EFI FOUNDATION

Integrated Product- and Entity-Level

CARBON ACCOUNTING

CASE STUDY

Steel Production Using Hydrogen Direct Reduced Iron–Electric Arc Furnace (H_2-DRI-EAF)

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This case studywas supported by a combination of unrestricted grant funds provided to the EFI Foundation as well as project-specific funding from ExxonMobil, Nucor, and Toyota Research Institute. The EFI Foundation thanks all the funding entities for sponsoring this work. The EFI Foundation is solely responsible for the final content of this report.

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EFI Foundation, *Integrated Product- and Entity-Level Carbon Accounting Case Study: Steel Production Using Hydrogen Direct Reduced Iron–Electric Arc Furnace (H_2-DRI-EAF)*, April 2026.

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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 fourth in a series of case studies that illustrate how an integrated product- and entity-level carbon accounting system can be put into practice. This case study focuses on an illustrative hypothetical steel production facility in the U.S. Midwest that uses direct reduced iron (DRI) and an electric arc furnace (EAF). In this scenario, over one month, a steel producer manufactures steel with the product carbon dioxide (CO_2) intensity (cradle-to-gate) of 0.3 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. 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:

- Uses 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, for example, 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.[1,2,3,4,5,6]

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, each case study 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 (e.g., 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 case study uses an illustrative steel supply chain based on a facility in the U.S. Midwest. A steel producer manufactures steel products using iron ore, limestone, scrap steel, coal, natural gas and electricity, and supplies the products 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. The study produces detailed mass and energy balances for the steel producer's 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. At the integrated steelmaking facility, natural gas, iron ore, electricity, and oxygen are converted into high-grade steel products through a three-stage system: blue hydrogen production, hydrogen direct reduction, and electric arc furnace melting. 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 that time, the steel producer manufactures 416,000 tons of steel by using 137,000 tons of iron ore, 4,500 tons of coal, 24,000 tons of limestone, 1,161 million cubic feet (MMcf) of natural gas, 333,100 tons of scrap steel, and 109 gigawatt-hours (GWh) of electricity.

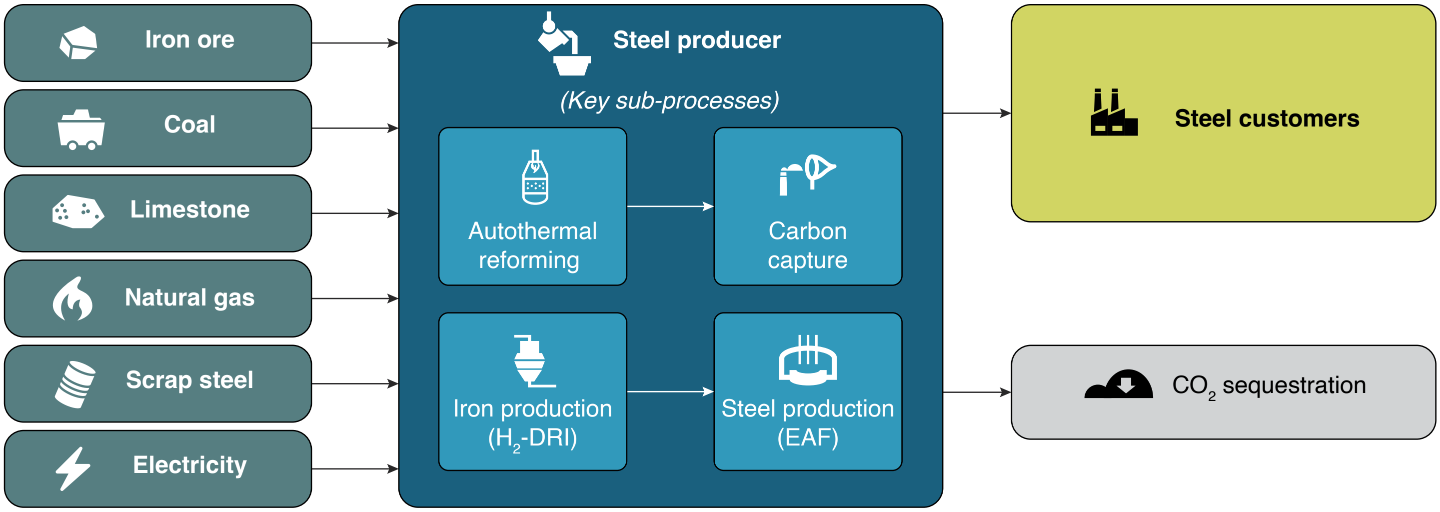
Case Study Results

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

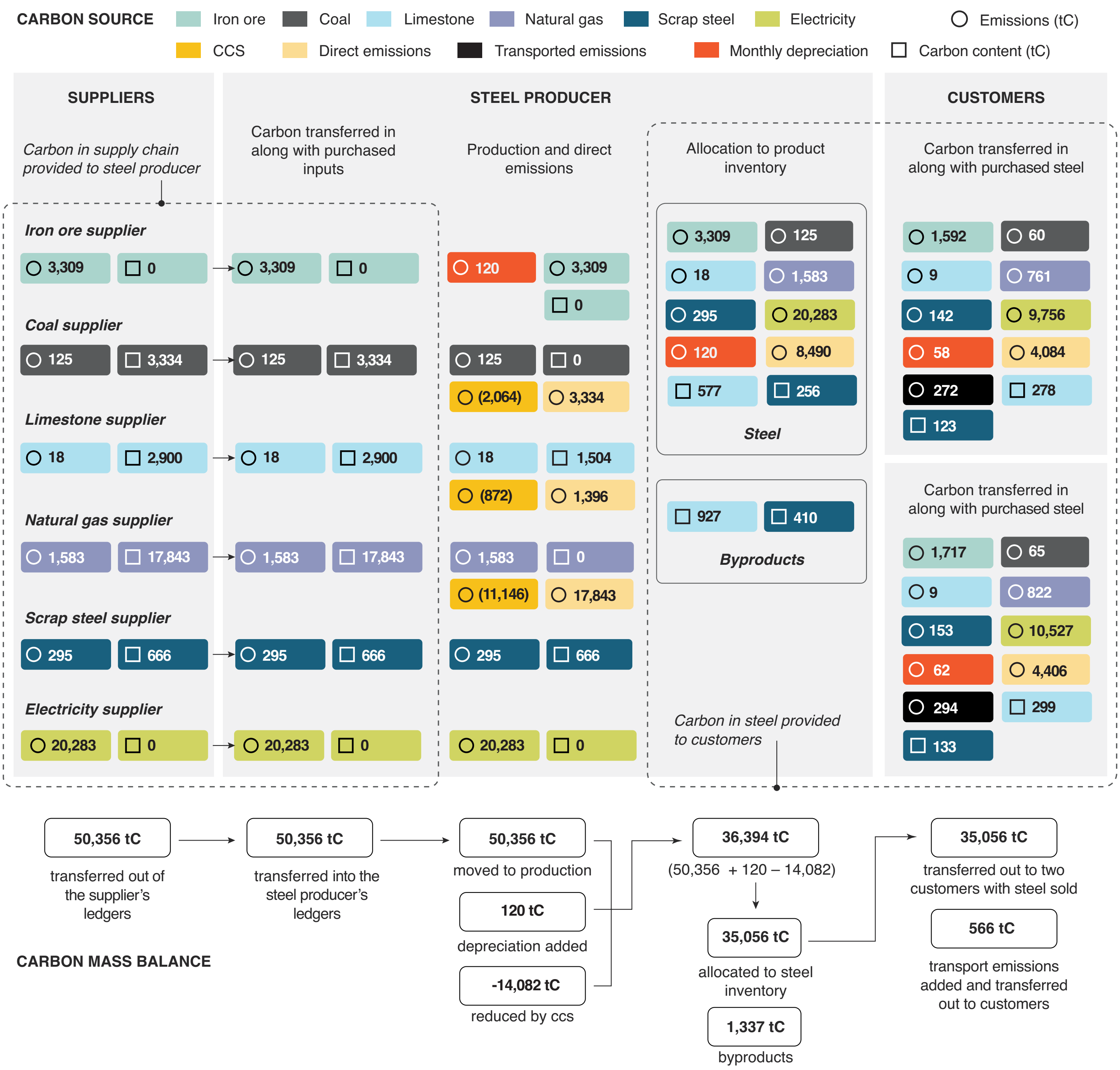
The process flow diagram, the mass and energy balances, and the resulting carbon flows are illustrated in Figures ES-1 and ES-2, respectively. Figure ES-1 illustrates the basic steps in the production of steel. Figure ES-2 focuses in detail on the steel production process. It presents the mass balance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

