METHODOLOGICAL FRAMEWORK FOR SCOPE 1–2 CO_2 EMISSIONS QUANTIFICATION IN INTEGRATED BF–BOF STEEL PRODUCTION AT THE PRODUCT LEVEL

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Abstract

Quantifying the emissions intensity of production at the product level is essential for assessing the environmental profile of high value-added steel products and supporting strategic decarbonization in the industry. A modular and systematic methodology enables CO_2 emissions calculation across Scope 1 and Scope 2 within a closed-loop BF-BOF (blast furnace – basic oxygen furnace) production cycle. The methodology breaks down the production process into individual technological steps, with each step evaluated based on its specific energy, fuel, and material inputs. Emission factors and technological constants are used to quantify both direct and indirect emissions. Consistency and reliability are maintained through real-data validation, energy balance control, and automated correction of deviations. The model allows transparent tracking of emissions per process step and final product, while supporting compliance with environmental reporting standards. The outlined methodology serves as a foundation for adaptable emissions accounting in primary steelmaking environments.

Keywords: Scope 1-2, BF-BOF, CO_2 emissions, steel production, product carbon footprint

1. INTRODUCTION

The decarbonization of primary steel production has become a key priority in the context of global climate targets, particularly within the framework of the European Green Deal and the EU Emissions Trading System (EU ETS). Integrated steelmaking routes based on blast furnace and basic oxygen furnace (BF–BOF) technologies remain the dominant pathway for large-scale flat steel production, but they are also among the most carbon-intensive industrial processes. Quantifying carbon dioxide (CO_2) emissions with high accuracy is essential not only for regulatory compliance, but also for internal process optimization, lifecycle assessment (LCA), and the development of product-level Environmental Product Declarations (EPDs). While total plant-level emissions are typically well documented, there is an increasing demand to resolve these emissions down to the level of individual products. This shift requires a methodological framework that can trace CO_2 emissions throughout the entire production chain, from raw material input to finished steel output, reflecting both direct (Scope 1) and indirect (Scope 2) emissions.

Existing research has predominantly focused on plant-level lifecycle assessments (LCAs), while product-level CO_2 quantification methodologies remain underdeveloped. Backes et al. presented a cradle-to-gate LCA for an integrated steel mill based on primary manufacturing data, demonstrating the importance of aligning emissions quantification with actual process flows and site-specific energy profiles [1]. Yu et al. extended this approach by modeling the environmental impact of carbon capture and utilization (CCU) technologies across BF–BOF steelmaking stages, emphasizing the need for granular Scope 1 and 2 differentiation when assessing mitigation potential [2]. Wang et al. proposed a process-integrated optimization framework that segments BF–BOF operations into discrete technological units and applies emission factors based on operational scenarios, supporting modular, step-specific carbon intensity calculations consistent with product allocation logic [3]. Madhavan et al. analyzed the direct CO_2 emissions arising specifically from the basic oxygen furnace stage, reinforcing the necessity for stage-level granularity within integrated steelmaking systems [4]. Hubatka et al. evaluated the projected effects of regulatory measures such as the Carbon Border Adjustment Mechanism (CBAM), and argued for verified, product-level data structures to support transparent emissions accounting and cross-border compliance [5]. Suer et al. applied energy transformation modeling in DRI–EAF-based production, illustrating the relevance of combining real operational inputs with process-level carbon footprints in the evaluation of hybrid steelmaking routes [6]. Zang et al. investigated lifecycle emissions trade-offs across multiple steel production pathways, highlighting the methodological implications of boundary selection and data quality when comparing Scope 1 and 2 outcomes at the process and product levels [7]. Biermann et al. addressed the complexity of CO_2 allocation in multi-product steel mills that co-process biogenic and fossil feedstocks, proposing accounting strategies that align with emerging regulatory and LCA frameworks [8]. Finally, Qian et al. provided a systematic overview of emissions inventory methodologies, verification procedures, and data-driven reduction pathways in the steel sector, calling for greater traceability and methodological rigor in CO_2 attribution practices [9].

