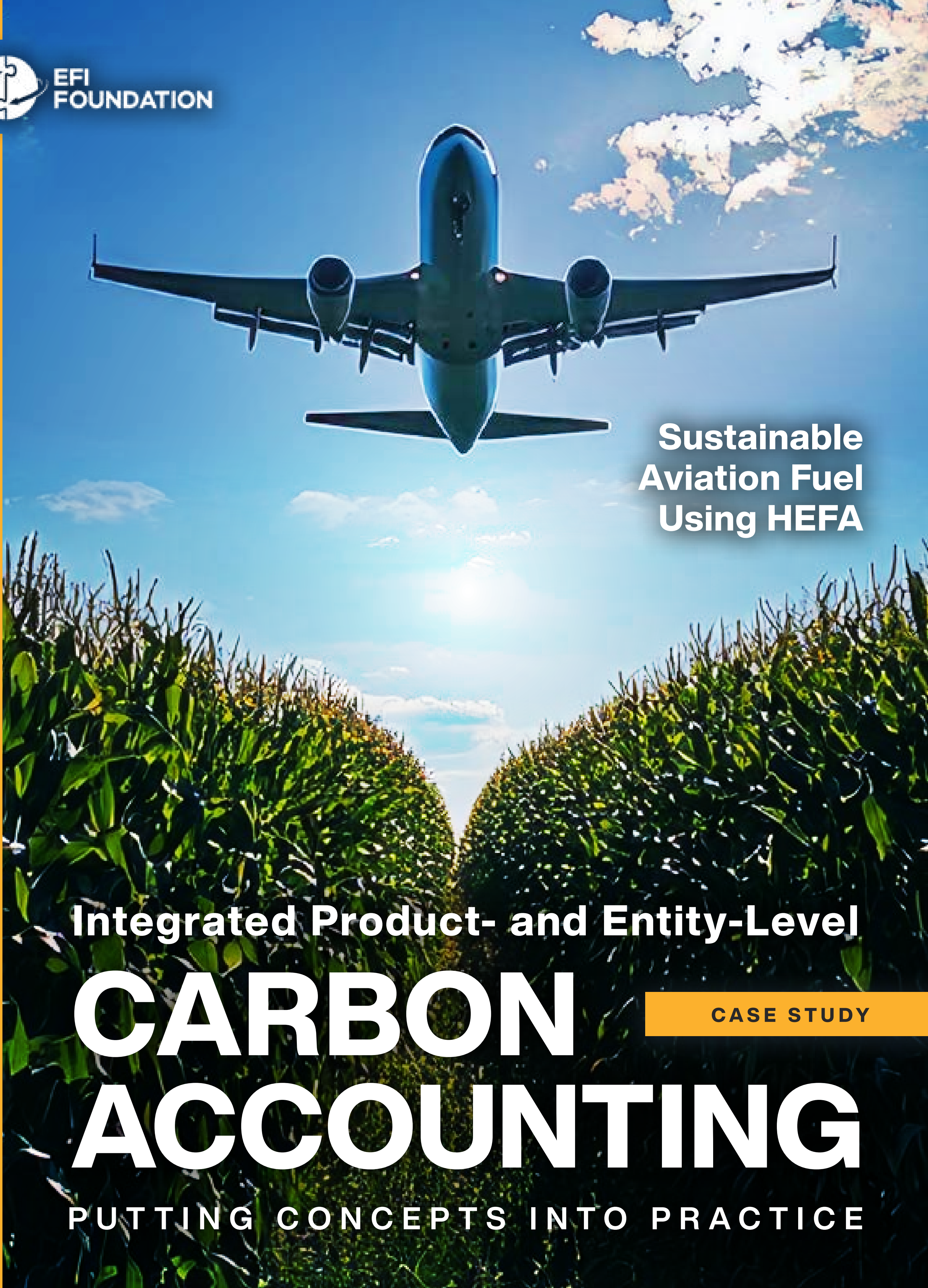

EFI FOUNDATION

Sustainable Aviation Fuel Using HEFA

Integrated Product- and Entity-Level CARBON ACCOUNTING

CASE STUDY

PUTTING CONCEPTS INTO PRACTICE

The EFI Foundation is an independent, nonpartisan leader tackling the toughest energy challenges of our time. Under the leadership of Ernest J. Moniz, the 13th U.S. Secretary of Energy, the EFI Foundation conducts rigorous research to accelerate the transition to a low-carbon economy through innovation in technology, policy, and business models. The EFI Foundation maintains editorial independence from its public and private sponsors.

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Table of Contents

Executive Summary

This case study demonstrates how a model comprehensive carbon dioxide (CO_2) emissions accounting system described in the October 2025 EFI Foundation (EFIF) report, Integrated Product- and Entity-Level Carbon Accounting, can be applied to sustainable aviation fuel (SAF) pathway. In this scenario, during a specific calendar quarter, a SAF producer supplies an airline with a 50% blend of conventional jet fuel and 50% SAF. The resulting blended fuel achieves a net-negative emissions intensity of -1.54 kilograms (kg) CO_2 per gallon—a 209% reduction compared to the 1.41 kg CO_2 per gallon intensity of locally produced commercial jet fuel.

The October EFIF report describes a model comprehensive CO_2 emissions accounting system that combines principles of financial accounting with engineering fundamentals. The accounting system framework:

- Establishes a ledger-based accounting system, with 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 established financial accounting principles;
- Allocates CO_2 emissions among final products, yielding product-based CO_2 emission intensity measures that can be fully integrated into a report of entity-wide total CO_2 and other greenhouse gas (GHG) emissions; and
- 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 several academic studies, with 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] The October 2025 EFIF report described how a model carbon accounting system could be reduced to practice, using the production of SAF via the hydroprocessed esters and fatty acids (HEFA) process. This report provides a more detailed description of that case study.

Case Study Description

The case study uses a hypothetical SAF supply chain based on a facility in Great Falls, Montana. The SAF product is combined with conventional jet fuel refined in the same region from Bakken crude oil to create a 50-50 SAF blend that is sold to a commercial airline customer.

The data and modeling for the case study derived from Sesame One, an industrial decarbonization platform from Sesame Sustainability that combines emissions modeling, techno-economic analysis, and system optimization. The model provides detailed mass and energy balances for the hypothetical SAF supply chain, assuming three primary upstream suppliers: a natural gas supplier, an electric utility, and a soybean oil supplier. The SAF production facility converts these inputs into several hydrocarbon products through steam methane reforming and the HEFA process—namely SAF jet fuel, naphtha, and liquefied petroleum gas (LPG). The SAF jet fuel is transported by truck to a blending terminal, where it is blended with conventional jet fuel before being delivered via pipeline to a nearby airport.

The study also models a parallel conventional jet fuel pathway from Bakken crude oil through a Montana refinery. While the conventional pathway demonstrates carbon intensity calculations and product allocation methods, the primary focus of the detailed ledger-based accounting demonstration is on the SAF supply chain, enabling comparison of accounting approaches between renewable and fossil fuel sources.

The case study covers an accounting period of one calendar quarter. Over this period of time, the SAF producer produces 9 million gallons of SAF, 0.73 million gallons of naphtha, and 1.4 million gallons of LPG, using 35,700 tons of soybean oil, 321,000 million cubic feet of natural gas, and 1,800 megawatt-hours of electricity. The SAF is sold for blending with conventional jet fuel to produce 18 million gallons of a 50-50 SAF blend fuel.

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 and CO_2 Emissions: The Engineer's Perspective

The process flow diagram, the mass and energy balances, and the resulting CO_2 emissions flows are illustrated in Figures ES-1 and ES-2 respectively. Figure ES-1 illustrates the basic steps in the production of conventional jet fuel and SAF from HEFA and resulting blending into a 50-50 SAF fuel mixture. Figure ES-2 focuses in detail on the SAF production process. It presents the complete carbon mass balance, including carbon content and CO_2 emissions, over the three-month period of operations. The CO_2 emissions data provides a comprehensive picture of CO_2 emissions attributed to incoming materials, direct CO_2 emissions from the SAF production process, and CO_2 emissions allocated among the final product slate (on the basis of product energy content) and CO_2 emissions and product carbon content transferred from the SAF producer's ledger to the airline customer's ledger.

Figure ES-1. **FULL SUPPLY CHAIN FOR 50-50 BLEND OF CONVENTIONAL JET AND SAF-HEFA**

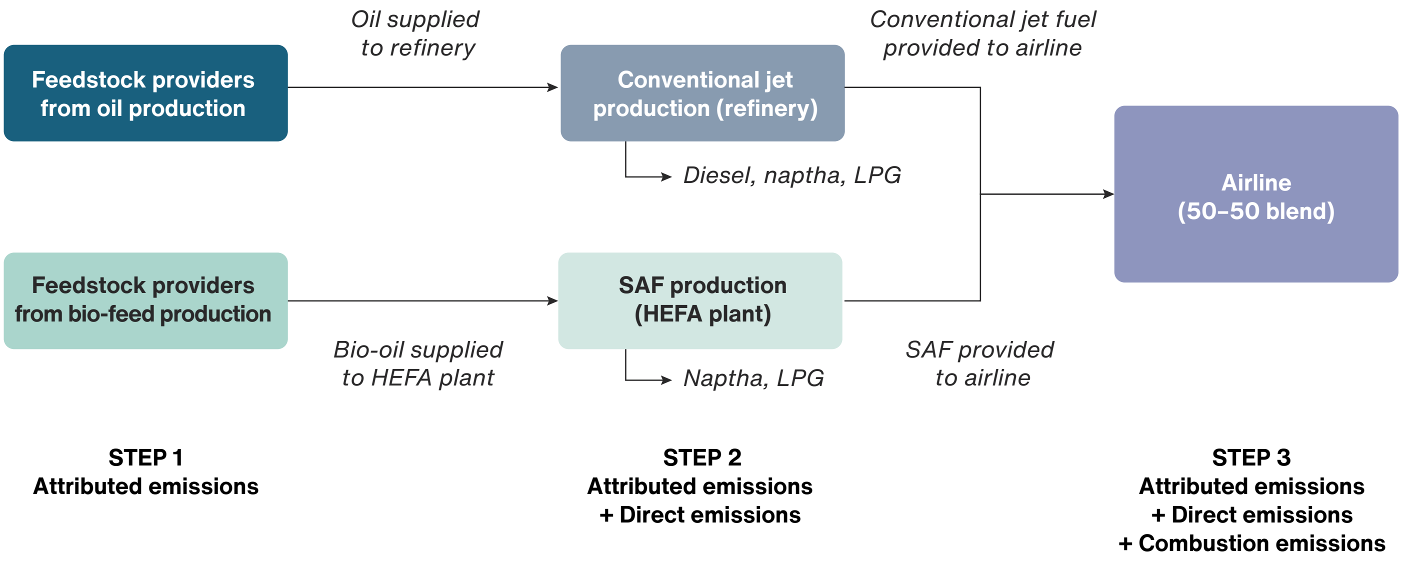
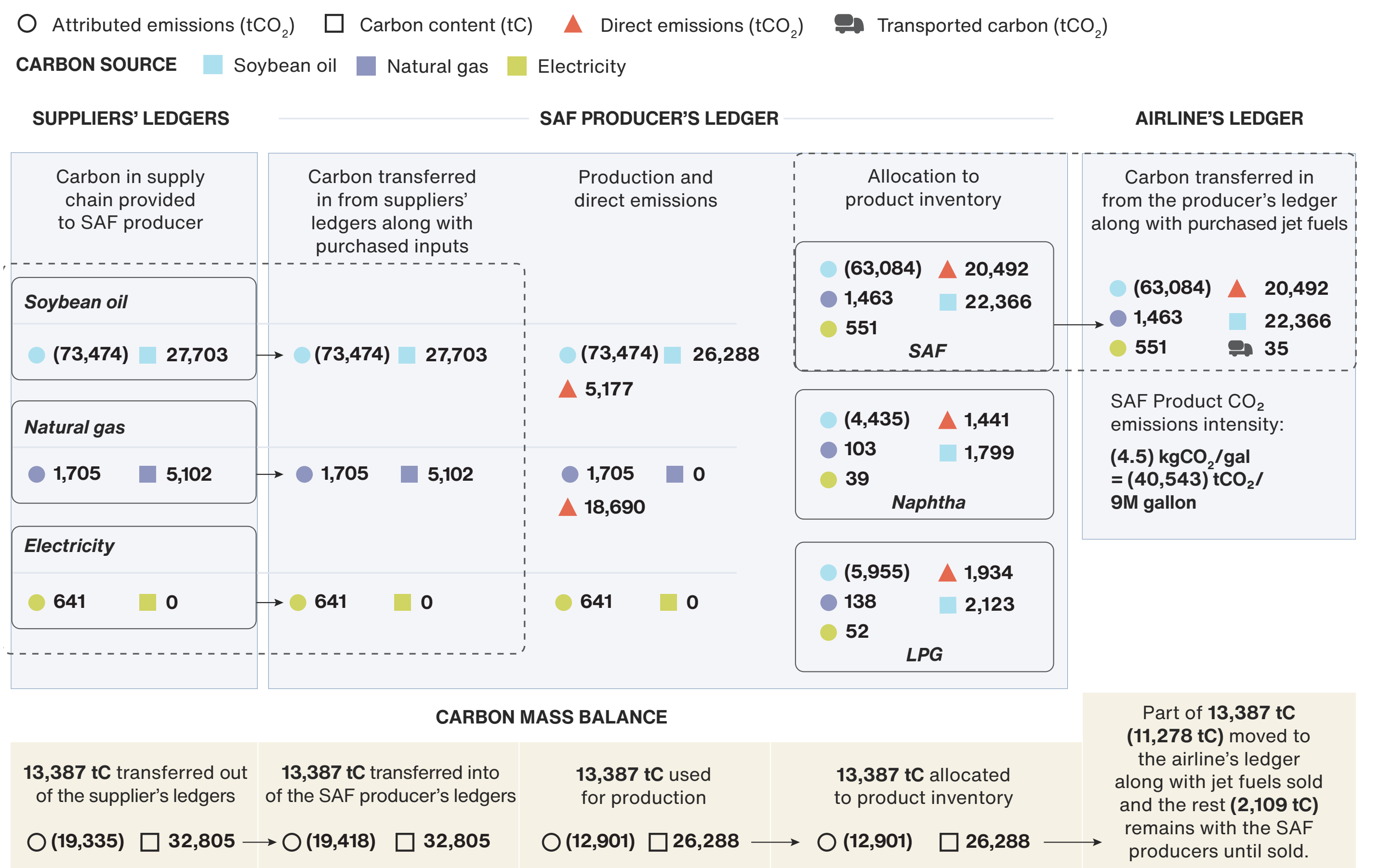


Figure ES-2. **TOTAL CARBON MASS BALANCE FOR THE SAF-HEFA SUPPLY CHAIN (DATA FOR ONE OPERATING QUARTER)**



Note especially that:

- Total flows into and out of the SAF producer are equal and the carbon is tracked at each step (13,387 tons of carbon [tC]). This mass balance is a built-in error-checking step in process engineering that helps ensure accuracy.

