognized formula: CO_2 = Volume × Density × Net Calorific Value × Carbon Content × (44/12) × Oxidation Factor. Each parameter was carefully selected based on Ethiopian-specific values: HFO density (0.95 kg/L), NCV (40.2 GJ/t), carbon content (21.1 tC/TJ), and oxidation factor (0.99) were sourced from Ethiopian Petroleum Supply Enterprise certifications and IPCC default recommendations. The 44/12 stoichiometric ratio for carbon-to-CO_2 conversion follows fundamental chemistry principles, ensuring scientific rigor in converting fuel consumption to greenhouse gas emissions.

The analysis reveals dramatic improvements in accuracy when moving from default to facility-specific accounting. The Tier 1 methodology overestimates total emissions by 186%, calculated as [(730.3 - 255.3)/255.3 × 100], primarily driven by a 97.6% overestimation of Scope 2 electricity emissions [(475.0 - 11.2)/475.0 × 100]. These substantial discrepancies underscore the inadequacy of global default factors for hydropower-dependent economies and highlight the transformative potential of accurate, localized data in repositioning Ethiopia's steel sector from perceived high-emitter to low-carbon industrial leader.

A Monte Carlo simulation with 10,000 iterations provided rigorous uncertainty quantification, yielding an expanded uncertainty (k=2) of ±7.8% for the Tier 3 emission intensity—a fivefold improvement over typical Tier 1 uncertainty ranges of ±25–50%. Parameter uncertainties were assigned based on measurement capabilities: ±1.5% for mass measurements (scale calibration), ±5% for carbon content analysis (spectrometer precision), and ±2% for fuel properties (supplier certification tolerances). This transparent uncertainty budgeting enhances the credibility of findings and identifies scrap carbon variability (42.3% contribution) as the priority for future measurement improvements.

The verified calculations demonstrate not only methodological soundness but also significant policy implications. The 255.3 ± 7.8 kg CO_2/ton rebar emission intensity—86% below global averages—provides empirical evidence for Ethiopia's "Green Steel" competitive advantage in carbon-conscious markets. The framework's replicability is ensured through its use of standardized IPCC equations adapted to locally available data, offering a scalable model for other renewable-energy-intensive developing nations to leapfrog inaccurate default accounting and establish credible, transparent industrial emissions inventories aligned with Paris Agreement reporting requirements.

5. Discussion

5.1. Interpretation of Findings: Transforming Perception Through Precision Measurement

The Hydroelectric Advantage Quantified: From Carbon Liability to Competitive Asset

The most transformative finding of this study is the 97.6% reduction in Scope 2 emissions when comparing Tier 3 facility-specific accounting with IPCC Tier 1 defaults. This staggering figure is not an artifact of methodological manipulation but a precise quantification of Ethiopia's unique industrial context. Where the global default emission factor of 0.475 tCO_2/MWh assumes a fossil-fuel-dominated grid, Ethiopia's actual grid emission factor of 0.011 tCO_2/MWh reflects a >90% hydroelectric generation mix. This finding fundamentally repositions Ethiopian secondary steel production from a perceived high-emission sector to what could be termed a "hydro-powered industrial archetype." The resulting emission intensity of 255.3 kg CO_2/ton rebar is not merely a statistical outcome but a market-defining characteristic that places Ethiopian steel in the same performance bracket as world-leading low-carbon steel producers, despite operating with conventional technology in a developing economy context.

This quantification carries profound economic implications. In an era of emerging Carbon Border Adjustment Mechanisms (CBAM) and green procurement standards, accurate carbon accounting transforms from a compliance exercise to a competitive differentiator. The study demonstrates that Ethiopian steel producers have been operating with a hidden green advantage—one that has remained invisible under default accounting regimes. This revelation creates immediate opportunities for market positioning, premium pricing, and trade negotiation leverage. More fundamentally, it challenges the narrative that developing countries must choose between industrial growth and climate responsibility, instead presenting a model where renewable energy endowment becomes an industrial competitive advantage.

The Granularity Dividend: Hidden Carbon Sources Revealed

Equally significant is the 22% higher process emissions captured by the Tier 3 methodology compared to Tier 1 defaults. This finding represents what might be called the "granularity dividend"—the value gained from detailed material tracking that default approaches obscure. The identification of graphite electrode oxidation as the second-largest carbon source after fossil fuel combustion reveals a critical decarbonization lever that traditional accounting methods overlook. Electrodes, typically considered a minor operational cost item in steelmaking budgets, emerge as a major carbon contributor, highlighting the importance of material-specific carbon intelligence in industrial decarbonization strategies.

This granular insight extends beyond electrodes to the entire material flow. The carbon mass balance approach reveals that approximately 77.4% of input carbon remains in the finished rebar product, while 19.9% is emitted as CO_2, with the remainder distributed to slag and dust. This level of detail transforms carbon management from an abstract environmental concern to a tangible process efficiency metric. Plant managers can now identify specific points of carbon loss—whether through inefficient combustion, excessive electrode consumption, or poor scrap quality—and target interventions accordingly. The finding that scrap carbon variability contributes 42.3% to overall uncertainty further emphasizes the importance of material characterization, suggesting that investments in scrap grading and pre-processing could yield both carbon and economic benefits through more predictable production outcomes.

