DRAFT FOR CONSULTATION

Integrated Product- and Entity-Level Carbon Accounting Case Study: Power Sector

September 2026

The EFI Foundation advances technically grounded solutions to climate change through evidence-based analysis, thought leadership, and coalition-building. 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. EFI Foundation maintains editorial independence from its public and private sponsors.

Foreword

This analysis is the fifth in a series of EFI Foundation case studies applying our integrated product- and entity-level carbon accounting framework to specific products and sectors. This body of work establishes a policy-agnostic and technology-neutral methodology for integrated entity-level and product-based carbon accounting, grounded in engineering fundamentals and modeled after financial accounting. This fifth case study applies that methodology to the power sector, following carbon stocks and flows through the generation, sale, and use of electricity. It includes options for accounting for the carbon attributes associated with contractual instruments.

Electricity is an especially important application of carbon accounting. Its role in the economy is growing with the electrification of transportation, buildings, and industry and increasing electricity demand from data centers. Electricity-related emissions can also represent a substantial share of the product carbon intensity of electricity-dependent products. At the same time, electricity presents distinct accounting challenges because it is generated from multiple sources, transmitted and delivered through an interconnected grid that must balance supply and demand in real time, and purchased and sold through markets with varying contractual terms and conditions.

The EFI Foundation is publishing this paper as a consultation draft to encourage broader engagement with the proposed methodology. Further work is needed to address the complexity of real-world electricity systems, and the framework will benefit from input from power sector participants, companies, financial institutions, policymakers, researchers, standards organizations, and others.

We welcome feedback that assesses the methodology, identifies gaps, and helps refine the framework. **Please submit your feedback using this form on EFIF's website: https://tf6gs.share.hsforms.com/2mgb82ehHQjuqejLMNT0lxw.**

Implementing reliable carbon accounting is not simple and will evolve over time as rules and data quality improve and more institutions and industries adopt them. We hope this consultation draft contributes to that process and advances the development of widely accepted carbon accounting principles and practices.

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Project Advisory Board

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

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Contents

Executive Summary

Product carbon intensity (PCI) is becoming a key measure in trade policy, economic competitiveness, and public and private sector procurement. Governments are regulating the carbon embedded in traded products, companies are asking suppliers for more granular emissions data, and buyers want credible ways to compare similar products by how they were made. Policies like the European Union's Carbon Border Adjustment Mechanism (CBAM), alongside corporate decarbonization commitments, are driving demand for reliable, comparable, product-level carbon information.

Electricity sits at the center of this shift. Globally, it accounts for approximately **21% of final energy consumption**, a share the International Energy Agency (IEA) projects will rise to **more than 25% by 2035,** driven by population growth, rising living standards, and the electrification of transportation, buildings, and industry.[1] Data center electricity consumption alone is projected to **more than double by 2030.**[2]

As electricity's economic role grows, so does its weight in the carbon intensity of dependent products. For electricity-intensive industries, that contribution is already substantial: A prior EFI Foundation report found electricity-related emissions can account for roughly 30% of the PCI of steel slab produced via the direct reduced iron-electric arc furnace pathway.[3]

Accurately assigning carbon attributes to electricity is both important and technically challenging. Electricity is generated from multiple sources and is transmitted and delivered through an interconnected grid that must balance supply and demand in real time. It is purchased and sold through layered markets with varying contractual terms and conditions, and managed and regulated under a multiplicity of governance structures. A rigorous framework must accommodate these transactions without compromising the underlying carbon balance.

This case study examines how the EFI Foundation's ledger-based carbon accounting framework can meet both goals. The framework records carbon within defined entity boundaries and transfers attributes through interoperable ledgers as products move through the value chain. Applied to the power sector, the framework creates a common accounting architecture for physical generation, grid electricity, and differentiated contractual attributes, while keeping carbon balanced systemwide.

The study process considered five different methodologies for accounting for the carbon attributes of energy attribute certificates (EACs) associated with renewable electricity generation. The case study adopted a methodology that assigns the value of the carbon attributes associated with an EAC based on value of average PCI of the electricity grid (without the renewable generators) that would otherwise be added to the grid in the absence of the low-carbon generators. This approach, compared to other possible approaches, requires further review and discussion.

Case Study Approach and Findings

The analysis applies the framework to a simplified grid based on New York Independent System Operator (NYISO) data. The scenarios hold the physical generation system constant while changing the contractual treatment of renewable electricity. The study does not advocate for contractual instruments, as that is a policy choice; rather, the cases seek to demonstrate how contractual instruments that exist in the market today can be treated in carbon accounting. The three scenarios include:

- **No Separate EAC Transactions:** Generators sell electricity into the wholesale market without power purchase agreements (PPAs) or EAC transactions. Carbon attributes are allocated based on the average carbon intensity of the physical electricity system.
- **Physically Directed PPAs with EACs:** Generators of renewable electricity (solar and wind) enter into PPAs with either a load-serving entity (LSE) or an industrial end-use customer, assigning the associated carbon attributes directly to those buyers while the grid operator and LSE deliver physical electricity under the financial terms and conditions contained in the PPA.
- **Separately Traded EACs:** Generators of renewable electricity register renewable energy certificates (RECs) to a central registry for sale, separate from the physical flow of electricity on the grid. The associated carbon attributes can be traded separately from physical electricity and purchased by entities within or outside the grid.

Across these scenarios, the analysis finds:

- Grounding PCI estimates in comprehensive carbon mass and energy balances enables complete, comparable, and verifiable accounting without gaps or duplication.
- Ledger-based accounting can establish an average PCI for grid electricity across a mix of generation sources with varying emissions. In Scenario 1, for example, the average PCI of grid electricity generated from a mix of nuclear, natural gas, solar, and wind, is 29.8 kilograms of carbon per megawatt-hour (kgC/MWh).
- The proposed methodology fixes a low-carbon generation source's carbon attribute value at the time of generation, enabling the grid (or market) to more accurately account for variations in grid carbon intensity from the significant temporal variations that occur in both supply and demand during market balancing.
- A comprehensive mass and energy balance can support policy choices that allow contractual carbon attributes to be assigned discretely without altering the grid's

physical carbon intensity. Physical average PCI stays at 29.8 kgC/MWh across all three scenarios.

- Under the proposed methodology, an EAC carries the carbon intensity established at the time of generation, and that value remains unchanged through subsequent transfer and retirement. Because accounting is performed using hourly carbon balances, retiring an EAC does not rewrite the carbon intensity of electricity consumed at another time or location; it transfers a fixed carbon attribute. As a result, the methodology avoids the need for time- and location-matching requirements that are necessary in proposed GHG Protocol Scope 2 updates to prevent low-quality EACs from being used to support emission claims that are disconnected from actual generation conditions.
- PCI values for electricity built on comprehensive carbon accounting give manufactured products and services—including those in cross-border trade—an accurate, consistent, and verifiable input for product-level carbon intensity.

This case study provides the foundational step toward a comprehensive carbon accounting architecture for the power sector.

Further work is needed to address imports and exports from neighboring grids, spinning reserves, energy storage, grid frequency and voltage control, and transmission and distribution losses.

The analysis shows that contractual carbon attributes can be incorporated within the accounting for physical carbon systems: **A ledger-based framework can preserve carbon mass balance across different policy constructs, which provides a stronger foundation for corporate reporting, product carbon accounting, trade, and investment.**

I. Introduction

Note to readers:

All data presented in this report is expressed in units of mass of carbon (tons of carbon, tC). The term "carbon emissions" refers to emissions of carbon dioxide (CO_2) and the term "carbon" refers to both carbon content of fuels and materials as well as CO_2 emissions from the combustion of hydrocarbon fuels. Expressing data in a common carbon mass unit allows for clear and consistent treatment of all forms of carbon in the carbon accounting ledgers, such as the conversion of the carbon content of hydrocarbon fuels into CO_2 emissions.

This study demonstrates how a comprehensive, ledger-based carbon accounting system can be applied to the electric power sector. It builds on the system described in the EFI Foundation (EFIF) report *Integrated Product- and Entity-Level Carbon Accounting: Putting Concepts into Practice* and previous case studies applying that system to sustainable aviation fuel production and steel production.[4,5,6,7,8]

This study extends the approach to a sector with fundamentally different structural characteristics: instantaneous supply-demand balancing, shared network infrastructure, heterogeneous demand, and layered market and contractual mechanisms.

Electricity generation is the second-largest source of greenhouse gas (GHG) emissions in the United States, accounting for approximately 25% of total anthropogenic emissions.[9] Globally, electricity and heat account for about 34% of GHG emissions.[10] Electricity also is ubiquitous in its applications, affecting the carbon intensity of all commodity products and services. The April 2026 EFIF steel case study, for example, found that emissions from electricity can account for about 30% of total product carbon intensity (PCI) of steel slab produced via the direct reduced iron-electric arc furnace route.[11]

Unlike commodity supply chains where physical products move sequentially from producer to consumer, electric power flows through a shared transmission and distribution network with complex flow characteristics, posing a unique set of challenges in assigning specific generation sources to specific consumers.[a]

[a] The challenge of accounting within a shared network also applies to natural gas, where volumes of natural gas from various producers, each with its own carbon footprint, are combined in a common pipeline network for transmission and distribution to various customers.