- Soybean oil feedstock has a negative CO_2 emissions value (i.e., CO_2 removal from the atmosphere) based on its biogenic production cycle. For the purpose of this analysis, it is assumed that the growth of the soybeans to produce soybean oil removes 101,458 tCO_2 from the atmosphere. Processing the soybeans into 35,700 tons of soybean oil and transporting to the SAF producer results in CO_2 emissions of 27,984 tCO_2, leaving a net-negative value of attributed CO_2 emissions of -73,474 tCO_2.

Electricity flows do not contain carbon per se, but electricity does carry with it the CO_2 emissions attributed from its generation.[i]

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i For this case study, the CO_2 emissions attributed to the electricity supply are based on Montana-specific grid emissions factors projected by the National Renewable Energy Laboratory: 40% hydroelectric, 34% coal, 22% wind, 4% solar photovoltaic, and 1% natural gas.

Ledger-Based CO_2 Emissions Accounting: The Accountant's and Auditor's Perspective

The carbon mass and energy balance data provide the inputs for the transactions to be recorded in the SAF producer's accounting ledger. Tables ES-1 and ES-2 summarize two possible approaches for how the ledger is organized from the underlying transactions in a way similar to financial accounting. There are others in the academic literature as well.

Stocks and flows ledger accounting: 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. This ledger organizational model aligns the carbon mass and energy balance data to transactions on the chart of accounts in the ledger. Individual transactions are recorded on the ledger in double-entry bookkeeping format of debits and credits to the two sides of the ledger. One side records transactions affecting stocks (i.e., the level of attributed CO_2 emissions and carbon content held within the entity) and the other records transactions affecting flows (i.e., attributed CO_2 emissions, direct CO_2 emissions, and carbon content entering and exiting the entity boundaries). The ledger then records the allocation of all incoming attributed CO_2 emissions and all direct emissions to the slate of the three products (SAF, naphtha, and LPG). This in turn supports the calculation of the product CO_2 emissions intensity for each product that is sold to customers. A sample CO_2 ledger, with a high-level summary of transactions, is shown in Table ES-1 (the complete ledger is shown in Appendix A).

Table ES-1. **CO_2 EMISSIONS AND CARBON CONTENT TRANSACTIONS RECORDED IN ACCOUNTING LEDGER WITH STOCKS AND FLOWS FORMAT**

CO_2 stocks (CO_2 held within entity) (tCO_2)		Flows of CO_2 emissions (entering and exiting entity boundaries) (tCO_2)	
Beginning stocks balance (A)	**0**	**Beginning flows balance (A)**	**0**
Stocks added (before production)		**Flows added (before production)**	
Attributed CO_2 emissions to soybean oil supply	-73,474	Attributed CO_2 emissions transferred in	-71,128
Attributed CO_2 emissions to natural gas supply	1,705		
Attributed CO_2 emissions to electricity supply	641		
Subtotal (B)	**-71,128**	**Subtotal (B)**	**-71,128**
Stocks added (via production/sales)		**Flows added (via production/sales)**	
Attributed and direct CO_2 emissions allocated to SAF	-40,578	Direct CO_2 emissions	23,867
Attributed and direct CO_2 emissions allocated to LPG	-3,830	CO_2 emissions from transporting SAF sold to customer	35
Attributed and direct CO_2 emissions allocated to naphtha	-2,853		
CO_2 emissions from transporting SAF sold to customer	35		
Subtotal (C)	**-47,226**	**Subtotal (C)**	**23,902**
Stocks Subtracted		**Flows Subtracted**	
Attributed CO_2 emissions to soybean oil used for production	-73,474	SAF sold to customer	-40,543
Attributed CO_2 emissions to natural gas used for production	1,705		
Attributed CO_2 emissions to electricity used for production	641		
SAF sold to customer	-40,543		
Subtotal (D)	**-111,671**	**Subtotal (D)**	**-40,543**
Ending stocks balance (A+B+C-D)	**-6,683**	**Ending flows balance (A+B+C-D)**	**-6,683**

Note: This case study assumes free on delivery (FOD) terms between the SAF producer and the airline, under which the SAF producer retains ownership and responsibility for all carbon emissions associated with transporting the product. Accordingly, the emissions from SAF transportation are recorded in the SAF producer's ledger.

For each accounting period, such as the three-month period of the case study, the ledger is kept in balance by the relationship that changes in the balance of CO_2 emissions stocks equals the net flow of CO_2 emissions entering and existing the entity's boundaries. Confirming all stock changes equal all flow changes at the end of a period is a built-in error-checking step in accounting that helps ensure accuracy.

Note that, in the table, the ending balance of a net total of -6,718 tCO_2 represents the total CO_2 emissions (attributed and direct) allocated to the LPG and naphtha products remaining in inventory within the SAF producer's boundaries at the end of the accounting period. The net total (attributed and direct) of -40,543 tCO_2 emissions allocated to the SAF product was transferred from the SAF producer's ledger to the customer's ledger with the sale of the product. A complete ledger containing all individual transactions in the product supply chain is provided in Appendix A.

E-asset and E-liability ledger accounting: The October 2025 EFIF report also described another way to record transactions derived from the E-Ledgers accounting concept, organized on the basis of assets and liabilities. In E-Ledgers, all transactions affecting CO_2 emissions are recorded as liabilities, with CO_2 removals recorded as assets. In this system, the acquisition of soybean oil feedstock is recorded as an E-asset, since its net-negative attributed CO_2 emissions result from CO_2 removals from the atmosphere in the soybean growing process. Attributed emissions associated with incoming natural gas and electricity are recorded as liabilities. The direct CO_2 emissions from the SAF production process is then added to the liability column. Finally, the slate of CO_2 liabilities is deducted from the liability side of the ledger and transferred to the customer's ledger along with the SAF product. The ledger transactions are summarized in Table ES-2, with a complete ledger provided in Appendix B.

Table ES-2. **CO_2 EMISSIONS TRANSACTIONS RECORDED IN ACCOUNTING LEDGER DERIVED FROM E-LEDGERS INSTITUTE'S ORGANIZATION OF ASSETS AND LIABILITIES**

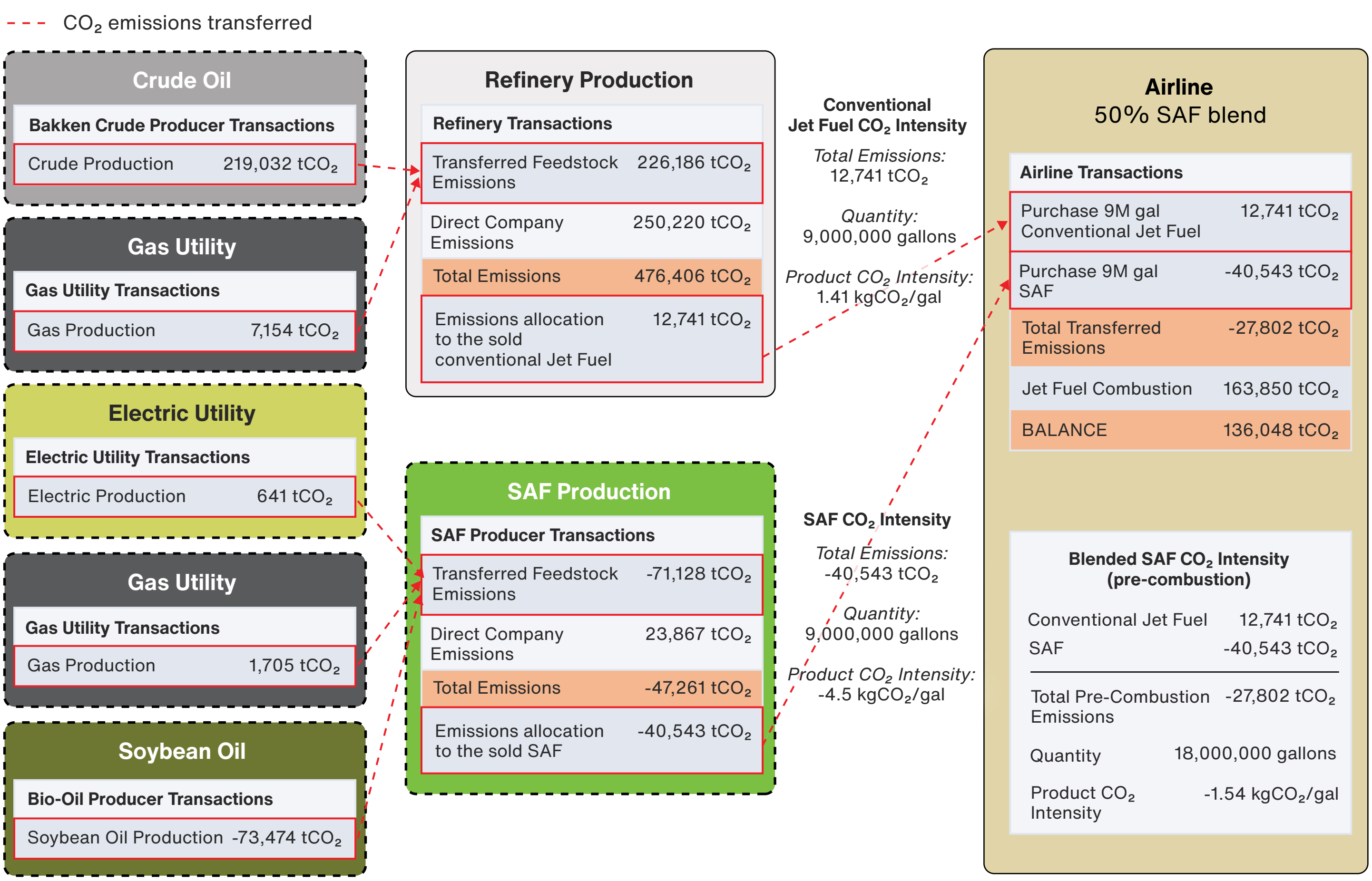
CO_2 emissions assets (tCO_2)		CO_2 emissions liabilities (tCO_2)	
Net CO_2 removals attributed to soybean oil transferred in	73,474	Attributed CO_2 emissions to electricity transferred in	641
		Attributed CO_2 emissions to natural gas transferred in	1,705
		Direct CO_2 emissions	23,867
Subtotal	**73,474**	**Subtotal**	**26,213**
Net CO_2 balance (assets minus liabilities)	**47,261**		
SAF product allocation factor	85.86%		
Net CO_2 allocated to SAF sold	**40,578**		
		CO_2 emissions from transporting SAF sold to SAF customer	35
Net CO_2 transferred to SAF customer	**40,543**		

The ledger shows a net total of 40,578 tons of CO_2 removals allocated to the SAF product. After adjustment of CO_2 emissions from product transportation, a net total of 40,543 tons of CO_2 removals are transferred from the SAF producer's ledger to the airline customer's ledger. A summary of the E-asset and E-liability accounting for the complete supply chains for SAF and conventional jet fuel, as well as final transfers to the airline customer, is provided in Appendix B.

Key comparisons: Both ledgers illustrate the transfers of CO_2 emissions (including the net CO_2 emissions resulting from CO_2 removals) are transferred from the ledgers of suppliers to the SAF producer. Both ledgers also show the allocation of emissions to the SAF product and the transfer of the resulting total of 40,543 tons of net negative CO_2 emissions from the SAF producer ledger to the customer ledger. The stocks and flows ledger records additional detailed transactions, drawing from the detailed data from the carbon mass balances on the individual sources of attributed CO_2 emissions and the conversion of carbon content to CO_2 emissions. The stock and flows ledger also provides information on carbon content of the product streams to enable customers to estimate future CO_2 emissions product usage. Only CO_2 emissions are included in the E-liability records. Data on carbon content of fuels, materials, and products that would allow for reconciliation of the mass and energy balances are separate.

Flow diagram of all CO_2 emissions: Figure ES-3 illustrating all sources of CO_2 emissions at each stage of the SAF production process. In the figure below, the CO_2 emissions data is extracted from the detailed carbon mass and energy balances displayed in Figure ES-2.

Figure ES-3. **ALL STREAMS OF CO_2 EMISSIONS DERIVED FROM LEDGER TRANSACTIONS**



Source: Sesame Sustainability.

The figure provides a complete picture of the CO_2 emissions attributed to and transferred from suppliers along with supply chain materials, direct CO_2 emissions from SAF production, allocation of CO_2 emissions among products, and CO_2 emissions transferred to the ledgers of customers along with final products.

This data provides the basis for all reports on entity-level total emissions and product CO_2 emissions intensity metrics described in the next section.

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

The ledger is technology neutral and agnostic with respect to its application. It provides a data set that is universal to a variety of reporting formats and is agnostic with respect to management or policy applications. Figure ES-3 and Table ES-2, described below, illustrate several different reporting formats for the CO_2 emissions accounting data.

Figure ES-4 illustrates a sample report on product CO_2 emissions intensities that could be provided to management and to customers. The product CO_2 emissions intensity reports include total CO_2 emissions as well as a disaggregation of the total among attributed CO_2 emissions from the supply chain and direct CO_2 emissions intensities from production of final products—conventional jet fuel, SAF (and its byproducts), and the resulting SAF blend. The resulting product CO_2 emission intensities show that a 50-50 SAF blend reduces the CO_2 emissions intensity by 209% relative to conventional jet fuel.