Figure ES-2 shows the entire mass balance of carbon content and CO_2 emissions (expressed in terms of 50,356 tons of carbon) flowing through the steel production during a one-month accounting period. Carbon transferred in from suppliers is either captured during production, retained within the steel producer's boundary as carbon in byproducts, or transferred out with sold steel products. The sum of these carbon flows exactly matches the initial 50,356 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 based on 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 ISO 14044:2006.[7,a] Under the International Organization for Standardization (ISO) system expansion methodology, slag is not assigned a share of the steelmaking emissions; instead, the life cycle system receives credits for the emissions avoided when slag displaces clinker in cement production. This study does not assume the reuse or sales of slag. Ash is treated as a residual waste stream and therefore is not assigned attributed emissions. Although byproducts do not receive any emissions allocation, their carbon content is reflected in the mass balance. Figure ES-2 shows that 1,337 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). 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 in a 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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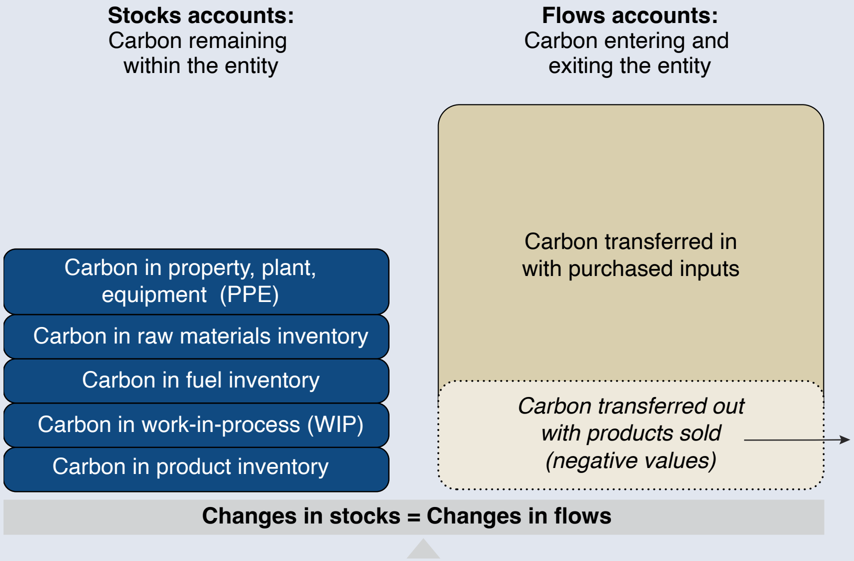
[a] ISO 14044:2006 is an international standard that establishes requirements and guidelines for conducting life cycle assessments.

Box ES-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 one for 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 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.

Table ES-1. RECORDS OF THE STEEL PRODUCER'S CARBON LEDGER, ONE MONTH OF OPERATION, TONS 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**	**Sequestered emissions**	**Carbon content with products sold**	**Emissions with products sold**	**Flows total**
Beginning balance	**43,575**	**1,783**	**1,811**	**1,667**	**62**	-	-	-	-	-	-	-	-	-	**48,899**	**3,450**	**74,499**	-	-	**(29,050)**	**48,899**
Purchase iron ore from supplier			3,309												**3,309**		3,309				**3,309**
Purchase coal from supplier				3,334	125										**3,459**	3,334	125				**3,459**
Purchase limestone from supplier		2,900	18												**2,918**	2,900	18				**2,918**
Purchase natural gas from supplier				17,843	1,583										**19,426**	17,843	1,583				**19,426**
Purchase electricity from supplier						20,283									**20,283**		20,283				**20,283**
Purchase scrap steel from supplier		666	295												**961**	666	295				**961**
Transfer raw materials to production			(3,622)		(1,708)	(20,283)		25,613							-						-
Direct emissions from production		(3,566)		(21,177)			2,171		22,572						-						-
Direct emissions captured and sequestered									(15,647)						**(15,647)**			(15,647)			**(15,647)**
Direct emissions from CCS process									1,565						**1,565**			1,565			**1,565**
Transfer carbon in WIP to products							(833)	(25,613)	(8,490)	833	25,613		8,490		-						-
Allocate depreciation of PPE to products	(120)											120			-						-
Transfer carbon content from WIP to byproducts							(1,337)							1,337	-						-
Transfer carbon in products to customers with products sold										(833)	(25,613)	(120)	(8,490)		**(35,056)**				(833)	(34,223)	**(35,056)**
Direct emissions from product transport					566										**566**		566				**566**
Transfer transport emissions to customers					(566)										**(566)**					(566)	**(566)**
Ending balance	**43,456**	**1,783**	**1,811**	**1,667**	**62**	-	-	-	-	-	-	-	-	**1,337**	**50,116**	**28,193**	**100,678**	**(14,082)**	**(833)**	**(63,839)**	**50,116**

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.

Source: EFI Foundation and Sesame Sustainability.

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 completeness and accuracy:

- **Beginning balances:** The total of 48,899 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 the initial inventory of two weeks of raw material and coal inventories. The estimated 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.

- **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, 50,356 tC enter the steel producer's ledger via purchased inputs: 3,309 tC from iron ore, 3,459 tC from coal, 2,918 tC from limestone, 19,426 tC from natural gas, 20,283 tC from electricity, and 961 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, 22,575 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 (15,647 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 Sequestered Emissions Transferred Out account. Once sequestration is complete, emissions from transport and sequestration processes (1,565 tC) are adjusted accordingly.

- **Allocation of entity emissions to products:** Upon completion of production, attributed emissions (25,613 tC) and net direct emissions (8,490 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 (35,056 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 inventory. 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.[8,9] For example, the proposed E-ledgers accounting framework, noted in other papers, is organized based on 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 applicable 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, along with a disaggregation of that total among attributed CO_2 emissions from the supply chain, direct CO_2 emissions from production of final products, and 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	
Direct, entity-specific CO_2 emissions	0.20 $kgCO_2/kg$
CO_2 emissions abated via CCS	(0.12) $kgCO_2/kg$
Attributed CO_2 emissions from suppliers	
Raw materials	0.03 $kgCO_2/kg$
Energy (fuels and electricity)	0.19 $kgCO_2/kg$
Plant, property, and equipment	0.001 $kgCO_2/kg$
CO_2 emissions from transporting final products	**0.005 $kgCO_2/kg$**
Total product CO_2 emissions intensity in steel	**0.3 $kgCO_2/kg$**

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 based upon the ability to verify product carbon intensity. For the steel producer, the product CO_2 emissions intensity provides a key performance indicator (KPI) to identify and assess opportunities to reduce the 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).

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

Steel producer
Entity-level CO_2 emissions statement
January 2025

Direct emissions	
Direct, entity-specific CO_2 emissions (gross)	82,682 tCO_2
CO_2 emissions abated via CCS	(51,584) tCO_2
Total direct emissions (net)	*31,098 tCO_2*
Attributed emissions	
Raw materials	13,174 tCO_2
Energy (fuels and electricity)	79,696 tCO_2
Plant, property, and equipment	436 tCO_2
Transporting final products	2,062 tCO_2
Total attributed emissions	*95,368 tCO_2*
Total entity-level CO_2 emissions	**126,466 tCO_2**

Source: Sesame Sustainability.

This sample report provides a complete record of total emissions, with no gaps or duplication in coverage. As 100% of the entity-level emissions are allocated to steel products, the total entity-level CO_2 emissions of 126,466 tCO_2 equal the CO_2 emissions transferred out with the steel products sold. The ability to record CO_2 emissions only once and transfer those emissions from the ledgers of the suppliers to the steel producer and ultimately to the customer avoids any inadvertent double counting of CO_2 emissions. It also provides a complete and transparent audit trail 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.

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

Table ES-4 compares the product carbon emissions intensities of steel produced via the blast furnace-basic oxygen furnace process (BF-BOF) and steel produced via the hydrogen direct reduced iron-electric arc furnace (H_2-DRI-EAF) process. 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 remains 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 (kilogram of CO_2/kilogram of steel)	**H_2-DRI-EAF pathway** (kilogram of CO_2/kilogram of steel)
Direct, entity-specific CO_2 emissions	1.78 $kgCO_2$/kg	0.20 $kgCO_2$/kg
CO_2 emissions abated via CCS	-1.00 $kgCO_2$/kg	-0.12 $kgCO_2$/kg
CO_2 emissions from suppliers		
Raw materials	0.05 $kgCO_2$/kg	0.03 $kgCO_2$/kg
Energy (fuels and electricity)	0.27 $kgCO_2$/kg	0.19 $kgCO_2$/kg
Plant, property, and equipment	0.001 $kgCO_2$/kg	0.001 $kgCO_2$/kg
CO_2 emissions from transporting final products	0.005 $kgCO_2$/kg	0.005 $kgCO_2$/kg
Total product CO_2 emissions intensity in steel	**1.11 $kgCO_2$/kg**	**0.3 $kgCO_2$/kg**

Source: Sesame Sustainability.

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 built around hydrogen-based direct reduced iron and electric arc furnace (H_2-DRI-EAF) steelmaking. The system represents a fundamental shift from current carbon reporting methods by applying established financial accounting principles to achieve rigorous carbon accounting across a multi-entity industrial network.

Steel remains one of the most difficult sectors to decarbonize because of its historical dependence on fossil fuel-intensive production processes. While the conventional blast furnace-basic oxygen furnace (BF-BOF) route relies heavily on coal-derived coke as both the fuel and primary reducing agent, alternative pathways, including hydrogen-based direct reduction paired with electric melting, offer promising routes to substantially lower emissions. In the United States, steelmaking contributes roughly 6%-7% of national industrial greenhouse gas (GHG) emissions.[10,11]

With demand for steel projected to rise steadily through midcentury—driven by infrastructure modernization, electrification, automotive lightweighting, and renewable energy deployment—sector-wide emissions could increase unless cleaner production pathways scale rapidly.

Despite growing interest in low-carbon steel, commercial deployment of hydrogen-based steelmaking remains limited. Several obstacles have slowed adoption: the high capital cost of new DRI and EAF installations; limited access to low-carbon hydrogen; uncertain electricity prices and grid emissions factors; and the lack of a consistent carbon accounting framework that can evaluate the carbon intensity (CI) of emerging steelmaking routes.

Federal policy, including the Inflation Reduction Act (IRA), seeks to accelerate deployment through tax incentives such as the Section 45V hydrogen production credit and expanding clean procurement standards. Yet implementation challenges persist. Differing interpretations of life cycle emissions modeling—for example, whether to apply Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET)[b] or alternative models—create uncertainty in how hydrogen CI should be measured for steel applications.

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[b] GREET is a life cycle analysis to assess the environmental impacts of technologies, fuels, products, and energy systems, developed by Argonne National Laboratory.