These challenges are compounded by the rapid growth of contractual instruments[b]—including power purchase agreements (PPAs) and energy attribute certificates (EACs), commonly known as renewable energy certificates (RECs) in the United States—which create contractual claims on generation that are separate from physical delivery patterns.

This study proposes a carbon accounting method for the power sector to address this challenge based on two fundamental assumptions:

- **Power sector carbon accounting should follow the core algorithm of carbon accounting.** Each unit of electricity carries uniquely associated carbon attributes. These carbon attributes, documented through carbon mass and energy balances, should be recorded only once in a ledger-based system and transferred along the value chain from raw material suppliers, to electricity generators, to providers of transmission and distribution system services, and ultimately to final customers.
- **Carbon accounting should be policy agnostic and technology neutral. Accounting should not impose new restrictions on investments in low-carbon power generation, as that is a policy choice.** Certain contractual instruments exist today that unbundle carbon attributes from the physical flow of electricity, enabling markets to assign incremental value to electricity generation from low-carbon sources and thus incentivize investment in these generation sources.

This study illustrates the proposed carbon accounting method through three simplified scenarios in a simple model grid. The case study excludes complex grid dynamics, such as installed capacity market, the emissions impacts associated with energy storage, electricity imports and exports, transmission and distribution (T&D) losses, or emissions from T&D infrastructure and ancillary services. The implications of these dynamics for carbon accounting are left for future research, while this study serves as an initial step in advancing discussion on carbon accounting in the power sector.

[b] As used in this report, the term "contractual instruments" is defined in the same manner as in the Greenhouse Gas Protocol. It defines contractual instruments as any type of contract between two parties for the sale and purchase of energy bundled with attributes about energy generation or for unbundled attribute claims. They include energy attribute certificates (e.g., renewable energy certificates, guarantees of origin, green electricity certificates).

II. Challenges to Product Carbon Accounting for Electricity-Related Emissions

The inherent characteristics of power systems pose significant challenges for carbon accounting. Power systems are characterized by several structural features that shape how electricity is generated, delivered, and accounted for:

1. Significant temporal variations in both supply and demand create instantaneous balancing challenges, as generation and consumption must be continuously matched in real time to maintain system stability.
2. Power systems operate through a shared network architecture, where multiple generators and consumers are interconnected through the same T&D infrastructure. Once electricity enters a shared network, individual electrons cannot be traced back to specific generators, making it difficult to attribute electricity to a specific generation source or end user.
3. U.S. power systems involve multiple market layers and business models, including independent power producers, independent system operators (ISOs), regional transmission organizations (RTOs), distribution operators, and a variety of load-serving entities (LSEs),[c] each with distinct contractual structures that shape how electricity—and its associated emissions—are delivered, tracked, and reported.
4. Carbon attributes can be unbundled and sold separately from the underlying electricity through EACs, unlike other products where emissions are tied to physical products and transferred to customers alongside those products in the carbon accounting process.[d] The EAC market is substantial. PPAs and purchases of EACs reduced 73% to almost 100% of the electricity-related emissions of the four leading hyperscalers in 2024 (see Appendix A for details).

The interplay of these characteristics compounds these challenges.

[c] Different types of load-serving entities (LSEs) exist depending on ownership, governance, and regulatory structure. The major types of LSEs include investor-owned utilities (IOUs), public power utilities (federal, state, and municipal entities), electric cooperatives, competitive retail electricity suppliers, and community choice aggregators.
[d] More instances of unbundling carbon attributes from physical products are emerging in fuel and commodity markets, although such practices remain less common than in the power market.

III. The Comprehensive Ledger-Based Carbon Accounting Framework

The basic algorithm of ledger-based carbon accounting, based on the work of Kaplan and Ramanna,[12] provides that each entity in the supply chain records the carbon emissions within its boundary in a ledger-based accounting system and transfers that carbon across ledgers alongside the products it sells.

Previous EFI Foundation reports outlined a comprehensive carbon accounting system (Box 1) built from this algorithm. The framework is derived from financial accounting principles and methods. It is policy agnostic, technology neutral, and universally applicable to all industries and products, including electricity. This framework has been reduced to practice through a series of case studies.

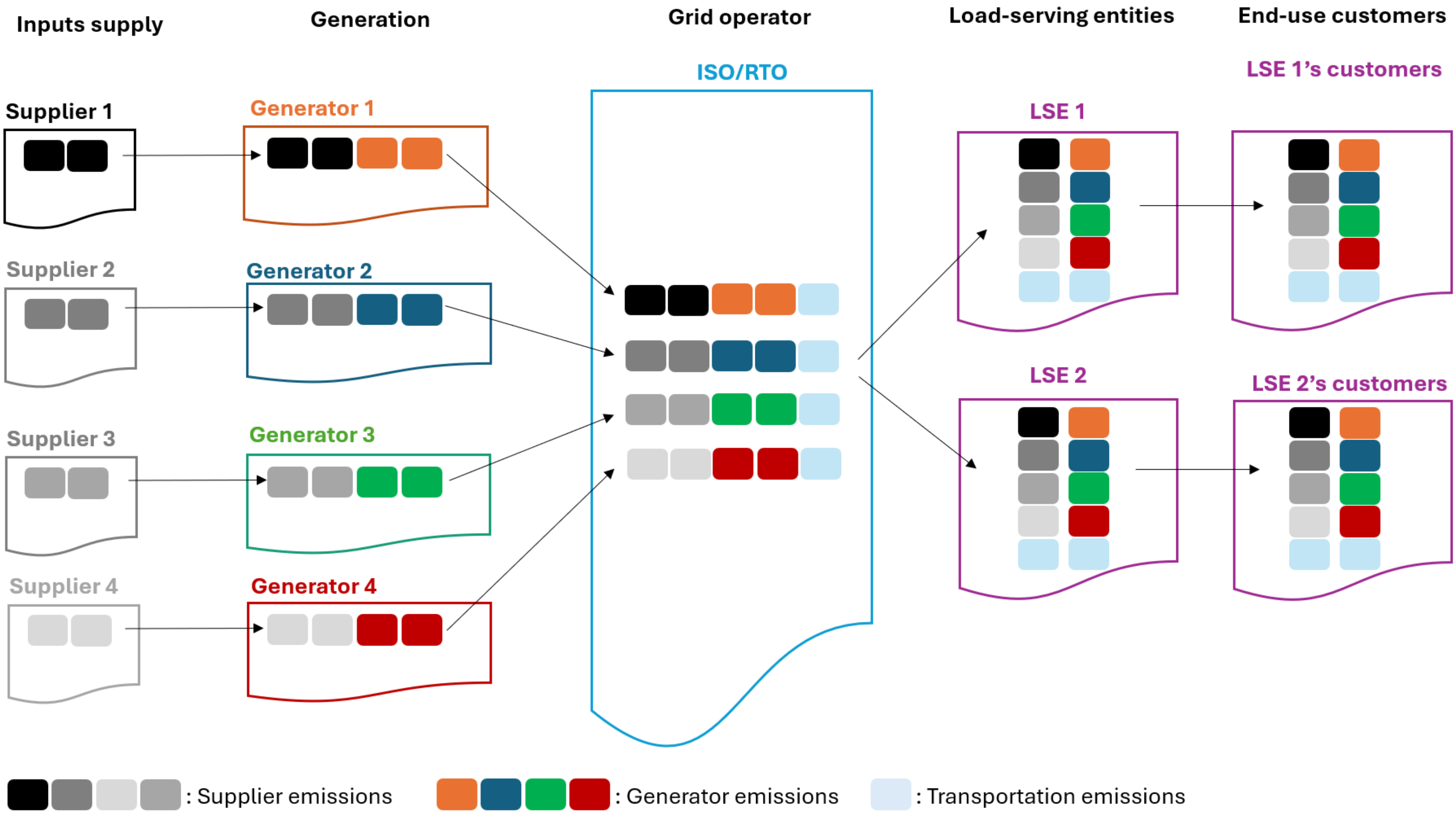
Box 1. A comprehensive carbon accounting system

- ***Purpose***: To serve as an integrated product- and entity-level carbon accounting system that is policy agnostic, technology neutral, and universally applicable
- ***Basic algorithm***: Emissions are recorded only once, by each entity within a product value chain, with the data transferred to customers across the value chain
- ***Fundamental principles***: Drawn from well-established and widely accepted financial accounting principles, including: faithful representation, relevance, comparability, transparency, and verifiability.
- ***Framework elements***: Ledger-based, including:
  - Gate-to-gate boundaries aligned with legal ownership and financial accounting boundaries
  - Dual-sided ledger organization: stocks and flows with double-entry bookkeeping
  - Chart of accounts drawn from carbon mass and energy balances
  - Transactions based: Date- and quantity-specific transactions
- ***Data quality***: All data drawn from comprehensive carbon mass and energy balances
  - Facility-specific primary data (measurable or calculated based on measurable data) where possible
  - Secondary data sources (including industry averages) that are consistent with the mass balance
- ***Rule book***: Specific methodologies, including:
  - Guidelines for assigning values to ledger accounts
  - Methods for allocating emissions among multiproduct lines based on mass, energy, or value
- ***Reports***: Product carbon intensity (PCI) metrics
  - Time bound and reconciled with an entity's total emissions
  - Applicable for internal key performance indicators (KPIs), investment planning, voluntary public reporting, product labeling, or compliance with mandatory standards (where applicable)

Accounting for Physical Flow of Electricity

Figure 1 provides a conceptual illustration of how a comprehensive carbon accounting system can be applied to the physical flow of electricity across the electricity supply chain (excluding EACs).