Figure ES-4. **PRODUCT CO_2 EMISSIONS INTENSITY REPORTS DERIVED FROM THE LEDGER**

Jet fuel producer

Conventional jet fuel CO_2 intensity

Direct, entity-specific CO_2 emissions:	0.55 $kgCO_2$/gal
Feedstock CO_2 emissions transferred from suppliers' ledgers:	
Raw materials:	0.84 $kgCO_2$/gal
Energy (gas +electricity)	0.02 $kgCO_2$/gal
Product CO_2 emissions intensity:	1.41 $kgCO_2$/gal

* Emissions intensity reports on other refinery products (gasoline, diesel etc.) are not shown

SAF producer

SAF CO_2 intensity

Direct, entity-specific CO_2 emissions:	2.28 $kgCO_2$/gal
Feedstock CO_2 emissions transferred from suppliers' ledgers:	
Raw materials:	-7.01 $kgCO_2$/gal
Energy (gas +electricity)	0.22 $kgCO_2$/gal
Product CO_2 emissions intensity:	-4.5 $kgCO_2$/gal

LPG CO_2 intensity

Direct, entity-specific CO_2 emissions:	0.21 $kgCO_2$/gal
Feedstock CO_2 emissions transferred from suppliers' ledgers:	
Raw materials:	-0.66 $kgCO_2$/gal
Energy (gas +electricity)	0.02 $kgCO_2$/gal
Product CO_2 emissions intensity:	-0.43 $kgCO_2$/gal

Naphtha CO_2 intensity

Direct, entity-specific CO_2 emissions:	0.16 $kgCO_2$/gal
Feedstock CO_2 emissions transferred from suppliers' ledgers:	
Raw materials:	-0.49 $kgCO_2$/gal
Energy (gas +electricity)	0.01 $kgCO_2$/gal
Product CO_2 emissions intensity:	-0.32 $kgCO_2$/gal

SAF blend supplier

SAF blend (50:50) CO_2 intensity

Direct, entity-specific CO_2 emissions:	1.42 $kgCO_2$/gal
Feedstock CO_2 emissions transferred from suppliers' ledgers:	
Raw materials:	-3.08 $kgCO_2$/gal
Energy (gas +electricity)	0.12 $kgCO_2$/gal
Product CO_2 emissions intensity:	-1.54 $kgCO_2$/gal

Source: Sesame Sustainability.

Complete and transparent reports of CO_2 emissions intensity provide important information to both the SAF producer as well as the customer airline. For the airline customer, the product CO_2 emissions intensity report provides the data needed to support its own strategic planning and marketing objectives, including its willingness to pay for lower carbon differentiated products. For the SAF producer, the product CO_2 emissions intensity provides a key performance indicator to identify and assess opportunities to reduce product CO_2 emissions intensity through the implementation of additional decarbonization strategies. These strategies could include, for example, the purchase of lower CO_2 emissions intensity feedstocks or electricity, or the abatement of CO_2 emissions generated from the SAF production process.

Table ES-3 provides a sample comprehensive CO_2 emissions statement of direct CO_2 emissions by the SAF producer, CO_2 emissions attributed to energy and materials supply chains (and transferred from supplier ledgers), as well as the allocation of the entity-level totals to products.

Table ES-3. **SAF PRODUCER'S ENTITY-LEVEL AND PRODUCT-LEVEL TOTAL CO_2 EMISSIONS REPORT**

	Emissions category	Value	Allocation rate
Direct CO_2 emissions	Direct CO_2 emissions allocated to **SAF** product	20,492 tCO_2	85.9%
	Direct CO_2 emissions allocated to **LPG** product	1,934 tCO_2	8.1%
	Direct CO_2 emissions allocated to **naphtha** product	1,441 tCO_2	6.0%
	Total ***entity-level*** direct CO_2 emissions	23,867 tCO_2	100%
Attributed CO_2 emissions	Attributed CO_2 emissions allocated to **SAF** product	-61,070 tCO_2	85.9%
	Attributed CO_2 emissions allocated to **LPG** product	-5,765 tCO_2	8.1%
	Attributed CO_2 emissions allocated to **naphtha** product	-4,293 tCO_2	6.0%
	Total ***entity-level*** direct CO_2 emissions	-71,128 tCO_2	100%
Transport CO_2 emissions	CO_2 emissions from transporting **SAF** sold to customer	35 tCO_2	Actual value
Total CO_2 emissions (direct CO_2, attributed CO_2 and transport CO_2 emissions)	Total CO_2 emissions allocated to **SAF** product	-40,543 tCO_2	NA
	Total CO_2 emissions allocated to **LPG** product	-3,830 tCO_2	NA
	Total CO_2 emissions allocated to **naphtha** product	-2,853 tCO_2	NA
	Total ***entity-level*** direct CO_2 emissions	-47,226 tCO_2	NA

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

I. Introduction

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

SAF is one of the only viable near-term option to decarbonize the aviation sector, as alternative technologies—such as hydrogen- or electricity-powered planes—are not yet technologically mature. In the United States, aviation accounts for about 3% of total greenhouse gas (GHG) emissions.[7] With U.S. air travel growing at an annual rate of 2% to 3%, aviation-related emissions are projected to nearly double by 2050 without significant decarbonization efforts.[8] Globally, emissions from international aviation are expected to more than double by 2050 without additional policies or actions.[9]

SAF is not scaling rapidly because of a range of challenges, including high production costs, limited infrastructure, and uncertain long-term demand for this lower-emission alternative. The United States has supported SAF production through federal tax credits, the Renewable Fuel Standard (RFS), and state-level incentives. However, these efforts have been hampered by the absence of a unified carbon accounting standard to accurately measure the carbon intensity (CI) of different SAF pathways. For example, determining CI values for SAF under the clean fuel production credit (Section 45Z) has revealed mixed views among stakeholders regarding which models and methodologies should be used. In addition, airline customers need reliable CI data to justify paying a premium for SAF-fueled flights. For these reasons, establishing a standardized carbon accounting framework for SAF is essential to unlocking demand, ensuring policy consistency, and enabling market growth.

At its core, ledger-based carbon accounting treats carbon like financial accounting treats money—every transaction is recorded, transfers between entities are tracked, and complete balances are maintained. Carbon ledgers track carbon flows through emissions by species—carbon dioxide (CO_2), methane (CH_4), carbon monoxide (CO), volatile organic compounds (VOCs)—and carbon content (future emissions potential).

The key innovation in the ledger-based carbon accounting is the carbon ledger itself: a systematic, transaction-based record that captures all carbon movements within defined entity boundaries and time periods.[ii] Unlike current GHG inventories, the ledger approach requires tracking of carbon as it is transferred from supplier to producer to customer. This creates an unbroken chain of custody and accountability throughout the supply chain. The elegance of this ledger-based innovation is that it parallels how businesses record financial transactions today, and can therefore scale by building on existing enterprise systems for recording transactions.

This case study demonstrates these concepts through an SAF supply chain, showing how:

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

The implementation follows the eight core principles of carbon accounting, outlined in the EFI Foundation report *Framework for a Comprehensive New Product- and Entity-Level, Ledger-Based Carbon Accounting System.* The principals are: accuracy (using verified emissions factors), completeness (tracking all carbon sources), transparency (providing detailed documentation), comparability (applying consistent methods), relevance (including all material flows), materiality (focusing on significant impacts), unbiasedness (using neutral data sources), and verifiability (creating transparent and accurate records). By walking through actual ledger entries, carbon transfers, and allocation methods, this case study bridges the gap between the theoretical framework and practical implementation, demonstrating how ledger-based carbon accounting can provide the foundation required for emerging carbon-differentiated commodities and products.

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ii Appendix A illustrates the carbon ledger of the SAF producer assumed in this study.

iii 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 an SAF supply chain centered on a hypothetical hydrotreated esters and fatty acids (HEFA)[iv] production facility in Great Falls, Montana, a location representative of regions where SAF production naturally emerges because of the agricultural feedstock supplies, natural gas resources, and existing energy infrastructure. While the facility configuration is hypothetical, all technical parameters, conversion efficiencies, and carbon intensity values are derived from authoritative sources including Argonne National Laboratory's GREET model pathways,[v] U.S. Environmental Protection Agency (EPA) Emissions & Generation Resource Integrated Database (eGRID) data for regional electricity emissions, and peer-reviewed literature on HEFA process performance. The supply chain encompasses multiple entities across the value chain, from agricultural feedstock producers and utilities to the final airline customer. The system demonstrates the flow of carbon emissions and physical materials through a multi-entity network under free on delivery (FOD) accounting terms.

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

The case study assumes three primary upstream suppliers providing essential inputs from distinct geographic locations (see Figure 1). Natural gas is assumed to originate from the Williston Basin in northeastern Montana, the region's primary extraction hub, and travel via pipeline to the Great Falls facility. Soybean oil feedstock is modeled as sourced from a soybean processing plant in Spiritwood, North Dakota, and transported by rail to the production site. A regional electric utility supplies grid power to the facility operations. These materials flow to the central SAF production facility, which converts raw inputs into multiple hydrocarbon products through the HEFA process. The facility's jet fuel output is then transported by truck to a blending terminal before being sold to airline

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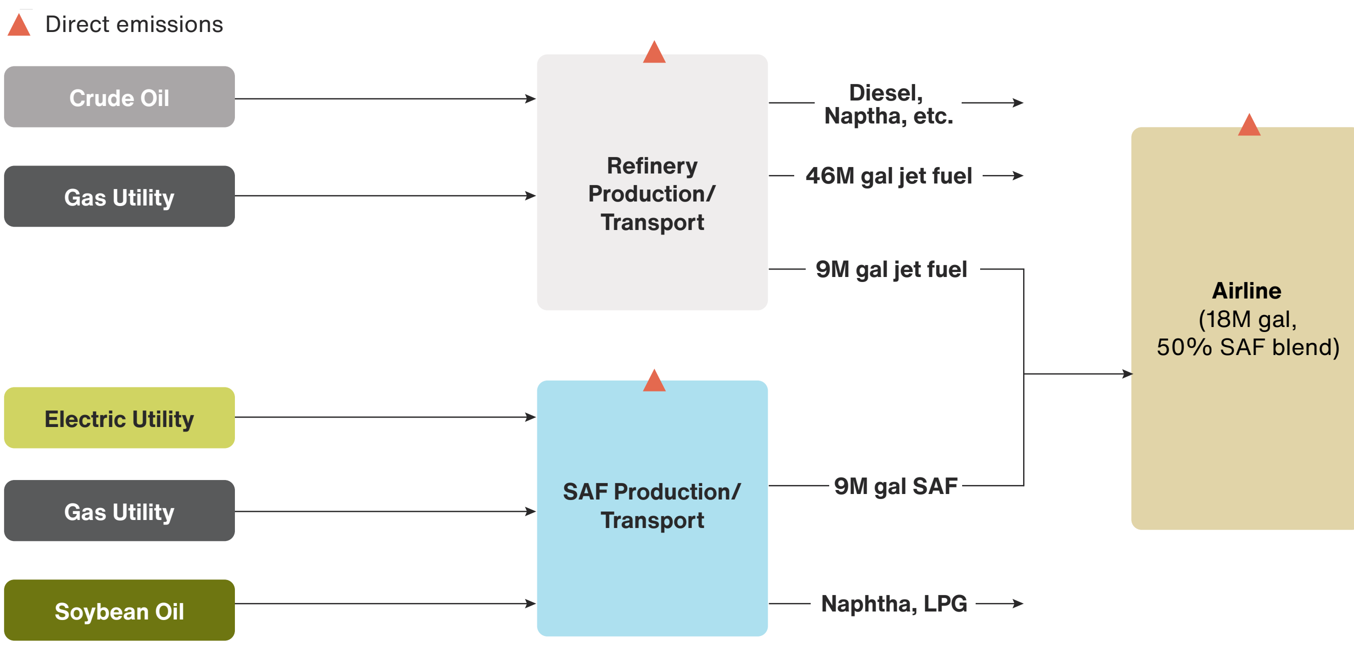
iv Hydrotreated esters and fatty acids (HEFA) is one of the pathways to produce sustainable aviation fuel, refining vegetable oils, waste oils, or fats into SAF through a process using hydrogen.

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

customers, who blend it with conventional jet fuel produced at a standard coking refinery before pipeline transport to a nearby airport and combustion in flight operations.

The integrated supply chain structure creates multiple emissions transfer points where responsibility shifts between entities. Each supplier maintains its own **gate-to-gate** (plus cradle-to-gate from its sub-tier suppliers) accountability for its products before transfer to the SAF producer, which receives both physical materials and their associated carbon footprints from all upstream suppliers. The SAF producer then accounts for these inherited emissions plus its own gate-to-gate operational emissions. The airline customer represents the final link in the chain, receiving blended fuel with its full cradle-to-gate carbon footprint and managing combustion emissions during flight operations.

Figure 1. **OVERVIEW OF FUEL SUPPLY CHAINS AND ENTITY LEDGER RELATIONSHIPS FOR ONE QUARTER**



Source: Sesame Sustainability.

System Boundaries and Accounting Entity Structure

The carbon accounting framework recognizes multiple distinct entities with specific responsibilities, with the exact number depending on supply chain configuration. In this case study, suppliers (soybean oil producers, natural gas suppliers, and electric utilities) own carbon associated with their respective production processes, including captured and stored biogenic carbon , upstream extraction/processing emissions, and direct land use change emissions.[vi] The SAF production facility accounts for direct processing emissions plus transferred upstream emissions from all feedstock suppliers. In parallel, the conventional refinery processes crude oil and allocates emissions across multiple petroleum products including jet fuel. The airline (end user) manages both distribution/ blending operations and final fuel consumption, receiving products from the SAF facility and conventional refinery before blending and combustion.

Emissions transfers occur at delivery points consistent with financial transactions, with the free on delivery structure ensuring transportation emissions remain with the supplying entity until transfer of custody. Under FOD terms, the seller retains ownership and responsibility for goods—including associated emissions—until delivery at the buyer's location. This means transportation emissions are attributed to the upstream entity delivering the product. Key transportation segments include natural gas pipeline transport (gas utility is responsible), bio-oil rail transport to the HEFA facility (bio-oil producer is responsible), jet fuel truck transport to the airline blending terminal (SAF producer is responsible), and terminal to airport delivery (airline is responsible).

SAF Producer Feedstock and Supplier Relationships

The SAF producer has established supply agreements with multiple upstream entities to secure the three critical inputs required for HEFA processing. Each upstream entity reports full cradle-to-gate emissions by species (CO_2, CH_4, CO, VOCs) for its delivered products:

Soybean oil supplier: The facility sources soybean oil feedstock from agricultural commodity suppliers. For simplicity, the soybean oil entity is assumed to own the entire farming and processing value chain, from seed planting through oil extraction and delivery. The reported carbon intensity for soybean oil is negative per our system because the accounting includes biogenic carbon sequestration during soybean cultivation, where growing plants remove CO_2 from the atmosphere. This cradle-to-gate assessment encompasses all agricultural operations, processing energy, and transportation to the facility gate.