Downstream buyers, including automakers, appliance manufacturers, and construction firms, increasingly require transparent and verifiable product-level carbon intensity data to qualify suppliers and justify procurement premiums for near-zero-emissions steel. A standardized, supply chain-wide carbon accounting approach is therefore essential for unlocking market differentiation, aligning incentives, and mobilizing investment in decarbonized steel.

Ledger-based carbon accounting applies the logic of financial accounting—transaction-based, double-entry bookkeeping and verifiable cross-entity balances—to carbon flows. Each carbon ledger records carbon movements by species—carbon dioxide (CO_2), methane (CH_4), carbon monoxide (CO), and volatile organic compounds (VOCs)—and tracks the physical carbon content of materials as a cross-check ensuring mass balance integrity.

Unlike existing GHG inventories, which aggregate emissions by scope and often rely on static emissions factors, the ledger approach requires carbon to be tracked dynamically as it is transferred from upstream suppliers to the producer and ultimately to downstream customers. This creates a continuous, auditable chain of carbon custody across the supply chain.

This case study applies these concepts to a steel supply chain centered on on-site blue hydrogen production (via autothermal natural gas reforming with carbon capture), a hydrogen-based DRI unit, and an EAF steelmaking facility that operates with a charge mix of 80% scrap and 20% DRI. It demonstrates how:

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

By walking through actual ledger entries, emissions transfers, blue hydrogen production flows, direct reduction reactions, electric arc furnace operations, and carbon allocation across outputs, this case study demonstrates how ledger-based carbon accounting enables rigorous, transparent, and interoperable carbon intensity reporting for next-generation low-carbon steelmaking pathways.

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[c] 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.

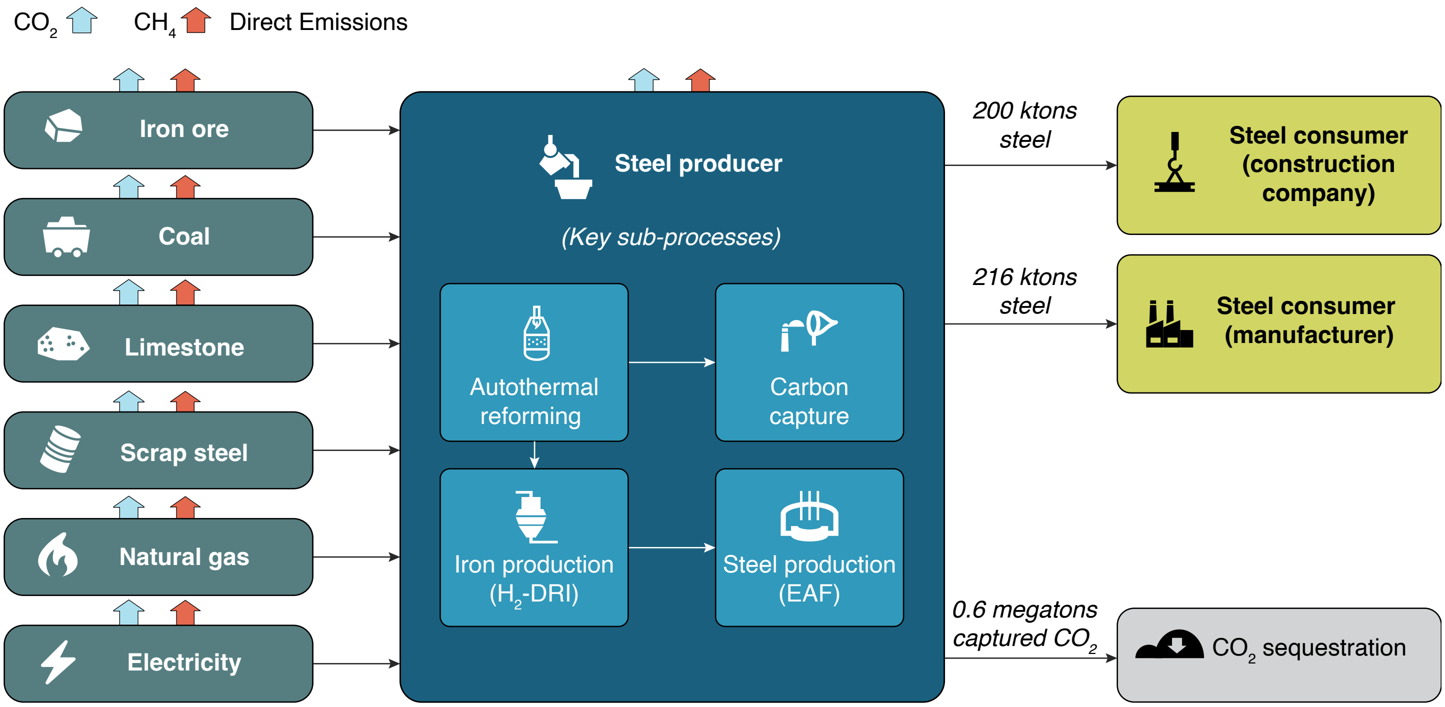
II. Production Pathway Overview and Supply Chain

This case study examines a steel supply chain centered on a hypothetical blue hydrogen-enabled DRI-EAF production facility located in the U.S. Midwest. The site configuration reflects the growing trend toward integrating hydrogen production, direct reduction, and electric steelmaking within a single industrial campus to reduce transportation emissions, streamline operations, and improve overall energy efficiency. Technical parameters, conversion efficiencies, and emissions factors are drawn from authoritative sources including Argonne National Laboratory's GREET model, the U.S. Environmental Protection Agency's eGRID regional electricity data,[12] and peer-reviewed literature on hydrogen-based steelmaking and EAF performance.

The supply chain encompasses multiple upstream entities—iron ore pellet producers, scrap processors, natural gas suppliers, electricity providers, and a regional carbon capture and storage (CCS) operator—and downstream customers in the construction sector. The system demonstrates the flow of carbon emissions and physical materials through a multi-entity network under FOD accounting terms, in which carbon responsibility transfers at each delivery point.

Because supplier-specific product carbon intensity (PCI) data for hydrogen, electricity, pellets, and scrap are not yet widely available at commercial scale, this case study uses literature-based values from widely accepted life cycle assessment (LCA) databases such as GREET, Ecoinvent, and eGRID. In actual implementation, these data will be replaced by supplier-verified emissions information and environmental product declarations.

Figure 1. **KEY ENTITY RELATIONSHIPS FOR INTEGRATED BLUE H_2-DRI-EAF STEEL PRODUCTION**



Source: Sesame Sustainability.

Upstream Supply Chain and Material Inputs

The case study assumes five primary upstream suppliers delivering essential inputs from distinct geographic locations in the Midwest and Great Lakes region (see Figure 1):

- **Iron ore pellet supplier (direct reduction-grade pellets):** DR-grade oxide pellets are sourced from the Mesabi Iron Range in Northern Minnesota, where high-purity magnetite and hematite deposits support pelletizing operations suitable for hydrogen direct reduction. The supplier is assumed to control the full upstream value chain—from mining, crushing, and concentrating to pelletizing and rail loading. Attributed cradle-to-gate emissions include diesel use for mining equipment, natural gas for pellet induration, and rail shipment to the DRI plant.

- **Scrap steel supplier:** Obsolete, shredded, and prime scrap are sourced from regional scrap processors within an approximately 30-mile radius of the steelmaking site. Scrap suppliers report emissions associated with shredding, sorting, shearing, baling, and short-haul trucking. As scrap represents a largely recycled feedstock, physical carbon content is low, but upstream emissions from processing and transport remain relevant in the ledger.

- **Limestone supplier:** Limestone is sourced from Rogers City, Michigan, and transported by water to the steel facility. The supplier reports emissions associated with quarrying, crushing, and barge transport. In the DRI-EAF process, limestone is used as a fluxing agent primarily in the electric arc furnace to remove impurities from the molten steel and direct reduced iron, facilitating slag formation and helping control sulfur and other unwanted elements.

- **Natural gas supplier (for blue hydrogen):** Natural gas is delivered via interstate pipeline from the Williston Basin to the on-site hydrogen production unit, where it serves as the primary feedstock for autothermal reforming (ATR). The natural gas supplier provides cradle-to-gate emissions data covering extraction, processing, compression, transmission, methane leakage, and delivery to the facility boundary.

- **Electricity supplier:** Grid electricity is supplied by a regional utility (e.g., Midcontinent Independent System Operator Zone 4), with a carbon intensity reflecting the projected 2025 generation mix. Electricity is a major contributor to attributed emissions, powering the EAF, compression, and purification systems in the hydrogen plant, blowers and compressors in the DRI shaft furnace, and various auxiliary systems.

Under FOD terms, all upstream suppliers retain responsibility for transport emissions until delivery to the steelmaking site. Rail emissions for pellets, truck emissions for scrap, pipeline emissions for natural gas, and transmission/distribution (T&D) losses for electricity remain on the respective supplier ledgers.

Integrated Blue Hydrogen-DRI-EAF Steelmaking System

At the integrated site, natural gas, iron units, electricity, and oxygen are converted into high-grade steel products through a three-stage system: blue hydrogen production, hydrogen direct reduction, and electric arc furnace melting.

1. Blue Hydrogen Production With Carbon Capture (On-Site ATR + CCS)

Natural gas is reformed to produce hydrogen, with carbon capture. The hydrogen plant receives natural gas and electricity under FOD terms, records upstream attributed emissions by species, and then accounts for:

- CO_2 captured and transferred to the CCS operator.

- CO_2 and CH_4 emitted directly.

- Hydrogen transferred out to the DRI unit.

- Electricity consumption for gas compression, CO_2 purification, and plant auxiliaries.

Captured CO_2 is compressed and transported to a regional geological storage operator, creating a verifiable carbon sink entry in the hydrogen plant's ledger.