Figure 1. Illustration of carbon accounting for the physical flow of electricity across its supply chain



Source: EFI Foundation, adapted from Kaplan and Ramanna, https://hbr.org/2021/11/accounting-for-climate-change.

In the figure, each box represents a discrete unit of activity with associated carbon attributes that are recorded in the entity's carbon accounting ledger. Each entity that has ownership and control of a step in the physical flow of electricity is responsible for maintaining a carbon accounting ledger. Entities that provide products and services to the entities with ownership and control also maintain ledgers for their transactions. The ledger transactions from each entity are then transferred to the ledger of its customer and ultimately to the end user of the electricity.

The resulting picture captures the complete cradle-to-gate record of carbon emissions across the value chain. For example:

- Each ***supplier*** in the value chain records the emissions attributed to fuels and equipment and transfers these records to the electricity generators.
- The ***generators*** record the emissions transferred from their suppliers together with their own direct emissions.
- These emissions are then transferred to the ledger of the ***grid operator*** when electricity is delivered to the grid, averaging the carbon attributes of the various generation sources. The accounting for transmission losses and ancillary services are added.
- The grid operator, in turn, allocates emissions to the electricity delivered to each ***load-serving entity*** and transfers the associated emissions along with that electricity. The load-serving entity transfers the carbon accounting transactions to its ledger with adjustments associated with the operation of the local distribution system.
- Finally, the load-serving entity allocates emissions among ***end-use customers***.

This illustration applies only to the physical flows of electricity. The use of EACs unbundles the carbon attributes of electricity generated from certain low-carbon sources from the physical supply, creating an additional layer of transactions to be incorporated into the carbon accounting system. These are discussed in the next section.

Carbon Accounting for Energy Attribute Certificates

An energy attribute certificate (EAC) is a contractual instrument that conveys the environmental or other non-power attributes of a unit of electricity.

- In the U.S., the most common EACs in the power sector are renewable energy certificates (RECs), associated with a megawatt-hour (MWh) of electricity generated from a renewable energy source (e.g., wind, solar, biomass, geothermal, and certain hydropower).
- Other forms of EACs include green electricity certificates (GECs) in China, guarantees of origin (GOs) in Europe, and zero-emission credits used in several U.S. states.

EACs comprise a significant share of electricity markets. In the United States, sales of RECs in voluntary bilateral transactions reached 319 TWh in 2023, representing about 44% of non-hydropower renewable electricity sales.[13] In China, 2,947 TWh of GECs were issued in 2025, representing more than 70% of renewable electricity generation.[14] In Europe, more than 1,094 TWh of GOs were issued, representing more than 60% of renewable electricity generation across 36 European countries.[15]

Table 1. EACs in the U.S., China, and Europe

	Type of EACs	Volume
U.S.	Renewable Energy Certificates (RECs)	• No single aggregated national issuance figure • In 2023, 319 TWh of RECs were sold in voluntary bilateral transactions—about 44% of all U.S. non-hydropower renewables
China	Green Electricity Certificates (GECs)	• In 2025, 2,947 TWh of GECs were issued, and 930 TWh were traded • The GECs issued represent more than 70% of renewable electricity generation in China
Europe	Guarantees of Origin (GOs)	• In 2025, over 1,094 TWh of GOs were issued, and over 978 TWh were retired • The GOs issued represent more than 60% of renewable electricity generation in 36 European countries

Renewable Energy Certificates (RECs) were originally developed to support compliance with renewable portfolio standards (RPS), providing a mechanism to incorporate renewable electricity generation across interconnected grids where physical electricity flows cannot be directly traced. REC markets later expanded beyond compliance applications into voluntary markets, where corporate purchasers use RECs to support claims of renewable or low-carbon electricity use.

RECs are denominated in MWh of generation rather than specific carbon attributes. While this is generally sufficient for RPS compliance, it creates challenges for carbon accounting when RECs are used to make emissions claims. In particular, purchasers often apply RECs against electricity consumption occurring at different times and under different grid conditions than when the associated electricity was generated.

The use of RECs is a policy choice, and current approaches differ across jurisdictions. The EFI Foundation carbon accounting approach is based on a framework that is policy agnostic and technology neutral. The application of this approach to the power sector should reflect whatever policies are in place, i.e., accounting should follow policy. Importantly, even if future policy decisions were to limit the use of RECs, carbon accounting frameworks would still need to accommodate them during any transition period and for legacy contractual arrangements.

This raises two fundamental questions for carbon accounting:

1. How should the value of the carbon attributes of a REC (or any other form of EAC) be determined?
2. If the REC is assigned a specific carbon attribute value, how does this affect the value of carbon attributes assigned to the physical supply of the renewable electricity generation provided to the grid?

Carbon accounting could address accounting for RECs in several ways. Five alternative methodologies are summarized in Box 2. Option 5 is based on assigning a "carbon credit" attribute to each REC based on its value to the grid at the time it was generated. The case study illustrates the use of the carbon credit methodology.

Box 2. Methodological options for accounting for EACs

Option 1: Exclude EACs from carbon accounting and follow physical electricity delivery only. Under this option, entities account only for carbon attributes directly associated with physical electricity and EACs are excluded from carbon accounting. A limitation of this option is that it eliminates the value of EACs as a carbon management tool, and create dual estimates of the PCI values of the electricity received by a customer—the value with the application of the REC and the value recorded on the carbon accounting ledger absent the REC.

Option 2a: Follow the current GHG Protocol Scope 2 Guidance for market-based Scope 2 emissions reporting. Under this option, EACs are accounted for by assigning a zero-emission factor to all electricity volumes covered by EACs, regardless of when and where they are generated or retired. Because the value of the carbon attributes of EACs at the time of generation may not match those at the time of application, carbon attributes can be overstated or understated. As a result, carbon mass balance is not maintained, potentially leading to gaps or double counting.

Option 2b: Follow the proposed GHG Protocol Scope 2 updates for time matching and deliverability requirements. Under the proposed updates, entities could account for the values of EACs only if the generation and retirement of the EAC occurred in the same time period and within the same grid where the generator and consumer of the EAC were physically interconnected. The proposed accounting treatment would impose a new de facto policy barrier invalidating the use of most current EACs and could create a disincentive to investments in new carbon-free generation

Option 3. Include EACs in electricity product carbon accounting only if the EACs are bundled with physical electricity sale through a physically directed PPA. Under this option, the physical supply and associated carbon attributes of low carbon electricity bundled in a bilateral contractual agreement between a generator and customer within the same physical grid would be segregated from the grid average values and recorded separately in the carbon accounting ledger assigned to that customer. The value of the carbon attributes would be determined on the basis of the value chain emissions associated with the generation of the EAC. This approach provides a method that allows the customer to capture the value of the carbon attributes while maintaining the overall carbon mass balance of the grid. However, the proposed accounting treatment would impose a new policy barrier invalidating the use of most current EACs which are unbundled from a physically directed PPA.

Option 4: Exchange the value of the carbon attributes between the buyer of seller of an EAC. Under this option, the seller assigns a value to the carbon attributes of the EAC at its time of generation, and the buyer identifies the value of the emissions reduction at the same time. The difference in values is incorporated into the PCI of the generator. The exchange of values maintains the carbon mass balance. However, there may be issues associated with timing, because the REC transaction likely would not occur at the same time as the REC is generated, and consequently the seller would not know the difference in values based upon the application of the REC by the buyer. Consequently, this option would be difficult to implement in practice.

Option 5: Assign the value of carbon attributes as "credits" to each EAC at the time of its generation, with an offsetting equivalent adjustment to the residual value of attributes of the physical grid electricity. The value of the credit would be fixed and then applied by the buyer of the EAC at a different time, but only in the amount of the fixed value. This option would achieve the same objective of the proposed amendments to Scope 2 GHG guidelines (Option 2b above) without the need for time and location matching.[e] This option is adopted in this study and demonstrated in Scenarios 2 and 3 of the case study.

[e] The GHGP approach and its issues are discussed in more detail in Appendix A.

IV. An Illustrative Power Grid Case Study

This case study illustrates how the concepts of a comprehensive carbon accounting system, as outlined previously, could be reduced to practice through a case study of the power sector. The case study presented here uses a simplified model of the electricity grid for purposes of illustrating how carbon accounting can be applied to three different scenarios for EACs. Additional scenarios with further detailed conditions can be added over time.