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vi The soybean oil carbon intensity value includes direct land-use change (DLUC) emissions but excludes indirect land-use change (ILUC) effects. We acknowledge that some SAF emissions quantification schemes—such as the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) and R&D GREET—incorporate ILUC factors. However, under carbon accounting—following an attributional approach with a gate-to-gate boundary—ILUC emissions are excluded because they lie outside the boundaries of any individual entity in the supply chain and are consequential emissions—indirect impact evaluated against a counterfactual baseline.

Natural gas supplier: The natural gas provider delivers fuel via pipeline to the SAF facility. The supplier reports full cradle-to-gate emissions covering upstream extraction, processing, pipeline transportation, and delivery to the facility. Natural gas serves dual purposes in the HEFA process: steam methane reforming (SMR) to produce unabated hydrogen[vii] required for hydroprocessing reactions, and combustion to generate process heat and steam for the various thermal processing steps.

Electricity supplier: The regional utility provides grid electricity to power facility operations. The reported carbon intensity reflects the full cradle-to-gate emissions from the utility's generation portfolio, including fuel extraction, processing, transportation, power generation, and transmission and distribution.

SAF Production Process

Soybean oil and other bio-oils can be converted into high-value hydrocarbon blends via hydroprocessing, specifically hydrotreated esters and fatty acids (HEFA) processing. The HEFA process consists of three main stages that transform raw bio-oils into finished hydrocarbon products. Raw bio-oils are pretreated to remove impurities and prepare them for hydroprocessing. SMR produces unabated hydrogen from natural gas, which is then used in hydrodeoxygenation, isomerization, and hydrocracking reactions to convert the pretreated feedstock. Natural gas also generates process steam required for various thermal processing steps within the HEFA facility. The processed stream of materials is separated into various hydrocarbon products, including jet fuel, naphtha, and liquefied petroleum gas (LPG), through product separation and purification systems.

Upstream and direct emissions are allocated among these co-products via energy-based allocation (i.e., fuel energy content based on its lower heating value).[viii] The SAF jet fuel product is sold directly to a single airline customer, facilitating clear emissions transfer accountability and product traceability through the supply chain. The other co-products and their attributed carbon emissions remain on the SAF producer's ledger until sale.

SAF Distribution, Blending, and End Use

The airline customer purchases SAF from the producer and manages the subsequent blending and distribution operations. For this analysis, the airline is assumed to own the blending operations and pipeline transport from the blending

vii In this case study, hydrogen production from SMR does not assume use of additional low-carbon technologies (e.g., carbon capture and storage) to reduce the carbon intensity of hydrogen.

viii Energy-based allocation assigns emissions proportionally based on the energy content (lower heating value) of each co-product. This approach is appropriate for fuel products where the primary value derives from combustion energy. For HEFA processing, jet fuel, naphtha, and LPG each receive emissions proportional to their share of total energy output. Alternative allocation methods include mass-based allocation (appropriate for non-energy commodities where physical quantity drives value) or economic allocation (based on market prices). The chosen allocation method significantly impacts calculated carbon intensities and must be clearly documented for accounting transparency.

terminal to the airport, taking responsibility for the volume, downstream activities, and their associated emissions.

The produced SAF undergoes 50% blending with conventional jet fuel, procured from a different supplier, creating 18 million U.S. gallons of total blended fuel for consumption. This blending requirement aligns with ASTM D7566 specifications, which currently limit HEFA-derived SAF to a maximum 50% blend ratio to ensure compatibility with existing aircraft and infrastructure.[ix,10] The blending process creates a drop-in fuel that meets aviation specifications while also providing carbon intensity benefits compared with conventional jet fuel alone. The airline uses the blended fuel across its flight operations, where combustion emissions become part of its direct operational footprint.

While this case study tracks carbon from feedstock through combustion, intermediate operations at the airport—fuel storage, hydrant distribution, and refueling vehicles handling the blended fuel—are excluded for simplicity. The ledger-based framework could readily incorporate these activities as additional transfer points between airport delivery and aircraft tanks, though their contribution to total life cycle emissions would be minimal.

Conventional Jet Fuel Production and Distribution

The conventional jet fuel pathway begins with crude oil extraction from the Bakken formation on the Montana/North Dakota border. This light, low-sulfur crude yields a high proportion of transportation fuels and is transported to the Par Montana Refinery in Billings, Montana. The refinery configuration includes a delayed coker, fluidized catalytic cracker, catalytic reformer, and standard hydrotreating units, representing a higher-complexity facility.

The refinery produces multiple products from the crude oil feedstock: gasoline, jet fuel, diesel, heavy fuel oil (HFO), residual fuel oil (RFO), hydrogen, and coke. Process heat and electricity for refinery operations come from an on-site natural gas power plant, which represents the primary source of facility emissions. These direct emissions are allocated across all refinery products using process energy allocation methodology: Each product stream receives a share of total emissions based on the cumulative energy required for its pathway through specific refinery subunits. Complex products like gasoline require more energy-intensive processing through multiple units compared to simpler products like jet fuel. The jet fuel portion then travels to blending terminals where it serves as the conventional component for SAF blending before final distribution to airports. This multi-product refinery configuration demonstrates how conventional jet fuel production is integrated within a complex petroleum refining system, where emissions allocation across co-products becomes critical for accurate carbon accounting.

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ix Under ASTM D7566 Annex 2, HEFA-derived SAF must be blended with conventional jet fuel at a maximum ratio of 50%. Once blended and meeting ASTM D7566 requirements, the fuel automatically receives ASTM D1655 certification, making it a fully compliant drop-in replacement for conventional Jet A/A-1 fuel.

III. Sesame One Modeling Engine

Sesame One is an industrial decarbonization platform that combines emissions modeling based on life cycle analysis, techno-economic analysis, and system optimization into a single, consistent platform. The technology integrates plant-level information with rich databases and flexible first-principles models to capture key technical, economic, and regulatory considerations across energy transition investments.

Sesame One employs a comprehensive bottom-up molecular accounting approach to resolve mass and energy balances across the conventional jet fuel and HEFA pathways, transport systems, and emissions tracking. This modeling framework provides the analytical foundation for the carbon accounting demonstrated in this case study through two integrated components:

Mass and Energy Balance Resolution

The primary balance calculations resolve fundamental process relationships across the SAF production system. For the HEFA facility, the model calculates feed and product rates based on reaction stoichiometry and thermal efficiency parameters, with reaction yield and product recovery parameters dictating net process conversion from soybean oil feedstock to jet fuel, naphtha, and LPG products. The system also tracks fuel and electricity consumption requirements, accounting for natural gas utilization in both unabated hydrogen production through steam methane reforming and process heat generation.

Transport models incorporate the spatial logistics demonstrated in this case study, including natural gas pipeline transport, bio-oil rail transport, and downstream fuel distribution. The framework includes energy intensity calculations and process combustion tracking for each transport mode, ensuring comprehensive coverage of transport-related emissions. The models account for product loss and recovery balances across these transport segments, ensuring mass balance closure from feedstock origins to final delivery points.

Closed mass balances are critical for entity-level carbon accounting, ensuring that a majority of carbon atoms are tracked throughout the process and preventing discrepancies or double counting between input and output streams. This first-principles approach enables confident emissions calculations and accurate carbon allocation across co-products, clearly tracking how soybean oil carbon is distributed among jet fuel, naphtha, and LPG outputs.

Greenhouse Gas Emissions Tracking

Sesame One tracks multiple emissions species throughout the supply chain, including carbon dioxide (CO_2), methane (CH_4), carbon monoxide (CO), nitrous oxide (N_2O), sulfur oxides (SO_x), and volatile organic compounds (VOCs). For this carbon accounting case study, we focus specifically on carbon-containing species, calculating direct emissions from the production of conventional jet fuel and natural gas combustion in the HEFA process, with carbon balances closed via carbon mass accounting for all hydrocarbon fuels. The system applies emissions factors based on specific technologies, drawing from authoritative sources including Argonne National Laboratory data.

Carbon-containing emissions species are tracked individually by species (CO_2, CH_4, CO, VOCs) with their carbon mass equivalents calculated—using carbon mass ratios, not global warming potentials (GWPs)—enabling the mass balance closure approach demonstrated in the physical carbon content calculations. This ensures that constituent emissions from sources like methane leakage are properly accounted for by species in carbon mass equivalent terms for comprehensive emissions reporting and consistent accounting framework application. The framework tracks carbon whether emitted as CO_2, leaked as methane, or embedded in products, maintaining carbon atom accountability throughout the system.

IV. Case Study Inputs and Assumptions

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

Carbon Emissions Intensities of Feedstock and Fuels

Table 1 presents attributed emissions by species (well-to-gate emissions already released during production) for each input. Diesel carbon intensity uses the R&D GREET 2024 well-to-pump standard pathway result reported in CO_2 mass equivalent (CO_2e) terms, applied for both locomotive and truck transportation modes. Natural gas carbon intensity follows the GREET 2024 well-to-gate pathway for conventional natural gas (NG) up to the pipeline delivery point, also reported in CO_2 mass equivalent terms. Electricity carbon intensity is based on Montana-specific grid emissions factors derived from National Renewable Energy Laboratory (NREL) projections. This value is assumed for all processes using electricity throughout the supply chain. To provide a fossil fuel baseline for comparison with sustainable aviation fuel pathways, conventional jet fuel carbon intensity is modeled and similarly employs GREET 2024 data for crude and fuel feedstock emissions intensities. Soybean-based bio-oil upstream emissions include the emissions from fertilizer use, farming and harvesting equipment, and the oil production process, while also accounting for biogenic carbon sequestration during soybean growth, where atmospheric CO_2 is captured and stored in plant biomass.

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

Feedstock/fuel	Product carbon emissions intensity (cradle-to-gate)	Source(s)	Details
Electricity	• 363.81 grams (g) of CO_2 per kilowatt-hour (gCO_2/kWh) • 0.59 gCH_4/kWh • 0.12 gCO/kWh • 0.03 gVOC/kWh	Argonne GREET Model, 2024[11]	GREET 2024 "wall outlet" emissions at user site. Montana grid mix derived from NREL Standard Scenarios 2023 Mid-case for 2024: 40% hydroelectric, 34% coal, 22% wind, 4% solar photovoltaic, 1% natural gas. Includes upstream and direct emissions.
Natural gas	• 4.53 gCO_2 per megajoule (MJ) • 0.11 gCH_4/MJ • 0.01 gCO/MJ • 0.01 gVOC/MJ	Argonne GREET Model, 2024	Standard North American natural gas pathway (75% shale gas, 25% conventional). Well-to-gate emissions include extraction and processing. Combined methane leakage rate of 0.48% across recovery/processing.
Bio-oil (soybean)	• -2,071 gCO_2 per kilogram (kg) • (-2,842 g/kg for biogenic carbon, 771.5 g/kg for farming, DLUC, and processing) • 0.52 gCH_4/kg • 0.47 gCO/kg • 0.68 gVOC/kg	Farming & oil processing: Argonne GREET Model, 2024 DLUC: Alcock et al., 2022[12]	Includes: Soybean farming, soy oil extraction and relevant transportation steps, and DLUC of 0.52 $kgCO_2e$/kg oil, representative of a cool, reduced till soil environment in the USA. ILUC not considered.
Diesel	• 12.01 gCO_2/MJ • 0.10 gCH_4/MJ • 0.01 gCO/MJ • 0.01 gVOC/MJ	Argonne GREET Model, 2024	Standard well-to-distribution-gate pathway.
Conventional Bakken crude	• 6.06 gCO_2/MJ • 63.7 gCH_4/gigajoule (GJ) • 3.8 gCO/GJ • 0.1 gVOC/GJ	Argonne GREET Model, 2024	Crude extraction emissions derived from GREET petroleum pathway. Crude Assay data gathered from Chevron's Assay Library.

Transportation Parameters and Modeled Carbon Intensities

Transportation carbon intensities are calculated using energy consumption and operational characteristics of each transport mode. For the SAF pathway, bio-oil rail transport uses a diesel-powered locomotive with an energy intensity of 179 kJ/ton·km (273 Btu/ton·mile)[x] over a distance of 500 miles from feedstock processing facilities to the HEFA refinery. Heavy-duty truck transport for jet delivery from both the SAF plant and refinery employs diesel fuel with a fuel economy of 7 miles per gallon, carrying a payload of 25 tons over a 20-mile distance from the refinery to distribution terminals, with back-haul trip emissions excluded. For the conventional jet pathway, crude oil transport emissions factors are derived from the default, average GREET U.S. Crude Transport Pathway,[13] while refined jet fuel moves 20 miles by truck to blending terminals. Natural gas pipeline transport operates over a distance of 300 miles with an energy intensity of 1.64 Btu/kgNG·mile,[xi] using 98% natural gas fuel share (balanced by electricity) with methane leakage rates of 0.26% per 680 miles. Terminal to airport pipeline transport for both SAF and conventional jet fuel covers a short 5 mile distance with electricity requirements of 0.118 kWh/ton·mile for pumping operations, representing final distribution infrastructure. All transport carbon intensities by species include well-to-pump emissions for diesel fuel and well-to-gate emissions for natural gas, consistent with the life cycle boundary definitions applied to feedstock carbon intensity calculations.

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x kJ/ton·km = kilojoules per ton-kilometer, kilojoules needed to transport 1 ton of cargo over 1 kilometer; Btu/ton·mile = British thermal units per ton-mile, Btu of energy needed to transport 1 ton of cargo over 1 mile.

xi Btu/kgNG·mile = British thermal units per kilogram of natural gas per mile, Btu of energy needed to transport 1 kilogram of natural gas over 1 mile.