2. Hydrogen-Based Direct Reduction (H_2-DRI)

DR-grade pellets are reduced in a shaft furnace using hydrogen as the primary reductant. Hydrogen reacts with oxygen in the iron ore to produce direct reduced iron and water vapor. The process requires no coke or coal, and only negligible natural gas usage for startup or emergency preheating. Upstream emissions from pellets, hydrogen, and electricity are transferred into the DRI entity ledger, while direct emissions are minimal. The DRI output—carrying its aggregated attributed emissions—is transferred to the EAF.

3. Electric Arc Furnace (EAF) With 80% Scrap and 20% DRI Feed

The EAF melts a charge consisting of 80% scrap steel and 20% DRI, using electricity as the main energy input. Small amounts of carbon (such as anthracite or injected carbon), fluxes (e.g., lime, dolomite), and oxygen support refining reactions and slag formation. The EAF ledger accounts for:

- Upstream attributed emissions from scrap, DRI, and electricity.
- Direct emissions from oxidation of injected carbon and electrode consumption.
- Physical carbon content embedded in finished steel.

The EAF's output is crude steel, which is subsequently cast and rolled on-site or at affiliated downstream facilities.

System Boundaries and Accounting Entity Structure

The carbon accounting framework treats each major participant in the steel supply chain as a distinct accounting entity with defined responsibilities. These entities include:

- Iron ore pellet supplier.
- Scrap steel supplier.
- Natural gas supplier.
- Electricity supplier.
- Coal supplier.
- Limestone supplier.
- Steel producer: on-site hydrogen production unit, H_2-DRI plant, and EAF.

- Carbon capture and storage operator.
- Construction customer.

Under FOD terms, each entity retains responsibility for all emissions—including transport-related emissions—until its product crosses the facility boundary of the receiving entity. Upon delivery, the receiving entity inherits:

- Physical carbon content (if any).
- Attributed cradle-to-gate emissions by species (CO_2, CH_4, CO, VOCs).

The steel producer's ledger aggregates all upstream and gate-to-gate emissions and allocates them to outputs using a mass-based approach. Since steel is the only valuable product, all emissions are allocated to the steel products for this case study.

Steel Distribution and End Use

Finished steel products—hot-rolled, cold-rolled, or galvanized—are sold to two customers under FOD terms. Downstream logistics from the steel facility to construction sites are owned by the construction firm. Upon delivery, the customer also receives:

- The full cradle-to-gate carbon intensity of the steel product.
- The physical carbon content embedded in the steel.
- Disaggregated carbon emissions by species.

These data support embodied carbon accounting in buildings, infrastructure projects, and procurement programs. While downstream fabrication and installation processes (e.g., cutting, welding, assembly) generate additional carbon flows, they are outside the boundary of this case study but could be incorporated in future extensions of the ledger-based framework.

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 analytical framework. The platform connects plant-level operational data with comprehensive databases and first-principles engineering models, enabling consistent evaluation of technical, economic, and regulatory dimensions of decarbonization strategies across heavy industry. In the context of hydrogen-based steelmaking, Sesame One provides a detailed, molecular-level representation of the mass, energy, and carbon flows spanning upstream resource extraction, hydrogen production, direct reduction, electric melting, and downstream product flows.

For this case study, Sesame One applies a bottom-up, atomically explicit carbon accounting framework to resolve the full mass and energy balances of the H_2-DRI-EAF steel production pathway. This includes upstream raw material supply (iron ore pellets, scrap steel, natural gas, electricity), on-site hydrogen generation via natural gas reforming with carbon capture, direct reduction in a hydrogen shaft furnace, EAF smelting and refining, co-product handling, and downstream transfer of steel products. This modeling framework forms the analytical foundation for the ledger-based carbon accounting results presented in this report.

Mass and Energy Balance Resolution

The primary calculations within Sesame One resolve the fundamental thermodynamic and process relationships governing hydrogen-based steelmaking. For the integrated facility, the model calculates input and output flows using reaction stoichiometry, reduction and melting efficiency, thermal integration, and auxiliary energy requirements.

Blue Hydrogen Production (ATR + CCS)

The hydrogen plant mass and energy balance tracks natural gas feedstock consumption, reforming reactions, process heat demand, hydrogen purification, and CO_2 capture and compression loads. The model resolves:

- Conversion efficiency from natural gas to hydrogen.
- The split between process and combustion CO_2 streams.
- Capture efficiency for each stream.
- Compression energy, auxiliary loads, and purge gas compositions.

Hydrogen Direct Reduction (H_2-DRI)

The DRI shaft furnace balance represents the reduction of iron oxide pellets by hydrogen:

$$Fe_2O_3 + 3H_2 \longrightarrow 2Fe + 3H_2O.$$

The model tracks:

- Hydrogen consumption (stoichiometric + recycle/make-up).
- Shaft gas temperature and composition.
- Water vapor removal and off-gas handling.
- DRI metallization and yield.
- Electricity use for blowers, compressors, and gas circulation.
- Heat integration between the hydrogen plant and the DRI unit.

Electric Arc Furnace (EAF)

The EAF balance resolves:

- Smelting energy requirements for an 80% scrap/20% DRI charge.
- Electricity inputs for the arc and auxiliary systems.
- Carbon injection for slag foaming and metallurgical adjustment.
- Oxygen flows for post-combustion and refining.
- Flux consumption and slag production.
- Electrode consumption rates.
- Off-gas flow, composition, and energy recovery.

Logistics and Transport

Transport models incorporate scrap trucking, pellet rail delivery, natural gas pipeline transmission, and CO_2 pipeline delivery to the storage operator. Energy intensity, fuel consumption, and emissions for each mode are explicitly represented using GREET-based parameters. Material loss factors and recovery rates during transport and handling are also incorporated to maintain mass conservation.

Across all stages, the model enforces closed mass and energy balances, ensuring that all atoms—especially carbon—are accounted for through transformation, transfer, or storage. This approach provides the foundation for transparent, verifiable carbon accounting within and across entities.

Greenhouse Gas Emissions Tracking

Sesame One tracks emissions of multiple species across the entire supply chain: CO_2, CH_4, CO, nitrous oxide (N_2O), sulfur oxides (SO_x), nitrogen oxides (NO_x), and VOCs. For the purposes of ledger-based carbon accounting, this case study focuses on carbon-containing species: CO_2, CH_4, CO, and VOCs.

Hydrogen Production Emissions

Sesame One characterizes:

- Process CO_2 generated inside the reformer.
- Fuel combustion CO_2.
- Residual CO_2 not captured by CCS.
- CH_4 losses and unconverted hydrocarbons.
- Electricity-related emissions for hydrogen compression and purification.

Direct Reduction and EAF Emissions

The DRI furnace generates minimal direct carbon emissions, as hydrogen reduction produces water vapor. Any residual emissions arise from trace carbon in pellets or small auxiliary natural gas use.

The EAF generates direct emissions primarily through oxidation of injected carbon, electrode consumption, and carbonate decomposition from flux additions. These emissions are tracked by species and incorporated directly into the steel producer's ledger.

Carbon Mass Accounting

Rather than relying on global warming potentials (GWPs), Sesame One uses carbon atom-based accounting, converting each species to carbon mass based on molecular composition:

- CO_2 (C mass fraction = 0.273).
- CH_4 (C mass fraction = 0.750).
- CO (C mass fraction = 0.429).
- VOCs (representative C mass fraction ≈ 0.85).

This carbon-centric approach ensures internal mass balance closure and avoids double counting across entities. All carbon entering the system—from natural gas, iron ore impurities, injected carbon, scrap, and electrodes—is traced through its eventual fate: emitted as CO_2, vented as CH_4, oxidized as CO, retained in steel, or transferred to geological storage via CCS.

This approach enables rigorous entity-level emissions tracking across blue hydrogen production, direct reduction, and electric steelmaking while maintaining precise accountability of carbon flows throughout the supply chain. It also supports transparent, auditable product-level carbon intensity calculations in alignment with regulatory requirements, voluntary reporting frameworks, and emerging clean procurement standards.

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 for the blue hydrogen-enabled H_2-DRI-EAF steel production system.

Carbon Emissions Intensities of Feedstock and Fuels

Table 1 presents attributed emissions by species—well-to-gate emissions already released during production—for each major external input to the blue H_2-DRI-EAF steelmaking process. As in the BF-BOF case study, these values are derived from established life cycle databases to ensure consistency with standard industry practice. In actual implementation, carbon intensities would be obtained directly from supplier-specific product carbon footprint (PCF) data or environmental product declarations (EPDs); here, literature-based values are used for demonstration.

Iron ore pellet emissions are derived from the Ecoinvent v3.11 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.[13] These values are applied to DR-grade pellets used in the hydrogen shaft furnace, with the understanding that site- and supplier-specific values could differ.

Electricity emissions follow Argonne GREET 2024 data for wall-outlet delivery under a Midwestern grid mix consistent with the NREL Standard Scenarios Mid-Case for 2024. 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. These values are applied to electricity consumed by the hydrogen plant, DRI shaft, EAF, and auxiliary systems.

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. This profile includes upstream extraction, processing, and compression, and assumes a combined methane leakage rate of 0.48% across recovery and processing. Natural gas serves as the primary feedstock in the on-site hydrogen production unit.

Scrap steel is modeled using Ecoinvent dataset for unsorted iron scrap, with attributed emissions of 3.24 gCO_2/kg and no CH_4, CO, or VOC emissions reported. These emissions reflect upstream collection, processing, and short-haul transport, and are transferred into the steelmaker's ledger under FOD terms.