Despite these advances, there remains a notable methodological gap in quantifying Scope 1 and Scope 2 CO_2 emissions at the product level in a verifiable and traceable manner, particularly within integrated BF–BOF routes. To address this, a modular and systematic approach has been developed, tailored to the specific characteristics of primary steelmaking. The methodology divides the production chain into discrete technological steps, assigns real operational data to each step, and applies verified emission factors to determine CO_2 intensity. This enables transparent allocation of emissions not only to individual processes, but also to final products with high resolution and consistency. The proposed framework aligns with international standards such as the Greenhouse Gas Protocol and the EU ETS, and supports robust data integration, verification readiness, and compliance with both regulatory and market-driven sustainability goals.

2. METHODOLOGICAL FRAMEWORK FOR CO_2 EMISSIONS QUANTIFICATION

The presented methodology is designed to quantify CO_2 emissions arising from both direct and indirect energy flows within an integrated BF–BOF steel production route. In alignment with the Greenhouse Gas Protocol and ISO 14064 standards, the calculation model distinguishes between:

- Scope 1 emissions, representing direct CO_2 emissions from on-site sources such as fuel combustion, process gases, and metallurgical reactions.
- Scope 2 emissions, capturing indirect CO_2 emissions from the consumption of purchased electricity and imported thermal energy (e.g., steam or heating water).

The organizational boundary is established through the operational control approach, where only those facilities and processes under full operational authority are included. The system boundary, in turn, is process-based and encompasses the full production chain, starting from raw material treatment (e.g., coking, sintering), through primary metallurgy (e.g., blast furnace ironmaking, basic oxygen steelmaking), secondary metallurgy, casting, hot and cold rolling, surface treatments, and final product dispatch. This approach ensures that all emission-relevant activities within the BF–BOF process route are accounted for, while emissions from upstream supply chains and downstream use (Scope 3) phases are explicitly excluded from the Scope 1–2 framework.

Emissions are calculated using a mass and energy balance approach, linking input flows to emission factors. The model enables disaggregation at the product level by assigning CO_2 intensity (tCO_2 per ton of steel) according to specific production routes. This supports traceability, dynamic recalculation, and alignment with

EU ETS and product-level declarations such as EPDs, ensuring both verification readiness and customer-facing transparency.

To enable accurate and process-specific CO_2 emissions quantification, the methodology employs a modular structure, in which each technological step within the BF–BOF production chain is represented as an independent calculation module. Each module is assigned process-specific input data (energy, fuels, material throughput), emission factors, and calculation logic, allowing for a high-resolution representation of emission sources throughout the plant. The modular approach reflects the sequential and interconnected nature of steel production, where outputs from one technological unit often serve as inputs for the next. This logical linkage enables emissions to be traced and aggregated across the full process flow, from raw material transformation to the final delivery of finished products.

A representative modular chain includes the following core stages:

- Raw Material Processing: Sintering and coking operations, where solid fuels are pre-treated, account for a significant portion of Scope 1 emissions.
- Primary Metallurgy: Blast furnaces (BF) and basic oxygen furnaces (BOF) are modeled as separate units, with detailed tracking of process gases (e.g., coke oven gas, blast furnace gas, BOF gas).
- Secondary Metallurgy and Casting: Further steel refining and slab casting are evaluated with respect to energy consumption and operational parameters.
- Hot and Cold Rolling: Rolling mills and finishing lines are considered in terms of both direct gas use and purchased electricity consumption.
- Surface Treatment and Final Processing: Units such as annealing, coating, and slitting lines are included based on their energy profiles and material flows.

Each module integrates the following components:

- Input quantities, such as tons of material processed, or MWh of electricity consumed.
- Emission factors, adapted to each fuel or energy source (e.g., $tCO_2 \cdot GJ^{-1}$, $tCO_2 \cdot MWh^{-1}$).
- Process-specific constants, such as combustion efficiencies, off-gas calorific values, or technology-specific emission intensities.
- Emission outputs calculated as total CO_2 emitted (in tCO_2) and normalized per ton of product where applicable.

This decentralized and granular structure enables not only the precise quantification of CO_2 emissions per process step, but also the dynamic reassignment of emissions to specific products, production orders, or periods (e.g., monthly, annually). It further allows for modular updates, facilitating future incorporation of process innovations, energy efficiency measures, or low-carbon input substitutions. By adopting a modular methodology, the model supports transparent reporting, internal performance benchmarking, and targeted decarbonization planning — all essential tools in the transition towards sustainable steel production.

