EFI FOUNDATION

Integrated Product- and Entity-Level CARBON ACCOUNTING

CASE STUDY

Steel Production Using Blast Furnace-Basic Oxygen Furnace (BF-BOF)

EFI FOUNDATION

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Project Advisory Board

The EFI Foundation wishes to thank the following individuals for providing independent expert advice to this study project. Their active engagement with the project team has been enormously important. The participation of the Project Advisory Board members does not imply endorsement of the analysis, approach, or conclusions in this report.

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Executive Summary

This report is the third in a series of case studies designed to illustrate how an integrated product- and entity-level carbon accounting system can be put into practice. This case study focuses on an illustrative steel production facility in East Chicago, Indiana, that uses the blast furnace-basic oxygen furnace (BF-BOF) process. In this scenario, over one month, a steel producer manufactures steel with the product carbon dioxide (CO_2) intensity (cradle-to-gate) of 1.1 tons of CO_2 (tCO_2) per ton of steel and supplies it to customers.

In October 2025, the EFI Foundation (EFIF) published a paper titled *Integrated Product- and Entity-Level Carbon Accounting*, proposing a model ledger-based CO_2 emissions accounting system.[1] The proposed system combines the engineering fundamentals of carbon mass and energy balances with financial accounting principles. In parallel, EFIF has been conducting a series of case studies to reduce this model ledger-based system into practice.

The model ledger-based comprehensive CO_2 accounting system:

- Establishes a ledger for each entity within a product supply chain that records data on CO_2 emissions and removals only once and transfers the data across ledgers along with materials, fuels, and products.
- Builds from engineering fundamentals of carbon mass and energy balances within defined organizational (gate-to-gate) boundaries.
- Records all time-based carbon-related transactions in a dual-sided ledger of stocks (accumulated within the entity) and flows (entering or leaving the entity's boundary) of all forms of carbon (e.g., carbon dioxide, methane, physical carbon content) following principles derived from generally accepted accounting principles.
- Allocates each stream of CO_2 emissions among final products, yielding product-level CO_2 emissions intensity measures that can be fully integrated into a report of entity-wide total CO_2 and other greenhouse gas emissions.
- Enables a wide variety of reports such as CO_2 emissions statements and balance sheets.

The basic concepts of a carbon accounting system have been advanced in a number of academic studies, with several variations on how such a system should be organized. The system described in the October 2025 EFIF report is based on a dual-sided ledger of stocks and flows. A pioneering study of carbon accounting by the E-ledgers

Institute is based on a different ledger organization of carbon assets and liabilities. All of these studies, however, have been largely conceptual with relatively few real-world examples of detailed reductions to practice outside of conceptual illustrations.[2,3,4,5,6,7]

Following the October 2025 report, two case studies on sustainable aviation fuel (SAF) demonstrated how a model carbon accounting system could be reduced to practice in the SAF supply chains. The first case study, which focused on SAF produced via the HEFA (hydroprocessed esters and fatty acids) process, showed how the system can be reduced to practice under relatively simple baseline conditions. The second case study, on SAF produced via the alcohol-to-jet (AtJ) pathway, demonstrated how the system functions in a more complex supply chain incorporating decarbonization strategies, namely carbon capture and storage (CCS) and the purchase of third-party carbon removal credits. Together, these case studies demonstrated that the carbon accounting system can generate integrated product- and entity-level carbon data based on site-specific records from each entity in the supply chain.

The case study in this report extends the application of the ledger-based carbon accounting system to a steel supply chain. It examines how the system operates under the following conditions:

- A steel producer manufactures steel products and generates byproducts (i.e., slag, ash) that have low economic value.
- The producer maintains two weeks of raw material and coal inventories.
- The producer adopts a decarbonization technology: CCS.
- The producer built the production facility 20 years ago, generating 261,687 tCO_2 of emissions during construction. These emissions were capitalized and have been depreciated over the past 20 years, with 30 years of depreciation remaining based on an assumed 50-year useful life of the facility.

Case Study Description

The BF-BOF steel case study uses an illustrative steel supply chain based on a facility in East Chicago, Indiana. A steel producer manufactures steel products using iron ore, limestone, scrap steel, coal, natural gas, and electricity, and supplies to two customers—a downstream manufacturer and a construction company.

The case study draws data from Sesame One, an industrial decarbonization platform from Sesame Sustainability that combines emissions modeling, techno-economic analysis, and system optimization.[8] The study produces detailed mass and energy balances for an illustrative steel supply chain, assuming six upstream suppliers: an iron ore producer, a limestone producer, a scrap steel supplier, a coal supplier, a natural gas supplier, and an electric utility. Iron ore, metallurgical coal, and fluxes such as limestone are delivered to the integrated steelmaking facility, where they are processed through the BF-BOF route.

In this process, the blast furnace reduces iron ore into molten iron using coke (derived from coal) and fluxes, while the basic oxygen furnace subsequently refines the molten iron into steel by blowing oxygen to remove impurities. The resulting crude steel is then cast, rolled, and shaped into various products. Finished steel products—hot-rolled, cold-rolled, or galvanized—are transported by rail or truck to the manufacturer and construction company.

The case study covers an accounting period of one month. Over one month, the steel producer manufactures 416,000 tons of steel and generates 23,000 tons of slag and 29,000 tons of ash by using 235,000 tons of iron ore, 222,000 tons of coal, 40,300 tons of limestone, 2,212 million cubic feet (MMcf) of natural gas, 91,700 tons of scrap steel, and 123 gigawatt-hours (GWh) of electricity.

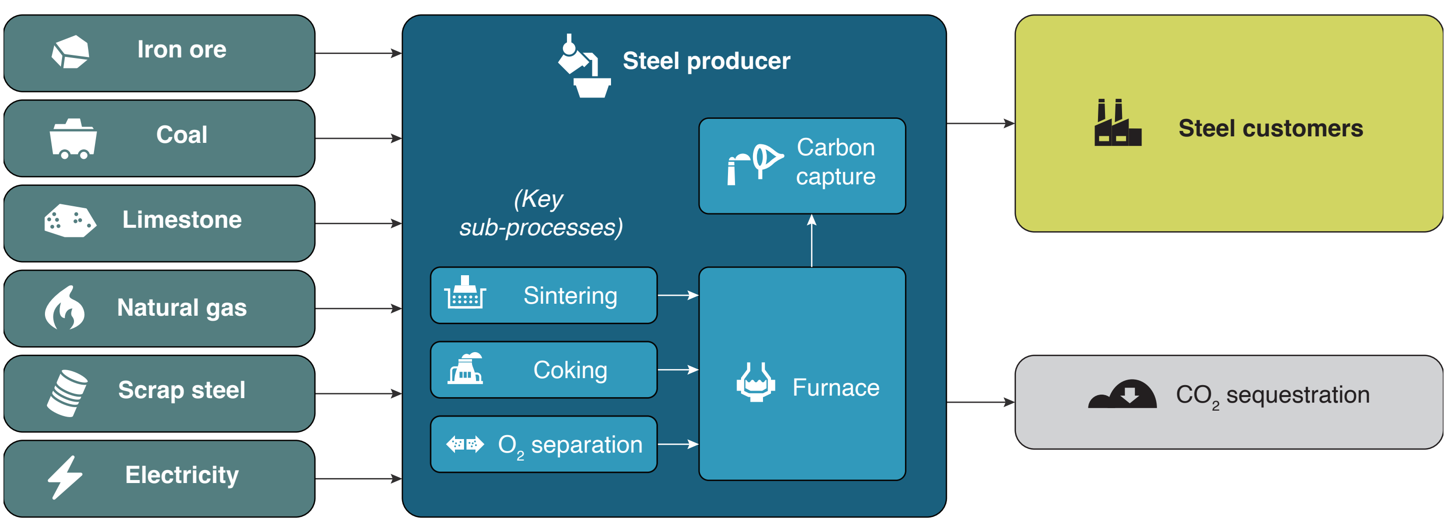
Case Study Results

The results of the case study modeling are presented from three perspectives: 1) the carbon mass and energy balances that provide the foundational data for the accounting ledger; 2) the CO_2 emissions accounting ledger itself; and 3) reports of product CO_2 emissions intensity and total CO_2 emissions derived from the ledger data.

Carbon Mass and Energy Balances: The Engineer's Perspective

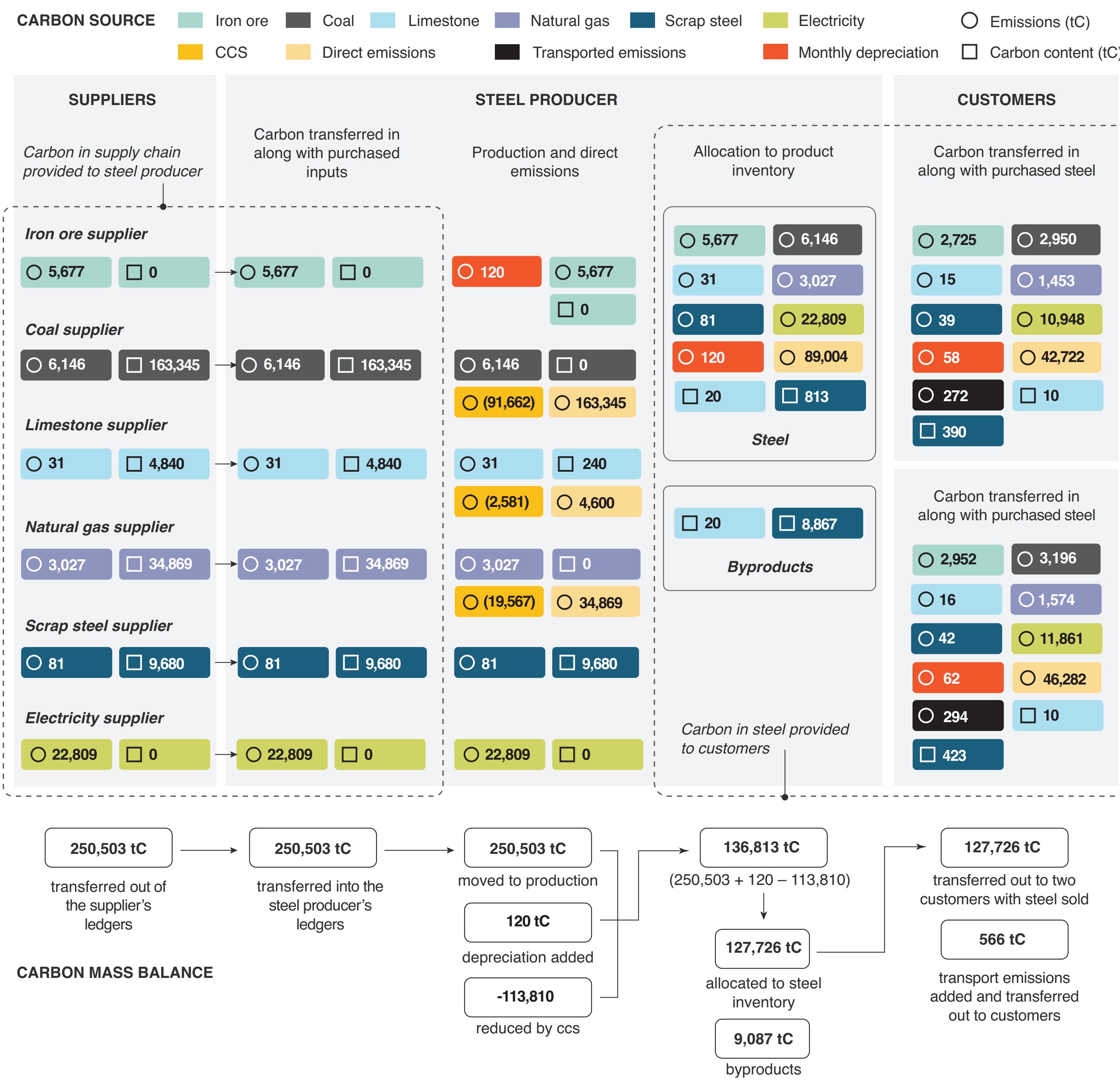
The process flow diagram, the mass and energy balances, and the resulting carbon flows are illustrated in Figures ES-1 and ES-2, respectively. Figure ES-1 illustrates the basic steps in the production of steel. Figure ES-2 focuses in detail on the carbon mass balance of the steel production process. It presents the mass balance of carbon content and emissions over the one-month period of operations.

Figure ES-1. **OVERVIEW OF MASS AND ENERGY FLOWS IN THE MODELED STEEL SUPPLY CHAIN**



Source: Sesame Sustainability.

Figure ES-2. **CARBON MASS BALANCE FOR THE STEEL BF-BOF SUPPLY CHAIN, ONE MONTH OF OPERATION**



Note: This figure shows the mass balance for all forms of carbon, including CO_2, methane (CH_4), carbon monoxide (CO), volatile organic compounds (VOCs), and carbon content. Emissions are the total of CO_2, CH_4, CO, and VOCs. Ton of carbon = tC. Source: EFI Foundation and Sesame Sustainability.