Lime (used as a flux in the EAF) is modeled analogously to unprocessed limestone in Ecoinvent, with reported emissions of 2.78 gCO_2/kg and negligible CH_4, CO, and VOC emissions. In practice, lime production may generate additional process emissions from calcination; for this case study, these are included in the attributed CO_2 intensity.

Table 1 summarizes the cradle-to-gate emissions intensities used for the primary energy and material inputs.

Table 1. **CARBON EMISSIONS INTENSITY BY INPUT (BLUE H_2-DRI-EAF CASE)**

Feedstock/fuel	Product carbon emissions intensity (cradle to gate)	Source(s)	Details
Iron ore pellets	87.8 gCO_2/kg 0.26 gCH_4/kg 0.45 gCO/kg 0.21 gVOC/kg	Ecoinvent v3.11	Global market for iron ore concentrate (65% iron, dry basis), applied to DR-grade pellets used in direct reduction.
Electricity	675.28 gCO_2/kWh 1.18 gCH_4/kWh 0.24 gCO/kWh 0.07 gVOC/kWh	Argonne GREET 2024	“Wall outlet” emissions at user site; Midwestern grid mix from NREL Standard Scenarios 2023 Mid-Case (2024).
Natural gas	4.53 gCO_2/MJ 0.11 gCH_4/MJ 0.01 gCO/MJ 0.01 gVOC/MJ	Argonne GREET 2024	Standard North American natural gas pathway (75% shale, 25% conventional); well-to-gate emissions including extraction, processing, and compression.
Scrap steel	3.24 gCO_2/kg 0 gCH_4/kg 0 gCO/kg 0 gVOC/kg	Ecoinvent v3.11	Market for “iron scrap, unsorted,” representing typical upstream processing and transport for EAF scrap.
Lime (flux)	2.78 gCO_2/kg 0 gCH_4/kg 0 gCO/kg 0 gVOC/kg	Ecoinvent v3.11	Market for “limestone, unprocessed”; used as a proxy for lime/flux emissions in the EAF.

Hydrogen itself is modeled as an intermediate product generated on-site from natural gas and electricity. Its effective carbon intensity—after accounting for CO_2 capture and storage—is derived endogenously within the model from the natural gas and electricity inputs and is not treated as an independent upstream feedstock in Table 1. Since the hydrogen plant is part of the steel manufacturing plant, the steel producer’s ledger records hydrogen production, the captured CO_2 transferred to the CCS operator and the residual emissions associated with hydrogen delivered to the DRI shaft furnace.

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, iron ore pellets are delivered by rail, and scrap is delivered by heavy-duty truck from regional scrap processors. Captured CO_2 is transported by pipeline to a regional geological storage site. Finished steel products are delivered by rail to construction customers.

Natural gas is transported via pipeline over 200 miles, with an energy intensity and methane leakage rate consistent with GREET defaults. The resulting transport emissions are attributed to the natural gas supplier under FOD terms and reflected in the cradle-to-gate natural gas intensities used by the hydrogen unit.

Iron ore pellets are shipped approximately 650 miles by rail from the Mesabi Iron Range to the steelmaking site. Scrap steel is delivered over an average distance of 50 miles by heavy-duty diesel truck from regional scrap processors. Captured CO_2 is compressed and piped approximately 60 miles to a saline formation or dedicated storage hub, with pipeline energy use and fugitive losses included in the CCS operator’s ledger. For downstream logistics, steel is delivered by rail to construction companies over a 200-mile distance.

All transport-related emissions are modeled using GREET-based energy intensities and fuel-cycle emissions and are expressed by species (CO_2, CH_4, CO, VOCs). Electricity transmission and distribution are excluded from transport emissions calculations and are instead incorporated in the electricity intensity values described above.

Table 2. **CARBON EMISSIONS INTENSITY BY TRANSPORT MODE (BLUE H_2-DRI-EAF CASE)**

Transport mode	Distance	Modeled transport carbon emissions intensity	Note
Natural gas pipeline	200 miles (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 (Argonne GREET 2024). Emissions are included in natural gas cradle-to-gate intensities.
Iron ore rail transport	650 miles (1,046 km)	30.0 $kgCO_2$/ton; small CH_4, CO, VOC components	Rail energy intensity derived from GREET locomotive pathways; emissions attributed to pellet supplier under FOD terms.
Scrap steel truck transport	30 miles (48.3 km)	4.0 $kgCO_2$/ton; minor CH_4, CO, VOC	Short-haul heavy-duty diesel truck delivery from regional scrap processors.
Captured CO_2 pipeline	60 miles (96.6 km)	3.0 $kgCO_2$/ton CO_2 transported; minor CH_4 and VOCs	Pipeline compression and transport for CO_2, accounted for in CCS operator ledger.
Steel to construction customer – rail	200 miles (321.9 km)	16.7 $kgCO_2$/ton 0.06 $kgCH_4$/ton 0.02 kgCO/ton 0.02 kgVOC/ton	Rail delivery to construction site; emissions attributed to the steel producer under FOD terms.

Source: Argonne GREET Model, 2024.

All modeled emissions include well-to-pump life cycle emissions of fuels and species-level tracking (CO_2, CH_4, CO, VOCs), consistent with the broader life cycle boundaries used across the carbon accounting framework.

Blue Hydrogen-DRI-EAF Steel Production Models

The blue H_2-DRI-EAF system is modeled using plant-level parameters anchored in first-principles mass and energy balances. The model simulates an integrated facility that produces 5 million tons of crude steel per year, transforming DR-grade iron ore pellets, scrap steel, natural gas, electricity, oxygen, and fluxes into finished steel products.

In the hydrogen unit, natural gas is converted to hydrogen via autothermal reforming with carbon capture. The model specifies:

- A natural gas-to-hydrogen conversion efficiency consistent with state-of-the-art reformers.
- CO_2 capture rates (e.g., 90%-98%) for synthetic gas and flue gas streams.
- Compression and purification energy requirements.

Hydrogen output is supplied to the DRI shaft furnace, carrying residual attributed emissions after capture and storage.

In the H_2-DRI furnace, DR-grade pellets are reduced by hydrogen to produce DRI, with water vapor as the primary reaction product. The model assumes:

- A hydrogen consumption rate of approximately 50-60 kg H_2 per ton of DRI.
- Metallization levels above 92%-95%.
- Electricity demand for gas circulation and control systems.

In the EAF, a charge mix of 80% scrap and 20% DRI is melted and refined using electricity as the dominant energy input. The model assumes:

- EAF electricity consumption of approximately 400-550 kWh per ton of crude steel.
- Carbon injection and electrode consumption consistent with modern EAF practice.
- Flux addition and slag generation rates appropriate for an 80% scrap charge.

The modeling framework enforces closed carbon mass balances, capturing direct process emissions (from reforming, EAF carbon oxidation, and flux decomposition), indirect energy emissions (from purchased electricity and upstream fuel production), and co-product flows (such as slag). Emissions are tracked by species (CO_2, CH_4, CO, VOCs) and by process step, allowing for transparent allocation across entities and products.

Physical Properties and Physical Carbon Content Calculations

Physical carbon content calculations form the foundation for mass-balance closure and emissions allocation across the blue H_2-DRI-EAF production system. Building on the attributed emissions intensities presented above, this section focuses on the carbon atoms contained within fuels, materials, and emissions species.

Carbon mass ratios are determined from molecular composition, and all emissions species are converted to carbon mass equivalents using the molecular carbon content of each:

- CO_2: carbon mass ratio = 0.273 (1 ton CO_2 contains 0.273 tons C).
- CH_4: carbon mass ratio = 0.750.
- CO: carbon mass ratio = 0.429.
- VOCs: carbon mass ratio = 0.85 (consistent with GREET assumptions)

These conversions allow carbon flows across different species to be expressed on a consistent carbon mass basis, ensuring that total carbon input equals total carbon output across the system (products + emissions + storage).

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

Species/material	Carbon mass ratio	Energy content
Natural gas	0.722	47.14 MJ/kg
Injected carbon/electrodes	1.000	30-32 MJ/kg (representative)
Scrap steel	0.002	–
Limestone/lime	0.12 / 0	–
Steel	0.002	–
CO_2	0.273	–
Carbon (reference)	1.000	–

Source: R&D GREET 2024 and representative literature values.

These standardized carbon mass ratios are applied throughout the ledger-based accounting system to validate that carbon content and emissions allocations remain consistent, enabling robust cross-checks between physical flows and ledger balances.

Accounting Ledger Assumptions

This case study employs several simplifying assumptions to highlight core emissions transfer and accounting principles for the blue H_2-DRI-EAF pathway:

- **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 the case study to focus on the essential features of the ledger-based carbon accounting framework—particularly the treatment of blue hydrogen production, direct reduction, electric melting, and CCS—while maintaining analytical clarity for transaction-based emissions transfers across entities.

V. Results and Carbon Impact Analysis

Mass and Energy Balance Overview

The Sesame One carbon accounting model generates detailed mass and energy balances that serve as the foundation for emissions allocation and carbon tracking across the blue H_2-DRI-EAF steelmaking system. The annual production scenario models an integrated facility producing 5 million tons of crude steel per year using a combination of direct reduced iron and scrap steel.

In the modeled configuration, this output requires on an annual basis:

- DR-grade iron ore pellets for DRI production.
- Scrap steel to supply 80% of the metallic charge to the EAF.
- Natural gas as feedstock and fuel for on-site blue hydrogen production.
- Electricity to power the hydrogen plant, DRI shaft furnace auxiliaries, and EAF operations.
- Lime and other fluxes for impurity removal and slag formation.
- Oxygen for refining and post-combustion reactions in the EAF.

Hydrogen produced from natural gas reforming with carbon capture is supplied internally to the DRI shaft furnace. The DRI unit converts oxide pellets into metallic iron using hydrogen as the reductant, producing water vapor as the primary reaction product. The DRI is then charged, together with scrap, to the EAF, where the mixture is melted and refined using electricity as the principal energy input.