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

Transport mode	Distance	Modeled transport carbon emissions intensity	Note
Natural gas pipeline	• 300 miles (mi) • 482.8 kilometers (km)	• 27.6 kgCO_2/ton • 1.4 kgCH_4/ton • 348 gCO/ton • 68 gVOC/ton	Pipeline energy intensity and leakage rate consistent with GREET default (Argonne GREET Model, 2024)
Bio-oil rail transport	• 500 mi • 804.7 km	• 12.4 kgCO_2/ton • 16 gCH_4/ton • 8 gCO/ton • 5 gVOC/ton	Railcar energy intensity consistent with GREET default (Argonne GREET Model, 2024)
SAF jet fuel to blending	• 20 mi • 32.2 km	• 1.3 kgCO_2/ton • 1.6 gCH_4/ton • 2.6 gCO/ton • 0.2 gVOC/ton	Payload and fuel economy consistent with GREET pathways (Argonne GREET Model, 2024)
Crude to refinery	• -	• 0.9 gCO_2/MJ • 1.5 gCH_4/GJ • 6.2 gCO/GJ • 1.5 gVOC/GJ	Consistent with GREET Average U.S. Crude Transport Pathway (Argonne GREET Model, 2024)
Crude refinery to blending	• 20 mi • 32.2 km	• 1.3 kgCO_2/ton • 1.6 gCH_4/ton • 2.6 gCO/ton • 0.2 gVOC/ton	Payload and fuel economy consistent with GREET pathways (Argonne GREET Model, 2024)
Terminal to airport pipeline	• 5 mi • 8.05 km	• 214.6 gCO_2/ton • 0.3 gCH_4/ton • 0.1 gCO/ton • 0.02 gVOC/ton	Hydrocarbon pipeline energy intensity consistent with GREET default (Argonne GREET Model, 2024)

SAF Production Models

The steam methane reforming (SMR) process produces hydrogen for the HEFA conversion process, with all process parameters based on the National Energy Technology Laboratory report *Comparison of Commercial, State-of-the-Art, Fossil-Based Hydrogen Production Technologies.*[14] Operating at a baseline cold gas efficiency of 0.72 MJH_2/MJNG,[xii] emissions are modeled from plant data with an overall carbon balance performed to ensure accurate emissions data. A gas boiler efficiency of

xii MJH_2/MJNG = megajoules of hydrogen per megajoule of natural gas.

86% supports steam generation requirements across both processes. Net electricity consumption for the SMR unit is 150 kWh/tonH_2, covering compression, pumping, and control systems.

The HEFA process operates with 94.9% net-carbon conversion efficiency, producing multiple hydrocarbon products through Fischer-Tropsch synthesis. Product distribution by mass includes jet fuel (84.9%), naphtha (6.57%), and light gases/propane (8.35%). The process requires additional hydrogen feed at 0.028 kgH_2/kg bio-oil to achieve complete hydrogenation of the bio-oil feedstock. Electricity consumption for the HEFA unit is 61 kWh/ton of jet fuel, supporting process heating, separation, and product finishing operations. Required process heat is minimal at 4.79 MJ/kg bio-oil due to the exothermic nature of the hydroprocessing reactions and effective heat integration within the process design. Process parameters are consistent with GREET 2024 and CORSIA pathway assumptions, which were developed based on the research of Han et al. (2013) with updated process heat/hydrogen requirements from GREET 2024.[15]

Conventional Jet Refining Models

The conventional jet fuel pathway uses a delayed coking refinery configuration processing Bakken crude oil. The refinery operates with established unit operations including atmospheric distillation, delayed coking, fluidized catalytic cracking, catalytic reforming, and hydrotreating units. Crude assay data determines product cut distributions and properties, while empirical refinery data informs individual unit performance parameters. Refinery process parameters and unit specifications are derived from Kaiser et al. (2020).[16]

The refinery requires 4.52 kWh of electricity and 390.4 MJ of process heat per barrel of crude processed. Process heat generation uses multiple sources: Refinery gas combustion provides 44% of direct facility emissions, while fluid catalytic cracking (FCC) coke combustion contributes 22%. An on-site combined heat and power (CHP) natural gas combined cycle plant operates at 77.9% overall efficiency, providing both electricity and a portion of process heat requirements. Additional process heat needs are met through a natural gas boiler operating at 86% efficiency, consistent with the efficiency parameters used in the SAF facility modeling.

Physical Properties and Physical Carbon Content Calculations

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

Carbon mass ratios are determined from molecular composition analysis, and all species are converted to carbon mass equivalent terms using the molecular carbon content of each species: CO_2 (carbon mass ratio = 0.273, meaning 1 ton CO_2 contains 0.273 tons carbon), CH_4 (carbon mass ratio = 0.750, meaning 1 ton CH_4 contains 0.750 tons carbon), CO (carbon mass ratio = 0.429, meaning 1 ton CO contains 0.429 tons carbon), and VOCs (carbon mass ratio taken to be 0.85, consistent with the GREET model). This standardized approach allows us to compare carbon flows across different emissions species while maintaining mass balance closure where total carbon input equals total carbon output (products + emissions across all species).

Co-product allocation uses lower heating values to distribute both attributed carbon by species and carbon content across jet fuel, naphtha, and LPG based on their relative energy contributions to total product output.

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

Species	Carbon mass ratio	Energy content
Soybean oil	0.776	-
Natural gas	0.722	47.14 MJ/kg
Jet fuel	0.846	142.43 MJ/gallon (gal)
Naphtha	0.856	123.36 MJ/gal
Propane (LPG)	0.816	50.16 MJ/kg
CO_2	0.273	-
Carbon	1	-

Source: R&D GREET 2024.

Accounting Ledger Assumptions

- This case study employs key simplifying assumptions to highlight core emissions transfer principles:
- **Inventory boundaries:** Steady-state operations without beginning inventory, work-in-process, or finished goods storage considerations.
- **Capital equipment:** Property, plant, and equipment (PP&E) attributed emissions are excluded to focus on operational carbon flows.
- **Temporal scope**: Single quarterly production period without seasonal variation considerations.

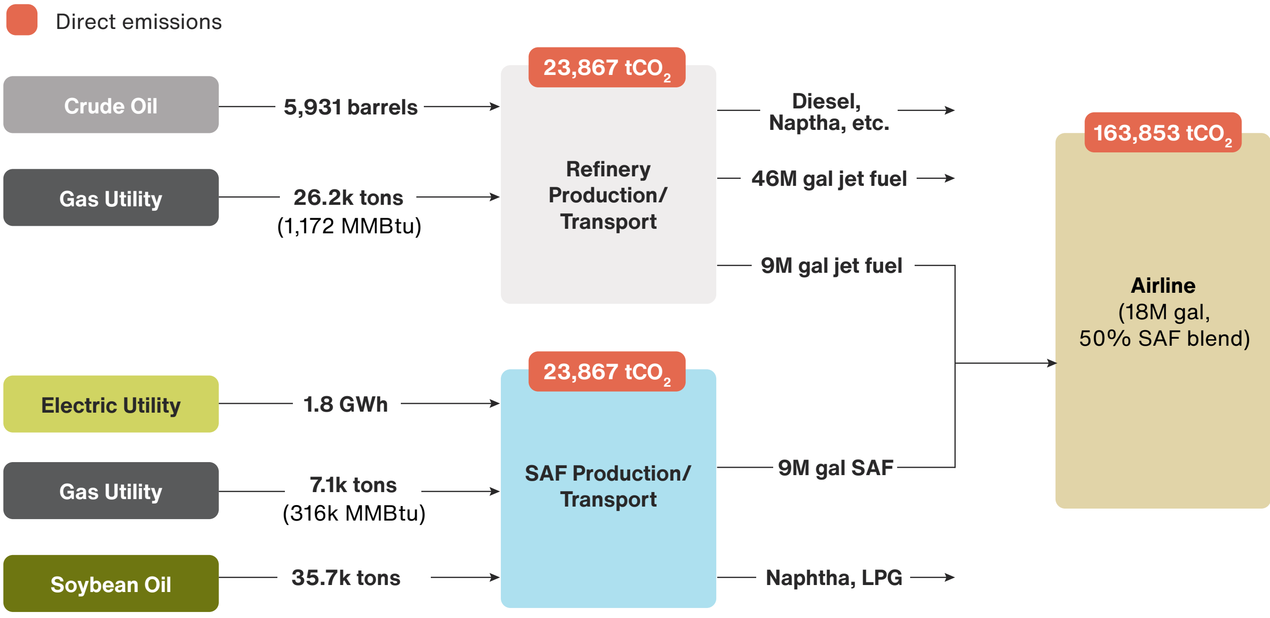
These assumptions allow focus on the essential carbon accounting framework while maintaining analytical clarity for transaction-based emissions transfers.

V. Results and Carbon Impact Analysis

Mass and Energy Balance Overview

The Sesame carbon accounting model generates comprehensive mass and energy balances that form the foundation for emissions allocation and carbon tracking. The quarterly production scenario processes 35,700 tons of soybean oil feedstock along with 7,066 tons (334k GJ) of natural gas and 1.8 GWh of electricity to produce multiple HEFA products. The Fischer-Tropsch synthesis yields approximately 26,440 tons of jet fuel (84.9% by mass), 2,100 tons of naphtha (6.75%), and 2,600 tons of light gases/propane (8.35%), totaling 31,140 tons of hydrocarbon products. The conventional refinery processing 65,000 barrels of crude oil per day produces 175,000 tons of jet fuel (24%), 120,000 tons of diesel (17%), 397,000 tons of gasoline (55%), 16,700 tons of residual fuel oil (2%), 1,430 tons of hydrogen (<1%) and 8,840 tons of coke (1%) quarterly. Of the 175,000 tons of conventional jet fuel produced, 26,500 tons are sent to the case study airline for blending. These mass flows provide the basis for both physical carbon content calculations and energy-based allocation factors used throughout the carbon accounting framework.

Figure 2. **QUARTERLY MASS AND ENERGY FLOWS FOR PARALLEL SAF AND CONVENTIONAL JET FUEL PRODUCTION**



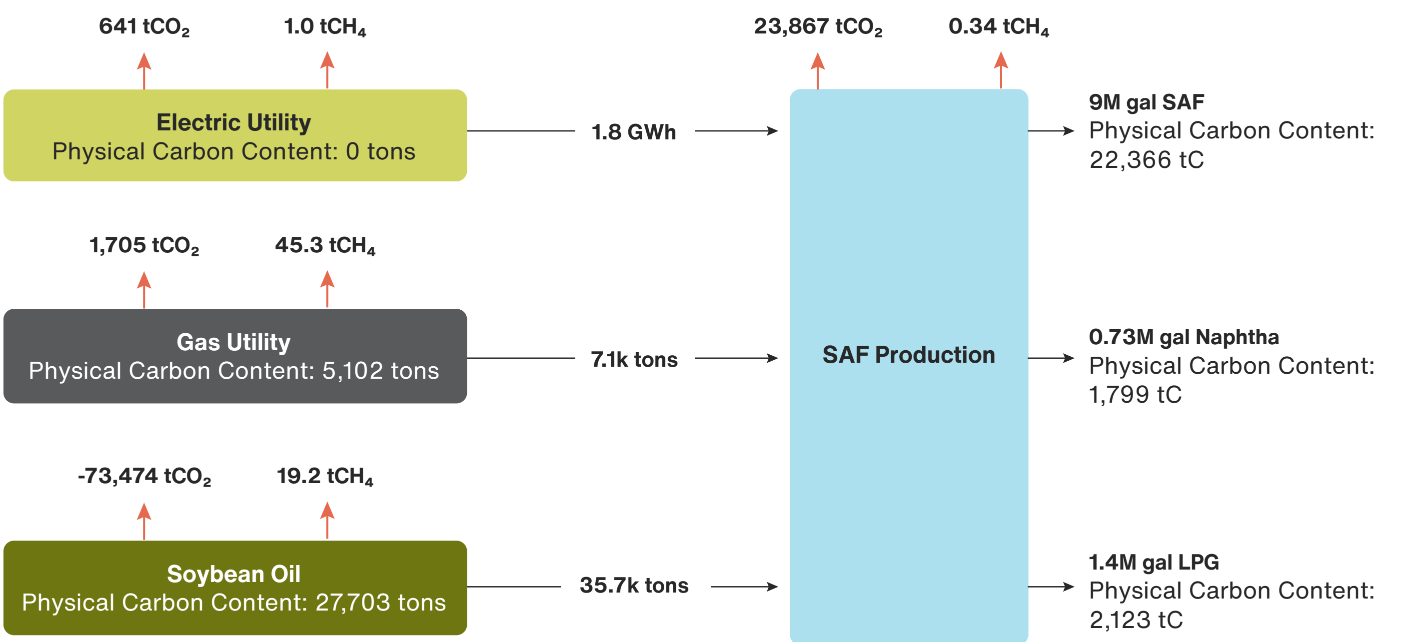
Note: Values shown include material inputs (black) and direct facility emissions (orange). Both provide 9 million gallons of jet fuel to the airline for 50% blending. The refinery produces an additional 46M gallons of jet fuel sold to other airline customers. Only CO_2 emissions shown in figure for clarity. tCO_2 = ton of carbon dioxide; MMBtu = million British thermal units; GWh = gigawatt-hours; gal = gallon. Source: Sesame Sustainability.

SAF Producer Ledger Records and Reporting

Recording Carbon Emissions and Content Transfers In

The quarterly production scenario demonstrates how upstream suppliers transfer both materials and their carbon footprints by species to the SAF producer under the FOD accounting framework. Each input arrives with two carbon components: attributed carbon emissions by species (CO_2, CH_4, CO, VOCs already released from upstream production and transport) and physical carbon content (Figure 3). Attributed emissions from electricity (641 tCO_2 and 1.0 tCH_4), natural gas (1,681 tCO_2 and 44.9 tCH_4), and soybean oil (–73,474 tCO_2 and 19.2 tCH_4) are transferred into SAF production along with these inputs. These attributed emissions, together with the direct emissions from the SAF producer (23,867 tCO_2 and 0.34 tCH_4), are then allocated among the three final products upon completion of production.

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



Note: The diagram illustrates how individual emissions species from upstream suppliers transfer to the SAF facility alongside material flows. CO and VOC are omitted for clarity. Source: Sesame Sustainability.

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

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

Input	Quantity	Attributed CO_2 (tC)	Attributed CH_4 (tC)	Attributed CO and VOC (tC)	Total attributed emissions (tC)	Physical carbon content (tC)
Electricity	1.76 GWh	175.0	0.8	0.1	175.9	0
Natural gas	7,072 tons	465.4	33.9	5.4	504.7	5,101.9
Soybean oil	35,699 tons	(20,058.4)	14.4	28.2	(20,015.8)	27,702.7
Total	-	**(19,418)**	**49.1**	**33.7**	**(19,335.2)**	**32,804.6**

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

The ledger entries in Figure 4 demonstrate the systematic recording of carbon transfers under the FOD framework and would be similar to the financial transactions recorded for price and volume. Corresponding mirror transactions appear on each supplier's ledger, with reverse debits and credits to reflect the transfer from their perspective. Each purchase generates distinct entries in the SAF producer's ledger that maintain carbon accounting integrity:

- **Carbon content transferred in:** The physical carbon atoms embedded in each purchase of materials (27,702.7 tC for soybean oil, 5,101.9 tC for natural gas) are debited to respective stock accounts and are credited to the *Carbon Content Transferred In* account.