The carbon mass balance data provide a comprehensive picture of carbon attributed to incoming materials, direct gross and net emissions from the production process, carbon allocated to the final product, and emissions and product carbon content transferred from the steel producer's ledger to the two customers' ledgers.

Figure ES-2 shows the entire mass balance of carbon content and emissions (expressed in terms of 250,503 tons of carbon) flowing through the steel production during a one-month accounting period. Carbon transferred in from suppliers is either captured during production (113,810 tC), retained within the steel producer's boundary as carbon in byproducts (9,087 tC), or transferred out with sold steel products (127,606 tC = 127,726 tC − 120 tC).[a] The sum of these carbon flows exactly matches the initial 250,503 tC. This mass balance is a built-in error-checking step in process engineering that helps ensure accuracy.

For simplicity, this study assumes identical carbon allocations across multiple steel products at the initial stage of the steel production process and accordingly allocates all carbon to a single steel inventory. Further processing of the initial steel into specific products, such as hot-rolled or cold-rolled steel sheet, tubular steel, or structural steel configurations, would result in additional CO_2 emissions that would be assigned to products on the basis of the carbon mass and energy requirements associated with each individual process step.

The carbon mass balance elements for slag and ash are assigned consistent with the ISO 14044:2006.[9,b] Under the International Organization for Standardization (ISO) system expansion methodology, slag is not assigned a share of the steelmaking emissions; instead, the system receives credits for the emissions avoided when slag displaces clinker in cement and concrete production. This study does not assume the reuse or sales of slag. Ash is treated as a residual waste stream and therefore does not receive any allocated emissions. Although byproducts do not receive any emissions allocation, they receive carbon content, which is physically moved. Figure ES-2 shows that 9,087 tC of carbon content is included in the byproducts generated during the accounting period. This study assumes no off-gases as byproducts. The treatment of byproducts for ash, slag, and off-gasses has a small impact on reported emissions for the steel product, but consistent treatment across producers will be important to enable comparison among steel product sold to customers.

Ledger-Based Emissions Accounting: The Accountant's and Auditor's Perspective

The October 2025 EFIF report described a two-sided ledger design based on the stocks and flows of all forms of carbon, including carbon content of materials as well as CO_2 emissions (see Box ES-1 for details, next page).

This ledger organizational model aligns the carbon mass and energy balance data with transactions on the chart of accounts in the ledger. Individual transactions are recorded on the ledger in double-entry bookkeeping format, using at least two accounts to ensure the stocks and flows remain balanced. The accounts on the stocks side record transactions affecting stocks (i.e., carbon held within the entity), and the accounts on the flows side record transactions affecting flows (i.e., carbon entering and exiting the entity boundaries). The ledger also records the allocation of all carbon to the final products. This in turn supports the calculation of the product CO_2 emissions intensity for product that is sold to customers.

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a The 120 tC of depreciation represents a monthly share of previously accounted attributed emissions in production facilities; as such, it does not constitute a new carbon flow during the accounting period.

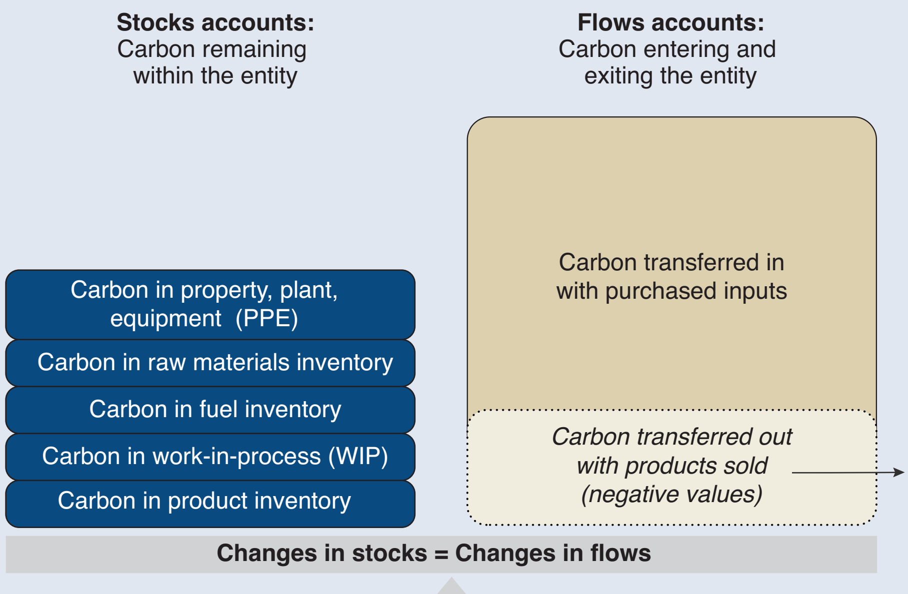
b ISO 14044:2006 is an international standard that establishes requirements and guidelines for conducting life cycle assessments.

Box 1:

Structure of a Carbon Ledger

A carbon ledger is the foundational record of an entity's carbon-related transactions, organized by accounts. It utilizes a chart of accounts to categorize, track, and balance carbon stocks and flows.

Figure ES-3. **ILLUSTRATION OF THE DUAL-SIDED CHART OF ACCOUNTS IN A CARBON LEDGER**



Source: EFI Foundation.

The chart is divided into two sections, one for stock accounts and one for flow accounts. Each section includes specific accounts to track different forms of carbon.

The stock accounts, for example, include accounts for fuel feedstocks, including both an account for Carbon Content in Fuel and Attributed Emissions to Fuel. The Attributed Emissions to Fuel account can also have subaccounts to track CO_2, CH_4, CO, and VOCs separately. The stocks side of the carbon ledger also records the carbon associated with the fabrication of the fixed production assets within the entity's boundary. Emissions that occurred during building or production of the entity's property, plant, and equipment (PPE), along with the carbon contained in the PPE itself, are recorded in the Carbon in PPE account. Emissions and carbon content associated with raw materials are recorded in the Carbon in Raw Materials Inventory accounts.

In the production process, attributed emissions and the carbon content of raw materials and fuels used, along with direct emissions generated during production, are transferred to separate Carbon in Work-in-Process (WIP) accounts.

Once production is complete, all carbon accumulated in the WIP accounts is allocated to a set of accounts for finished products in inventory. The finished product accounts are organized by product lines to allow for allocation of total emissions to the product level. (In this case study, the product accounts are shown as a single total for simplicity of presentation). At the time of sale, the carbon content of the products sold is transferred from the steel producer's ledger to the customer.

On the flows side of the carbon ledger, the accounts record carbon entering and exiting the entity's boundary. Carbon content and attributed emissions associated with purchased inputs are recorded in the Carbon Transferred In account at the time of purchase. Carbon content and direct and attributed emissions are transferred out with products sold and recorded in the Carbon Transferred Out account. Because carbon transferred out represents an outflow, the balance in this account is a negative value.

The total balances of the stock accounts always equal the total balances of the flow accounts. This indicates that the difference between carbon transferred in and carbon transferred out equals the remaining carbon within the entity.

The engineer's view of carbon mass and energy balance data described in the previous section provides the inputs for recording transactions in the steel producer's accounting ledger. Table ES-1 (next page) summarizes the records in the steel producer's ledger for one month of operation. In the carbon ledger, all transactions are recorded using a common base unit—ton of carbon (tC)—to ensure that carbon mass balance is consistently maintained. While the table appears complex, the entity's automated bookkeeping system would generate this view based on transactions used to track material flows, similar to how financial transactions are tracked today.

The ledger remains in balance because the change in carbon stocks equals the net flow of carbon entering and leaving the entity's boundaries. Confirming all stock changes equal the net change in flows at the end of a period is a built-in error-checking step in accounting that helps ensure accuracy:

- **Beginning balances:** The total of 138,475 tC at the beginning of the accounting period includes the remaining balance of attributed emissions in the production facility (physical assets) after 20 years of depreciation, as well as the carbon content and attributed emissions associated with two weeks of raw material and coal inventories.[c] The attributed emissions associated with the fixed production assets in the facility total 43,575 tC, reflecting the net of the capitalized emissions (72,625 tC) at the time of occurrence, less the accumulated depreciation (29,050 tC) taken over 20 years of use. The fixed assets are assumed to have a 50-year life, and the attributed emissions are depreciated on a straight-line basis.

c For simplicity, this study does not account for carbon transferred in and out over the past 20 years of operation. It assumes the steel producer has recently adopted a carbon accounting system and, for historical emissions, has recorded only the carbon attributed to its property, plant, and equipment (PPE) and its inventories.

Table ES-1. **RECORDS OF THE STEEL PRODUCER'S CARBON LEDGER, ONE MONTH OF OPERATION, TON OF CARBON (TC)**

	STOCKS ACCOUNTS															FLOWS ACCOUNTS					
		Carbon in production inputs					Carbon in work-in-process (WIP)			Carbon in product inventory						Carbon transferred in		Carbon transferred out			
Transaction	**Carbon in PPE (net attrib. emissions to PPE)**	**Carbon content in raw materials**	**Attrib. emissions to raw materials**	**Carbon content in fuels**	**Attrib. emissions to fuels**	**Attrib. emissions to electricity**	**Carbon content in WIP**	**Attrib. emissions in WIP**	**Direct emissions in WIP**	**Carbon content in products**	**Attrib. emissions to products**	**Depr. allocated to products**	**Direct emissions to products**	**Carbon content in byproducts**	**Stocks total**	**Carbon content**	**Attrib. emissions**	**Storage emissions**	**Carbon content with products sold**	**Emissions with products sold**	**Flows total**
Beginning balance	**43,575**	**7,260**	**2,894**	**81,672**	**3,073**	-	-	-	-	-	-	-	-	-	**138,475**	**88,932**	**78,593**	-	-	**(29,050)**	**138,475**
Purchase iron ore from supplier			1,419												**1,419**		1,419				**1,419**
Purchase coal from supplier				40,836	1,537										**42,373**	40,836	1,537				**42,373**
Purchase limestone from supplier		4,840	31												**4,871**	4,840	31				**4,871**
Purchase natural gas from supplier				34,869	3,027										**37,896**	34,869	3,027				**37,896**
Purchase electricity from supplier						22,809									**22,809**		22,809				**22,809**
Purchase scrap steel from supplier		4,840	41												**4,881**	4,840	41				**4,881**
Purchase iron ore from supplier			1,419												**1,419**		1,419				**1,419**
Purchase coal from supplier				40,836	1,537										**42,373**	40,836	1,537				**42,373**
Purchase iron ore from supplier			1,419												**1,419**		1,419				**1,419**
Purchase coal from supplier				40,836	1,537										**42,373**	40,836	1,537				**42,373**
Purchase scrap steel from supplier		4,840	41												**4,881**	4,840	41				**4,881**
Purchase iron ore from supplier			1,419												**1,419**		1,419				**1,419**
Purchase coal from supplier				40,836	1,537										**42,373**	40,836	1,537				**42,373**
Transfer raw materials to production			(5,788)		(9,173)	(22,809)		37,769							**-**						**-**
Direct emissions from production		(14,520)		(198,214)			9,920		202,814												**-**
Direct emissions captured and sequestered									(126,456)						**(126,456)**			(126,456)			**(126,456)**
Direct emissions from CCS process									12,646						**12,646**			12,646			**12,646**
Transfer carbon in WIP to products							(833)	(37,769)	(89,004)	833	37,769		89,004		**-**						**-**
Allocated depreciation of PPE to products	(120)											120			**-**						**-**
Transfer carbon content from WIP to byproducts							(9,087)							9,087	**-**						**-**
Transfer carbon in products to customers with products sold										(833)	(37,769)	(120)	(89,004)		**(127,727)**				(833)	(126,893)	**(127,727)**
Direct emissions from product transport					566										**566**		566				**566**
Transfer transport emissions to customers					(566)										**(566)**					(566)	**(566)**
Ending balance	**43,456**		**2,894**	**81,672**	**3,073**	-	-	-	-	-	-	-	-	**9,087**	**147,442**	**301,666**	**116,928**	**(113,810)**	**(833)**	**(156,510)**	**147,442**

Note: The accounting entries in this table cover all forms of carbon, including carbon content and emissions of CO_2, CH_4, CO, and VOCs. All numbers are rounded. Source: EFI Foundation and Sesame Sustainability.

- **Purchase of production inputs (iron ore, coal, limestone, natural gas, electricity, and scrap steel):** Upon delivery of each production input, the carbon content and attributed emissions are recorded in both the stocks and flows accounts. In total, 250,503 tC enters the steel producer's ledger via purchased inputs: 5,677 tC from iron ore, 169,491 tC from coal, 4,871 tC from limestone, 37,896 tC from natural gas, 22,809 tC from electricity, and 9,761 tC from scrap steel.