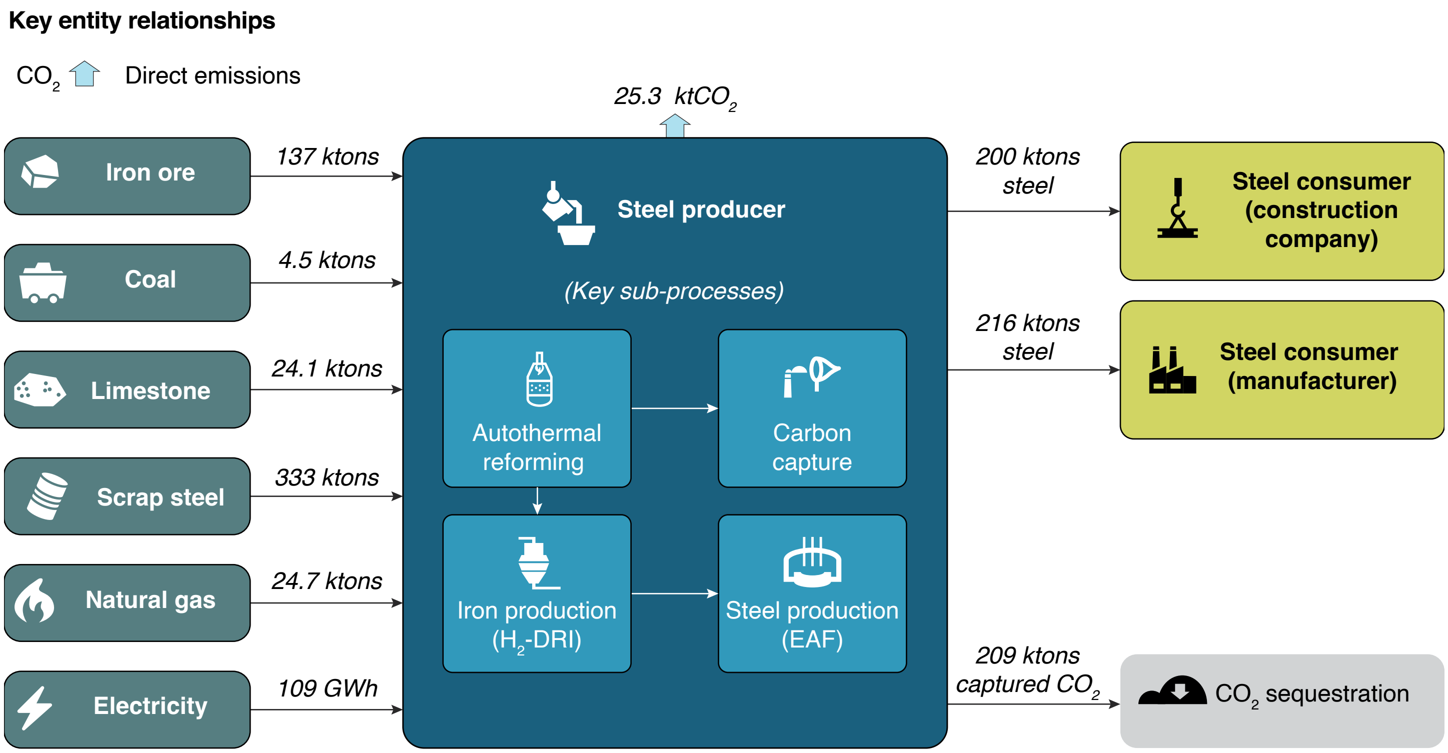
The system yields a primary product mix consisting of:

- 5,000,000 tons of crude steel (core output) per year.
- 416,400 tons of slag per year.
- 7,200 tons of ash per year.

These mass flows are used to calculate carbon flows and allocation factors for cradle-to-gate emissions accounting. ISO 14044 requires allocation only when multiple products are produced and when subdivision or system expansion is not feasible.[d] In such cases, ISO 14044 and ISO 14067 recommend allocation based on physical causality—such as mass, energy content, or chemical relationships—while economic allocation is used only when physical relationships cannot be established.[14,15,e] EN 15804 and world steel LCA methodology similarly favor mass-based allocation for primary steelmaking and recognize that low-market-value co-products (e.g., slag or EAF dust) that do not influence process economics do not require allocation.[16,17,f] Consistent with these standards and typical practice in steel life cycle studies, all emissions in this case study are allocated to steel, which is the sole product and the functional driver of the production system.

Figure 2 summarizes the mass and energy flows for the integrated blue H_2-DRI-EAF facility, including raw material inputs, hydrogen and electricity consumption, direct emissions, and steel output, for one month of operation. This study translates the annual production scenario into monthly production, as the accounting period is one month.

Figure 2. **MASS AND ENERGY FLOWS FOR INTEGRATED BLUE H_2-DRI-EAF STEEL PRODUCTION, ONE MONTH**



Note: Values shown include material inputs (black) and direct facility CO_2 emissions (blue).
Source: Sesame Sustainability.

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[d] ISO 14044 is an international standard that establishes requirements and guidelines for conducting life cycle assessments.

[e] ISO 14067 is an international standard that establishes requirements and guidelines for the quantification and reporting of the carbon footprint of a product.

[f] EN 15804 is the European standard in the field of environmental product declarations in the construction industry.

Steel Producer Ledger Records and Reporting

Recording Carbon Emissions and Content Transfers In

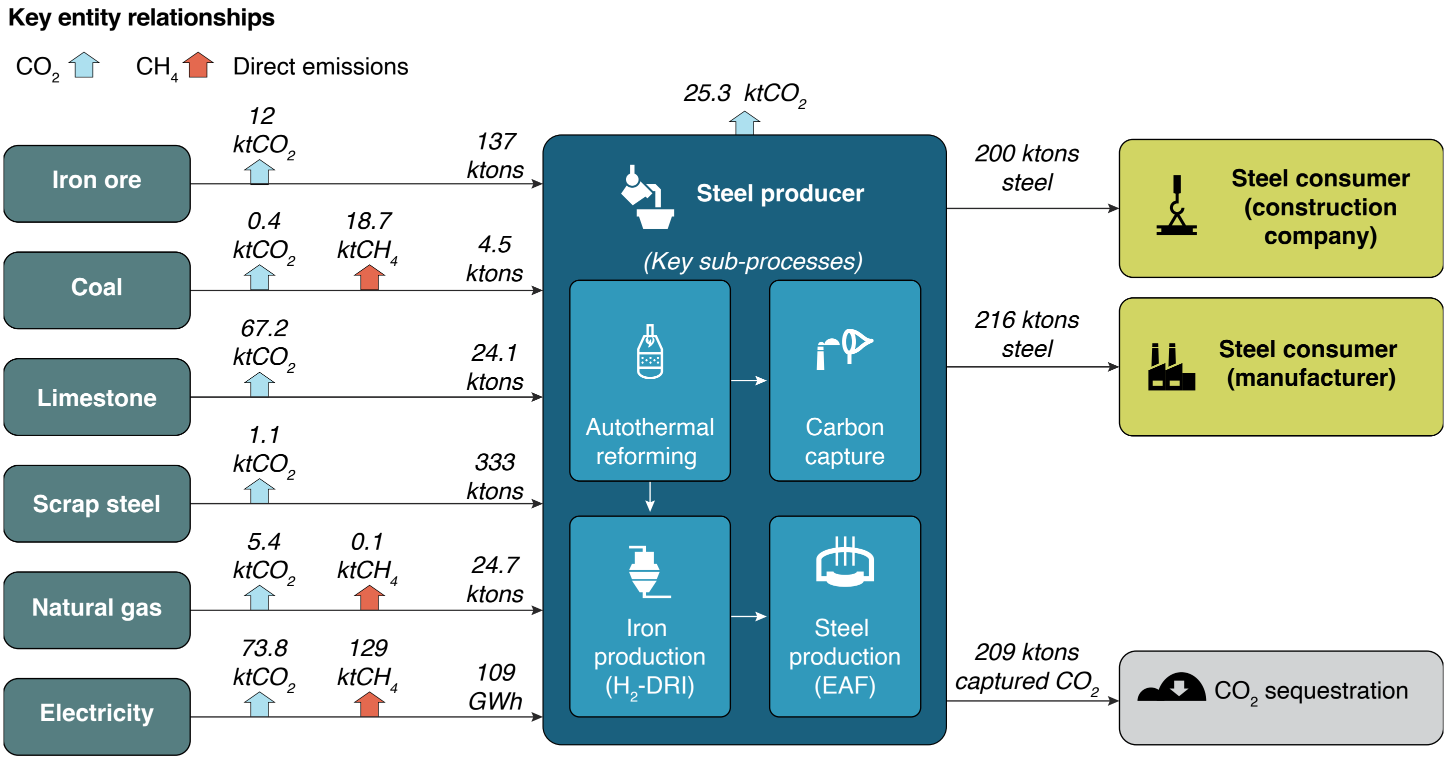
The production scenario demonstrates how upstream suppliers and on-site process units transfer both materials and their associated carbon footprints to the steel producer under the FOD accounting framework. From the perspective of the steel producer (covering DRI and EAF operations), each input arrives with two distinct carbon components:

- Attributed carbon emissions by species (CO_2, CH_4, CO, VOCs) already released during upstream production and transport.

- Physical carbon content embedded in the incoming materials (e.g., in scrap, injected carbon, electrodes, and fluxes).

Hydrogen, produced on-site from natural gas with carbon capture, enters the DRI facility as an intermediate product with negligible physical carbon content but with residual attributed emissions associated with incomplete CO_2 capture, electricity use, and upstream natural gas emissions. Scrap steel, DRI, and fluxes carry both physical carbon (where applicable) and upstream attributed emissions.