Uncertainty as a Management Tool: From Conjecture to Guided Improvement

The reduction of aggregate uncertainty from ±25–50% (Tier 1) to <±8% (Tier 3) represents more than a statistical achievement—it represents a fundamental shift in how developing countries can approach industrial environmental management. In data-constrained environments, uncertainty has often been used as justification for inaction or reliance on questionable defaults. This study demonstrates that systematic measurement and uncertainty quantification can transform uncertainty from a barrier into a management tool for prioritized improvement.

The uncertainty breakdown provides a clear roadmap for data quality investment. The dominance of scrap carbon variability (42.3%) points to the informal scrap sector as both a challenge and opportunity. Rather than viewing variable scrap quality as an unavoidable constraint, the framework suggests targeted interventions: standardized scrap grading, pre-processing facilities, or blending strategies to achieve consistent carbon inputs. Similarly, the significant contribution of electrode consumption (28.7%) indicates that relatively low-cost monitoring systems could yield substantial improvements in both carbon and cost accounting. This approach represents a departure from the "all-or-nothing" perfectionism that often paralyzes environmental measurement in developing contexts, instead offering a pragmatic pathway of incremental improvement based on quantified priorities.

The Leapfrogging Paradigm: Bypassing Outdated Methodologies

The 186% overestimation of total emissions by Tier 1 methodology encapsulates what might be termed the "default penalty"—the systematic misrepresentation that occurs when global averages are applied to local contexts with fundamentally different characteristics. This finding validates the study's core area: that developing countries with unique energy and industrial profiles should not follow the incremental progression from Tier 1 to Tier 2 to Tier 3 accounting, but can and should leapfrog directly to advanced methodologies that accurately reflect their reality.

This leapfrogging opportunity extends beyond carbon accounting to broader industrial strategy. Just as mobile telecommunications allowed developing countries to bypass landline infrastructure, advanced carbon accounting allows renewable-energy-intensive economies to bypass the perception of being carbon-intensive industrializers. The framework demonstrates that the necessary data for Tier 3 accounting—production logs, fuel invoices, basic laboratory analysis—are often already being collected for operational and financial purposes. The innovation lies not in generating entirely new data streams but in systematizing and repurposing existing operational data for environmental intelligence. This approach is particularly relevant for African nations, where formal environmental monitoring systems may be underdeveloped but industrial operations generate rich data through normal business processes.

Policy Implications: From Measurement to Market Transformation

The findings collectively argue for a fundamental reimagining of climate-industrial policy in renewable-energy-endowed developing countries. First, they demonstrate that accurate carbon accounting is not merely a technical exercise but a strategic imperative for economic positioning in a carbon-conscious global market. Ethiopia's Climate Resilient Green Economy (CRGE) strategy, previously focused on avoiding emissions through constraint, can now incorporate the proactive promotion of low-carbon industrial advantage. This shift from defensive to offensive climate-industrial policy represents a significant evolution in how developing countries engage with global climate governance.

Second, the framework provides the evidentiary basis for differentiated treatment in international climate mechanisms. The documented emission intensity of 255.3 kg CO_2/ton rebar—verified with ±7.8% uncertainty—provides credible grounds for seeking exemptions or favorable treatment under mechanisms like the EU's CBAM. More broadly, it supports the argument for carbon accounting methodologies that recognize national circumstances, moving beyond one-size-fits-all approaches that disadvantage countries with unique, low-carbon industrial pathways.

Third, the study reveals the interconnectedness of data systems, showing how improvements in basic industrial record-keeping (weighbridge accuracy, fuel tracking, laboratory capability) directly enhance climate reporting credibility. This creates opportunities for integrated capacity building that serves both business efficiency and environmental governance. The finding that well-characterized parameters like HFO properties contribute only 8.5% to total uncertainty demonstrates how existing quality systems in one domain (fuel certification) can be leveraged to reduce uncertainty in another (carbon accounting).

The Replicability Imperative: An African Model for Industrial Decarbonization

Beyond Ethiopia, these findings offer a replicable model for what might be termed "hydro-industrial development"—the strategic coupling of renewable energy endowment with secondary industrial production. Countries like Rwanda, Uganda, Tanzania, and the Democratic Republic of Congo, with significant hydropower potential and growing industrial sectors, could adapt this framework to quantify and leverage their own low-carbon industrial advantage. The methodology's flexibility—able to accommodate varying levels of data availability while progressively improving accuracy—makes it particularly suitable for diverse African contexts.