- **Production and direct emissions:** When production inputs begin to be used, the attributed emissions and carbon content in these inputs are moved to the Carbon in Work-in-Process (WIP) account. As fuels are burned and raw materials are processed, 202,814 tC of direct emissions occur and are recorded in the Direct Emissions in WIP account, with an equivalent reduction in the carbon content of raw materials and fuels. Part of these direct emissions (126,456 tC) is captured and transferred out of the entity for sequestration, recorded as a subtraction in both the Direct Emissions in WIP account and the Emissions Transferred Out for Sequestration account. Once sequestration is complete, emissions from transport and sequestration processes (12,646 tC) are adjusted accordingly.

- **Allocation of entity emissions to products:** Upon completion of production, attributed emissions (37,769 tC) and net direct emissions (89,004 tC) are allocated to products. Carbon content is physically transferred to outputs and recorded in the Carbon Content in Products and Carbon Content in Byproducts accounts. A monthly share of depreciated emissions (120 tC) is also allocated to products.

- **Transfer of carbon to customers with products sold:** Upon sale and delivery, direct, attributed, and depreciated emissions, plus carbon contained in products sold (127,727 tC), are transferred from the steel producer's ledger to customers' ledgers. Under free on delivery (FOD) terms, the producer retains responsibility for transport emissions (566 tC), which are recorded in both stocks and flows accounts and transferred to customers' ledgers.

- **Ending balances:** Similar to the beginning balances, the ending balances include the remaining attributed emissions in the production facility after depreciation and the carbon content and emissions attributed to two weeks of raw material and coal remaining in inventories. The carbon content in byproducts also has a positive balance as it remains within the entity.

The stocks and flows carbon accounting ledger presented here is one of several carbon accounting ledgers that have been proposed in the literature.[10,11] For example, the proposed E-ledgers accounting framework, noted in other papers, is organized on the basis of an entity-level balance sheet of carbon assets and carbon liabilities. An illustration of how the transactions described in this case study could be recorded within a possible E-ledgers framework is shown for comparative purposes in Appendix A. There are different views on how a carbon emissions ledger should be organized (e.g., chart of accounts). Carbon Measures, a global coalition of more than 25 companies established in 2025, is now seeking to develop consensus on a global framework for product-level carbon accounting.

Product CO_2 Emissions Intensity and Entity Total Emissions Reports: Management and Policymaker Perspectives

The dual-sided comprehensive carbon accounting ledger presented in this case study is technology neutral and agnostic with respect to its application. It provides a dataset that is universal to a variety of reporting formats and is agnostic with respect to management or policy applications. Tables ES-2 and ES-3 illustrate several different reporting formats for the CO_2 emissions accounting data.

Table ES-2 illustrates a sample report on product CO_2 emissions intensity of the steel producer that could be provided to management and to customers. The product CO_2 emissions intensity reports include total CO_2 emissions as well as a disaggregation of the total among attributed CO_2 emissions from the supply chain and direct CO_2 emissions from production of final products as well as abated CO_2 emissions via CCS.

Table ES-2. **PRODUCT CO_2 EMISSIONS INTENSITY REPORT DERIVED FROM THE LEDGER, ONE MONTH OF OPERATION**

Steel Producer
Product CO_2 Intensity Statement
January 2025

Steel	**CO_2 intensity** *($kgCO_2/kg$)*
Direct, entity-specific CO_2 emissions	1.78
CO_2 emissions abated via CCS	(1.00)
CO_2 emissions from suppliers	
Raw materials	0.05
Energy (fuels and electricity)	0.27
Plant, property, and equipment	0.001
CO_2 emissions from transporting final products	0.005
Total product CO_2 emissions intensity in steel	**1.11**

Source: Sesame Sustainability.

Complete and transparent reports of CO_2 emissions intensity provide important information to both the steel producer and customers. For the customers, the product CO_2 emissions intensity report provides the data needed to support their own strategic planning and marketing objectives, including their willingness to pay for lower carbon differentiated products. For the steel producer, the product CO_2 emissions intensity provides a key performance indicator to identify and assess opportunities to reduce product CO_2 emissions intensity through additional decarbonization strategies.

Table ES-3 provides a sample statement of entity-level direct CO_2 emissions by the steel producer and CO_2 emissions attributed to energy and materials supply chains (and transferred from supplier ledgers).

The sample comprehensive CO_2 emissions report provides a complete record of total emissions, with no gaps in coverage, along with complete and transparent allocation of CO_2 emissions among products. The ability to record CO_2 emissions only once and transfer the CO_2 emissions from the ledgers of the suppliers to the steel producer and ultimately to the customer avoids inadvertent double counting of CO_2 emissions. It also includes built-in error checking to support accuracy and provides a complete and transparent record to facilitate third-party verification to ensure completeness of the report and protect against gaps or errors in the allocation of entity-level CO_2 emissions among individual products.

Table ES-3. **STEEL PRODUCER'S ENTITY-LEVEL CO_2 EMISSIONS REPORT, ONE MONTH OF OPERATION**

Steel Producer
Entity-Level CO_2 Intensity Statement
January 2025

Direct emissions	
Direct, entity-specific CO_2 emissions	742,908 tCO_2
CO_2 emissions abated via CCS	(416,886) tCO_2
Total direct emissions (net)	*326,022 tCO_2*
Attributed emissions	
Raw materials	21,040 tCO_2
Energy (fuels and electricity)	113,040 tCO_2
Plant, property, and equipment	436 tCO_2
Transporting final products	2,062 tCO_2
Total attributed emissions	*136,578 tCO_2*
Total entity-level CO_2 emissions	**462,600 tCO_2**

Source: Sesame Sustainability.

Comparison of Product-Level CO_2 Emissions Intensities Among Steel Production Pathways

Table ES-4 compares the product carbon emissions intensities of the steel produced via BF-BOF (developed in this case study) and the steel produced via the hydrogen direct reduced iron-electric arc furnace (H_2-DRI-EAF) process (from the companion steel case study). Users of this information—including investors, policymakers, and customers—can readily compare product CO_2 emissions intensity data across the supply chains and production processes for steel produced by these two methods. For instance, Table ES-4 shows that even with CCS, the CO_2 intensity of steel products made via BF-BOF is nearly four times that of products made via H_2-DRI-EAF, primarily because of the BF-BOF route's high direct emissions. Because all carbon intensities are calculated using the same ledger-based accounting methodology, the results are directly comparable.

Table ES-4. **PRODUCT CO_2 EMISSIONS INTENSITY FOR STEEL PRODUCTS**

	BF-BOF pathway *(kgCO_2/kg of steel)*	**H_2-DRI-EAF pathway** *(kgCO_2/kg of steel)*
Direct, entity-specific CO_2 emissions	1.78	0.20
CO_2 emissions abated via CCS	-1.00	-0.12
CO_2 emissions from suppliers		
Raw materials	0.05	0.03
Energy (fuels and electricity)	0.27	0.19
Plant, property, and equipment	0.001	0.001
CO_2 emissions from transporting final products	0.005	0.005
Total product CO_2 emissions intensity in steel	**1.11**	**0.3**

I. Introduction

This case study illustrates how a comprehensive product- and entity-level, ledger-based carbon accounting system operates in practice, using a steel supply chain. The system represents a fundamental shift from current carbon reporting methods by applying established financial accounting principles to achieve rigorous carbon accounting.

Steel is one of the most challenging sectors to decarbonize because of its reliance on carbon-intensive production processes—especially the blast furnace-basic oxygen furnace (BF-BOF) route, which uses coal-derived coke as both a fuel and a reducing agent. In the United States, steel production accounts for approximately 6%–7% of industrial greenhouse gas (GHG) emissions.[12,13] With demand for steel projected to increase steadily through midcentury—driven by growth in construction, transportation, and renewable infrastructure—emissions from the sector could rise significantly without major decarbonization interventions.[14,15]

Despite growing interest in low-carbon steel, scaling up cleaner production methods has been slow. Key challenges include the high cost and limited availability of low-carbon feedstocks such as green hydrogen, the need for retrofitting or replacing existing infrastructure, and policy uncertainty regarding carbon pricing and emissions accounting.

Although federal programs such as the Inflation Reduction Act (IRA) and regional initiatives are beginning to incentivize cleaner steel production through tax credits and procurement standards, progress is hindered by the lack of a unified carbon accounting framework that can consistently evaluate the carbon intensity of different steelmaking pathways. For example, under Section 45V hydrogen tax credits, differing interpretations of life cycle emissions modeling (e.g., GREET vs. other models) have raised questions about how low-carbon hydrogen should be qualified for use in steelmaking.

Moreover, steel buyers—including automakers and construction firms—require transparent and verifiable carbon intensity data to support green procurement and justify paying a premium for low-emissions steel. As such, establishing a standardized, sector-specific carbon accounting approach is critical for unlocking demand, aligning incentives, and accelerating investment in decarbonized steel.

At its core, ledger-based carbon accounting treats carbon like financial accounting treats money—every transaction is recorded, transfers between entities are tracked, and complete balances are maintained. Carbon ledgers track carbon flows through emissions by species—carbon dioxide (CO_2), methane (CH_4), carbon monoxide (CO), volatile organic compounds (VOCs), and carbon content (used as a cross-check to validate that total mass flows and emissions allocations are internally consistent at the molecular level).

The key innovation in the ledger-based carbon accounting is the carbon ledger itself: a systematic, transaction-based record that captures all carbon movements within defined entity boundaries and time periods. Unlike current GHG inventories, the ledger approach requires tracking of carbon as it is transferred from supplier to producer to customer. This creates an unbroken chain of custody and accountability throughout the supply chain.

This case study demonstrates these concepts through a steel supply chain, showing how:

- Each entity maintains its own carbon ledger with a chart of accounts.
- Carbon is "transferred" between entities at delivery points under free on delivery (FOD) terms.[d]
- Both physical carbon content and carbon emissions by species (CO_2, CH_4, CO, VOCs) are tracked in parallel.
- Mass balance principles ensure all carbon is accounted for without gaps or double counting.
- Product-level carbon intensities emerge directly from the ledger entries.

By walking through actual ledger entries, carbon transfers, and allocation methods, this case study bridges the gap between the theoretical framework and practical implementation, demonstrating how ledger-based carbon accounting can provide the foundation required for emerging carbon-differentiated commodities and products.

d Under FOD terms, the selling entity retains ownership and responsibility for all carbon emissions associated with a product—including production, processing, and transportation—until physical delivery at the buyer's location. This ensures clear carbon accountability boundaries. The seller owns all upstream emissions until the moment of delivery, at which point both the physical product and its accumulated carbon footprint transfer to the buyer.

II. Production Pathway Overview and Supply Chain

This case study examines a steel supply chain centered on an illustrative blast furnace-basic oxygen furnace (BF-BOF) production facility in East Chicago, Indiana, a strategic site for an integrated steel operation because of its proximity to raw material supplies and transportation routes via the Great Lakes. While the facility configuration is hypothetical, all technical parameters, conversion efficiencies, and carbon intensity values are derived from authoritative sources, including Argonne National Laboratory's GREET model pathways,[e] U.S. Environmental Protection Agency eGRID data for regional electricity emissions,[16] and peer-reviewed literature on BF-BOF process performance.[17]

The supply chain encompasses multiple entities across the value chain, from iron ore feedstock producer, scrap steel producer, and utilities, to the final construction customer. The system demonstrates the flow of carbon emissions and physical materials through a multi-entity network under FOD accounting terms.

Without existing entity-specific carbon data, the case study sources carbon intensity values for primary feedstocks and energy inputs from established life cycle assessment databases to ensure consistency with standard industry practices. In actual implementation, carbon data would be obtained directly from supplier-specific product carbon footprint (PCF) data or supplier environmental product declarations (EPDs). This case study uses literature-based values from established databases for demonstration purposes.

The case study assumes four primary upstream suppliers providing essential inputs from distinct geographic locations (see Figure 1). Iron ore is sourced from Duluth, Minnesota, while coal is supplied from Conneaut, Ohio. Natural gas originates from the Williston Basin and is delivered via pipeline. Limestone is procured from Rogers City, Michigan. All solid materials—iron ore, coal, and limestone—are transported by vessel and barge through the Great Lakes system to the fully integrated BF-BOF steelmaking facility in East Chicago, Indiana, leveraging the region's waterborne freight infrastructure. These inputs are used to produce 5 million tons of raw steel annually, which is further processed into hot-rolled, cold-rolled, and hot-dip galvanized products, primarily for the construction sector.