Figure 3. **CARBON FLOW DIAGRAM OF INPUTS TO STEEL PRODUCTION WITH ATTRIBUTED EMISSIONS BY SPECIES (BLUE H_2-DRI-EAF), ONE MONTH**



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

Source: Sesame Sustainability.

In the carbon ledger, all transactions are recorded in a common base unit—tons of carbon (tC)—to ensure that the carbon mass balance is consistently maintained. Accordingly, all attributed emissions transferred in are converted to tC, based on species-specific carbon mass ratios. For clarity, CO and VOCs may be combined into a single "CO & VOC" column where their contribution is relatively small compared with CO_2 and CH_4.

Table 4 summarizes the attributed emissions and physical carbon content associated with the major inputs to the steel producer's operations (DRI + EAF) over the reporting period.

Table 4. **ATTRIBUTED EMISSIONS AND CARBON CONTENT BY INPUT (ILLUSTRATIVE BLUE H_2-DRI-EAF CASE), ONE MONTH**

Input	Quantity	Attributed CO_2 (tC)	Attributed CH_4 (tC)	Attributed CO & VOC (tC)	Total attributed emissions (tC)	Physical carbon content (tC)
Electricity	109.4 GWh	20,167	97	19	20,283	0
Natural gas	24.7 ktons	1,479	89	14	1,582	17,843
Iron ore pellets	137.2 ktons	3,283	0	26	3,309	0
Scrap steel	333.1 ktons	295	0	0	295	666
Limestone	24.1 ktons	18	0	0	18	2,900
Coal	4.5 ktons	110	14	1	125	3,333
Total	–	**25,352**	**200**	**60**	**25,612**	**24,742**

Source: Sesame Sustainability.

The ledger entries demonstrate the systematic recording of carbon transfers under the FOD framework. Mirror transactions appear on each supplier's ledger to reflect the transfer from their perspective. For each purchase, the steel producer records:

- **Carbon content transferred in:** Physical carbon atoms embedded in purchased materials (e.g., in scrap, injected carbon, electrodes, and lime) are recorded to respective stock accounts and to the Carbon Content Transferred In account.
- **Attributed emissions transferred in:** Attributed upstream emissions associated with each material or energy input are recorded by species (CO_2, CH_4, and CO & VOCs) to stock accounts and credited to the Attributed Emissions Transferred In account.

The balanced ledger entries ensure complete carbon accountability across the steel production system. Individual emissions species are tracked separately, providing detailed visibility into the carbon profile of each upstream feedstock—including electricity for the EAF and hydrogen plant, hydrogen supplied to the DRI shaft furnace, DR-grade pellets, scrap steel, and fluxes.

The total attributed upstream emissions recorded in the ledger represent the cradle-to-gate emissions inherited from material extraction, processing, hydrogen production, and transport. The physical carbon content in incoming materials serves as an important cross-check on model integrity, supporting verification of carbon conservation throughout the system.

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

	STOCKS ACCOUNTS						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		3,309				**3,309**		3,309	**3,309**
Purchase coal from supplier			3,334	125		**3,459**	3,334	125	**3,459**
Purchase limestone from supplier	2,900	18				**2,918**	2,900	18	**2,918**
Purchase natural gas from supplier			17,843	1,583		**19,426**	17,843	1,583	**19,426**
Purchase electricity from supplier					20,283	**20,283**		20,283	**20,283**
Purchase scrap steel from supplier	666	295				**961**	666	295	**961**

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.

The steel producer operates as the central transformation point in the supply chain, converting upstream feedstocks—hydrogen, DR-grade pellets, scrap steel, electricity, injected carbon, and fluxes—into finished steel products while maintaining complete carbon accountability. For the modeled production of steel, the steel producer's ledger aggregates:

- Upstream attributed emissions by species from all inputs.
- Direct emissions from hydrogen reforming (post-capture residual), EAF carbon oxidation, electrode consumption, and flux decomposition.
- Physical carbon content retained in finished steel.

Unlike the BF-BOF pathway, where most of the physical carbon enters the system via metallurgical coal and is oxidized in the blast furnace and BOF, the blue H_2-DRI-EAF system introduces most carbon as natural gas (NG) feedstock to the hydrogen plant and a relatively small quantity of injected carbon and electrode material in the EAF. Hydrogen itself carries negligible physical carbon, and direct reduction produces water rather than CO_2, significantly shifting the locus of carbon flows toward the hydrogen unit and EAF refining steps.

The facility produces primarily:

- 5 million tons of crude steel (core output) per year.
- 416,400 tons of slag per year.
- 7,200 tons of ash per year.

The physical carbon content of steel remains low (~0.05-0.1% by mass) but is explicitly tracked for mass balance closure and potential downstream accounting. The difference between carbon entering the system (e.g., in natural gas, injected carbon, and lime) and carbon retained in products represents carbon emitted as CO_2 and CH_4 or stored via CCS.

The ledger-based system tracks each carbon-containing species (CO_2, CH_4, CO, VOCs) separately and allocates emissions to products using a mass-based method aligned with the total output mass of steel and any co-products. For this case study, all emissions are allocated to steel, consistent with the BF-BOF case, because byproducts—slag and ash—are assumed to have negligible economic value.

Figures 5 and 6 contain the full transaction log, which can be summarized as:

- Transfer to work-in-process (WIP): Physical carbon content and attributed emissions are moved from upstream stock accounts to WIP when materials enter production.
- Allocation to finished steel: Upon completion of melting and refining, emissions are allocated from WIP to finished steel inventory.

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			(3,622)		(1,708)	(20,283)		25,613							-		-
Direct emissions from production		(3,566)		(21,177)			2,171		22,572						-		-
Direct emissions captured and sequestered									(15,647)						**(15,647)**	(15,647)	**(15,647)**
Direct emissions from CCS process									1,565						**1,565**	1,565	**1,565**
Transfer carbon in WIP to products							(833)	(25,613)	(8,490)	833	25,613		8,490		-		-
Allocated depreciation of PPE to products	(120)											120			-		-
Transfer carbon content from WIP to byproducts							(1,337)							1,337	-		-

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)	(25,613)	(120)	(8,490)	**(35,056)**		(833)	(34,223)	**(35,056)**
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 provides an illustrative summary of the allocation of carbon content and emissions to steel products for the blue H_2-DRI-EAF system.

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

Product	Production	Mass allocation share	Total allocated emissions (tC)	Physical carbon content (tC)
Steel	416 ktons	92.2%	34,222	833.3
Slag	34.7 ktons	7.7%	0	1,319.9
Ash	0.6 ktons	0.1%	0	17.1
Total	**451 ktons**	**100%**	**34,222**	**2,170.3**

In cases where slag or ash are sold into secondary markets (e.g., cement or aggregate), emissions could be allocated proportionally by mass, using the same ledger architecture.

Transport emissions incurred during delivery from the steel facility to downstream customers are recorded at the time of shipment and added to the cradle-to-gate profile of the steel product, ensuring full accountability for both cost and carbon through the point of delivery.

Ending Ledger of Carbon Stocks and Flows

Figure 7 summarizes the balances of carbon stocks and flows in the steel producer's ledger at the end of one month of operation for the blue H_2-DRI-EAF configuration.

Figure 7. **STEEL PRODUCER'S SUMMARY OF ACCOUNT BALANCES AS OF THE END OF ONE MONTH OF OPERATION**

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	100,678
Depreciation	(29,170)	Carbon content transferred in	28,193
Carbon in raw materials inventory		**Carbon transferred out**	
Attributed emissions in raw materials	1,811	Emissions transferred out with product sold	(63,839)
Carbon content in raw materials	1,783	Carbon content transferred out with product sold	(833)
Carbon in fuels inventory			
Attributed emissions in fuels	62		
Carbon content in fuels	1,667		
Carbon in product inventory		**Carbon abatement**	
Emissions in product	–	Carbon transferred out for sequestrations	(14,082)
Carbon content in product	–		
Carbon in byproduct			
Carbon content in byproduct	1,337		
Total emissions	**45,329**	**Total emissions flow**	**(36,839)**
Total carbon content	**4,787**	**Total carbon content flow**	**27,360**
		Total abatement flow	**(14,082)**
Total carbon stock	**50,116**	**Total carbon flow**	**50,116**

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 entering and leaving the company through material purchases, internal transfers, emissions, and product sales. Source: Sesame Sustainability.

The ending ledger presents a complete carbon balance for the facility, showing:

- Carbon stock retained within the entity boundary (e.g., in unsold steel inventory or work-in-process, raw materials, and fuel inventories).
- Carbon transferred in from upstream suppliers and internal hydrogen production.

- Carbon transferred out in sold steel products.
- Carbon released to the atmosphere or transferred to geological storage via CCS.

For the representative reporting period, the ledger demonstrates that all incoming carbon is conserved and reallocated without loss or double counting. Physical carbon retained in steel inventory reflects unshipped material still within the facility boundary, while direct emissions and captured CO_2 are explicitly recorded as separate flows, distinguished by species and sink (atmospheric vs. storage).

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, 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 (BLUE H_2-DRI-EAF)**

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	0.032	0.000
Emissions from electricity use	0.177	0.851
Emissions from fuel combustion	0.198	0.000
Emissions abated via CCS	(0.124)	0.000
Emissions from fuel production and transport	0.014	0.905
Emissions from production of equipment used	0.001	0.006
Emissions from transport of products	0.005	0.017
Emissions offsets used	0.001	0.006
Product carbon emissions intensity in steel	**0.305**	**1.786**

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

For the modeled blue H_2-DRI-EAF configuration, the cradle-to-gate product carbon intensity for steel is significantly reduced relative to the BF-BOF case. An illustrative outcome for the base configuration is:

- **CO_2 intensity:** 0.3 kgCO_2 per kg of steel.
- **CH_4 intensity:** 1.79 gCH_4 per kg of steel.