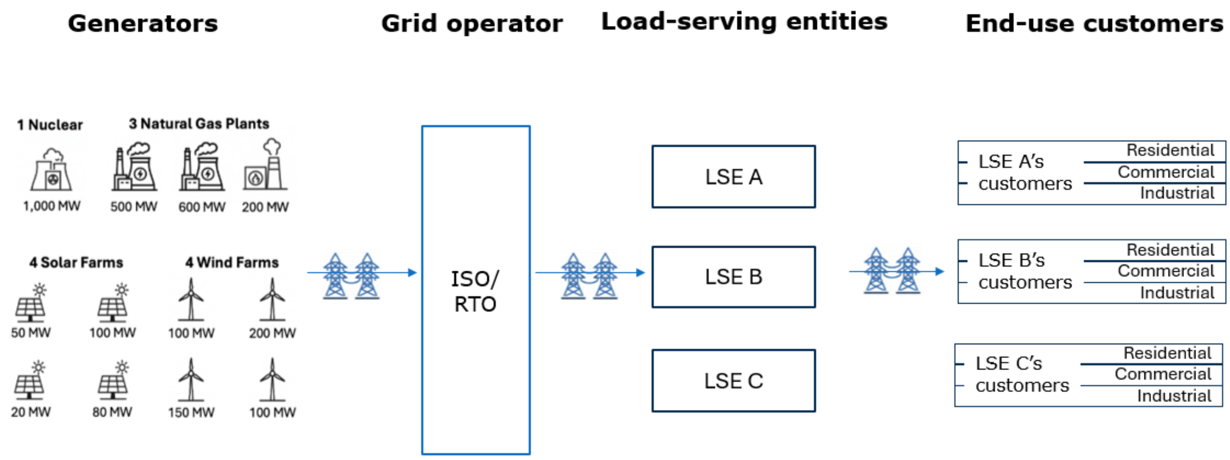
Illustrative Grid

For purposes of the case study, the illustrative grid is based on data drawn from the New York Independent System Operator (NYISO) system. NYISO operates one of seven organized regional electricity markets in the United States and is responsible for operating New York's bulk power grid and administering the state's wholesale electricity markets.

The NYISO system encompasses New York state and includes more than 400 entities, including electricity suppliers and transmission system owners. In 2025, the system served approximately 20 million customers and 151,059 gigawatt-hours (GWh) of electricity demand. NYISO also managed 41,858 megawatts (MW) of electricity supply capacity, including 3,168 MW, or approximately 7.5%, contracted from outside the NYISO system boundary. The system is interconnected with neighboring power systems in New England, the Mid-Atlantic, Ontario, and Québec, allowing electricity to move across state and international borders.

The case study draws selected data from NYISO to create a simplified representation of the grid, shown in Figure 2.

Figure 2. An illustrative grid for case study



Source: EFI Foundation and Sesame Sustainability.

Figure 2 shows:

- Generation from 12 generators with a mix of generation technologies representative of the NYISO region. These include renewable electricity (wind and solar), nuclear, and natural gas (with both combined cycle and simple cycle combustion turbines).
- A single grid operator coordinates electricity generation and transmission to three LSEs through transmission networks. (NYISO, for example, purchases the generation on a "flash title" basis and sells it to the LSEs.)
- Total demand is allocated among the three LSEs. In later scenarios represented, demand is allocated on a monthly average basis, such that 50% of the customer demand is served by LSE A, 30% by LSE B, and 20% by LSE C.

The illustrative grid is simplified by excluding:

- Spinning reserves
- Transmission and distribution (T&D) losses
- Ancillary services, including voltage and frequency control
- Distributed energy resources
- Behind-the-meter generation
- Demand response

These elements can be added once the basic carbon accounting framework has been established.

The accounting for the case study is on an hourly basis. The hourly load for 11 a.m.-12 p.m. (noon) on January 1, 2025 is based on NYISO load profiles derived from the National Renewable Energy Laboratory's 2023 Cambium scenario.[16] The load profiles are scaled from 163,500 GWh/year to 15,290 GWh/year to match the capacity of the 12-generator system.

The carbon mass balances and the resulting carbon accounting are on an hourly basis. The use of hourly accounting in this case study is based on the assumption that hourly data are fully available to all entities. In practice, entities may apply different temporal resolutions, such as daily, monthly, or other accounting periods depending on data availability, operational constraints, and alignment with financial accounting data.

Further details on the data and method used in the case study are provided in Appendix B.

Distinguishing Energy Attribute Certificates as "Products"

In order to determine the product carbon intensity of electricity provided to customers, both the physical electricity supply (i.e., grid electricity) provided to end-use customers and any EACs are treated as separate "products."

Energy attribute certificates (EACs) refer to the carbon attributes of a REC. The EACs of a REC can "flow" through the grid from generator to end-use customer in several ways, either bundled with or unbundled from the flow of the physical supply of electricity generation on which it is based.

- The EAC can be purchased (directly or through the third-party registry) by an LSE and used to satisfy an RPS requirement.
- The EAC can be purchased by an LSE, separate from an RPS requirement, and marketed to end-use customers as a differentiated "green electricity" product with a price premium.
- The EAC can be transferred directly from the generator to an end-use customer as part of a bilateral power purchase agreement (PPA), enabling the customer, such as a corporation, to reduce its reported electricity-related emissions. The EAC can either be bundled together with the purchase and sale of the underlying physical electricity generation, or it can be unbundled from the physical generation.
- The EAC can be unbundled from the physical electricity generation and placed on a third-party registry for purchase by an end-use customer.

Case Study Scenarios

The case study includes three scenarios to demonstrate how comprehensive carbon accounting could be applied to EACs. Each scenario is based on the same mix of electricity generators and end-use customers, with different pathways for assignment of EACs.

1. **No Separate EAC Transactions**: Generators sell electricity into the wholesale market to LSEs, and the grid operator manages the transmission. The LSEs sell electricity to end-use customers with a product carbon intensity representing the weighted average carbon attributes of the generation sources. While the grid includes renewable electricity generators, there are no separate transactions of the EACs associated with the renewable electricity supply.
2. **Physically Directed PPA with EACs**: All renewable electricity generators have a physically directed PPA with an LSE or an individual end-use customer within the grid. The EACs associated with the renewable electricity generation are bundled with the sale of the physical supply to that customer. The EAC transaction is between the generator and the customer; the grid operator is responsible for any specific terms and conditions surrounding the sale of the electricity generation that created the EACs.
3. **Separately Traded EACs**: All renewable electricity generators issue and register RECs and associated EACs in a central registry for sale to any party. Buyers can purchase EACs from the registry separate from the underlying generation. Buyers can include an LSE within the grid, an LSE outside the grid, and individual end-use customers within or outside the grid.

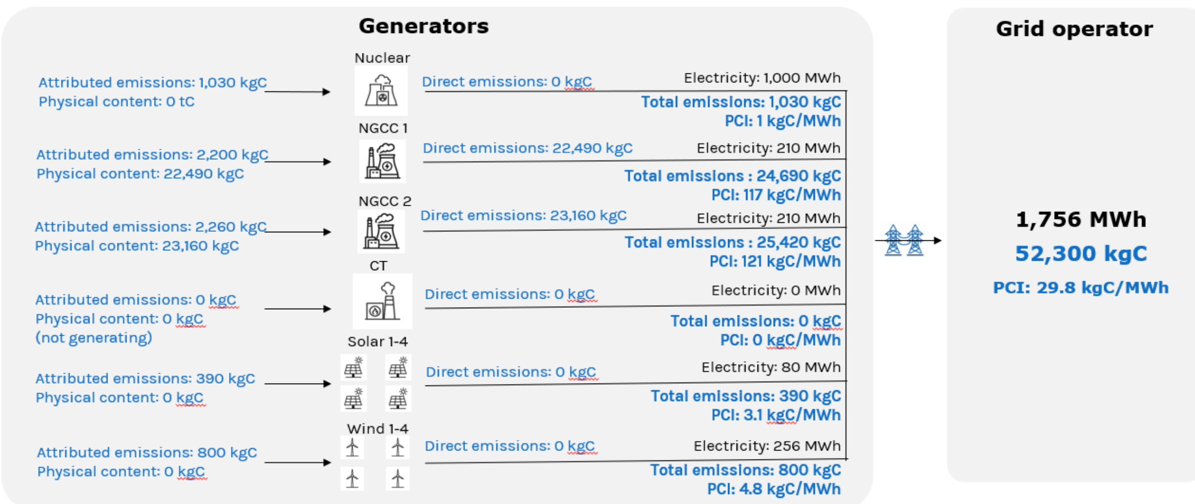
Case Study Findings

Electricity Generation Mix and Carbon Attributes Common to All Scenarios

The illustrative grid is supplied by a mix of generation sources, described earlier, that is common to all scenarios. Each generator supplying the illustrative grid maintains a ledger of stocks and flows, including the transfer of transactions from its supply chain, with transactions recorded on an hourly basis. Figure 3 illustrates the flow of electricity and associated carbon from each generator to the grid during a representative hour of operation—January 1, Hour 12 (11 a.m.-12 p.m.).

Figure 3. Generation mix and carbon attributes: Flow diagram and mass balance

Accounting period: January 1, Hour 12 (11 a.m.-12 p.m.)



Note: natural gas combined cycle = NGCC, combustion turbine = CT.

Total emissions transferred out with electricity supplied to the grid, including emissions attributed to generation inputs and direct emissions from fuel combustion.

Source: Sesame Sustainability.

Each generator accounts for attributed emissions and the physical carbon contained in inputs used in production, including fuels, materials, and equipment, as well as direct emissions from fuel combustion. The total emissions, comprising both direct and attributed emissions, are then transferred to the grid operator's ledger along with the physical supply of electricity. During this one-hour period, a total of 1,756 MWh of electricity is generated, with attributed emissions totaling 52.3 tons of carbon (tC).

Table 2 illustrates how one of the generators—natural gas combined cycle (NGCC) 1—records these transactions in its carbon accounting ledger during a one-hour period. The ledger is dual-sided and organized on the basis of stocks and flows of carbon within the boundary conditions set by the generator and within the hourly time period of January 1 at Hour 12 (11 a.m.-12 p.m.).