The accuracy and reliability of CO_2 emissions quantification in integrated steel production is highly dependent on the quality and granularity of input data, as well as the consistent application of validated emission factors. The presented model relies primarily on real operational data, collected from internal reporting systems and process monitoring tools, and is updated regularly to reflect actual production conditions. These input parameters cover both direct energy carriers and auxiliary process media that significantly contribute to the energy and emission profile of each production unit. A structured overview of the monitored input data types, including their measurement units, is presented in **Table 1**.

Table 1 Input energy and utility media monitored across BF–BOF production units

Input Data - Energy	Unit	Input Data - Energy	Unit
Electrical Energy - Generated	[MWh]	Nitrogen 2 MPa	[thous.m^3]
Electrical Energy - Purchased	[MWh]	Blown Air	[thous.m^3]
Technological Steam	[GJ]	Oxygen 85%	[thous.m^3]
Heating Water	[GJ]	Nitrogen 95%	[thous.m^3]
Coke Oven Gas (COG)	[GJ]	Demineralized Water	[thous.m^3]
Blast Furnace Gas (BFG)	[GJ]	Argon	[thous.m^3]
Natural Gas (NG)	[GJ]	Nitrogen 99.9%	[thous.m^3]
Basic Oxygen Furnace Gas (BOFG)	[GJ]	Compressed Air	[thous.m^3]
Acetylene	[Kg]	Oxygen 99.5%	[thous.m^3]

Ensuring the methodological robustness of CO_2 quantification requires systematic validation of input data and the application of correction procedures to address potential inconsistencies. The presented framework incorporates a multi-tier validation approach, focusing on both energy balance coherence and emission factor integrity across the entire BF–BOF process chain.

Prior to emissions computation, all input data related to energy and media consumption are normalized to standardized energy units (GJ) and subsequently aggregated per process module as shown in **Figure 1**. These module-level values are then compared against the site-wide energy consumption, which is subject to regular internal auditing on monthly and annual bases.

Figure 1 Methodology of modular CO_2 accounting for product-level Scope 1–2 emissions in BF–BOF steel production.

This reconciliation serves as a critical validation layer, ensuring:

- Coherence between bottom-up process-level data and top-down corporate energy accounting,
- Identification and mitigation of potential data gaps, redundancies, or allocation errors within specific technological units.
- Only after achieving agreement within acceptable tolerance thresholds is the dataset accepted for further CO_2 emissions modeling.

3. INTEGRATED MODEL FOR PRODUCT-LEVEL CO_2 EMISSIONS ALLOCATION

The on-site generation of secondary energy carriers—such as technological steam, compressed air, or heating water—is based on the combustion of a multi-component fuel mix, comprising process off-gases (coke oven gas, blast furnace gas, basic oxygen furnace gas), natural gas, and solid fossil fuels. Due to the varying calorific values and CO_2 intensities of these fuels, a precise quantification of associated Scope 1 emissions requires a harmonized and process-reflective calculation approach.

To address this, the methodology defines a composite emission factor for internally generated energy, represented as EF_{EN} (Emission Factor – Energy), which expresses the amount of CO_2 emitted per unit of delivered energy ($tCO_2 \cdot GJ^{-1}$). Unlike conventional weighted averages based solely on default emission factors, this calculation integrates actual CO_2 mass outputs and energy content of each fuel stream, combined with their respective shares in the energy generation mix. The composite emission factor (1) is derived according to the following equation:

$$EF_{EN} = \left(\frac{BOF\_GAS\_CO_2}{BOF\_GAS\_GJ} * \omega_{BOF}\right) + \left(\frac{BF\_GAS\_CO_2}{BF\_GAS\_GJ} * \omega_{BF}\right) + \left(\frac{COKE\_GAS\_CO_2}{COKE\_GAS\_GJ} * \omega_{COKE}\right) + \left(\frac{NG\_GAS\_CO_2}{NG\_GAS\_GJ} * \omega_{NG}\right) + \left(\frac{COAL\_CO_2}{COAL\_GJ} * \omega_{COAL}\right) \quad (1)$$

Where: X_CO_2 represents the total mass of CO_2 emissions generated by fuel X (in tons), X_GJ is the total calorific value of fuel X (in gigajoules), ω_X - proportion of fuel *X* in the overall fuel mix used for internal energy generation, based on energy content.