Exact values depend on the assumed hydrogen capture rate, grid emissions factor, and scrap share. These values are derived from the aggregation of upstream and direct emissions across all relevant source categories in the ledger.

Figure 9. **STEEL PRODUCER'S ENTITY-LEVEL CARBON EMISSIONS STATEMENT FOR ONE MONTH OF OPERATION (BLUE H_2-DRI-EAF)**

Steel Producer
Entity-Level Carbon Emissions Intensity Statement
January 2025

Direct emissions	**tCO_2**	**tCH_4**
Gross direct emissions	82,682.28	
CCS abatement, net	(51,583.85)	
Total direct emissions, net	*31,098.43*	
Attributed emissions		
Emissions attributed to purchased electricity	73,874.17	129.04
Emissions attributed to purchased machinery	0.00	0.00
Emissions attributed to purchased raw materials	13,173.78	0.00
Emissions attributed to purchased fuels	5,821.57	137.21
Total attributed emissions	*92,869.53*	*266.25*
Total carbon emissions	**123,967.96**	**266.25**
Carbon offsets obtained		
Carbon removal	0.00	
Environmental attribute certificates	0.00	
Total carbon offsets obtained	**0.00**	
Net total carbon emissions	**123,967.96**	**266.25**

Note: The statement shows direct facility emissions and attributed upstream emissions by species, with CO and VOCs excluded from presentation where immaterial.
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' Ledger Records and Reporting

The two customers receive the finished steel product from the H_2-DRI-EAF facility with the product carrying its full cradle-to-gate carbon profile—including both physical carbon content and attributed emissions by species from upstream and production operations. These emissions are transferred at the point of delivery under FOD terms, ensuring that transportation emissions incurred during delivery remain on the steel producer's ledger until the steel reaches the customers.

The product-level accounting enables clear traceability and transfer of carbon responsibility. Upon receipt, the cradle-to-gate emissions profile of the steel becomes part of the downstream entity's carbon records, whether that be the construction firm, a fabricator, or the ultimate building owner. Since steel is not combusted during use, all embedded and attributed emissions remain associated 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, including:

- Emissions from raw material extraction and processing.
- Energy use and production operations in hydrogen, DRI, and EAF units.
- Carbon capture and storage activities.
- Transport emissions incurred by the producer.
- Residual physical carbon embedded in 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 and CH_4 intensities of the steel product, derived directly from the ledger, provide a robust basis for comparing blue H_2-DRI-EAF steel with conventional BF-BOF products in procurement and policy contexts.

VI. Summary and Discussion

This study demonstrates the practical application of a ledger-based carbon accounting system for multiple steelmaking pathways, including conventional integrated production, integrated production with carbon capture, natural-gas-based DRI with EAF melting, and blue hydrogen-enabled DRI-EAF steelmaking. Each entity in the supply chain maintains a complete, auditable gate-to-gate carbon mass balance, transferring both physical carbon content and attributed emissions by species (CO_2, CH_4, CO, VOCs) to downstream customers under free-on-delivery (FOD) terms.

The carbon accounting ledger's support of detailed reporting of carbon product emissions intensity and carbon product content significantly improves the ability to compare carbon characteristics at the product level. Table 6 compares the product carbon emissions intensity of steel produced via DRI-EAF (developed in this case study) and steel produced via BF-BOF (from the previous case study). Users of this information—including investors, policymakers, and customers—can easily compare different steel products based on disaggregated emissions data.

Table 6. **PRODUCT CO_2 EMISSIONS INTENSITY COMPARISON ACROSS STEELMAKING PATHWAYS**

Emissions source	BF-BOF ($kgCO_2$/kg steel)	BF-BOF + CCS ($kgCO_2$/kg steel)	Blue H_2-DRI-EAF ($kgCO_2$/kg steel)
Emissions from raw material production and transport	0.15	0.17	0.05
Emissions from electricity use	0.12	0.2	0.17
Process emissions	1.6	1.87	0.2
Emissions from transport of products	0.004	0.004	0.004
Emissions abated via CCS	0	(1.11)	(0.14)
Product carbon emissions intensity (cradle to gate)	1.9	1.1	0.3

Note: Electricity demand and intensity vary by grid mix. NG-DRI produces CO_2 during reduction of iron ore with synthetic gas; this is not combustion-free unless CCS is added. Source: Sesame Sustainability.

This comparative analysis offers stakeholders insights into carbon-mitigation opportunities, including:

1. BF-BOF IS THE HIGHEST-EMISSIONS PATHWAY

At roughly 1.9 kgCO_2/kg steel, the integrated BF-BOF route is dominated by coal-derived carbon in coke production and molten iron reduction reactions. CH_4 and CO emissions are minor contributors.

2. CCS SUBSTANTIALLY REDUCES BF-BOF EMISSIONS

Applying high-capture blast furnace gas + BOF gas capture can reduce emissions by roughly 40%-55%, but significant residual CO_2 remains from uncaptured process streams, coke plant emissions, grid electricity, and remaining fossil fuel inputs.

3. NG-DRI-EAF OFFERS MAJOR REDUCTIONS WITHOUT HYDROGEN

Natural-gas-based DRI paired with an EAF yields roughly 0.6-0.7 kgCO_2/kg steel, cutting emissions by more than 70% relative to BF-BOF.

The main contributors are upstream NG methane leakage, CO_2 generation during NG-based direct reduction, and electricity for the EAF.

Further reductions require CCS or replacing NG with low-carbon hydrogen.

4. BLUE H_2-DRI-EAF PROVIDES THE LOWEST EMISSIONS AMONG FOSSIL-BASED ROUTES

With high CO_2 capture on ATR reforming and a low-carbon electricity mix, emissions can drop to 0.3 kgCO_2/kg steel, approaching—or beating—low-carbon steel from scrap-only EAFs depending on electricity source.

This study, together with the case study on BF-BOF pathways, demonstrates both the feasibility and added value of applying comprehensive, ledger-based carbon accounting across the steel supply chain. While traditional LCA methodologies have been useful for estimating emissions in the steel sector, they exhibit clear limitations in providing complete, comparable, and verifiable carbon information to support stakeholder decision-making. Life cycle emissions results for steel can vary widely depending on the selected model, allocation rules, system boundaries, and data quality assumptions—making it difficult to compare BF-BOF, DRI-EAF, and hydrogen-based pathways on an equal footing.

By comparison, comprehensive carbon accounting substantially improves the completeness, traceability, and comparability of carbon information across steelmaking routes. By recording actual carbon flows at the entity and product level—rather than relying on modeling assumptions—this approach strengthens stakeholder confidence and provides a consistent basis for evaluating decarbonization strategies such as CCS, scrap utilization, process electrification, and hydrogen substitution.

As a result, the ledger-based system can accelerate the scale-up of low-carbon steel by enabling transparent product differentiation, reducing uncertainty for investors, and supporting clean procurement programs.

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 Institute's 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,[18] is shown in Table A1. The ledger shows a net total of 124,404 tons of CO_2 emissions allocated to the steel product. After adjustment of CO_2 emissions from product transportation, a net total of 60,830 tons of CO_2 emissions are transferred from the steel producer's ledger to the construction company's ledger, and a net total of 65,636 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)	163,799
		Attributed CO_2 emissions to iron ore supply	12,027
		Attributed CO_2 emissions to coal supply	401
		Attributed CO_2 emissions to limestone supply	67
		Attributed CO_2 emissions to natural gas supply	5,421
		Attributed CO_2 emissions to scrap steel supply	1,079
		Attributed CO_2 emissions to electricity supply	73,874
		Subtotal (B)	**92,869**
		Net CO_2 balance (A+B)	**256,668**

Steel production

CO$_2$ emissions assets *(tCO$_2$)*		**CO$_2$ emissions liabilities** *(tCO$_2$)*	
Beginning balance	0	Beginning balance (A)	163,799
		Attributed CO$_2$ emissions to iron ore supply	12,027
		Attributed CO$_2$ emissions to coal supply	401
		Attributed CO$_2$ emissions to limestone supply	67
		Attributed CO$_2$ emissions to natural gas supply	5,421
		Attributed CO$_2$ emissions to scrap steel supply	1,079
		Attributed CO$_2$ emissions to electricity supply	73,874
		Direct gross CO$_2$ emissions	82,682
		CO$_2$ abatement	(51,584)
		Depreciation (monthly share of emissions attributed to PPE)	436
		Depreciation allocated to products	(436)
		Subtotal (B)	**123,967**
		Steel product allocation factor	100%
		Net CO$_2$ allocated to steel inventory*	124,404
		Share of steel sold to construction company	48.1%
		Net CO$_2$ allocated to steel sold to construction company	59,838
		CO$_2$ emissions transporting steel to construction company (C)	992
		Net CO$_2$ transferred to construction company (D)	(60,830)
		Share of steel sold to manufacturer	51.9%
		Net CO$_2$ allocated to steel sold to manufacturer	64,566
		CO$_2$ emissions transporting steel to manufacturer (E)	1,070
		Net CO$_2$ transferred to manufacturer (F)	(65,636)
		CO$_2$ emissions liabilities balance (A+B+C+D+E+F)	**163,363**

* 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	60,830
		Subtotal	**60,830**

Transfer of steel products to manufacturer

CO_2 emissions assets *(tCO_2)*		**CO_2 emissions liabilities** *(tCO_2)*	
		Attributed CO_2 emissions to steel transferred in	65,636
		Subtotal	**65,636**

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