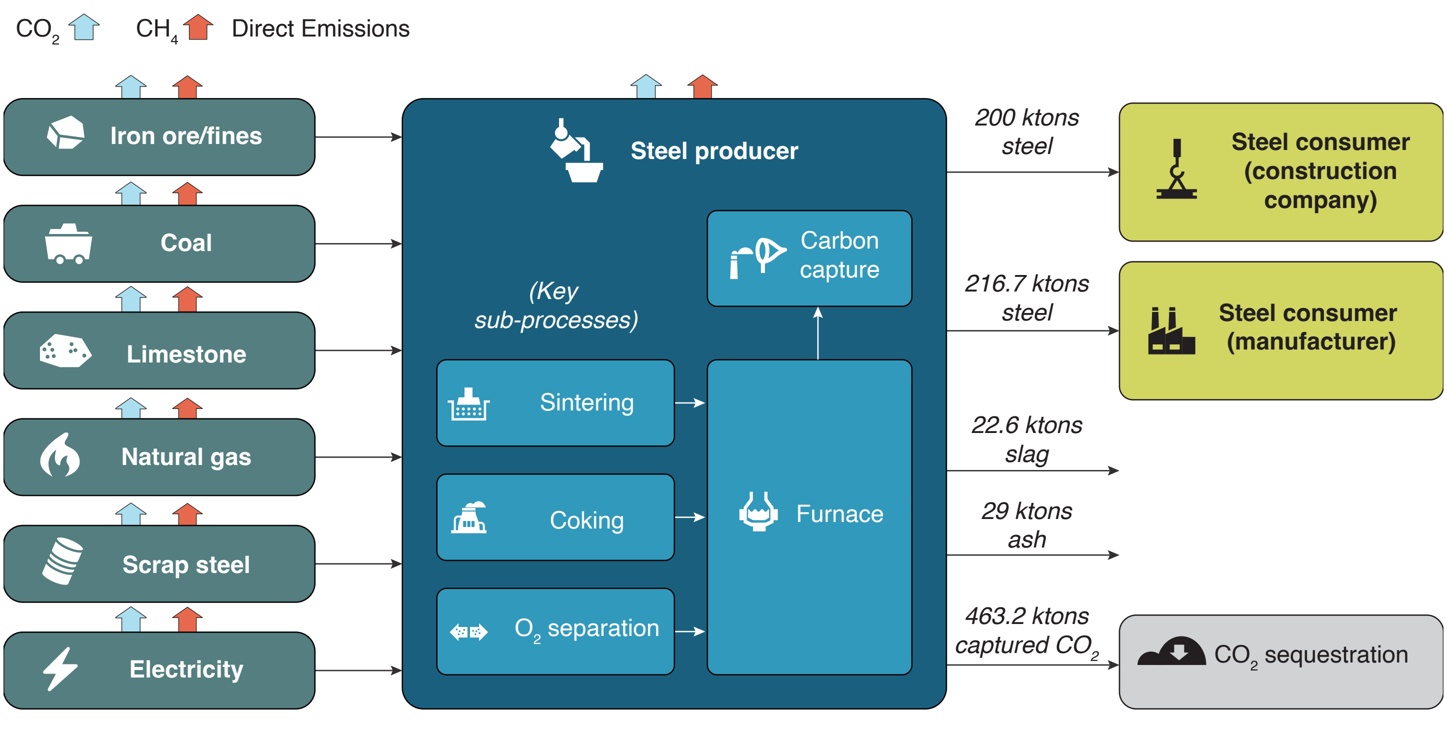
The integrated supply chain creates multiple emissions transfer points where carbon responsibility shifts between entities. Under FOD terms, transportation

e Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) is a life cycle analysis to assess the environmental impacts of technologies, fuels, products, and energy systems.

emissions remain with the delivering party, while the steel producer inherits upstream cradle-to-gate emissions from all feedstocks upon delivery. The steelmaker then adds its own gate-to-gate operational emissions, including those from coke production, iron reduction, steel refining, electricity use, and other on-site processes, along with capital equipment emissions.

A mass-based allocation approach should be applied to distribute total cradle-to-gate emissions among co-products. Since steel is the only valuable product, all emissions are allocated to steel product for the case study. The analysis is conducted on a steady-state, one-month basis and includes inventory balances and infrastructure impacts. Final customers—a construction company and a manufacturer—receive steel products with their full embedded carbon intensity, forming the basis for product-level carbon accounting and emissions disclosure.

Figure 1. **KEY ENTITY RELATIONSHIPS FOR BF-BOF STEEL PRODUCTION**



Note: Ktons = kilotons. Source: Sesame Sustainability.

System Boundaries and Accounting Entity Structure

The carbon accounting framework recognizes multiple distinct entities with defined responsibilities, with the exact number depending on the configuration of the steel supply chain. In this case study, upstream suppliers—iron ore miners, coal suppliers, limestone quarries, natural gas providers, and electric utilities—are accountable for the carbon emissions associated with their respective extraction and production processes. This includes upstream emissions from resource extraction, material processing, and fuel combustion, as well as capital equipment impacts where applicable. The integrated steel production facility assumes responsibility for its gate-to-gate processing emissions, while also inheriting the cradle-to-gate upstream emissions transferred from all raw material suppliers.

Emissions transfers occur at designated delivery points, and the FOD structure ensures that transportation-related emissions remain with the supplying entity until the point of custody transfer. As a result, emissions from Great Lakes vessel and barge transport of iron ore, coal, and limestone are attributed to the respective suppliers. Similarly, pipeline transport of natural gas is accounted for by the gas supplier and electricity-related emissions are owned by the regional utility. The steelmaker assumes ownership of material- and energy-related emissions at the point of receipt and allocates total emissions—upstream and operational—across final steel products using a mass-based allocation method.

Steel Producer Feedstock and Supplier Relationships

The steel producer has established supply agreements with multiple upstream entities to secure the five critical inputs required for BF-BOF steelmaking. Each upstream entity reports cradle-to-gate emissions by species—CO_2, CH_4, CO, nitrous oxides (NO_x), and VOCs—for its delivered products:

- **Iron ore supplier:** The facility sources iron ore from mining operations in Duluth, Minnesota. For simplicity, the iron ore supplier is assumed to control the entire upstream value chain—from ore extraction and primary crushing to rail or barge loading and delivery. The cradle-to-gate carbon intensity of iron ore includes emissions from diesel-powered mining equipment, crushing and screening processes, and transportation via Great Lakes vessels to the East Chicago facility.
- **Coal supplier:** Metallurgical coal is sourced from Conneaut, Ohio, and delivered by barge through the Great Lakes system. The supplier reports full cradle-to-gate emissions encompassing coal mining, washing, handling, and transport, including methane emissions from coal seams and fuel use in logistics. The coal is primarily used in the coke ovens for carbon-rich coke production, which serves as both a fuel and reducing agent in the blast furnace.
- **Limestone supplier:** Limestone is sourced from Rogers City, Michigan, and similarly transported by water to the steel facility. The supplier reports emissions associated with quarrying, crushing, and barge transport. Limestone

is used as a fluxing agent in the blast furnace to remove impurities from molten iron by forming slag.

- **Natural gas supplier:** Natural gas is delivered via pipeline from the Williston Basin in eastern Montana, western North and South Dakota, and southern Saskatchewan, and is used in various auxiliary heating and reforming processes at the facility (e.g., ladle preheating, drying). The supplier provides cradle-to-gate emissions covering extraction, processing, compression, transmission, and on-site delivery.

- **Electricity supplier:** A regional utility provides grid electricity to the facility. The reported carbon intensity reflects the utility's full generation mix, including upstream fuel extraction (e.g., for coal, gas, or nuclear), generation efficiency, and transmission and distribution losses. Electricity is used throughout the plant for drives, motors, air separation units, control systems, and downstream rolling and finishing operations.

Each upstream supplier delivers products and associated emissions data to the steelmaker under FOD terms, ensuring consistency in ownership boundaries across the supply chain. These cradle-to-gate values are incorporated into the steelmaker's life cycle assessment (LCA) and carbon accounting framework.

Steel Production Process With Carbon Capture (BF-BOF + CCS)

Iron ore, coal, limestone, and other essential materials are converted into high-value steel products through the BF-BOF process. The pathway consists of several major stages that transform raw inputs into finished steel products. First, iron ore is combined with coke (derived from metallurgical coal) and fluxes (e.g., limestone) in the blast furnace, where intense heat and chemical reduction reactions produce molten pig iron. This molten iron is then transferred to the basic oxygen furnace, where high-purity oxygen is injected to remove carbon and other impurities, converting the iron into crude steel.

Throughout this process, natural gas may be used for auxiliary heating (e.g., ladle preheating, reheating furnaces), and electricity powers various systems including casting, rolling, and finishing. The facility is equipped with carbon capture systems with a 90% capture rate, which separate CO_2 from blast furnace gas and BOF off-gases. The captured CO_2 is compressed and sent for permanent geological storage via the regional carbon capture and storage (CCS) infrastructure, significantly reducing the facility's cradle-to-gate carbon intensity.

Steel production yields multiple co-products including hot-rolled, cold-rolled, and galvanized steel, as well as slag and ash byproducts. The case study simplifies the system by allocating all the emissions to the steel product. Captured CO_2 is accounted for as a deduction in net emissions and is tracked separately in the facility's carbon ledger.

Primary steel products flow to downstream customers with clear, auditable emissions transfer. Byproducts such as slag and recovered gases are assumed to have no onward use in this analysis and are therefore treated as waste.

Steel Distribution and End Use

The customers purchase finished steel products from the integrated BF-BOF facility and manage the downstream logistics, fabrication, and installation activities associated with end use. For this analysis, the customers are assumed to own and coordinate the transportation of steel products from the production facility to project sites, taking responsibility for these downstream activities and their associated emissions.

The produced steel is used in a range of structural and infrastructure applications. These materials are treated as final outputs from the steelmaking system, and the associated cradle-to-gate carbon intensity is transferred to the customers upon delivery. This ensures that emissions are accurately captured and passed downstream in alignment with product carbon accounting frameworks.

While this case study tracks carbon from raw material extraction through finished product delivery, intermediate operations at the construction site—such as storage, cutting, welding, and assembly—are excluded for simplicity. The ledger-based accounting framework, however, could readily incorporate these downstream processes as additional transfer points if needed, though their contribution to total life cycle emissions is expected to be relatively small compared to upstream steelmaking emissions.

III. Sesame One Modeling Engine

Sesame One is an industrial decarbonization platform that integrates life cycle emissions modeling, techno-economic analysis, and system-level optimization into a unified, consistent tool.[18] The platform connects plant-level operational data with comprehensive databases and flexible first-principles engineering models to evaluate the technical, economic, and regulatory dimensions of decarbonization strategies in the steel sector and other hard-to-abate industries.

For this case study, Sesame One applies a bottom-up, molecular-level carbon accounting framework to resolve detailed mass and energy balances across the BF-BOF steel production pathway, including upstream raw material supply, in-plant transformation processes, co-product handling, and emissions tracking. This modeling framework forms the analytical foundation for the carbon accounting results presented in the steel case study and is implemented through two integrated components:

Mass and Energy Balance Resolution

The primary balance calculations resolve fundamental process relationships across the BF-BOF steel production system. For the integrated facility, the model calculates input and output material flows based on reaction stoichiometry, process efficiency, and thermal energy requirements, with material yield, slag formation rates, and gas recovery factors dictating net conversion from iron ore, coal, limestone, and oxygen into molten steel, slag, and ash. The system also tracks fuel consumption and electricity demand, accounting for coal-derived coke used in iron reduction, natural gas used for auxiliary heating, and electricity drawn from the grid for downstream operations such as casting, rolling, and finishing.

Transport models incorporate the spatial logistics specific to this case study, including bulk vessel and barge transport via the Great Lakes for iron ore, coal, and limestone, as well as pipeline delivery for natural gas. The modeling framework includes energy intensity and combustion emissions for each transport mode, ensuring comprehensive accounting of transport-related emissions. Material loss factors and recovery rates are also considered across transport and handling stages to maintain mass balance closure from raw material extraction to final product delivery.

Closed mass balances are critical for entity-level carbon accounting, ensuring that the majority of carbon atoms introduced through coal, natural gas, and iron ore impurities are consistently tracked through the system. This includes carbon emitted as CO_2, retained in steel products, captured in slag, or released via fugitive or off-gas streams. By employing a first-principles modeling approach, the platform enables precise emissions calculations and transparent allocation of cradle-to-gate emissions across steel products and co-products, supporting rigorous carbon intensity assessments and avoiding double counting across upstream and downstream boundaries.

Greenhouse Gas Emissions Tracking

Sesame One tracks multiple emissions species across the entire steel supply chain, including carbon dioxide (CO_2), methane (CH_4), carbon monoxide (CO), nitrous oxide (N_2O), sulfur oxides (SO_X), nitrogen oxides (NO_X), and volatile organic compounds (VOCs). For this carbon accounting case study, we focus specifically on carbon-containing species, calculating direct emissions from major steelmaking processes—including coke production, blast furnace ironmaking, and basic oxygen steelmaking—as well as combustion of natural gas and electricity generation used throughout the facility. Carbon balances are resolved through carbon mass accounting, ensuring closure across all material and energy flows from feedstock inputs to final product outputs and emissions streams. Emissions factors are specific to process equipment and fuel types, drawing from authoritative sources such as Argonne National Laboratory, EPA AP-42, Ecoinvent v.3.11, and steel sector-specific LCA datasets.