This formulation captures both the specific emission rate of each fuel (i.e., its effective CO_2 intensity per unit of energy) and its relative contribution to the site's energy generation. For instance, if blast furnace gas constitutes 40% of the energy mix with a CO_2 intensity of 0.275 $tCO_2 \cdot GJ^{-1}$, and boiler coal contributes 30% with 0.093 $tCO_2 \cdot GJ^{-1}$, their respective contributions are weighted and summed to yield the final factor EF_{EN}.

The resulting composite emission factor is used to quantify Scope 1 emissions for each technological process unit based on its consumption of internally generated energy and utility media. The calculation (2) is formalized as:

$$Process_{tCO_2} = \sum Emissions_{Scope\ 1} = \sum(EF_{EN} * E_{energy-media}) + (EF_{BF,BOF,COKE,NG,COAL} * E_{BF,BOF,COKE,NG,COAL}) \quad (2)$$

In this formulation EF - the emission factor, expressing the amount of CO_2 emitted per unit of energy consumed (in $tCO_2 \cdot GJ^{-1}$ or $tCO_2 \cdot MWh^{-1}$), E - the energy consumption measured for each relevant energy carrier or fuel input (in GJ or MWh).

The first term accounts for emissions associated with the use of centrally generated energy and utility media, such as steam or compressed air, calculated using the previously derived composite emission factor EF_{EN}. The second term captures emissions resulting from the direct use of fuels—such as blast furnace gas, natural gas, or boiler coal—that are not part of centralized energy distribution but are consumed directly in specific technological processes (e.g., hot blast stoves or heating systems).

For Scope 2 emissions, which cover indirect emissions from externally purchased electricity, the following equation (3) is used:

$$Process_{tCO_2} = \sum Emissions_{Scope\ 2} = \sum(EF_{Energy\ mix} * E_{Purchased-Energy}) \quad (3)$$

$EF_{Energy-mix}$ represents the national grid electricity emission factor (in $tCO_2 \cdot MWh^{-1}$), reflecting the average CO_2 intensity of the electricity mix supplied by external energy providers. This value is multiplied by the process-specific electricity consumption $EF_{Purchased-Energy}$ ensuring full alignment with Scope 2 accounting principles under the Greenhouse Gas Protocol.

This enables model (**Figure 2)**, to allocate emissions with high resolution and reliability, preserving a direct link between energy use, fuel source, and environmental impact. The calculation is performed in synchronization with enterprise-wide energy and emission balances. As part of the verification process, the total modeled energy demand across all production steps (in GJ) is regularly compared with the actual energy production and consumption data at the plant level. This reconciliation, conducted monthly and annually, serves as a quality assurance mechanism. Any discrepancy between the modeled and verified data triggers a review of the energy inputs, measurement consistency, and allocation assumptions.