Table 2. NGCC 1's carbon accounting ledger

Accounting period: January 1, Hour 12 (11 a.m.-12 p.m.)

Unit: Ton of carbon (tC)

Transaction	Stocks Accounts					Flows Accounts			
	Attrib. emissions to natural gas	Carbon content in natural gas	Attrib. emissions to plant, property, and equipment (PPE)	Direct emissions	**Stocks Total**	Emissions transferred in	Carbon content transferred in	Emissions transferred out to grid	**Flows Total**
Beginning balance	***0***	***0***	***0***	***0***	***0***	***0***	***0***	***0***	***0***
Attributed emissions and carbon content transferred in along with natural gas	2.1	22.5	0.1		**24.7**	2.2	22.5		**24.7**
Burning natural gas releases its carbon content as direct emissions		-22.5		22.5	**0.0**				**0.0**
Emissions transferred to the grid along with electricity	-2.1		-0.1	-22.5	**-24.7**			-24.7	**-24.7**
Ending balance	***0.0***	***0.0***	***0.0***	***0.0***	***0.0***	***2.2***	***22.5***	***-24.7***	***0.0***

Note: For simplicity, this example does not include carbon accounting for inventories or work-in-process (WIP) accounts. An entity, for example, may record attributed emissions and carbon content associated with natural gas on a weekly or monthly basis in an inventory holding account and then allocate an hourly share to WIP accounts as the gas is used in production. Source: EFI Foundation and Sesame Sustainability.

The attributed emissions associated with the natural gas supply chain (2.1 tC) and the carbon content in the natural gas (22.5 tC) actually combusted in the accounting period are recorded on the stock accounts side under "attributed emissions to natural gas" and "carbon content in natural gas." The hourly share of depreciation of carbon associated with the fixed assets of the facility (0.1 tC) is recorded under "attributed emissions to PPE"—plant, property, and equipment. Corresponding entries are made on the flows side under "emissions transferred in" and "carbon content transferred in."

When natural gas is combusted and emissions are created, the emissions are recorded on the stock side of the ledger as "direct emissions," and the carbon content of the natural gas is reduced to zero. When the generated electricity is delivered to the grid, both attributed and direct emissions are reduced to zero within the facility boundary. These reductions are recorded as negative values under "emissions transferred out to grid," indicating that the emissions have been transferred to the ledger of the grid operator along with the electricity supplied.

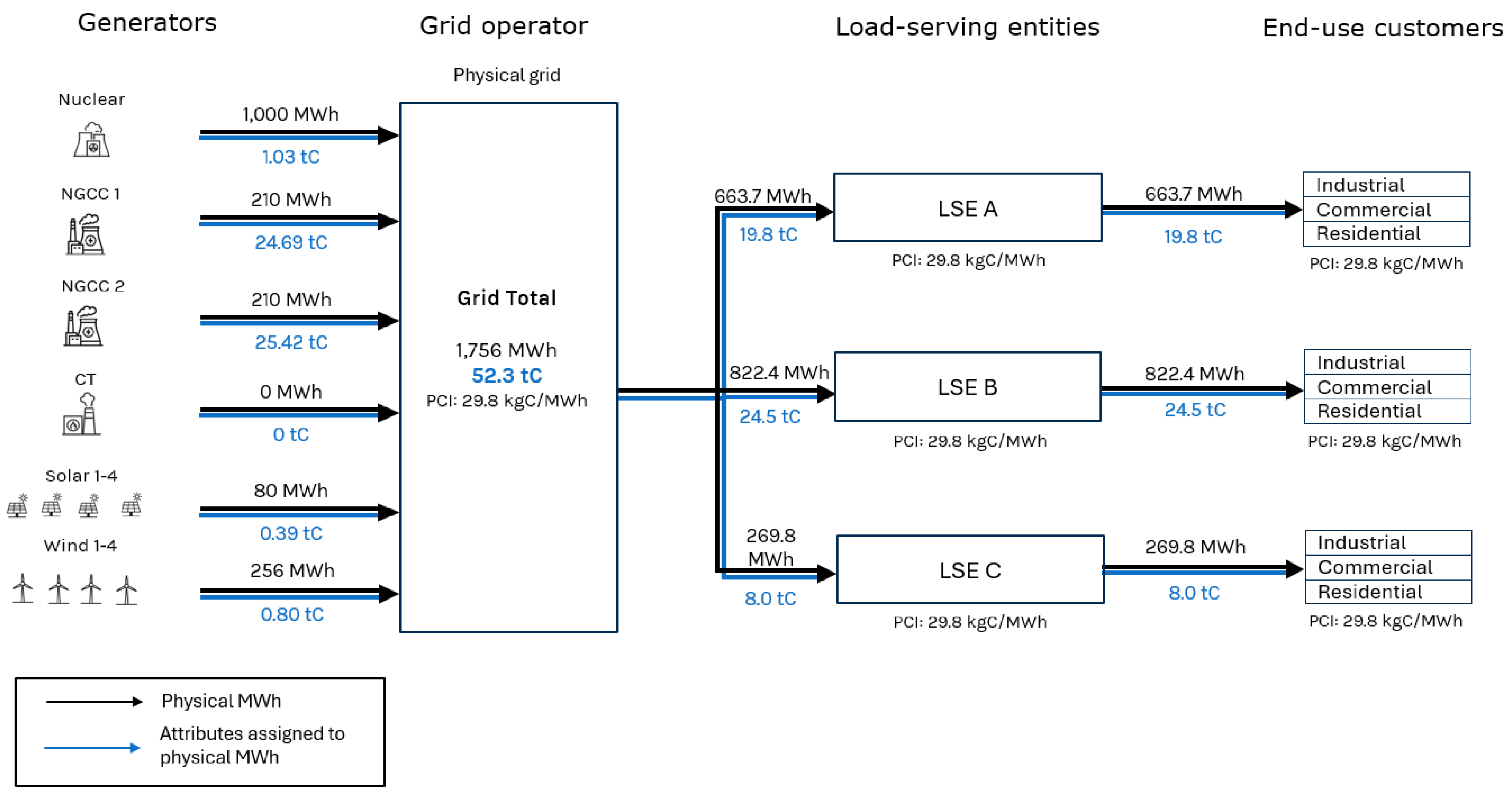
Scenario 1: No Separate EAC Transactions

Each generator, including the renewable electricity generators, supplies electricity and its attributed emissions to the grid with no differentiation of the carbon attributes of renewable electricity. Thus, only one product exists—grid electricity—which is sold to all customers.

Figure 4 shows the flow of electricity and associated carbon attributes from the generators, transmitted by the grid operator to LSEs and distributed to LSEs and to end-use customers. The black lines in the figure represent the physical flow of electricity. The blue lines represent the flow of carbon attributes associated with the physical flow.

Figure 4. Reference scenario with no EACs: Flow diagram and mass balance

Accounting period: January 1, Hour 12 (11 a.m.-12 p.m.)



Source: Sesame Sustainability.

During the one-hour accounting period, the grid receives a total supply of 1,756 MWh with attributed emissions totaling 52.3 tons of carbon. The grid electricity has a resulting average PCI value of 29.8 kgC/MWh. The electricity is distributed to the three LSEs according to demand. In this scenario, in Hour 12 (11 a.m.-12 p.m.), 38% of demand is from LSE A, 47% is from LSE B, and 15% serves LSE C. Each LSE receives electricity with the same PCI of 29.8 kgC/MWh. The LSEs, in turn distribute electricity to end-use customers with the same PCI.

The sample carbon accounting ledger of the grid operator, Table 3, shows how the various transactions are recorded at the stage where the grid operator receives and transmits the bulk power electricity supply.

Table 3. Reference scenario with no EACs: Grid operator's carbon accounting ledger

Accounting period: January 1, Hour 12 (11 a.m.-12 p.m.)

Unit: Ton of carbon (tC)

Transaction	Stocks Accounts							Flows Accounts				
	Carbon in electricity					Carbon in product inventory						
	Attrib. emissions to nuclear	Attrib. emissions to NGCC 1	Attrib. emissions to NGCC 2	Attrib. emissions to solar	Attrib. emissions to wind	Carbon in grid electricity	**Stocks total**	Carbon transferred in	Carbon transferred out to LSE A	Carbon transferred out to LSE B	Carbon transferred out to LSE C	**Flows total**
Beginning balance	***0.0***	***0.0***	***0.0***	***0.0***	***0.0***	***0.0***	***0.0***	***0.0***	***0.0***	***0.0***	***0.0***	***0.0***
Carbon transferred in with electricity from generators	1.0	24.7	25.4	0.4	0.8		***52.3***	52.3				**52.3**
Allocate carbon to products	-1.0	-24.7	-25.4	-0.4	-0.8	52.3	***0.0***					
Carbon transferred out with grid electricity						-52.3	***-52.3***		-19.8	-24.5	-8.0	**-52.3**
Ending balance	***0.0***	***0.0***	***0.0***	***0.0***	***0.0***	***0.0***	***0.0***	***52.3***	***-19.8***	***-24.5***	***-8.0***	***0.0***

Source: EFI Foundation and Sesame Sustainability.