Carbon-containing species are tracked individually (CO_2, CH_4, CO, VOCs), with their carbon mass equivalents calculated using carbon atom ratios, rather than global warming potentials (GWPs). This carbon-centric accounting approach supports a mass balance closure framework, ensuring that all carbon entering the system—whether as fixed carbon in coal, dissolved carbon in iron ore impurities, or carbon in fuels like natural gas—is traced through its eventual fate: emitted as CO_2 or CO, leaked as methane, retained in steel products, or stored in slag or off-gas recovery systems.

This approach allows for rigorous entity-level emissions tracking, capturing both combustion emissions and process emissions, while maintaining accountability of carbon atoms throughout the steelmaking system. It also supports consistent and transparent carbon intensity calculations across co-products and enables reliable emissions reporting aligned with regulatory and voluntary frameworks.

IV. Case Study Inputs and Assumptions

This section presents the key parameters, data sources, and methodological assumptions used in the life cycle carbon assessment model.

Carbon Emissions Intensities of Feedstock and Fuels

Table 1 (next page) presents attributed emissions by species—well-to-gate emissions already released during production—for each major input used in the BF-BOF steelmaking process. Iron ore emissions are derived from the Ecoinvent v.3.11 database and represent the global market for 65% iron ore concentrate on a dry basis, with emissions intensities of 87.8 grams of CO_2 per kilogram (gCO_2/kg), 0.26 gCH_4/kg, 0.45 gCO/kg, and 0.21 gVOC/kg.[19]

Coal is modeled as hard coal sourced from the North American market, also using Ecoinvent v.3.11, with considerably higher methane content—88.3 gCO_2/kg and 4.11 gCH_4/kg—reflecting upstream mining and processing characteristics.

Electricity emissions follow Argonne GREET 2024 data for wall-outlet delivery under Indiana's projected 2024 grid mix from the National Laboratory of the Rockies (NLR) Standard Scenarios Mid-Case.[20] The associated intensity is 675.28 gCO_2 per kilowatt-hour (kWh), along with 1.18 gCH_4/kWh, 0.24 gCO/kWh, and 0.07 gVOC/kWh.

Natural gas emissions are based on GREET's well-to-gate profile for the North American natural gas mix (75% shale gas, 25% conventional), reporting 4.53 gCO_2 per megajoule (MJ), 0.11 gCH_4/MJ, 0.01 gCO/MJ, and 0.01 gVOC/MJ, which includes upstream extraction, processing, and a methane leakage rate of 0.48%.

For limestone, Ecoinvent data shows low emissions (2.78 gCO_2/kg), with no methane, CO, or VOC emissions reported.[21] Scrap steel is also sourced from Ecoinvent as unsorted iron scrap and contributes 3.24 gCO_2/kg, with no CH_4, CO, or VOC emissions. These cradle-to-gate emissions intensities serve as the upstream emissions baselines for all inputs and are transferred into the steelmaker's carbon ledger prior to further processing and allocation.

Table 1. **CARBON EMISSIONS INTENSITY BY INPUT**

Feedstock/fuel	Product carbon emissions intensity (cradle-to-gate)	Source(s)	Details
Iron ore	87.8 gCO_2/kg 0.26 gCH_4/kg 0.45 gCO/kg 0.21 gVOC/kg	Ecoinvent v.3.11	Global market for iron ore concentrate (65% iron, dry basis), applied to consuming activities in iron and steelmaking.
Electricity	675.28 gCO_2/kWh 1.18 gCH_4/kWh 0.24 gCO/kWh 0.07 gVOC/kWh	Argonne GREET Model, 2024[22]	GREET 2024 "wall outlet" emissions at user site. Indiana grid mix derived from NLR Standard Scenarios 2023 Mid-Case for 2024.
Natural gas	4.53 gCO_2/MJ 0.11 gCH_4/MJ 0.01 gCO/MJ 0.01 gVOC/MJ	Argonne GREET Model, 2024	Standard North American natural gas pathway (75% shale gas, 25% conventional). Well-to-gate emissions include extraction and processing. Combined methane leakage rate of 0.48% across recovery/processing.
Coal	88.3 gCO_2/kg 4.11 gCH_4/kg 0.46 gCO/kg 0.29 gVOC/kg	Ecoinvent v.3.11	This is the market for hard coal, in the geography of Northern America.
Limestone	2.78 gCO_2/kg 0 gCH_4/kg 0 gCO/kg 0 gVOC/kg	Ecoinvent v.3.11	This is the market for limestone, unprocessed, in the Global geography.
Scrap steel	3.24 gCO_2/kg 0 gCH_4/kg 0 gCO/kg 0 gVOC/kg	Ecoinvent v.3.11	This is the market for iron scrap, unsorted, in the Global geography.

Transportation Parameters and Modeled Carbon Intensities

Transportation carbon intensities are calculated using energy consumption, material flows, and operational characteristics specific to each transport mode in the steel supply chain. For upstream inputs, natural gas is transported via pipeline over 200 miles, with an energy intensity of 1.64 British thermal units (Btu) per kilogram-mile (kg·mile), using 98% natural gas fuel share and a methane leakage rate of 0.26% per 680 miles, consistent with R&D GREET 2025 assumptions.

Iron ore, coal, limestone, and scrap steel are transported primarily via Great Lakes barge, with distances ranging from 5.6 nautical miles (scrap) to 889 nautical miles (coal). Emissions factors reflect GREET-based marine transport pathways, incorporating energy consumption per ton-kilometer and modal-specific emissions species (CO_2, CH_4, CO, VOCs). For example, coal barge transport contributes approximately 23.5 kgCO_2/ton, with small but non-negligible contributions from CH_4 and VOCs.

For downstream logistics, steel is delivered by rail to construction companies over a 5-mile distance. The short-haul nature of the delivery results in relatively high emissions per ton because of startup fuel demands and limited route efficiency, with an intensity of approximately 83.4 kgCO_2/ton. Emissions estimates include full well-to-pump life cycle emissions of diesel fuel used in rail transport and are consistent with GREET methodology.

Electricity distribution is excluded from transport emissions calculations, assuming standard grid-connected facility operations with no dedicated transport infrastructure. All modeled emissions include well-to-gate emissions for fuels and species-level tracking, aligned with the broader life cycle boundaries used across the carbon accounting framework for upstream and gate-to-gate steel emissions.

Table 2. **CARBON EMISSIONS INTENSITY BY TRANSPORT MODE**

Transport mode	Distance	Modeled transport carbon emissions intensity	Note
Natural gas pipeline	200 miles (mi) 321.9 kilometers (km)	27.6 kgCO_2/ton 1.4 kgCH_4/ton 348 gCO/ton 68 gVOC/ton	Pipeline energy intensity and leakage rate consistent with GREET default (Argonne GREET Model, 2024).
Iron ore barge	790 nautical miles (nmiles) 1,463.9 km	20.9 kgCO_2/ton 0.07 kgCH_4/ton 0.07 kgCO/ton 0.05 kgVOC/ton	Barge energy intensity consistent with GREET (Argonne GREET Model, 2024).
Coal barge	889 nmiles 1,646.5 km	23.5 kgCO_2/ton 0.08 kgCH_4/ton 0.08 kgCO/ton 0.06 kgVOC/ton	Barge energy intensity consistent with GREET (Argonne GREET Model, 2024).
Scrap steel barge	5.6 nmiles 10.4 km	0.59 kgCO_2/MJ 0.002 kgCH_4/ton 0.002 gCO/ton 0.002 kgVOC/ton	Very short-distance delivery; emissions per ton are minimal.
Limestone barge	401.8 nmiles 744.2 km	9.0 kgCO_2/ton 0.04 kgCH_4/ton 0.04 kgCO/ton 0.03 kgVOC/ton	Reflects marine barge emissions over medium distance.
Steel train	5 mi 8.05 km	83.4 kgCO_2/ton 0.29 kgCH_4/ton 0.09 kgCO/ton 0.10 kgVOC/ton	Short-distance rail delivery to construction site. Rail energy use aligned with GREET default.

BF-BOF Steel Production Models

The BF-BOF steelmaking system is modeled using plant-level parameters, anchored in first-principles mass and energy balances. The model simulates a fully integrated facility that produces 5 million tons of crude steel per year, converting iron ore, metallurgical coal, limestone, natural gas, and electricity into finished steel products such as hot-rolled, cold-rolled, and galvanized steel. Emissions and energy flows are benchmarked using values from the facility model and authoritative datasets such as Argonne GREET 2024 and Ecoinvent v.3.11.

In the blast furnace, carbon from coke (produced from metallurgical coal) reduces iron ore to molten pig iron. This is refined in the basic oxygen furnace via oxygen blowing to remove impurities and produce liquid steel. The model assumes a coke rate of approximately 400-500 kg/ton steel, with an associated CO_2 emissions intensity of ~2.0-2.2 tons CO_2 per ton of crude steel (pre-capture). Natural gas is used for auxiliary heating, preheating ladles, and supporting operations across finishing stages.

Electricity consumption is modeled at 480-520 kWh per ton of crude steel, covering all downstream operations including casting, rolling, and coating. Additional process heat is accounted for via gas combustion, with thermal efficiency assumptions of 85%-90% for steam generation and reheating processes.

The modeling framework performs a closed carbon mass balance, capturing direct process emissions (e.g., from coke combustion and decarburization reactions), indirect energy emissions (from purchased electricity and fuels), and co-product flows including slag, off-gases, and scrap return. All major emissions species—CO_2, CH_4, CO, and VOCs—are tracked by source and process step.

The model allocates all the emissions to the primary steel. The process assumptions align with recent industry literature and serve as a benchmark for comparing against alternative decarbonized pathways (e.g., BF-BOF, hydrogen-based direct reduced iron-, or electric arc furnace-based steelmaking).

Physical Properties and Physical Carbon Content Calculations

Physical carbon content calculations form the foundation for mass balance closure and emissions allocation across the production system. Building on the attributed carbon emissions by species presented in the Carbon Emissions Intensities of Feedstock and Fuels section of this report, this section addresses the physical carbon atoms contained within feedstocks and products.

Carbon mass ratios are determined from molecular composition analysis, and all species are converted to carbon mass equivalent terms using the molecular carbon content of each species: CO_2 (carbon mass ratio = 0.273, meaning 1 ton CO_2 contains 0.273 tons carbon), CH_4 (carbon mass ratio = 0.750, meaning 1 ton CH_4 contains 0.750

tons carbon), CO (carbon mass ratio = 0.429, meaning 1 ton CO contains 0.429 tons carbon), and VOCs (carbon mass ratio taken to be 0.85, consistent with the GREET model). This standardized approach allows us to compare carbon flows across different emissions species while maintaining mass balance closure where total carbon input equals total carbon output (products + emissions across all species).

Table 3. **CARBON MASS RATIO AND ENERGY CONTENT BY SPECIES**

Species	Carbon mass ratio	Energy content
Coal	0.734	28.9 MJ/kg
Natural gas	0.722	47.14 MJ/kg
Scrap steel	0.002	–
Limestone	0.12	–
Steel	0.002	–
CO_2	0.273	–
Carbon	1	–

Source: R&D GREET 2024.

Accounting Ledger Assumptions

This case study employs key simplifying assumptions to highlight core emissions transfer principles:

- **Inventory boundaries:** The producer maintains two weeks of raw material and coal inventories.
- **Capital equipment:** Property, plant, and equipment (PP&E) attributed emissions are included and allocated to the steel products.
- **Temporal scope:** Single monthly production period without seasonal variation considerations.
- **Product scope:** Steel is treated as a single product; any byproducts (e.g., slag) are assumed to have negligible economic value in this base case and do not receive allocated emissions.

These assumptions allow focus on the essential carbon accounting framework while maintaining analytical clarity for transaction-based emissions transfers.