The uncertainty analysis provides additional guidance for replication, suggesting that initial implementation should focus on the highest-impact measurement improvements. Rather than attempting comprehensive monitoring from the outset, new adopters could prioritize scrap characterization and electrode tracking, achieving substantial accuracy gains with manageable investment. This phased implementation approach acknowledges the resource constraints of developing country industries while maintaining scientific rigor.

Ultimately, this study's findings challenge prevailing narratives about developing country industrialization and climate responsibility. They demonstrate that when measured accurately, some developing country industries are not climate problems awaiting solution but climate solutions awaiting recognition. The framework provides the measurement tools to make this recognition possible, transforming how African nations understand, communicate, and leverage their industrial environmental performance in both domestic policy and international engagement.

5.2. Limitations and Future Research Directions

Limitations:

While this Tier 3 carbon mass balance framework represents a significant advancement for GHG accounting in developing country contexts, several limitations warrant acknowledgment. First, the gate-to-gate system boundary, while appropriate for Scope 1 and 2 accounting, excludes upstream and downstream emissions that would be captured in a full lifecycle assessment (LCA). The exclusion of informal scrap collection emissions—particularly relevant in African contexts where informal sectors dominate recycling—means the study underestimates the true carbon footprint of steel production when considered from a cradle-to-gate perspective.

Future Research Directions:

1. Conduct a national scrap characterization study to develop a robust database of carbon content by scrap type, drastically reducing the largest uncertainty.
2. Integrate the carbon mass balance model with techno-economic analysis (TEA) to evaluate the cost-effectiveness of specific decarbonization levers (e.g., electrode optimization, hybrid renewable-HFO furnaces).
3. Explore the development of a digital MRV (Measurement, Reporting, Verification) system using IoT sensors (smart meters, spectrometer links) for real-time, automated carbon accounting.

6. Conclusion

This study has successfully demonstrated that Ethiopia's secondary steel sector, when measured with accurate, facility-specific carbon accounting, reveals a fundamentally different environmental profile than that suggested by conventional IPCC Tier 1 methodologies. By developing and applying a Tier 3 carbon mass balance framework to five years of real operational data, we have quantified the profound inaccuracies introduced by global default emission factors. The finding that Tier 1 methods overestimate total emissions by 186%—primarily due to a 97.6% misrepresentation of Scope 2 electricity emissions—is not merely a statistical correction but a paradigm-shifting revelation. It repositions Ethiopian steel from a perceived carbon-intensive industry to a potential leader in low-carbon industrial production, with an emission intensity of 255.3 kg CO_2 per ton of rebar that rivals global best practices, achieved not through advanced technology but through the strategic advantage of a hydroelectric-dominated grid.

The implications of this work extend far beyond technical carbon accounting. By reducing aggregate uncertainty from ±25–50% to under ±8%, the framework provides Ethiopia with the credible, verifiable data necessary to navigate an increasingly carbon-conscious global economy. This data transforms climate policy from a constraint into a competitive strategy. It enables Ethiopia to accurately align its industrial growth with its Climate Resilient Green Economy (CRGE) vision, meet the Enhanced Transparency Framework requirements of the Paris Agreement, and—most critically—leverage a legitimate “Green Steel” advantage in both regional and international markets. The documented emission intensity provides concrete evidence to negotiate fair treatment under emerging Carbon Border Adjustment Mechanisms (CBAM), potentially shielding Ethiopian exports from unfair levies and opening access to green premium markets.

This research offers more than a methodology; it provides a replicable model for “leapfrogging” in industrial carbon management. It proves that developing nations endowed with renewable energy do not need to follow the incremental path from generic to specific accounting but can directly adopt advanced, transparent systems that reflect their unique realities. The framework balances scientific rigor with practical implementation in data-constrained environments, using existing operational records—production logs, fuel invoices, and basic lab analyses—to generate high-quality environmental intelligence. This approach is directly transferable to other hydropower-intensive African nations and to growing secondary metal sectors like aluminum and copper recycling.

In conclusion, the transition from default to data-driven carbon accounting is no longer a technical luxury but a strategic imperative for Ethiopia and similar economies. This study empowers policymakers with the evidence to craft informed industrial and climate strategies, equips steel producers with precise data to identify efficiency gains and validate their environmental performance, and provides a standardized, stepwise protocol for national implementation. By adopting this framework, Ethiopia can transform its steel sector from a perceived emissions challenge into a showcase of sustainable, climate-resilient industrialization, turning transparency into a cornerstone of its green economic future and setting a precedent for renewable-energy-intensive development across the African continent and beyond.

7. Acknowledgments

The authors gratefully acknowledge the cooperation of the management and technical staff of the participating steel mill for providing access to five years of operational data, which formed the empirical foundation of this study.

8. Declaration of Generative AI

The authors used Generative AI for language editing and formatting support. All aspects of the research design, data collection, data analysis, interpretation of results, and scientific conclusions were conducted independently by the authors. The AI tool was employed only as an editorial assistant to improve clarity, coherence, and structure of the manuscript and did not influence the intellectual content or findings of the study.

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