When electricity is delivered to the grid from each generator, the grid operator records in its ledger the transfer of 52.3 tC from the generators' carbon accounting ledgers, recording it in the "carbon transferred in" flow account. The grid operator records separately the carbon from each source (1.0 tC from nuclear, 24.7 tC from NGCC 1, 25.4 tC from NGCC 2, 0.4 tC from solar, and 0.8 tC from wind) in the corresponding stock accounts.

As there is a single product—grid electricity—in this scenario, all carbon transferred in is moved to a single "carbon in grid electricity" product stock account. When the grid electricity is delivered to each customer, all carbon attributed to the electricity is transferred to the ledger of the customers. The "carbon in grid electricity" balance on the grid operator's ledger is reduced to zero and recorded in the flow accounts as negative values under the "carbon transferred out to LSE A," "carbon transferred out to LSE B," and "carbon transferred out to LSE C" accounts.

Comparison with E-ledgers:

There are multiple carbon accounting systems described in academic literature. The accounting ledger described above was developed by EFI Foundation, drawing from the basic algorithm developed by the E-ledgers Institute.[17] The EFIF ledger was designed to capture comprehensive carbon mass and energy balances, including both emissions and carbon content in fuels and materials and their conversions. The purpose of the ledger is to provide a complete accounting for all stocks and flows of all forms of carbon affecting carbon product intensity.

The E-ledgers carbon accounting is organized to mirror financial balance sheet accounting of assets and liabilities, and it includes only data on emissions. An E-ledger "records emissions as liabilities (or "E-liabilities"), and it records indefinitely sequestered GHGs that are under the exclusive legal use of the entity as assets (or "E-assets")." Table 4 illustrates an accounting ledger for Scenario 1 in the asset/liability format of E-ledgers.[f]

Table 4. Scenario 1: No separate EAC transactions: Grid operator's E-ledger

	E-assets	E-liabilities
Beginning balance	***0.0***	***0.0***
Emissions transferred in (nuclear)		1.0
Emissions transferred in (NGCC1)		24.7
Emissions transferred in (NGCC 2)		25.4
Emissions transferred in (solar)		0.4
Emissions transferred in (wind)		0.8
Sale to LSE A		-19.8
Sale to LSE B		-24.5
Sale to LSE C		-8.0
Ending balance	***0.0***	***0.0***

This presentation shows that there were no assets added or subtracted during the one-hour accounting period for operation of the illustrative case study grid. The liability side of the ledger records emissions transferred in and transferred out to LSE customers. Because load losses were excluded in order to simplify the case study, the two balance out with a net ending liability of zero.

[f] The E-ledgers accounting ledger is applied here only to Scenario 1 (No EAC transactions). It is not applied in Scenarios 2 and 3 that follow due to uncertainty as to whether and how the E-ledgers methodology would apply to EAC transactions.

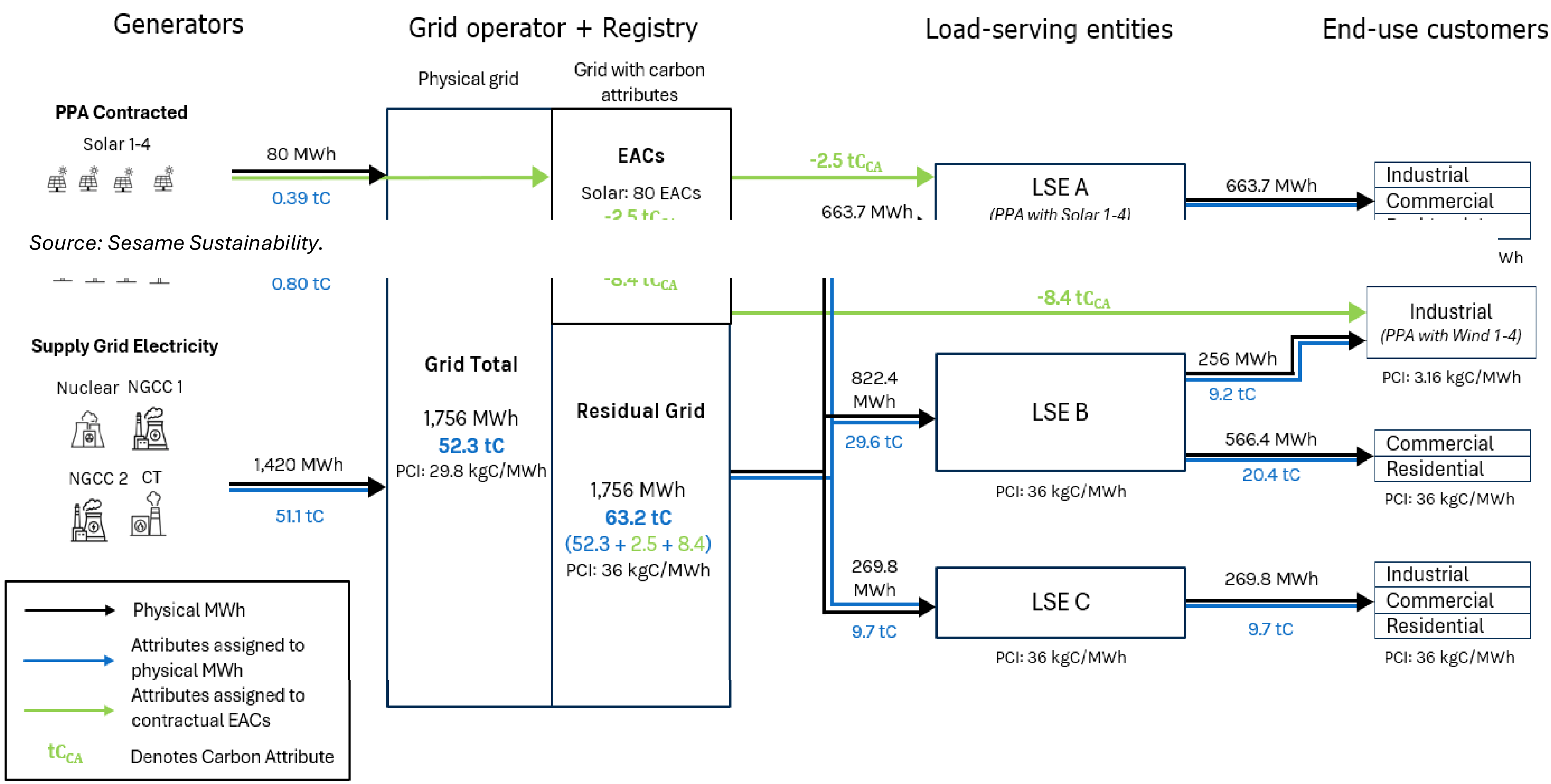
Scenario 2: Physically Directed PPAs with EACs

In this scenario, all renewable generators connected to the illustrative grid have physically directed power purchase agreements (PPAs). Four solar generators have a PPA with LSE A, which procures renewable electricity to comply with an RPS target. Four wind generators have a PPA directly with one end-use customer of LSE B; the customer procures low-carbon electricity for its decarbonization goals. The renewable generators supply electricity to the grid, where the physical supply is shared within the same network, but the financial and EAC terms and conditions of the PPA are recorded separately on the carbon accounting ledger of the grid operator and passed through to the LSEs and ultimately to the end-use customers.

Figure 5 illustrates the operation of the grid during the one-hour operating (and accounting) period. The black lines in the figure represent the physical flow of electricity. The blue lines represent the flow of carbon attributes associated with the physical flow. The green lines represent attributes assigned to EACs.

Figure 5. Physically directed PPA scenario: Flow diagram and mass balance

Accounting period: January 1, Hour 12 (11 a.m.-12 p.m.)



Source: Sesame Sustainability.

For purposes of the carbon mass balance, the electricity supply data for the grid operator is displayed in two ways.

The left side column shows the physical supply and its total attributed carbon emissions. Note that the attributed carbon emissions from the solar generators 1-4 (0.39 tC) and the wind generators 1-4 (0.8 tC) reflect the emissions transferred from the carbon accounting ledgers of their respective supply chains (e.g., attributed emissions to solar panels and wind turbines).[g]

The right-side column of the of the grid operator box shows separately the differentiated carbon attributes of the EACs associated with the physical MWh of the solar and wind generation and the adjusted attributed emissions of the physical grid. In this case, the grid operator assigns a carbon attribute (CA) value to the EACs that combines the attributed emissions of the renewable generation (i.e. the supply chain emissions attributed to its generation) together with an estimate of the carbon emissions avoided by the addition of the renewable electricity generation to the grid in the same time period. The value of the avoided emissions assigned to the EACs is calculated as the difference between the grid average PCI of the residual grid (in the absence of the renewable generation) and the PCI of renewable generators in the same time period. The net reduction is assigned as the CA value of the EACs, with a corresponding equal adjustment to the PCI of the grid total. In this scenario, the resulting values of the CA values are assigned by the grid operator to the EACs (2.5 tC for solar and 8.4 tC for wind) The renewable generators then issue RECs (based on MWh of generation) to the purchaser of the PPA, with the assigned CA values and a vintage of January 1, 2025, Hour 12. Step-by-step details of this calculation are shown in Box 4.