- **Emissions transferred in:** The attributed emissions associated with each material are debited separately for CO_2, CH_4, and combined CO & VOCs as to respective stock accounts and are credited to *Emissions Transferred In* account. Notable is the large negative CO_2 attribution for soybean oil (-20,058.4 tC), reflecting net biogenic carbon sequestration during crop growth that offsets processing emissions.

The balanced ledger entries ensure complete carbon accountability—the sum of debits equals credits for each transaction, while individual species tracking provides detailed visibility into the emissions profile of each feedstock. Total attributed emissions of -19,335.2 tC equivalent reflect the significant biogenic credits from soybean feedstock, while 32,804.6 tC of physical carbon content represents the carbon physically contained within the inputs delivered.

Figure 4. **SAF PRODUCER'S CARBON LEDGER ENTRIES FOR SOYBEAN OIL, NATURAL GAS, AND ELECTRICITY PURCHASES**

		Sum of Detailed Columns		Debit (Tons Carbon)				Credit (Tons Carbon)			
Memo	**Account**	**Debit**	**Credit**	**CO_2**	**CH_4**	**CO & VOC**	**Carbon**	**CO_2**	**CH_4**	**CO & VOC**	**Carbon**
Purchase 35.7k tons soybean oil	Carbon Content in Raw Materials	27,702.7	-				27,702.7				
Purchase 35.7k tons soybean oil	Attributed Emissions in Raw Materials	(20,015.8)	-	(20,058.4)	14.4	28.2					
Purchase 35.7k tons soybean oil	Carbon Content Transferred In	-	27,702.7								27,702.7
Purchase 35.7k tons soybean oil	Emissions Transferred In	-	(20,015.8)					(20,058.4)	14.4	28.2	
		7,687.0	**7,687.0**	**(20,058.4)**	**14.4**	**28.2**	**27,702.7**	**(20,058.4)**	**14.4**	**28.2**	**27,702.7**
Purchase 316k MMBtu NG	Carbon Content in Fuels	5,101.9	-				5,101.9				
Purchase 316k MMBtu NG	Attributed Emissions in Fuels	504.8	-	465.4	33.9	5.4					
Purchase 316k MMBtu NG	Carbon Content Transferred In	-	5,101.9								5,101.9
Purchase 316k MMBtu NG	Emissions Transferred In	-	504.8					465.4	33.9	5.4	
		5,606.7	**5,606.7**	**465.4**	**33.9**	**5.4**	**5,101.9**	**465.4**	**33.9**	**5.4**	**5,101.9**
Purchase 1.76 GWh electricity	Attributed Emissions in Electricity	176.0	-	175.0	0.8	0.1					
Purchase 1.76 GWh electricity	Emissions Transferred In	-						175.0	0.8	0.1	
		176.0	**176.0**	**175.0**	**0.8**	**0.1**	**0.0**	**175.0**	**0.8**	**0.1**	**0.0**

Note: Each transaction records debits and credits to appropriate carbon accounts by species, maintaining double-entry accounting principles. Source: Sesame Sustainability.

Recording SAF Production and Allocation

The SAF producer operates as the central transformation point in the supply chain, converting upstream feedstocks into finished hydrocarbon products while maintaining complete carbon accountability through parallel tracking of emissions by species and physical carbon content. The facility receives 32,804.6 tC of physical carbon content (carbon atoms in feedstock molecules) and attributed emissions by species from upstream suppliers (CO_2: -19,418 tC, CH_4: 49.1 tC, CO & VOCs: 33.7 tC, totaling -19,335.2 tC), with the negative CO_2 emissions reflecting substantial biogenic carbon credits from soybean cultivation.

The HEFA facility's operations generate direct emissions (6,515.6 tC of CO_2, 0.3 tC of CH_4, 1.0 tC of CO & VOCs, totaling 6,516.9 tC) through steam methane reforming for hydrogen production and natural gas combustion for process heat.[xiii] These direct emissions combine with upstream attributed emissions for total emissions by species available for allocation across products.

The facility produces three hydrocarbon streams—jet fuel, naphtha, and LPG—totaling 11.1 million gallons of products. Physical carbon content for each product is determined by molecular composition, with jet fuel containing (22,366 tC), naphtha (1,799.2 tC), and LPG (2,122.6 tC) based on their respective carbon ratios. The difference between input physical carbon (32,804.6 tC) and output physical carbon (26,287.8 tC total) represents carbon released during the SMR and HEFA conversion process. Importantly, the ledger system maintains conservation of both physical carbon and attributed emissions. No carbon atoms are created or destroyed, only transformed from feedstock molecules to products and process emissions, while all upstream attributed emissions are fully allocated across products with no loss or double counting.

The ledger system performs species-level allocation for all inputs—raw materials, fuels, and electricity—with each emissions species allocated separately using the same energy-based factors. Appendix A presents the detailed transaction flow:

- Carbon content and attributed emissions are first transferred from stock accounts to work-in-process (WIP) accounts as the materials are used for production.
- When production processes are completed and products are moved to inventory, carbon content and attributed emissions are systematically allocated from WIP accounts to individual product inventory.

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xiii The term tC of CO_2, CH_4, or CO and VOCs indicates that only the carbon portion of each species is accounted for

The following summary presents the total allocated emissions for each product after all allocations are complete:

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

Product	Production	Energy allocation share	Total allocated emissions (tC)	Physical carbon content (tC)
Jet fuel	• 26.4k tons • 9.0M gal • 214k barrels	85.9%	(11,005.5)	22,366.0
Naphtha	• 2.1k tons • 0.73M gal • 17.4k barrels	6.0%	(773.8)	1,799.2
LPG	• 2.6k tons • 1.4M gal • 33.2k barrels	8.1%	(1,038.9)	2,122.6
Total		100%	(12,818.2)	26,287.8

This allocation methodology ensures each product carries forward both its complete production emissions history by individual species and its physical carbon content determined by molecular structure. Transportation emissions to the airline blending terminal are recorded when incurred by the SAF producer and subsequently allocated to the delivered jet fuel product using the same energy-based allocation methodology, ensuring complete cost and emissions accountability through delivery.

Ending Ledger of Carbon Stocks and Flows

Figure 5 summarizes the balances of carbon stocks and flows in the SAF producer's ledger at the end of the first quarter of operation.

Figure 5. **SAF PRODUCER'S QUARTERLY SUMMARY OF ACCOUNT BALANCES**

Carbon stock (ton of carbon)		Carbon flow (ton of carbon)	
Carbon in plant, property and equipment		**Carbon transferred in**	
Attributed emissions in PPE	-	Attributed emissions transferred In	(19,325.4)
Carbon content in PPE	-	Carbon content transferred In	32,804.7
Depreciation	-		
Carbon in Raw Materials Inventory		**Carbon Transferred Out**	
Attributed emissions in raw materials	-	Direct emissions transferred out with product sold	(5,595.3)
Carbon content in raw materials	-	Attributed emissions transferred out with product sold	16,591.2
Carbon in fuels inventory		Carbon content transferred out with product sold	(22,366.0)
Attributed emissions in fuels	-	Carbon offsets transferred out with product sold	-
Carbon content in fuels	-		
Carbon in product inventory		**Carbon offsets**	
Direct emissions in product	921.6	**Carbon removals**	-
Attributed emissions in product	(2,734.2)	**EACs**	-
Carbon content in product	3,921.8		
Carbon offsets in product	-		
Unallocated Overhead			
Direct emissions overhead	-		
Attributed emissions overhead	-		
Carbon offsets overhead	-		
Total emissions	**(1,812.7)**	**Total emissions flow**	**(8,329.5)**
Total carbon content	**3,921.8**	**Total carbon content flow**	**10,438.7**
Total offsets	**-**	**Total offsets flow**	**-**
Total carbon stock	**2,109.2**	**Total carbon flow**	**2,109.2**

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

The cumulative impact of the various transactions described above are reflected in the ledger of carbon stocks and flows at the end of the reporting period. The ending ledger presents a complete view of the SAF producer's carbon balance by detailing the carbon stock held within the entity's boundaries (2,109.2 tC total), as well as the corresponding carbon flows—carbon entering the company (13,479.3 tC transferred in, net) and carbon leaving the company through sold products (11,370.1 tC transferred out with product sold, net).

The ledger entries demonstrate the comprehensive tracking capability of the ledger-based system, showing how 32.8k tC of input carbon from feedstocks is transformed into 3.9k tC of finished product inventory, with the difference representing carbon released as process emissions and carbon transferred out with sold jet fuel. The negative attributed emissions balance (-1,812.7 tC) reflects the substantial biogenic carbon credits from soybean feedstock that remain embedded in unsold inventory.

Drawing from the account balances, the SAF producer can issue both product-level and entity-level reports: *Product Carbon Emissions Intensity Statement*, and *Entity-Level Carbon Emissions Statement* (Figures 6 and 7).

Figure 6. **SAF PRODUCER'S PRODUCT CARBON EMISSIONS INTENSITY STATEMENT FOR THE FIRST QUARTER OF OPERATION**

SAF Producer
Product Carbon Emissions Intensity Statement
Q1 20XX

Sustainable jet fuel	CO_2 intensity ($kgCO_2$/gal)	CH_4 intensity (gCH_4/gal)
Emissions from raw material production and transport	(7.01)	1.83
Emissions from electricity use	0.06	0.10
Emissions from fuel combustion	2.28	0.03
Emissions from fuel production and transport	0.16	4.32
Emissions from production of equipment used	0.00	0.00
Emissions from transport of products	0.004	0.005
Emissions offsets used	0.00	0.00
Product carbon emissions intensity in jet fuel	(4.50)	6.28

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

The product carbon intensity statement demonstrates how the ledger-based system generates comprehensive product-level carbon data directly from recorded transactions. The statement distinguishes between product carbon emissions intensity by species (cradle-to-gate emissions from the production cycle: -4.50 $kgCO_2$/

gal and 6.28 gCH_4/gal) and physical carbon content (physical carbon atoms in the fuel: 2.49 kgC/gal).[xiv] The detailed breakdown by emissions source category enables transparent disclosure of the complete carbon profile across the supply chain, while the species-level reporting provides stakeholders with granular visibility into the emissions composition of the sustainable jet fuel product.

The ledger provides the necessary information for the SAF producer's entity-level carbon emissions reporting as well (Figure 7). The statement categorizes emissions into direct facility operations and attributed emissions from purchased inputs (electricity, raw materials, and fuels), with each category reported by emissions species. This entity-level view provides the foundation for comprehensive carbon disclosure to stakeholders.

Figure 7. **SAF PRODUCER'S ENTITY-LEVEL CARBON EMISSIONS STATEMENT FOR THE FIRST QUARTER OF OPERATION**

SAF Producer
Entity-Level Carbon Emissions Statement
Q1 20XX

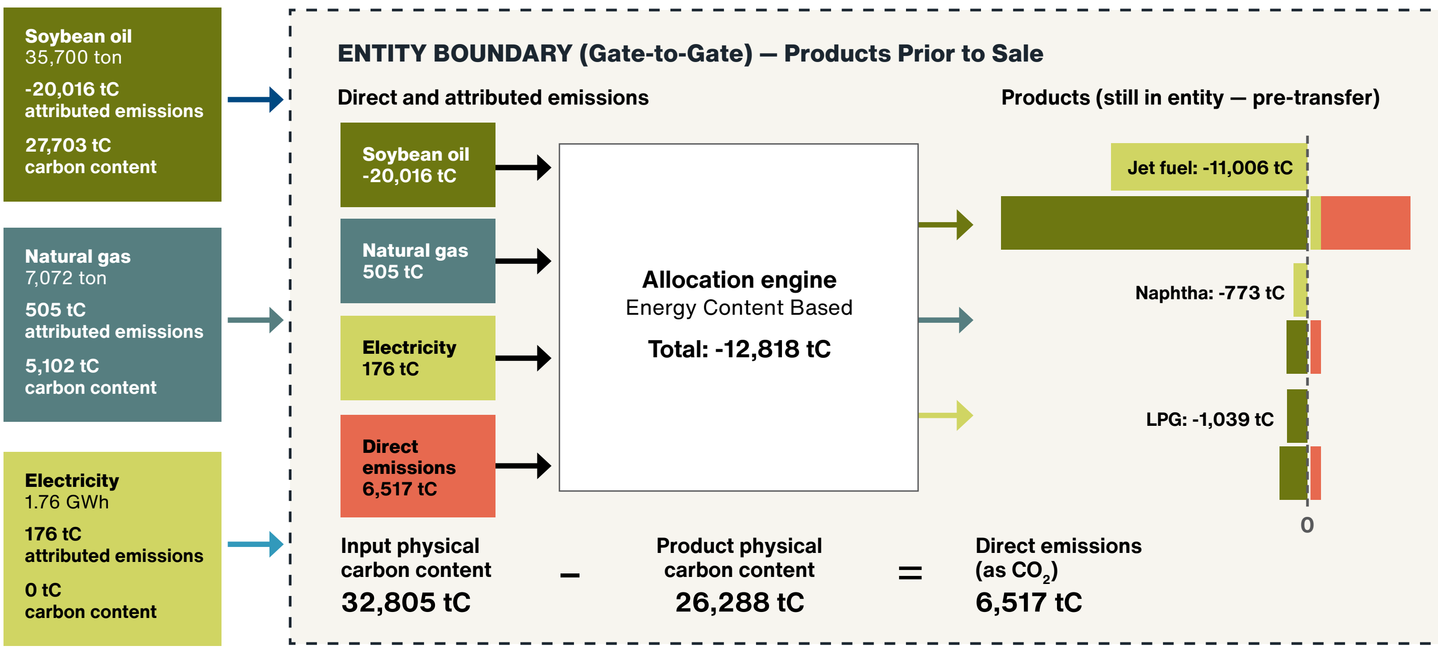
	tCO_2	tCH_4
Direct emissions	**23,866.63**	**0.34**
Attributed emissions		
Emissions attributed to purchased electricity	641.19	1.04
Emissions attributed to purchased machinery	0.00	0.00
Emissions attributed to purchased raw materials	(73,473.97)	19.18
Emissions attributed to purchased fuels	1,704.71	45.26
Total attributed emissions	**(71,128.07)**	**65.48**
Total carbon emissions	(47,261.43)	65.81
Carbon offsets obtained		
Carbon removal	0.00	
Environmental attrbute certificates	0.00	
Total carbon offsets obtained	**0.00**	
Net total carbon emissions	(47,261.43)	65.81

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

xiv Product carbon emissions intensity is measured on a cradle-to-gate basis and differs from the carbon intensity (CI) score, which is calculated on a cradle-to-grave basis. The cradle-to-grave approach includes future emissions that are estimated based on assumptions. The carbon ledger separately reports cradle-to-gate emissions intensity and carbon content, the latter of which may later become gate-to-grave emissions. This approach provides complete emissions accounting without relying on forecasts.