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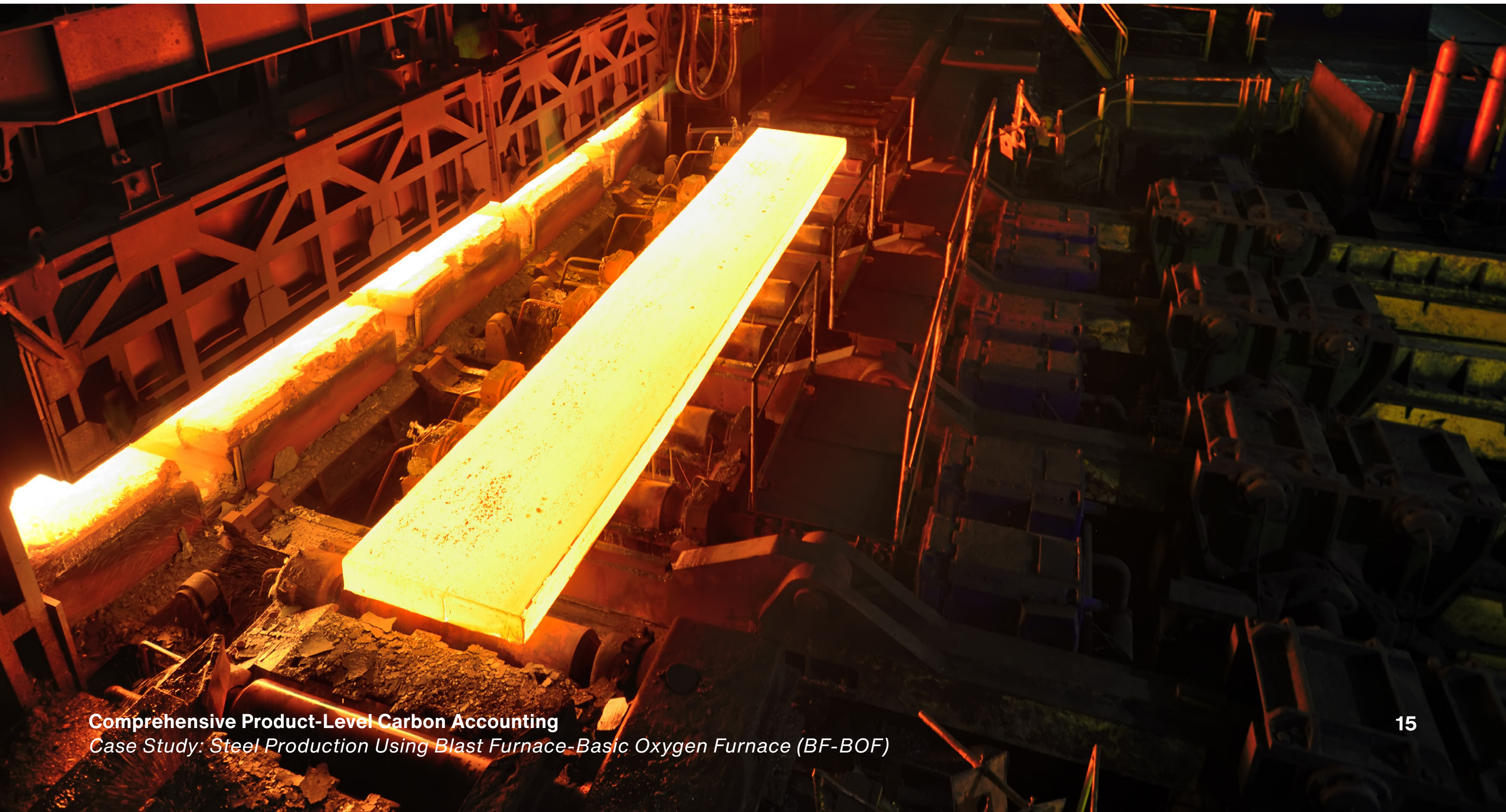
V. Results and Carbon Impact Analysis

Mass and Energy Balance Overview

The Sesame carbon accounting model generates detailed mass and energy balances that serve as the foundation for emissions allocation and carbon tracking across the BF-BOF steelmaking system. The annual production scenario models a fully integrated steel facility producing 5 million tons of crude steel per year. This requires the input of approximately 2.8 million tons of iron ore, 2.7 million tons of metallurgical coal (converted to coke), 0.5 million tons of limestone, 10.4 petajoules (PJ) of natural gas for auxiliary heating, and 1,476 gigawatt-hours (GWh) of electricity for various plant operations including casting, rolling, and finishing.

The blast furnace and basic oxygen furnace processes yield a primary product mix of:

- 5,000,000 tons of crude steel (core output) per year.
- 271,178 tons of slag (byproduct used in cement or road base) per year.
- 347,964 tons of ash per year.

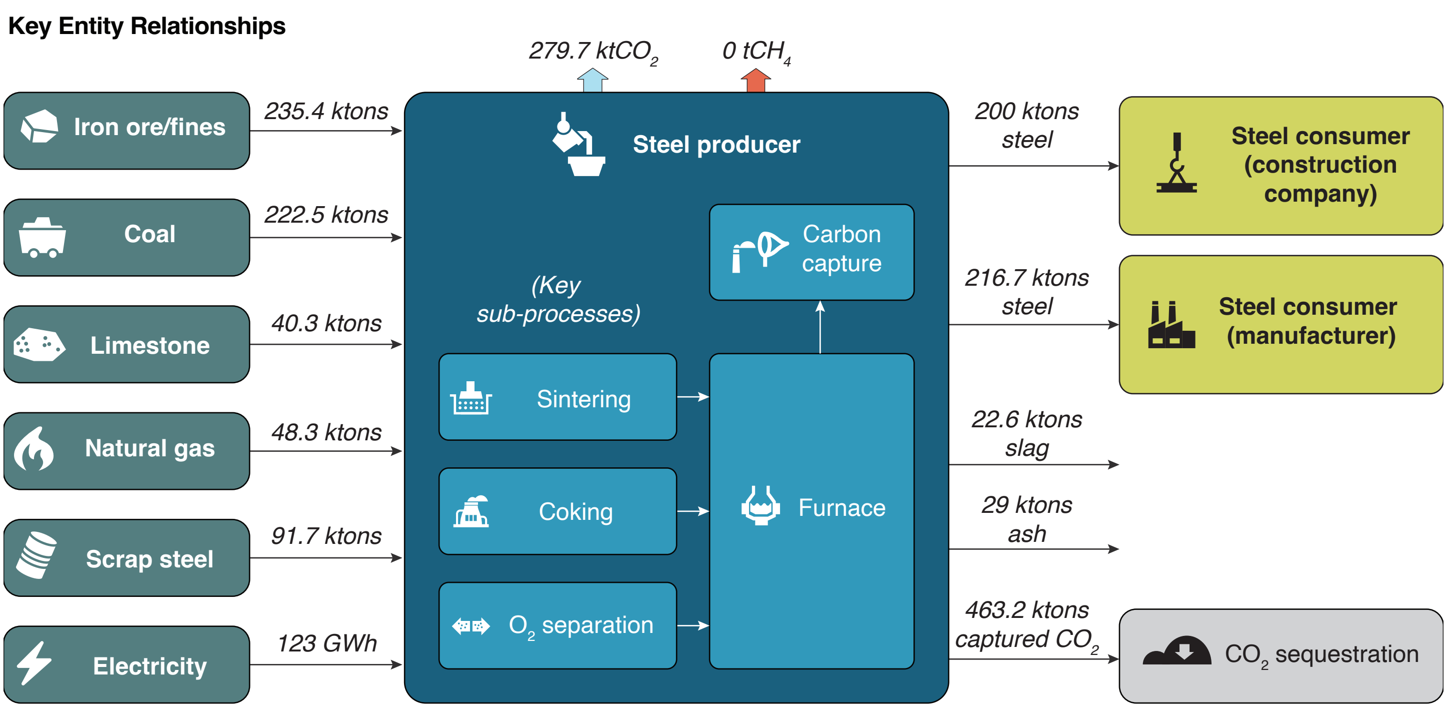


These mass flows are used to calculate the carbon flows and allocation factors for cradle-to-gate emissions accounting. The model applies mass-based allocation of upstream and process emissions across primary steel products and byproducts (e.g., slag), in alignment with ISO 14044 and product carbon intensity reporting practices.

In the baseline (no carbon capture, utilization, and storage) case, total direct CO_2 emissions exceed 10 million tons annually, primarily from coke combustion and decarburization reactions in the BOF. Emissions are allocated proportionally to output streams, ensuring traceability from feedstock carbon content to final product carbon intensity. These balances form the analytical backbone of the carbon accounting framework.

Because this study adopts a one-month accounting period, the mass and energy balance is shown on a monthly basis (Figure 2).

Figure 2. **MASS AND ENERGY FLOWS FOR INTEGRATED STEEL PRODUCTION, ONE MONTH**



Source: Sesame Sustainability.

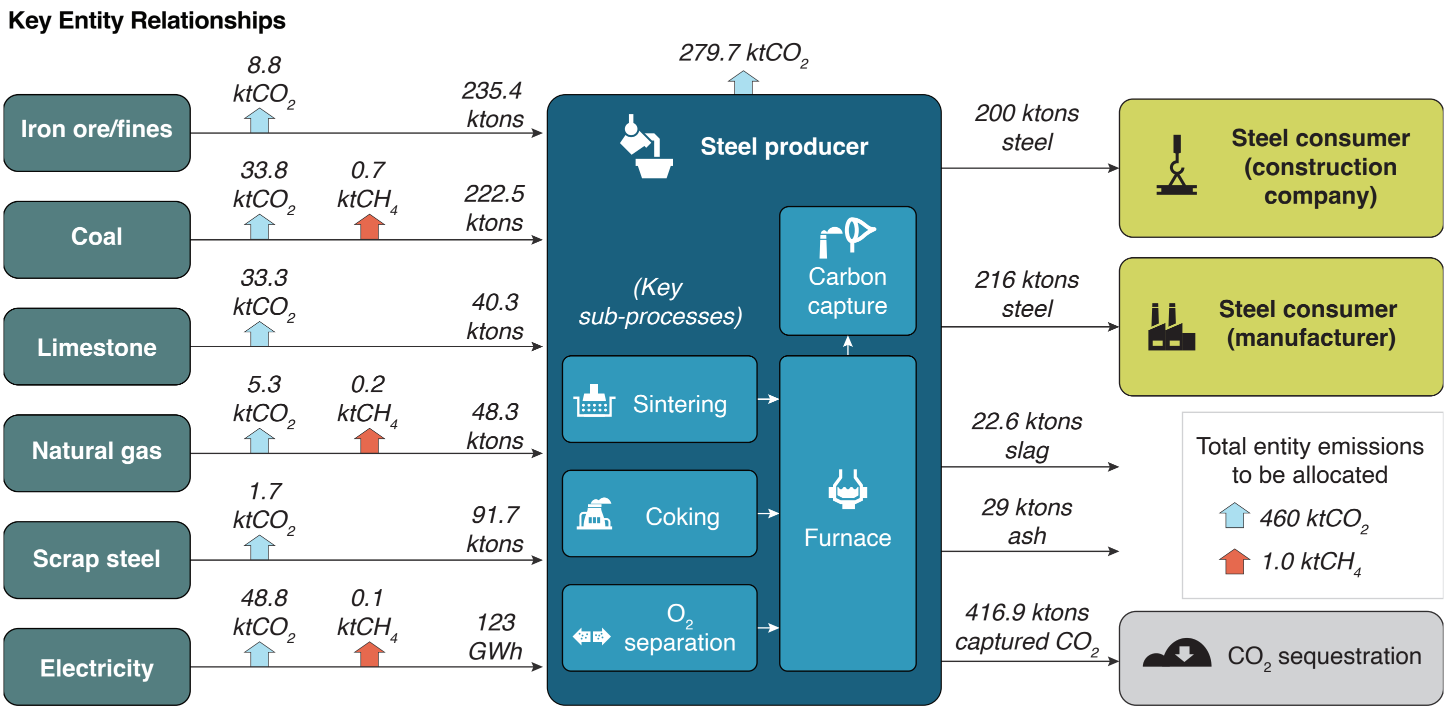
Steel Producer Ledger Records and Reporting

Recording Carbon Emissions and Content Transfers In

The annual production scenario demonstrates how upstream suppliers transfer both materials and their carbon footprints by species to the steel producer under the FOD accounting framework. Each input arrives with two carbon components: attributed carbon emissions by species (CO_2, CH_4, CO, VOCs already released from upstream production and transport) and physical carbon content (Figure 3).

In the carbon ledger, all transactions are recorded using a common base unit—ton of carbon (tC)—to ensure that the carbon mass balance is consistently maintained. Accordingly, all attributed emissions transferred in are converted to tC (Table 4, next page). For clarity and given that CO and VOCs mass is typically small relative to CO_2 and CH_4 mass, in this case study these species are combined in a single column. The ledger framework is fully scalable to track any number of individual emissions species as needed for specific applications.

Figure 3. **CARBON FLOW DIAGRAM OF INPUTS TO STEEL PRODUCTION, WITH ATTRIBUTED EMISSIONS BY SPECIES AND CARBON CONTENT, ONE MONTH**



Note: The diagram illustrates how individual emissions species from upstream suppliers transfer to the integrated steel production facility alongside material flows. CO and VOCs are omitted for simplicity. Source: Sesame Sustainability.

Table 4. **ANNUAL ATTRIBUTED EMISSIONS AND CARBON CONTENT BY INPUT**

Input	Quantity	Attributed CO_2 *(tC)*	Attributed CH_4 *(tC)*	Attributed CO and VOC *(tC)*	Total attributed emissions *(tC)*	Physical carbon content *(tC)*
Electricity	1,476 GWh	272,146	1,306	250	273,702	0
Natural gas	579,546 tons	33,799	2,195	324	36,318	418,432
Coal	2,670,484 tons	64,374	8,232	1,187	73,793	1,960,135
Iron ore	2,824,800 tons	67,585		533	68,118	0
Scrap steel	1,100,000 tons	973			973	2,200
Limestone	484,000 tons	367			367	58,080
Total	–	**439,244**	**11,733**	**2,294**	**453,271**	**2,438,847**

Note: Values shown are carbon mass equivalents for each species, calculated using the carbon mass ratio of each emissions species (CO_2: 0.273, CH_4: 0.750, CO: 0.429, VOC: 0.85). Total attributed carbon represents the sum across all emissions species tracked separately in the ledger system.