Box 4. Determining the value of carbon attributes (CA) of EACs

The value of carbon attributes (CAs) of EACs is calculated as the avoided carbon emissions relative to the PCI of the residual grid electricity (i.e., the PCI of the residual supply from all other generation sources connected to the grid) that would be added to the grid in the absence of the generator of the EAC within the same time period. The formula is shown as follows:

> *CA of EACs = carbon from the generators issuing EACs – carbon from the equivalent amount of residual grid electricity*

The PCI of the residual grid electricity is used as the baseline for the calculation rather than the total grid PCI or the PCI of marginal generation. The use of the PCI of residual grid electricity ensures that the carbon intensity of residual grid electricity (36 kgC/MWh = 51.1 tC/1,420.4 MWh) is identical to the carbon intensity received by customers who purchase electricity supplies from the grid but do not separately purchase EACs. In other words, once specific carbon attributes are separated, the remaining carbon attributes continue to be consistently allocated to general grid customers.

[g] Currently, RECs are assumed to have zero attributed carbon emissions because, in the absence of comprehensive carbon accounting, only the direct emissions, if any, are considered.

Using this approach, the EACs associated with Solar 1-4 are calculated as:

$$0.39 \text{ tC} - (36 \text{ kgC/MWh} * 80 \text{ MWh}) = \mathbf{-2.5 \text{ tC or } 2.5 \text{ tC}_{ca}}$$

Similarly, the EACs associated with Wind 1-4 are:

$$0.8 \text{ tC} - (36 \text{ kgC/MWh} * 255.6 \text{ MWh}) = \mathbf{-8.4 \text{ tC or } 8.4 \text{ tC}_{ca}}$$

To preserve carbon mass balance, equal and opposite amounts are added back to the residual grid electricity, reflecting the fact that the LSEs and ultimate end-use customers receive electricity with a PCI value that does not include the CA of the EACs. The formula for the adjustment to the residual grid is shown as follows:

$$52.3 \text{ tC} + 2.5 \text{ tC}_{ca} + 8.4 \text{ tC}_{ca} = \mathbf{63.2 \text{ tC adjusted}}$$

The carbon in residual grid electricity is increased by 10.9 tC_{ca}, reflecting the increased carbon emissions that would have been added to the grid in the absence of the renewable electricity generation. The resulting PCI of the grid electricity supplied to customers (other than the PPA purchasers) is 36 kgC/MWh. This PCI is then uniformly allocated among the LSEs served by the grid operator.

The PPA buyers can apply the EACs to adjust their reported attributed carbon emissions:

- The 80 EACs from Solar generators1-4, assigned 2.5 tC_{ca}, are transferred to LSE A. LSE A reduces its carbon from 23.9 tC to 21.4 tC by retiring the 80 EACs and delivers electricity with a PCI of 32.3 kgC/MWh, down from 36 kgC/MWh, to its end-use customers.
- The 256 EACs from Wind generators 1-4, assigned 8.4 tC_{ca}, are transferred to the industrial customer of LSE B. The customer lowers its carbon from 9.2 tC to 0.8 tC by retiring the 256 EACs, resulting in a PCI of 3.16 kgC/MWh, down from 36 kgC/MWh.

Table 5 shows the grid operator's recording of these transactions in its carbon accounting ledger.

Table 5. Physically Directed PPA Scenario: Grid operator's carbon accounting ledger

Accounting period: January 1, Hour 12 (11 a.m.-12 p.m.)

Transaction	Stocks Accounts					Flows Accounts					
		Carbon in Product Inventory									
	Carbon in electricity	Carbon in grid electricity	Carbon in EACs		Stocks total	Carbon transferred in	Carbon transferred out to LSE A	Carbon transferred out to LSE B	Carbon transferred out to LSE C	Carbon transferred out to EACs registry	Flows total
			Solar	Wind							
Beginning balance	***0.0***	***0.0***	***0.0***		***0.0***	***0.0***	***0.0***	***0.0***	***0.0***	***0.0***	***0.0***
Carbon transferred in with electricity from generators	52.3				***52.3***	52.3					***52.3***
Allocate physical carbon to products	-52.3	51.1	0.4	0.8	***0.0***						
Adjust values of carbon attributes		12.1	-2.9	-9.2	***0.0***						
Carbon transferred out with grid electricity		-63.2			***-63.2***		-23.9	-29.6	-9.7		***-63.2***
Carbon transferred out with EACs			2.5	8.4	***10.9***					10.9	***10.9***
Ending balance	***0.0***	***0.0***	***0.0***	***0.0***	***0.0***	***52.3***	***-23.9***	***-29.6***	***-9.7***	***10.9***	***0.0***

Note: The account of "carbon in electricity" consists of multiple subaccounts shown in the previous scenario. The subaccounts are not shown in this figure for simplicity. Source: EFI Foundation and Sesame Sustainability.

The total carbon transferred from the ledgers of the generators to the grid operator is recorded in the flow accounts as "carbon transferred in" and assigned in the stock accounts as "carbon in electricity." (As noted, this represents a rollup of the actual ledger showing the composition of carbon in each of the subaccounts for each generation source.)

The carbon recorded in the stock "carbon in electricity" account is then allocated across the product lines. The attributed carbon emissions associated with residual grid electricity (i.e., electricity supply other than the solar and wind (51.1 tC) is allocated to the "carbon in grid electricity" sub-account in the "Carbon in Product Inventory" account and the attributed emissions of the solar 1-4 generators (0.4 tC), and wind generators 1-4 (0.8 tC) are allocated to their respective "carbon in EACs" accounts. Next, the CA values of the solar (2.9 tC_{ca}) and wind (9.2 tC_{ca}) are assigned to their respective sub-accounts within the stocks account, with corresponding adjustment of 12.1tC to the "Carbon in Grid Electricity" sub-account.

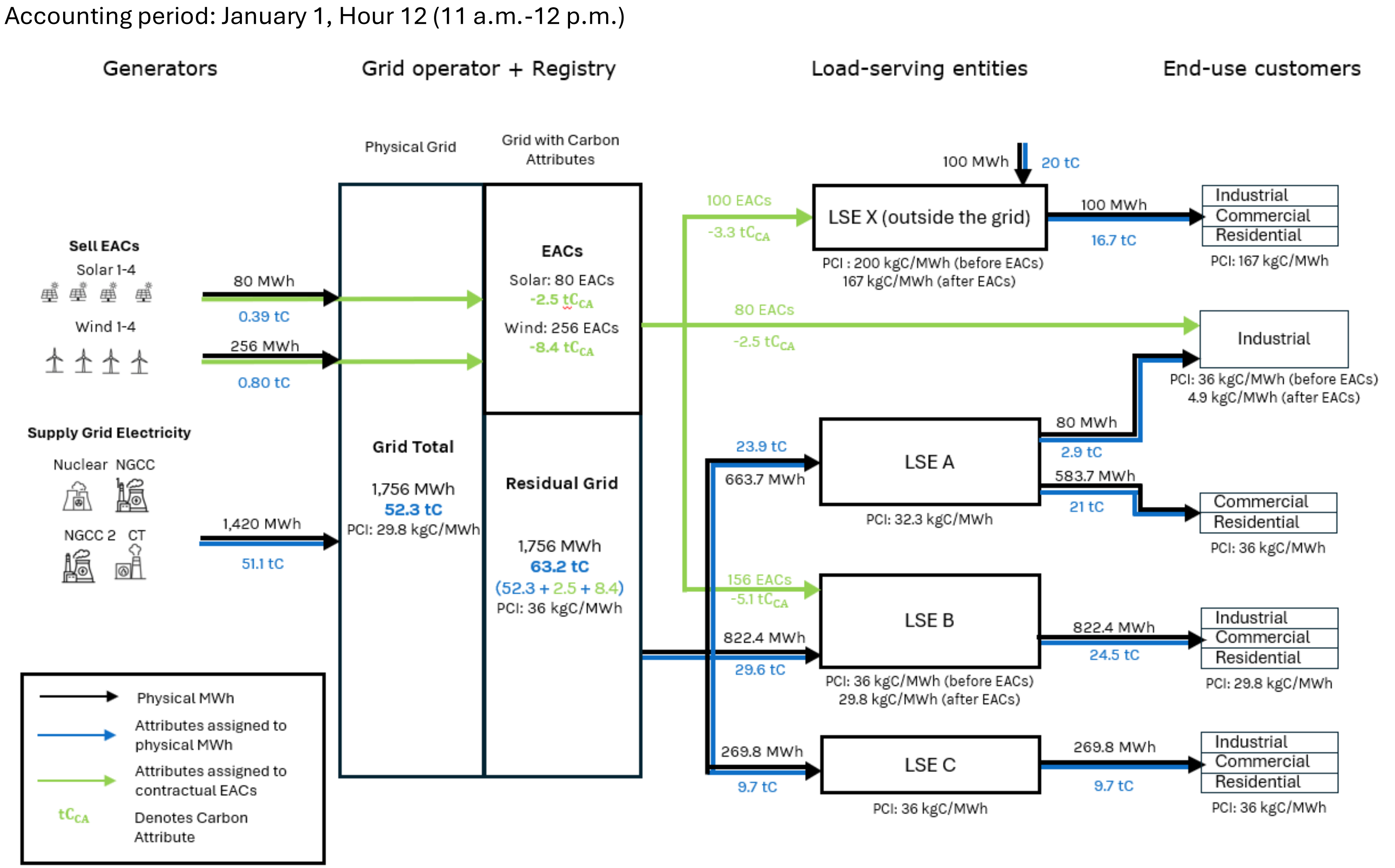
Upon the sale of electricity, the carbon in the "carbon in grid electricity" account (63.2 tC) is transferred to each LSE's ledger—LSE A (23.9 tC), LSE B (29.6 tC), and LSE C (9.7 tC)—in proportion to their electricity purchase. The CAs in the EACs accounts (2.5 tC_{ca} for solar and 8.4 tC_{ca} for wind) are transferred to the respective PPA customers. Because the grid operator takes electricity supply and transfers it to LSE on a "flash title" basis, it is assumed that the EACs are transferred within the same time period as the transfer of electrons.