Beyond these two statements, the SAF producer can generate various reports for policy commitments, sustainability disclosures, or internal carbon management. Figure 8 summarizes the carbon information in the SAF producer's ledger, covering both entity-level and product-level emissions and carbon content. With this information, the SAF 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.

Figure 8. **SUMMARY OF CARBON STOCKS AND FLOWS IN THE SAF PRODUCER'S LEDGER**



Jet fuel carbon intensity	
Attributed carbon breakdown	
Raw materials:	-17,185.0 tC
Energy (gas + electric):	584.0 tC
Total attributed emissions:	-16,601.0 tC
Direct emissions:	5,595.0 tC
Total production:	9,000,000 gal
Production carbon emissions intensity:	-1.2 kgC/gal
Production carbon content:	22,366.0 tC

Naphtha carbon intensity	
Attributed carbon breakdown	
Raw materials:	-1,209.0 tC
Energy (gas + electric):	42.0 tC
Total attributed emissions:	-1,167.0 tC
Direct emissions:	394.0 tC
Total production:	730,000 gal
Production carbon emissions intensity:	-1.1 kgC/gal
Production carbon content:	1,799.0 tC

LPG carbon intensity	
Attributed carbon breakdown	
Raw materials:	-1,622.0 tC
Energy (gas + electric):	55.0 tC
Total attributed emissions:	-1,567.0 tC
Direct emissions:	528.0 tC
Total production:	1,400,000 gal
Production carbon emissions intensity:	-0.7 kgC/gal
Production carbon content:	2,123.0 tC

Note: The values in the figure are rounded for clarity. Source: Sesame Sustainability.

Conventional Jet Fuel Producer Ledger Records and Reporting

The conventional refinery operates as a parallel transformation point to the SAF facility, processing 65,000 barrels per day of Bakken crude oil. The facility's quarterly operations yield multiple hydrocarbon products totaling 55 million gallons of jet fuel alongside gasoline, diesel, and other refined products.

Upstream crude emissions are allocated on an energy content basis, and the refinery's operational emissions—including natural gas combustion, refinery gas utilization, and coke combustion—are allocated across products using unit-specific energy requirements. Jet fuel production follows a simplified pathway through atmospheric distillation and kerosene hydrotreating only, while gasoline requires processing through multiple energy-intensive units, including catalytic reforming and FCC operations. This allocation assigns approximately 16% of the net refinery ledger emissions to the 55 million gallons of jet fuel, yielding an emissions intensity of 1.41 kg CO_2/gal.

Figure 9. **REFINERY'S PRODUCT CARBON EMISSIONS INTENSITY STATEMENT FOR CONVENTIONAL JET FUEL FOR THE FIRST QUARTER OF OPERATION**

Refinery
Product Carbon Emissions Intensity Statement
Q1 20XX

Conventional jet fuel	CO_2 intensity ($kgCO_2$/gal)	CH_4 intensity (gCH_4/gal)
Emissions from raw material production and transport	0.84	8.33
Emissions from electricity use	0.0	0.0
Emissions from fuel combustion	0.55	0.0
Emissions from fuel production and transport	0.02	0.09
Emissions from production of equipment used	0.0	0.0
Emissions from transport of products	0.004	4.62
Emissions offsets used	0.0	0.0
Product carbon emissions intensity in jet fuel	1.41	13.04

Note: The statement shows product carbon emissions intensity by species. Product-level carbon intensity calculations show how the facility's total carbon footprint is allocated across all products using energy-based allocation. Only the jet fuel portion transfers to the airline this quarter. Source: Sesame Sustainability.

Of the 62 million gallons of conventional jet fuel produced quarterly, 9 million gallons are designated for blending with HEFA-derived SAF to create the 50% blend required by ASTM specifications. The remaining 53 million gallons enter the market through separate distribution channels. The 9 million gallons transferred for blending carry both their allocated production emissions and physical carbon content, maintaining complete carbon accountability through the supply chain transfer to the airline customer. This parallel tracking enables direct comparison between conventional and renewable pathways while ensuring consistent carbon accounting principles across both production systems.

Airline Ledger Records and Reporting

The airline customer receives both SAF and conventional jet fuel through separate transactions, with each fuel carrying its complete carbon history by species from upstream operations. The ledger-based system tracks carbon transfers at the point of delivery, maintaining full accountability for both physical carbon content and accumulated emissions by species (Figure 10).

Figure 10. **AIRLINE'S CARBON LEDGER ENTRIES FOR SAF AND CONVENTIONAL JET FUEL PURCHASES**

		Sum of Detailed Columns		Debit (Tons Carbon)				Credit (Tons Carbon)			
Memo	**Account**	**Debit**	**Credit**	**CO_2**	**CH_4**	**CO & VOC**	**Carbon**	**CO_2**	**CH_4**	**CO & VOC**	**Carbon**
Purchase 9M gal Jet (SAF)	Carbon Content in Fuels	22,365.97	-				22,365.97				
Purchase 9M gal Jet (SAF)	Attributed Carbon in Fuels	(10,995.86)	-	(11,068.21)	42.41	29.94					
Purchase 9M gal Jet (SAF)	Carbon Content Transferred In	-	22,365.97								22,365.97
Purchase 9M gal Jet (SAF)	Emissions Transferred In		(10,995.86)					(11,068.21)	42.41	29.94	
		11,370.10	**11,370.10**	**(11,068.21)**	**42.41**	**29.94**	**22,365.97**	**(11,068.21)**	**42.41**	**29.94**	**22,365.97**
Purchase 9M gal Jet (Conventional)	Carbon Content in Fuels	22,365.97	-				22,365.97				
Purchase 9M gal Jet (Conventional)	Attributed Carbon in Fuels	3,548.31	-	3,478.52	56.85	12.94					
Purchase 9M gal Jet (Conventional)	Carbon Content Transferred In	-	22,365.97								22,365.97
	Emissions Transferred In		3,548.31					3,478.52	56.85	12.94	
		25,914.28	**25,914.28**	**3,478.52**	**56.85**	**12.94**	**22,365.97**	**3,478.52**	**56.85**	**12.94**	**22,365.97**
Transport 18M gal jet (SAF/ Conventional) to Airport	Transport in Jet	3.11	-	3.10	0.01	0.00					
Transport 18M gal jet (SAF/ Conventional) to Airport	Transport Jet	-	3.11					3.10	0.01	0.00	
		3.11	**3.11**	**3.10**	**0.01**	**0.00**	**-**	**3.10**	**0.01**	**0.00**	**-**
Aircraft Operation/Miles	Attributed Carbon in Operation	(7,447.55)	-	97,589.69)	99.26	42.88					
Aircraft Operation/Miles	Attributed carbon in Fuels	-	(7,447.55)					(7,589.69)	99.26	42.88	
Aircraft Operation/Miles	Transport in Operation	3.11	-	3.10	0.01	0.00					
Aircraft Operation/Miles	Transport in Jet	-	3.11					3.10	0.01	0.00	
Aircraft Operation/Miles	Combustion in Operation	44,731.94	-	44,731.94							
Aircraft Operation/Miles	Carbon Content in Fuels	-	44,731.94								44,731.94
		37,287.50	**37,287.50**	**37,145.35**	**99.27**	**42.88**	**-**	**(7,586.59)**	**99.27**	**42.88**	**44,731.94**

The airline's carbon accounting follows established ledger principles, with each transaction creating balanced entries by species. When the airline purchases 9 million gallons each of SAF and conventional jet fuel, each purchase creates ledger entries for physical carbon content in fuels (representing physical carbon that will be released upon combustion) and attributed emissions by species in fuels (emissions already released during production), both of which are transferred from suppliers. The airline also accounts for its own distribution activities, recording transport emissions by species from terminal to airport via pipeline and attributing these emissions to the fuel inventory through its end use.

When the blended fuel is combusted during flight operations (containing 2.22M GJ lower heating value), the carbon embodied in the fuels is released as direct emissions. For simplicity in this case study, complete conversion of fuel carbon to CO_2 during combustion is assumed, though the exact emissions profile would depend on specific airline operations and aircraft types. The complete ledger documentation ensures traceability of all carbon flows by species, with period subtotals showing 37,145 tC of net CO_2 flows for the quarter. This comprehensive recording system demonstrates how ledger-based carbon accounting maintains the same rigor and auditability as financial accounting, enabling accurate tracking of carbon through complex supply chains.

VI. Summary and Discussion

This case study demonstrates the practical application of a ledger-based carbon accounting system. The system elements—including transfer of custody at delivery points (i.e., clear system boundaries with specific points in time), comprehensive mass balance closure, and allocation mechanisms—ensure accuracy and completeness while enabling comparability across different supply chain configurations. Unlike existing carbon accounting approaches that often rely on estimates or averages, this ledger-based system creates an auditable trail of actual carbon flows, supporting the verifiability essential for market-based carbon differentiation.

The study also confirms that carbon ledgers support the establishment and implementation of a Product Carbon Intensity Standard (PCIS). In this case study, the carbon ledgers provide baseline product carbon intensities for both the SAF producer and the conventional jet fuel producer (Table 6). These baselines can serve as a foundation for each entity to set targets, develop reduction plans, and track progress through periodic reporting.

Buyers of these products also can set their own blending targets and roadmaps, and monitor progress based on suppliers' periodic reporting of product carbon intensities. Policymakers can use these baselines to define PCIS thresholds and design compliance mechanisms. Regular reporting allows policymakers to monitor whether an entity complies with PCIS thresholds, without imposing additional administrative burdens.

Table 6. **BASELINE PRODUCT CARBON INTENSITY FOR SAF AND CONVENTIONAL JET FUEL**

	SAF via HEFA	Conventional jet fuel
Baseline CO_2 intensity (cradle-to-gate)	-4.50 $kgCO_2$/gal	1.41 $kgCO_2$/gal
Baseline CH_4 intensity (cradle-to-gate)	6.28 gCH_4/gal	13.04 gCH_4/gal

An upcoming series of case studies will illustrate how product carbon intensities can be established in different settings—such as the adoption of carbon abatement technologies, the purchase of carbon offsets, the use of material recycling, and the depreciation of equipment and machinery. These case studies will provide insights into establishing baseline intensities across diverse contexts and into improvements in these intensities through the adoption of various strategies.

Quantifying the life cycle GHG emissions of SAF has heavily relied on models used in the GREET methodology and Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) methodology. The LCA emissions vary widely depending on the methodology and model used. For instance, the GREET model estimates corn ethanol's LCA emissions to be 60% lower than CORSIA's estimates, primarily due to differing estimates of indirect land use change (ILUC) emissions.[17] These discrepancies have fueled ongoing debates among stakeholders over model and methodology selection, which remain difficult to resolve because of the differing assumptions and high levels of uncertainty. Given this disagreement, the guidance on clean fuels production credits (Section 45Z), released in January 2025, allows for the use of either the GREET model or the CORSIA methodology to calculate SAF life cycle emissions.

While quantifying ILUC emissions is important, they should not be part of accounting. ILUC emissions occur outside of the boundary of any entity in the SAF supply chain, are consequential, and rely on complex modeling, which is difficult to verify. In this context, the recently passed "One Big Beautiful Bill" excluded ILUC emissions from determining emissions rates under Section 45Z. Instead of incorporating them into accounting, ILUC risks can be addressed through safeguard policies—for example, by disqualifying certain fuels with high ILUC risks from eligibility for clean fuel incentives.

Carbon accounting for products such as SAF should focus on carbon that is directly measurable and verifiable, rather than estimates of consequential emissions. Companies are more willing to invest in emissions reduction and carbon removal when emissions are measurable and within their control. The EFI Foundation's carbon accounting system is designed to support this approach.

Appendix A.
Description of Detailed Ledger Entries

This appendix describes the detailed set of entries to the ledger supporting the summary CO_2 ledger report described in Figure ES-2. As described in the report, the ledger is a dual-sided chart of accounts of all stocks and flows of all forms of carbon entering, processed within, and exiting the entity's boundaries.

For ease of discussion, the ledger entries are divided into two figures. Figure A1 shows the transfer of carbon accounting data from suppliers' ledgers to the entity's ledger and the carbon accounting associated with the SAF production process. The second figure, A2, shows the allocation of the entity's production process to the three products—SAF, LPG, and naphtha—and subsequent transfer of SAF from the entity's ledger to the customer's ledger.

Figure A1 illustrates the set of transactions recorded in the SAF producer's ledger from the point of transfer of feedstocks from suppliers' ledgers through the SAF production process. The SAF producer's ledger assumes that each supplier has its own complete ledger for the feedstocks being supplied to the SAF producer, with CO_2 transactions recorded only once, at the source, and then transferred from the suppliers' ledgers to the SAF producer's ledger.

The first set of transactions in the ledger show the transfer of ledger data (CO_2 emissions attributed to the development of the feedstocks as well as their physical carbon content) of the feedstocks from the suppliers' ledgers to the SAF producer's ledger. The next set of transactions recorded in the ledger show the processing of the feedstock materials in the SAF conversion process, including the conversion of the carbon content in fuels and feedstock to direct CO_2 emissions. All transactions are recorded in double-entry bookkeeping.

The conversion process yields three products: SAF, naphtha, and liquefied petroleum gas (LPG). The ledger shows the total amount of CO_2 emissions attributed to the product slate prior to allocation. Note that all data in the ledger (both emissions and carbon content) are recorded as tons of carbon (tC) to facilitate conversions of carbon content to CO_2 emissions in the same units.

Figure A1. **DETAILED LEDGER ENTRIES FOR TRANSFER OF FEEDSTOCK CO_2 EMISSIONS ATTRIBUTED TO SUPPLIERS FROM THEIR LEDGERS TO THE SAF PRODUCER'S LEDGER, AND CO_2 EMISSIONS GENERATED BY THE CONVERSION OF FEEDSTOCKS TO PRODUCTS (SAF, LPG, AND NAPHTHA)**

Accounting period: one calendar quarter.
All units in tons carbon (tC).