Because the accounting period of this study is one month, only one month of carbon flows is recorded in the ledgers. The ledger entries in Figure 4 demonstrate the systematic recording of carbon transfers under the FOD framework. Corresponding mirror transactions appear on each supplier's ledger from their perspective. Each purchase generates distinct entries in the steel producer's ledger that maintain carbon accounting integrity:

- **Carbon content transferred in:** The monthly physical carbon atoms embedded in each purchase of materials (34,869 tC for natural gas, 163,344 tC for coal, 9,680 tC for scrap steel, and 4,840 tC for limestone) are recorded to respective stock accounts and to the Carbon Content Transferred In account.
- **Emissions transferred in:** The attributed emissions associated with each material are recorded separately for CO_2, CH_4, and combined CO & VOCs to respective stock accounts and to the Attributed Emissions Transferred In account.

The balanced ledger entries ensure complete carbon accountability across the steel production system—every carbon transaction is mass-balanced, with the balance of stocks accounts equaling the balance of flows accounts. Individual emissions species are tracked separately, providing detailed visibility into the carbon profile of each upstream feedstock, including iron ore, metallurgical coal, limestone, natural gas, and electricity.

The total annual attributed upstream emissions represent the cradle-to-gate emissions inherited from material extraction, processing, and transport. Separately, the system receives 212,734 tC of physical carbon content embedded in incoming materials for one month. This physical carbon mass serves as an important cross-check on model integrity, providing a benchmark for validating that carbon inputs, outputs, and emissions are internally consistent across the entire production system. It ensures that the ledger tracks not only emitted carbon, but also carbon retained in products or transferred through byproducts—reinforcing the accuracy and transparency of the carbon accounting framework.

Figure 4. **LEDGER TRANSACTIONS: PURCHASE PRODUCTION INPUTS, TON OF CARBON**

	STOCKS						FLOWS ACCOUNTS		
	Carbon in production inputs						Carbon transferred in		
Transaction	**Carbon content in raw materials**	**Attrib. emissions to raw materials**	**Carbon content in fuels**	**Attrib. emissions to fuels**	**Attrib. emissions to electricity**	**Stocks total**	**Carbon content**	**Attrib. emissions**	**Flows total**
Purchase iron ore from supplier		1,419				**1,419**		1,419	**1,419**
Purchase coal from supplier			40,836	1,537		**42,373**	40,836	1,537	**42,373**
Purchase limestone from supplier	4,840	31				**4,871**	4,840	31	**4,871**
Purchase natural gas from supplier			34,869	3,027		**37,896**	34,869	3,027	**37,896**
Purchase electricity from supplier					22,809	**22,809**		22,809	**22,809**
Purchase scrap steel from supplier	4,840	41				**4,881**	4,840	41	**4,881**
Purchase iron ore from supplier		1,419				**1,419**		1,419	**1,419**
Purchase coal from supplier			40,836	1,537		**42,373**	40,836	1,537	**42,373**
Purchase iron ore from supplier		1,419				**1,419**		1,419	**1,419**
Purchase scrap steel from supplier			40,836	1,537		**42,373**	40,836	1,537	**42,373**
Purchase scrap steel from supplier	4,840	41				**4,881**	4,840	41	**4,881**
Purchase iron ore from supplier		1,419				**1,419**		1,419	**1,419**
Purchase coal from supplier			40,836	1,537		**42,373**	40,836	1,537	**42,373**

Note: This table is simplified for presentation. In the full ledger, each carbon stream is recorded by species (CO_2, CH_4, CO, and VOCs) using double-entry bookkeeping, with debits and credits. Source: EFI Foundation and Sesame Sustainability.

Recording Steel Production and Allocation

The steel producer operates as the central transformation point in the supply chain, converting upstream feedstocks into finished steel products while maintaining complete carbon accountability through parallel tracking of emissions by species and physical carbon content. The facility receives 212,734 tC of physical carbon content per month (mo)—representing the total carbon atoms contained in incoming feedstocks such as iron ore, metallurgical coal, limestone, natural gas, and electricity—along with attributed emissions by species from upstream suppliers, including CO_2 (36,604 tC/mo), CH_4 (977 tC/mo), and CO & VOCs (188 tC/mo). These upstream emissions reflect cradle-to-gate values for extraction, processing, and transport of each input, consistent with GREET and other source-specific datasets.

The BF-BOF steelmaking process generates direct emissions of 89,003 tC/mo of CO_2, largely from coke combustion in the blast furnace, decarburization reactions in the BOF, and supplemental fuel combustion for heat and power. These direct emissions are combined with upstream attributed emissions to form the total emissions inventory available for allocation across steel products and byproducts.

The facility produces three primary output streams with annual production levels:

- 5 million tons of crude steel per year.
- 271,178 tons of slag per year.
- 347,964 tons of ash per year.

The physical carbon content of each output is calculated based on the molecular composition and process-specific retention rates. Although steel contains only ~0.05-0.1% carbon by mass, this physical carbon is important to track for mass balance closure and potential downstream accounting. The difference between input physical carbon (212,734 tC) and output carbon retained in products (833 tC) represents carbon emitted during combustion and metallurgical conversion. The ledger ensures full conservation of carbon atoms, attributing all transformations from feedstocks to emissions or final products without duplication or loss.

The ledger-based system tracks each carbon species (CO_2, CH_4, CO, VOCs) individually, allocating emissions using a mass-based allocation methodology aligned with the total output mass of steel. Each species is assigned to product outputs separately, maintaining transparency across all flow stages.

Carbon Capture Treatment in the Ledger

Carbon capture is integrated into the ledger through a two-step accounting sequence that preserves full transparency of gross emissions, captured volumes, and net emissions attributable to steel products. First, the system records the full gross monthly emissions from BF-BOF operations of 202,813.9 tC across all species, reflecting the total carbon released before any abatement. The facility then captures 126,455.5 tC of CO_2, which is logged as a distinct negative flow associated with the capture unit. This captured CO_2 is subsequently conditioned, compressed, and transferred to long-term sequestration, with a corresponding ledger entry documenting removal from the steel producer's operational boundary. The net emissions, calculated as the difference between gross emissions and captured CO_2 (i.e., 76,358.4 tC), represent the emissions for allocation. All downstream product-level allocations are based on these net emissions rather than gross values, ensuring that the carbon intensity of steel accurately reflects the effects of carbon capture while maintaining atom-level mass balance and auditable traceability.

Figures 5 (below) and 6 (next page) present the detailed transaction log:

- Carbon content and attributed emissions are first moved from Carbon in Production Inputs accounts to work-in-process (WIP) accounts when raw materials enter production.
- Direct emissions occur, and a portion of these emissions is captured and transferred outside the entity's boundary for sequestration. Once sequestration is completed, emissions associated with transport and the sequestration process are accounted for and adjusted accordingly.
- Upon completion of processing and transfer to inventory, emissions are allocated from WIP to final steel and byproduct accounts.
- Upon the sale of products, the carbon associated with those products is transferred to customers.

Figure 5. **LEDGER TRANSACTIONS: PRODUCTION, DIRECT EMISSIONS, CCS, AND ALLOCATION, TON OF CARBON**

	STOCKS ACCOUNTS															FLOWS ACCOUNTS	
	Carbon in PPE	Carbon in production inputs					Carbon in production inputs			Carbon in product inventory							
Transaction	Depr.	Carbon content in raw materials	Attrib. emissions to raw materials	Carbon content in fuels	Attrib. emissions to fuels	Attrib. emissions to electricity	Carbon content in WIP	Attrib. emissions in WIP	Direct emissions in WIP	Carbon content in products	Attrib. emissions to products	Depr. allocated to products	Direct emissions to products	Carbon content in byproducts	Stocks total	Carbon transferred out; Emissions for sequestration	Flows total
Transfer raw materials to production			(5,788)		(9,173)	(22,809)		37,769							-		-
Direct emissions from production		(14,520)		(198,214)			9,920		202,814						-		-
Direct emissions captured and sequestered									(126,456)						**(126,456)**	(126,456)	**(126,456)**
Direct emissions from CCS process									12,646						**12,646**	12,646	**12,646**
Transfer carbon in WIP to products							(833)	(37,769)	(89,004)	833	37,769		89,004		-		-
Allocated depreciation of PPE to products	(120)											120			-		-
Transfer carbon content from WIP to byproducts							(9,087)							9,087	-		-

Note: This table is simplified for presentation. In the full ledger, each carbon stream is recorded by species (CO_2, CH_4, CO, and VOCs) using double-entry bookkeeping, with debits and credits. Source: EFI Foundation and Sesame Sustainability.

Figure 6. **LEDGER TRANSACTIONS: TRANSFER CARBON TO CUSTOMERS WITH PRODUCTS SOLD, TON OF CARBON**

	STOCKS ACCOUNTS						FLOWS ACCOUNTS			
	Carbon in production inputs	Carbon in product inventory					Carbon transferred in		Carbon transferred out	
Transaction	Attrib. emissions to PPE	Carbon content in products	Attrib. emissions to products	Depr. allocated to products	Direct emissions to products	Stocks total	Attrib. emissions	Carbon content transferred out with products sold	Emissions transferred out with products sold	Flows total
Transfer carbon in products to customers with products sold		(833)	(37,769)	(120)	(89,004)	**(127,727)**		(833)	(126,893)	**(127,727)**
Direct emissions from product transport	566					**566**	566			**566**
Transfer transport emissions to customers	(566)					**(566)**			(566)	**(566)**

Note: This table is simplified for presentation. In the full ledger, each carbon stream is recorded by species (CO_2, CH_4, CO, and VOCs) using double-entry bookkeeping, with debits and credits. Source: EFI Foundation and Sesame Sustainability.

Table 5 summarizes the allocation of carbon content and emissions to steel products and two byproducts. This allocation methodology presumes that steel is the primary marketed product of the integrated BF-BOF steelmaking system and therefore assigns all upstream and direct emissions exclusively to the steel output. The rationale is that byproducts such as slag and ash are generally reused internally or sold at relatively negligible value compared to the steel product. In those instances where byproducts are commercially sold (for example, slag used in cement manufacture or as road base aggregate), a mass-based allocation could be applied to distribute emissions proportionally among outputs. This is appropriate given that the steel product is defined by weight rather than energy content, and energy-based allocation would not reflect functional reality.

Table 5. **SUMMARY OF ALLOCATION OF ANNUAL CARBON CONTENT AND EMISSIONS TO PRODUCTS**

Product	Production	Mass allocation share	Total allocated emissions *(tC)*	Physical carbon content *(tC)*
Steel	5M tons	89%	89,003	833
Slag	271k tons	5%	0	4,130
Ash	348k tons	6%	0	4,956
Total	**–**	**100%**	**89,003**	**9,919**

Note: In cases where slag or ash is sold for secondary use (e.g., in cement), emissions can be allocated proportionally by mass or market value. This case study assumes 100% allocation to steel for simplicity. Source: Sesame Sustainability.

Transportation emissions incurred during delivery from the steel facility to downstream customers (e.g., fabricators or construction sites) are tracked at the time of shipment and added to the steel product's cradle-to-gate profile, ensuring full accountability for both cost and carbon through the point of delivery. This approach preserves transparency and traceability across the supply chain while aligning with ISO and environmental product declaration (EPD) carbon reporting standards.

Accounting for Plant, Property, and Equipment Emissions

Emissions associated with the construction and installation of plant, property, and equipment (PPE) are incorporated into the ledger through a structured amortization approach that aligns with the assumed 50-year operational lifetime of the steelmaking facility. The total embodied emissions from construction materials, machinery, and supporting infrastructure are first recorded as a one-time capitalized carbon entry in the ledger. These emissions are then amortized evenly across all months of the 50-year period, generating a monthly PPE-emissions allocation that reflects the portion of embodied carbon attributable to each month's production. This monthly amount is added to the facility's emissions inventory and allocated to steel products in the same manner as operational emissions. The remaining unallocated PPE emissions are maintained as a ledger balance that decreases each month until the full embodied carbon has been distributed, ensuring transparent, time-consistent treatment of capital-related emissions in product carbon intensities.

Ending Ledger of Carbon Stocks and Flows

Figure 7 summarizes the balance of carbon stocks and flows in the steel producer's ledger at the end of one month of operation.