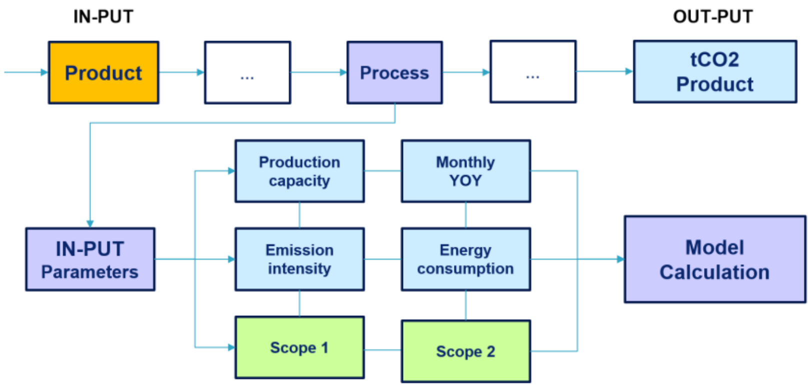

Figure 2 Scheme of the CO_2 Calculation Model for Scope 1 and Scope 2

4. RESULTS AND DISCUSSION

In the presented calculation framework **Figure 3**, the total Scope 1 carbon footprint of a steel product **Figure 3 (a)** is calculated by aggregating emissions across defined technological steps. The initial phase—tCO_2 Liquid Steel **Figure 3 (b)** —represents the cumulative emissions from all operations up to the stage of liquid steel production, including raw material processing, coking, sintering, blast furnace ironmaking, and basic oxygen steelmaking. These steps are shared across all product types and form a universal baseline for CO_2 allocation. Following crude steel production, the model branches into product-specific technological paths, which reflect the actual processing steps used for a given steel grade or format. While average Scope 1 carbon intensity in BF–BOF steelmaking is often cited around 2 tCO_2 per ton of steel, such plant-level values mask substantial differences between product routes. When disaggregated, emissions for liquid steel production—covering sintering, coking, blast furnace, and basic oxygen furnace operations—reach approximately 1.7 tCO_2/t, excluding secondary metallurgy. For hot-rolled coil, a globally traded commodity processed via hot rolling and pickling, the intensity rises to about 1.9 tCO_2/t. In contrast, non-oriented electrical steel, which involves multiple energy-intensive finishing steps, exceeds 2.4 tCO_2/t. These variations highlight the need for modular, product-specific accounting rather than reliance on average figures.

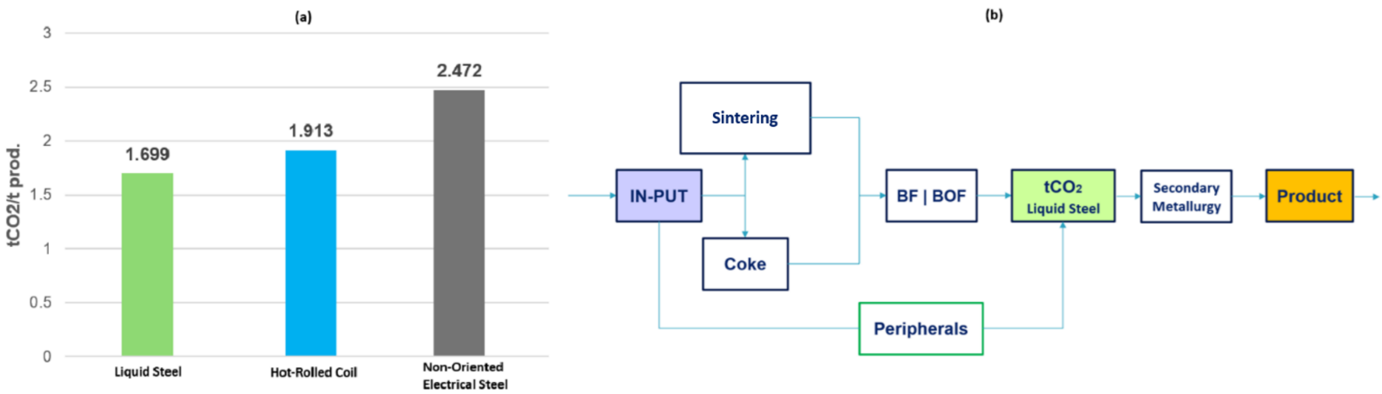

Figure 3 Product-Specific Emissions (a) Allocation Based on Technological Processing Routes (b) in Integrated Steelmaking

5. CONCLUSION

The presented methodological framework enables transparent and high-resolution quantification of Scope 1 and Scope 2 CO_2 emissions in integrated BF–BOF steel production at the product level. By combining modular process segmentation with real operational data and validated emission factors, the model ensures traceability, verification-readiness, and alignment with regulatory standards. Its application allows for precise product carbon footprint calculation, supports internal decarbonization strategies, and forms a robust foundation for lifecycle-based reporting and customer communication. The modular structure of the framework further provides substantial potential for generalization and replication across varying steel production configurations. In addition, methodology offers a scalable basis for benchmarking, scenario assessment, and potential integration with advanced digital tools such as production twins or emissions monitoring platforms. These characteristics support its applicability beyond the initial case and open pathways for ongoing methodological development.

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