PHASE 1
Transfer feedstock emissions and supporting carbon content from suppliers' ledgers to the SAF producer's ledger

ACCOUNT	DEBIT	CREDIT
Carbon transferred in from sotbean oil supplier		
Feedstock emissions (soybean oil)	**(20,015.8)***	-
Feedstock emissions transferred in	-	**(20,015.8)**
Feedstock carbon content (soybean oil)	**27,702.7**	-
Feedstock carbon content transferred in	-	**27,702.7**
Sum	***7,687***	***7,687***

* Negative emissions resulting from the capture and storage of biogenic carbon during soybean production

ACCOUNT	DEBIT	CREDIT
Carbon transferred in from natural gas supplier		
Feedstock fuels emissions (natural gas)	**504.8**	-
Feedstock emissions transferred in	-	**504.8**
Feedstock fuels carbon content (natural gas)	**5,101.9**	-
Feedstock carbon content transferred in	-	**5,101.9**
Sum	***5,606.7***	***5,606.7***
Carbon transferred in from electricity supplier		
Electricity emissions	**176**	-
Feedstock emissions transferred in	-	**176**
Sum	**176**	**176**

PHASE 2
Conversion of feedstocks to products and direct emissions

ACCOUNT	DEBIT	CREDIT
Moving feedstocks from inventory to production process		
Feedstock emissions (soybean oil) in work-in-process**	**(20,015.8)**	-
Feedstock emissions (soybean)	-	**(20,015.8)**
Feedstock fuels emissions (natural gas) in work-in-process	**504.8**	-
Feedstock fuels emissions (natural gas)	-	**504.8**
Electricity emissions in work-in-process	**176**	-
Electricity emissions	-	**176**
Feedstock carbon content (soybean oil) in work-in-process	***26,287.8***	-
Feedstock carbon content (soybean oil)	-	***26,287.8***
Sum	***6,952.8***	***6,952.8***

** Work-in-process refers to partially completed products. Carbon remains in work-in-process account until production is complete.

ACCOUNT	DEBIT	CREDIT
Direct emissions from production		
Direct entity emissions work-in process	**6,516.9**	-
Feedstock fuels carbon content (natural gas)	-	**5,101.9**
Feedstock carbon content (soybean oil)	-	**1,415**
Sum	***6,516.9***	***6,516.9***

SAF producer's ledger

Note: Each value in this figure represents the total of all carbon forms—CO_2, CH_4, CO, VOCs, and carbon content. The values are aggregated for presentation purposes, while the underlying ledger maintains disaggregated data for each carbon form. The ledger expresses all entries in tons of carbon, serving as a common unit to balance all carbon forms. Source: EFI Foundation and Sesame Sustainability.

Figure A2 shows the allocation of CO_2 emissions among the products, and transfer of the product-based CO_2 emissions to the airline customer ledger.

Figure A2. **DETAILED LEDGER ENTRIES FOR THE ALLOCATION OF ATTRIBUTED AND DIRECT CO_2 EMISSIONS TO PRODUCTS AND TRANSFER TO THE CUSTOMER'S LEDGER WITH PRODUCTS SOLD**

Accounting period: one calendar quarter.
All units in tons carbon (tC).

PHASE 3
Allocation of entity-level carbon to finished product inventory

ACCOUNT	DEBIT	CREDIT
Carbon allocated to SAF inventory		
Direct entity emissions allocated to SAF	5,595.3	-
Direct entity emissions	-	5,595.3
Feedstock emissions allocated to SAF	(17,185.3)	-
Feedstock emissions (soybean oil) in work-in process	-	(17,185.3)
Feedstock fuels emissions allocated to SAF	433.4	-
Feedstock fuels emissions in work-in process	-	433.4
Electricity emissions allocated to SAF	151.1	-
Electricity emissions in work-in process	-	151.1
Feedstock carbon content allocated to SAF	22,366	-
Feedstock carbon content in work-in process	-	22,366
Sum	***11,360.5***	***11,360.5***
Carbon allocated to naphtha inventory		
Direct entity emissions allocated to naphtha	393.4	
Direct entity emissions	-	393.4
Feedstock emissions allocated to naphtha	(1,208.2)	
Feedstock emissions (soybean oil) in work-in process	-	(1,208.2)
Feedstock fuels emissions allocated to naphtha	30.5	
Feedstock fuels emissions in work-in process	-	30.5
Electricity emissions allocated to naphtha	10.6	
Electricity emissions in work-in process	-	10.6
Feedstock carbon content allocated to naphtha	1,799.2	
Feedstock carbon content in work-in process	-	1,799.2
Sum	***1,025.5***	***1,025.5***
Carbon allocated to LPG inventory		
Direct entity emissions allocated to LPG	528.2	
Direct entity emissions	-	528.2
Feedstock emissions allocated to LPG	(1,622.3)	
Feedstock emissions (soybean oil) in work-in process	-	(1,622.3)
Feedstock fuels emissions allocated to LPG	40.9	
Feedstock fuels emissions in work-in process	-	40.9
Electricity emissions allocated to LPG	14.3	
Electricity emissions in work-in process	-	14.3
Feedstock carbon content allocated to LPG	2,122.6	
Feedstock carbon content in work-in process	-	2,122.6
Sum	***1,083.7***	***1,083.7***

PHASE 4
Transfer emissions from SAF producer's ledger to airline's ledger along with SAF sold

ACCOUNT	DEBIT	CREDIT
Carbon transferred out from SAF producer to airline		
(Carbon allocated to SAF sold plus emissions from transporting SAF)		
Emissions transferred out	(11,005.5)	-
Direct/feedstock/electricity emissions allocated to SAF**	-	(11,005.5)
Transport emissions transferred out	9.6	-
Transport emissions (from SAF producer to airline)	-	9.6
Carbon content transferred out	22,366	-
Feedstock carbon content allocated to SAF	-	22,366
Sum	***11,370.1***	***11,370.1***

** Multiple entries are summarized into one for simplicity.

No change in naphtha and LPG inventory accounts as they are not sold yet

ACCOUNT	DEBIT	CREDIT
Carbon transferred in from SAF producer		
Fuels emissions (SAF)	(10,995.9)	-
Fuels emissions tranferred in	-	(10,995.9)
Fuels carbon content (SAF)	22,366	-
Fuels carbon content transferred in	-	22,366
Sum	***11,370.1***	***11,370.1***
Carbon transferred in from conventional jet fuel producer		
Fuels emissions (conventional fuel)	3,548	-
Fuels emissions tranferred in	-	3,548
Fuels carbon content (conventional fuel)	22,366	-
Fuels carbon content transferred in	-	22,366
Sum	***25,914***	***25,914***

SAF producer's ledger   Airline's ledger

Note: Each value in this figure represents the total of all carbon forms—CO_2, CH_4, CO, VOCs, and carbon content. The values are aggregated for presentation purposes, while the underlying ledger maintains disaggregated data for each carbon form. The ledger expresses all entries in tons of carbon, serving as a common unit to balance all carbon forms.

Source: EFI Foundation and Sesame Sustainability.

Total CO_2 emissions are allocated among the three products based on the energy content. In this example, 85.9% of the combined total CO_2 emissions are allocated to SAF, with 6.0% allocated to naphtha and 8.1% allocated to LPG. The ledger then shows the CO_2 emissions accounting data for SAF product being transferred from the SAF producer's ledger to the customer's (the airline's) ledger with the sale of the SAF product. Finally, the transactions for transferred CO_2 emissions and carbon content of SAF are shown along with CO_2 emissions attributed to conventional jet fuel production transferred to the airline's ledger.

Appendix B.

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

The E-Ledgers accounting system is organized on the basis of assets and liabilities as compared to the stocks and flows organization discussed above. In the E-Ledgers system, carbon removals are recorded as assets, and all transactions affecting CO_2 emissions are recorded as liabilities. The system included 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 SAF production case study entity-level transactions, in the format of assets and liabilities derived from E-Ledger concepts,[18] is shown in Table B1.

Table B1. **SUMMARY OF TRANSACTIONS IN FORMAT DERIVED FROM E-LEDGERS ORGANIZATION OF ASSETS AND LIABILITIES: CO_2 EMISSIONS LEDGER WITH SINGLE-ENTRY BOOKKEEPING**

a) Crude oil refiner 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)	
		Attributed CO_2 emissions to natural gas transferred in	7,154
		Attributed CO_2 emissions to Bakken Crude transferred in	219,032
		Sub-Total	**226,186**
Net CO_2 Balance			**226,186**

Conventional jet fuel production

CO_2 Emissions Assets (tCO_2)		CO_2 Emissions Liabilities (tCO_2)	
		Attributed CO_2 emissions to natural gas transferred in	7,154
		Attributed CO_2 emissions to Bakken Crude transferred in	219,032
		Direct CO_2 Emissions Generated	250,220
		Sub-Total	**476,406**
Net CO_2 Balance			**476,406**
		Jet fuel product allocation factor	2.67%
Net CO_2 allocated to jet fuel			**12,741**

b) SAF 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)	
Net CO_2 removals attributed to soybean oil transferred in	73,474	Attributed CO_2 emissions to electricity transferred in	641
		Attributed CO_2 emissions to natural gas transferred in	1,705
Sub-Total	**73,474**	**Sub-Total**	**2,346**
Net CO_2 Balance	**71,128**		

SAF Production

CO_2 Emissions Assets (tCO_2)		CO_2 Emissions Liabilities (tCO_2)	
Net CO_2 removals attributed to soybean oil transferred in	73,474	Attributed CO_2 emissions to electricity transferred in	641
		Attributed CO_2 emissions to natural gas transferred in	1,705
		Direct CO_2 Emissions	23,867
Sub-Total	**73,474**	**Sub-Total**	**26,213**
Net CO_2 Balance	**47,261**		
SAF product allocation factor	85.9%		
Net CO_2 allocated to SAF	**40,543***		

* The value of 40,543 includes both allocated direct and attributed emissions (-40,578 tCO_2) and the emissions from transporting SAF to airline customer (35 tCO_2).

c) Airline customer ledger transactions in E-Ledger format

Transfer of jet fuels and use

CO_2 Emissions Assets (tCO_2)		CO_2 Emissions Liabilities (tCO_2)	
Net CO_2 removals attributed to SAF transferred in	40,543	Attributed CO_2 emissions to conventional jet fuel transferred in	12,741
Net CO_2 balance	**27,802**		
		Jet Fuel Combustion	163,850
Net CO_2 balance			**136,048**

In the E-Ledgers format, the net negative estimate of CO_2 emissions associated with the biogenic soybean oil is recorded as an asset, reflecting that its value reflects the net effect of atmospheric removal of CO_2 in the soybean growing process. Table 2 also shows the transfers of CO_2 emissions from the ledgers of the crude oil refiner and the SAF producer to the ledger of the airline. In this instance, it is assumed that the SAF fuel blend is combusted within the same accounting period. The ledger data is shown for entity-level totals only. Derivation of product CO_2 emissions intensity values would require matching the CO_2 emissions estimates with production estimates over the same accounting period.

References

1. Karthik Ramanna et al., "A Proto-Standard for Carbon Accounting and Auditing using the E-Liability Method," September 12, 2024, available at SSRN: https://ssrn.com/abstract=4957358 or http://dx.doi.org/10.2139/ssrn.4957358.

2. Stefan Reichelstein, "Corporate carbon accounting: balance sheets and flow statements," *Review of Accounting Studies* 29, no. 3 (2024): 2125-2156.

3. Robert Kaplan and Karthik Ramanna, "Accounting for climate change," *Harvard Business Review* 99, no. 6 (2021), https://hbr.org/2021/11/accounting-for-climate-change.

4. Jimmy Jia et al., "A reporting framework for general purpose life cycle assessment to align entity-level GHG accounting with general purpose financial statements," March 21, 2023, available at SSRN: https://ssrn.com/abstract=4395987 or http://dx.doi.org/10.2139/ssrn.4395987.

5. Stephen H. Penman, "Accounting for Carbon," January 1, 2024, available at SSRN: https://ssrn.com/abstract=4721974 or http://dx.doi.org/10.2139/ssrn.4721974.

6. Bastian Distler et al., "Incorporating Carbon Emissions into Decision-Making - The Case of Transactional Connectivity," September 30, 2024, available at SSRN: https://ssrn.com/abstract=4784259 or http://dx.doi.org/10.2139/ssrn.4784259.

7. Federal Aviation Administration, *United States 2021 Aviation Climate Action Plan*, 2021, https://www.faa.gov/sites/faa.gov/files/2021-11/Aviation_Climate_Action_Plan.pdf.

8. Jimmy Troderman, "U.S. production capacity for sustainable aviation fuel to grow," U.S. Energy Administration, U.S. Energy Information Administration, July 17, 2024, https://www.eia.gov/todayinenergy/detail.php?id=62504.

9. Climate Action Tracker, "International Aviation," accessed December 10, 2025, https://climateactiontracker.org/sectors/aviation/.

10. Alternative Fuels Data Center, "Sustainable Aviation Fuel," accessed July 1, 2025, https://afdc.energy.gov/fuels/sustainable-aviation-fuel.

11. Argonne National Labporatory, "R&D GREET Model," accessed December 31, 2024, **https://greet.anl.gov/**.

12. Thomas D Alcock et al., "More sustainable vegetable oil: Balancing productivity with carbon storage opportunities," *Science of the Total Environment* 829 (2022): 154539.

13. Argonne National Labporatory, "R&D GREET Model," accessed December 31, 2024, **https://greet.anl.gov/**.

14. Eric Lewis et al., *Comparison of commercial, state-of-the-art, fossil-based hydrogen production technologies*, No. DOE/NETL-2022/3241, National Energy Technology Laboratory (NETL), Pittsburgh, PA, Morgantown, WV, and Albany, OR (United States), 2022, **https://www.osti.gov/servlets/purl/1862910?trk=public_post_comment-text**.

15. Jeongwoo Han et al., "Life-Cycle Analysis of Bio-Based Aviation Fuels," *Bioresource Technology* 150 (2013): 447-56, **https://doi.org/10.1016/J.BIORTECH.2013.07.153**.

16. Mark J. Kaiser et al., "Petroleum Refining: Technology, Economics, and Markets," 2020, 690.

17. Jane O'Malley and Nikita Pavlenko, "Drawbacks of adopting a "similar" LCA methodology for U.S. sustainable aviation fuel (SAF)," International Council on Clean Transportation, September 2023, **https://theicct.org/wp-content/uploads/2023/09/ID-16-Briefing-letter-v3.pdf**.

18. Karthik Ramanna, private communication.

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