Figure 7. **STEEL PRODUCER'S MONTHLY SUMMARY OF ACCOUNT BALANCES**

Steel Producer
Summary of Account Balances as of End of January 2025

Carbon stock (ton of carbon)		**Carbon flow** (ton of carbon)	
Carbon in plant, property, and equipment		**Carbon transferred in**	
Attributed emissions in PPE	72,626	Attributed emissions transferred in	116,928
Depreciation	(29,170)	Carbon content transferred in	301,666
Carbon in raw materials inventory		**Carbon transferred out**	
Attributed emissions in raw materials	2,894	Emissions transferred out with product sold	(156,510)
Carbon content in raw materials	7,260	Carbon content transferred out with product sold	(833)
Carbon in fuels inventory			
Attributed emissions in fuels	3,073		
Carbon content in fuels	81,672		
Carbon in product inventory		**Carbon abatement**	
Emissions in product	–	Carbon transferred out for sequestrations	(113,810)
Carbon content in product	–		
Carbon in byproduct			
Carbon content in byproduct	9,087		
Total emissions	**49,423**	**Total emissions flow**	**(39,581)**
Total carbon content	**98,019**	**Total carbon content flow**	**300,833**
		Total abatement flow	**(113,810)**
Total carbon stock	**147,442**	**Total carbon flow**	**147,442**

Note: The statement provides a complete view of the steel producer's carbon balance, detailing carbon stock held within the entity's boundaries and carbon flows—carbon entering and leaving the company through material purchases and product sales. Source: Sesame Sustainability.

The cumulative impact of the transactions described above is captured in the ledger of carbon stocks and flows at the end of the reporting period. The ending ledger presents a complete carbon balance for the steelmaking facility, detailing both the carbon stock retained within the entity's boundaries (e.g., in unsold steel, work-in-process, raw materials and fuel inventories) and the carbon flows—including carbon entering the system via raw materials and fuel inputs and carbon leaving through sold steel products and emissions.

For this monthly reporting period, the ledger tracks carbon coming from inputs, which is then transformed through BF-BOF process operations. The final ledger entries illustrate the completeness and transparency of the ledger-based accounting system, demonstrating how incoming carbon is conserved and reallocated without loss or double counting. For example, the physical carbon content embedded in finished steel inventory reflects unshipped material still within the facility boundary, while process emissions and carbon exported via products are fully accounted for across outbound flows.

In addition, any attributed upstream emissions (from electricity, natural gas, or mining operations) are appropriately carried forward and allocated to steel outputs. In cases where co-products like slag are unsold, emissions are not allocated to them. However, if such byproducts are commercialized, a mass-based allocation could be applied.

Drawing from these ledger balances, the steel producer is equipped to issue both product-level and entity-level carbon accounting statements, as shown in Figures 8 and 9 (next page), including:

- A Product Carbon Emissions Intensity Statement.
- An Entity-Level Carbon Emissions Statement.

Figure 8. **STEEL PRODUCER'S PRODUCT CARBON EMISSIONS INTENSITY STATEMENT FOR ONE MONTH OF OPERATION**

Steel Producer
Product Carbon Emissions Intensity Statement
January 2025

Steel	CO_2 intensity *($kgCO_2/kg$)*	CH_4 intensity *(gCH_4/kg)*
Emissions from raw material production and transport	0.05	0.00
Emissions from electricity use	0.20	0.96
Emissions from fuel combustion	1.78	0.00
Emissions abated via CCS	(1.00)	0.00
Emissions from fuel production and transport	0.07	7.64
Emissions from production of equipment used	0.001	0.006
Emissions from transport of products	0.005	0.017
Emissions offsets used	0.00	0.01
Product carbon emissions intensity in steel	**1.11**	**8.63**

Note: The statement shows product carbon emissions intensity by species compiled directly from ledger account balances and calculated per tons of steel sold.
Source: Sesame Sustainability.

The Product Carbon Emissions Intensity Statement demonstrates how the ledger-based carbon accounting system delivers detailed, product-level emissions data by species. For steel produced via the BF-BOF pathway, the carbon intensity values for January 2025 are as follows:

- CO_2 intensity: 1.11 $kgCO_2$ per kg of steel.
- CH_4 intensity: 8.63 gCH_4 per kg of steel.

These values are derived from the aggregation of emissions across all relevant source categories in Figure 8.

This breakdown provides both cradle-to-gate transparency and species-level resolution, allowing stakeholders to understand not only the total carbon burden but also its composition—highlighting, for example, the high contribution of fuel-related CH_4 emissions and the impact of carbon capture on reducing net CO_2 intensity.

These figures support decarbonization planning, carbon disclosure, and supply chain transparency in the steel sector. They are directly generated from the ledger-based accounting system and align with emerging requirements for product-level environmental declarations (e.g., EPDs) and regulatory frameworks.

Figure 9. **STEEL PRODUCER'S ENTITY-LEVEL CARBON EMISSIONS STATEMENT FOR ONE MONTH OF OPERATION**

Steel Producer
Entity-Level Carbon Emissions Intensity Statement
January 2025

Direct emissions	tCO_2	tCH_4
Gross direct emissions	742,908	
CCS abatement, net	(416,886)	
Total direct emissions, net	*326,022*	
Attributed emissions		
Emissions attributed to purchased electricity	83,073	145
Emissions attributed to purchased machinery	-	-
Emissions attributed to purchased raw materials	21,040	-
Emissions attributed to purchased fuels	29,968	1,158
Total attributed emissions	*134,080*	*1,304*
Total carbon emissions	**460,102**	**1,304**
Net total carbon emissions	**460,102**	**1,304**

Note: The statement shows direct facility emissions and attributed upstream emissions by species, with CO and VOCs excluded for presentation clarity as these species are typically immaterial in the modeled pathways. Source: Sesame Sustainability.

Beyond these two statements, the steel producer can generate various reports for policy commitments, sustainability disclosures, or internal carbon management. With this information, the steel producer can report the carbon intensity of any product and any scope of entity-level emissions, including direct emissions, upstream indirect emissions, and even downstream indirect emissions estimated from carbon content data.

Customers' Ledgers Records and Reporting

The two customers receive the finished steel product from the integrated BF-BOF facility, with the product carrying its full cradle-to-gate carbon profile—including physical carbon content and attributed emissions by species (e.g., CO_2, CH_4) from upstream and production operations. These emissions are transferred at the point of delivery, consistent with free on delivery terms, which ensure that transportation emissions incurred during delivery are retained by the steel producer until the steel reaches the customer.

The product-level accounting enables clear traceability and transfer of carbon responsibility. Upon receipt, the entire cradle-to-gate emissions profile becomes part of the customers' carbon ledger. Since steel is not combusted during use, all embedded and attributed emissions remain with the product throughout its service life.

The steel producer's ledger ensures a complete record of carbon flows up to the point of delivery, with balanced entries by species that account for:

- Emissions from raw material extraction, energy use, and production operations.
- Carbon capture and storage (CCS) activities.
- Transport emissions incurred by the producer.
- Any residual physical carbon embedded in the steel.

This ledger-based carbon accounting framework provides the transparency and auditability needed for downstream stakeholders to integrate steel-related emissions into whole-building life cycle assessments, environmental product declarations, or compliance reporting under green building standards.

The resulting cradle-to-gate CO_2 intensity of the steel product—derived from the full ledger and accounting framework—is 1.11 kgCO_2 per kg of steel, with a CH_4 intensity of 8.63 gCH_4 per kg, as shown in the accompanying Product Carbon Emissions Intensity Statement.

VI. Summary and Discussion

This case study demonstrates the practical application of a ledger-based carbon accounting system for an integrated BF-BOF steelmaking facility. The system ensures transparency, accuracy, and verifiability by implementing key principles: clear transfer of custody at delivery points, mass and energy balance closure, and allocation of emissions by species using consistent rules. Unlike traditional accounting methods that commonly rely on generic emissions factors or industry averages, the ledger-based approach produces a traceable, auditable record of actual carbon flows, enabling credible product-level differentiation and more robust climate strategies.

The case study illustrates how carbon ledgers provide the foundation for establishing product carbon intensities. In this analysis, the ledger enables the steel producer to report a cradle-to-gate baseline product carbon intensity of:

- 1.11 kgCO_2 per kg of steel (cradle to gate).
- 8.63 gCH_4 per kg of steel (cradle to gate).

These baselines allow companies to establish emissions targets, design abatement strategies (e.g., through CCS or process electrification), and track reductions over time through regular reporting. Buyers of steel products—particularly those in sectors with embodied carbon requirements like construction or automotive—can use such data to evaluate supplier performance, develop procurement standards, and set their own emissions reduction roadmaps. Policymakers can leverage product carbon intensity baselines to establish relevant policies such as incentivizing low-carbon procurement or integrate these metrics into regulatory frameworks such as clean product standards, green building codes, or public infrastructure bids. Because the ledger system mirrors the structure of financial accounting, compliance monitoring becomes more transparent and less administratively burdensome.

More broadly, this study demonstrates that ledger-based accounting provides a complete record of total emissions, with no gaps in coverage, along with complete and transparent allocation of CO_2 emissions among products. The ability to record CO_2 emissions only once and transfer the CO_2 emissions from the ledgers of the suppliers to the steel producer and ultimately to the customer avoids inadvertent double counting of CO_2 emissions. It also includes built-in error checking to support accuracy and provides a complete and transparent record to facilitate third-party verification to ensure completeness of the report and protect against gaps or errors in the allocation of entity-level CO_2 emissions among individual products.

Appendix

Summary of Transactions in Format Derived from E-ledgers Organization of Assets and Liabilities: CO_2 Emissions Ledger With Single-Entry Bookkeeping

The E-ledgers accounting system is organized on the basis of assets and liabilities, as compared to the stocks and flows organization discussed above. In the E-ledgers system, carbon removals are recorded as assets, and all transactions affecting CO_2 emissions are recorded as liabilities. The system includes double-entry bookkeeping of transfers from one ledger to another across a supply chain, with single-entry bookkeeping of transactions within each entity's ledger. The ledger does not include data on carbon content of materials, fuels, or products.

A summary of the steel production case study's entity-level transactions, in the format of assets and liabilities derived from E-ledger concepts,[23] is shown in Table A1. The ledger shows a net total of 460,538 tons of CO_2 emissions allocated to the steel product. After adjustment of CO_2 emissions from product transportation, a net total of 222,510 tons of CO_2 emissions are transferred from the steel producer's ledger to the construction company's ledger, and a net total of 240,089 tons of CO_2 emissions are transferred from the steel producer's ledger to the manufacturer's ledger.

Table A1. **SUMMARY OF TRANSACTIONS IN FORMAT DERIVED FROM E-LEDGERS ORGANIZATION OF ASSETS AND LIABILITIES: CO_2 EMISSIONS LEDGER WITH SINGLE-ENTRY BOOKKEEPING**

a) Steel producer ledger transactions in E-ledger format

Transfer of raw materials and energy inputs

CO_2 emissions assets *(tCO_2)*		**CO_2 emissions liabilities** *(tCO_2)*	
Beginning balance	0	Beginning balance (A)	177,357
		Attributed CO_2 emissions to iron ore supply	20,630
		Attributed CO_2 emissions to coal supply	19,650
		Attributed CO_2 emissions to limestone supply	112
		Attributed CO_2 emissions to natural gas supply	10,317
		Attributed CO_2 emissions to scrap steel supply	297
		Attributed CO_2 emissions to electricity supply	83,073
		Subtotal (B)	**134,079**
		Net CO_2 balance (A+B)	**311,436**

Steel production

CO_2 emissions assets *(tCO_2)*		CO_2 emissions liabilities *(tCO_2)*	
Beginning balance	0	Beginning balance (A)	177,357
		Attributed CO_2 emissions to iron ore supply	20,630
		Attributed CO_2 emissions to coal supply	19,650
		Attributed CO_2 emissions to limestone supply	112
		Attributed CO_2 emissions to natural gas supply	10,317
		Attributed CO_2 emissions to scrap steel supply	297
		Attributed CO_2 emissions to electricity supply	83,073
		Direct gross CO_2 emissions	742,908
		CO_2 abatement	(416,886)
		Depreciation (monthly share of emissions attributed to PPE)	436
		Depreciation allocated to products	(436)
		Subtotal (B)	**460,101**
		Steel product allocation factor	100%
		Net CO_2 allocated to steel inventory*	460,538
		Share of steel sold to construction company	48.1%
		Net CO_2 allocated to steel sold to construction company	221,518
		CO_2 emissions transporting steel to construction company (C)	992
		Net CO_2 transferred to construction company (D)	(222,510)
		Share of steel sold to manufacturer	51.9%
		Net CO_2 allocated to steel sold to manufacturer	239,019
		CO_2 emissions transporting steel to manufacturer (E)	1,070
		Net CO_2 transferred to manufacturer (F)	(240,089)
		CO_2 emissions liabilities balance (A+B+C+D+E+F)	**176,921**

* CO_2 emissions allocated to steel inventory include direct emissions, attributed emissions, and the monthly share of depreciation allocated to products.

b) Customers' ledger transactions in E-Ledger format

Transfer of steel products to construction company

CO_2 emissions assets *(tCO_2)*		**CO_2 emissions liabilities** *(tCO_2)*	
		Attributed CO_2 emissions to steel transferred in	222,510
		Subtotal	**222,510**

Transfer of steel products to manufacturer

CO_2 emissions assets *(tCO_2)*		**CO_2 emissions liabilities** *(tCO_2)*	
		Attributed CO2 emissions to steel transferred in	240,089
		Subtotal	**240,089**

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