Scenario 3: Separately Traded EACs

In this scenario, all renewable electricity generators connected to the illustrative grid generate and register RECs with associated EACs with a third-party registry, separate from the physical flow of electricity supplied to the grid. Any eligible entity, including an LSE or end-use customer, whether located within or outside the illustrative grid, can purchase the registered RECs with the associated CA of their EACs.

Figure 6 illustrates the operation of the grid during the one-hour operating (and accounting) period in this scenario. The blue lines represent the flow of carbon attributes associated with the physical flow. The green lines represent attributes assigned to EACs.

Figure 6. EACs trading scenario: Flow diagram and mass balance



Source: Sesame Sustainability.

The left side column of the grid operator box shows the physical electricity supply and its total attributed carbon emissions, the same as in Scenario 2.

The right-side column shows separately the differentiated CAs of the EACs associated with the physical MWh of the solar and wind generation and the adjustments to the attributed emissions of the physical grid. As in Scenario 2, the CA values of the EACs are calculated on the basis of the values of average PCI of the electricity grid (without the renewable generators) that would otherwise be added to the grid in the absence of the low-carbon generators. Therefore, in this scenario, the carbon attributes are allocated as below:

- Solar EACs: 0.39 tC – (36 kgC/MWh * 80 MWh) = **-2.5 tC or 2.5 tC_{ca}**
- Wind EACs: 0.8 tC – (36 kgC/MWh * 255.6 MWh) = **-8.4 tC or 8.4 tC_{ca}**
- Grid electricity: 52.3 tC + 2.5 tC_{ca} + 8.4 tC_{ca} = **63.2 tC adjusted.**

These values are the same as those in Scenario 2, demonstrating that the methodology for calculating the CA values of the EAC is based on the time of its generation and independent upon its disposition via a physically directed PPA or a sale and purchase on a REC registry, neutral to the type of contractual arrangement.

In this scenario, three entities purchase the EACs from the REC registry, separate from their purchase of physical electricity from the grid:

- An individual end-use customer purchases 80 EACs associated with 80 MWh of solar generation from RECs on the registry in order to reduce the emissions associated with its 80 MWh of electricity purchased from its LSE. The 80 EACs have a carbon attribute value of 2.5 tC_{ca}. By applying the 80 EACs to offset the carbon attributes of the grid electricity, the customer reduces the PCI of its electricity use from 36 kgC/MWh to 4.9 kgC/MWh.
  - By comparison, under the current GHGP Scope 2 reporting guidelines, the customer could report zero market-based Scope 2 emissions, as the 80 MWh of electricity is matched with 80 EACs on a MWh-to-MWh basis. Under the carbon accounting methodology, however, emissions are not reduced to zero because CA value for the solar generator includes attributed emissions transferred to its carbon accounting ledger from the ledgers of its supply chain.
- LSE B purchases 156 EACs associated with 156 MWh of RECs from wind generation from the registry in order to reduce the average product carbon intensity associated with its purchase of 822.4 MWh of grid electricity. The 156 EACs have a carbon attribute value of 5.1 tC_{ca}. By applying the carbon attributes associated with the EACs, LSE B reduces the PCI of the electricity delivered to its customers to 29.8 kgC/MWh, compared with the grid electricity PCI of 36 kgC/MWh.
- LSE X, an LSE in another grid, purchases 100 EACs from the registry to reduce the emissions associated with the 100 MWh of electricity supply it receives from its grid, which has a much higher carbon intensity. The 100 EACs have a carbon attribute value of 3.3 tC_{ca}. By retiring the 100 EACs, LSE X reduces the PCI of its electricity from 200 kgC/MWh to 167 kgC/MWh.

- By comparison, under current GHGP Scope 2 reporting guidelines, LSE X could report zero market-based Scope 2 emissions, as its 100 MWh of electricity is matched with 100 EACs. Under this allocation methodology, however, LSE X can reduce only 17% of the emissions associated with its electricity. *This highlights that the carbon attribute value assigned to an EAC is fixed at the time of generation and cannot be used to offset more emissions than the carbon attribute value determined at the time of generation*. Furthermore, because the carbon attributes of the 100 EACs are fully accounted for, there is no double counting of the carbon attributes once they are purchased and retired by LSE X in another grid.

Table 6 shows the records of these transactions in the grid operator's carbon accounting ledger. The records are the same as those in Scenario 2 because the transactions that generate and register the EACs are identical at the boundaries of the grid operator. The differences lie in the ledgers of the downstream entities.

Table 6. EACs trading scenario: Grid operator's carbon accounting ledger

Accounting period: January 1, Hour 12 (11 a.m.-12 p.m.)

Transaction	**Stocks Accounts**					**Flows Accounts**					
	Carbon in electricity	Carbon in Product Inventory			**Stocks total**	Carbon transferred in	Carbon transferred out to LSE	Carbon transferred out to LSE B	Carbon transferred out to LSE	Carbon transferred out to EACs	**Flows total**
		Carbon in grid electricity	Carbon in EACs								
			Solar	Wind							
Beginning balance	***0.0***	***0.0***	***0.0***		***0.0***	***0.0***	***0.0***	***0.0***	***0.0***	***0.0***	***0.0***
Carbon transferred in with electricity from generators	52.3				***52.3***	52.3					***52.3***
Allocate physical carbon to products	-52.3	51.1	0.4	0.8	***0.0***						
Adjust values of carbon attributes		12.1	-2.9	-9.2	***0.0***						
Carbon transferred out with grid electricity		-63.2			***-63.2***		-23.9	-29.6	-9.7		***-63.2***
Carbon transferred out with EACs			2.5	8.4	***10.9***					10.9	***10.9***
Ending balance	***0.0***	***0.0***	***0.0***	***0.0***	***0.0***	***52.3***	***-23.9***	***-29.6***	***-9.7***	***10.9***	***0.0***

Note: The account of "carbon in electricity" consists of multiple subaccounts shown in the previous scenario. The subaccounts are not shown in this figure for simplicity. Source: EFI Foundation and Sesame Sustainability.

Table 7, on the following page, shows the transactions recorded in LSE X's carbon accounting ledger during the same accounting period.

Table 7. EACs trading scenario: LSE X's carbon accounting ledger

Accounting period: January 1, Hour 12

Transaction	Stocks Accounts			Flows Accounts			
	Carbon in electricity	EACs	**Stocks Total**	Carbon transferred in	EACs transferred in	Carbon transferred out to customers	**Flows Total**
Beginning balance	***0.0***	***0.0***	***0.0***	***0.0***	***0.0***	***0.0***	***0.0***
Carbon transferred in with electricity	20.0		***20.0***	20.0			***20.0***
EACs purchased		-3.3	***-3.3***		-3.3		***-3.3***
Carbon transferred out to customers	-20.0		***-20.0***			-20.0	***-20.0***
EACs transferred out to customers		3.3	***3.3***			3.3	***3.3***
Ending balance	***0.0***	***0.0***	***0.0***	***20.0***	***-3.3***	***-16.7***	***0.0***

Source: EFI Foundation and Sesame Sustainability.

When LSE X purchases electricity from its own grid, 20 tC is recorded in the "carbon in electricity" and "carbon transferred in" accounts. When LSE X purchases EACs, the associated CA value of 3.3 tC_{ca} is recorded in the "EACs" and "EACs transferred in" accounts.

When electricity is delivered to its end-use customers, it is assumed that the REC, along with the CA value of associated EAC, is applied to sale of electricity within the same time period. Consequently, the balances in both the "carbon in electricity" and "EACs" accounts are reduced to zero, with the corresponding amounts recorded as negative values in the "carbon transferred out to customers" flow account. The ending balance of 16.7 tC in the "carbon transferred out to customers" account represents the net carbon delivered to end-use customers.

Value-Matching of Carbon Attributes as an Alternative to Physical Time-Matching

The CA value of EAC is fixed based on the avoided carbon emissions on the grid at the time that the REC was generated. The CA value of the EAC will vary based upon the time of day of the REC. The variation in CA values of wind and solar generation at varying times during the day is illustrated in Box 5.

Box 5. Valuation of the EACs associated with RECs based on the time of generation

The variation in the value of EACs associated with a REC, based on its time of generation, using this allocation methodology for carbon accounting, is illustrated in Table 8.

Table 8. Comparison of EACs in different time frames

		January 1, Hour 12 (11 a.m.-12 p.m.)	January 1, Hour 2 (1 a.m.- 2 a.m.)	January 1, Hour 18 (17 p.m.-18 p.m.)
Grid total (all generators)	Electricity (MWh)	1,756	1,409	1,810

	Carbon (tC)	52.3	30.0	86.2
	PCI (kgC/MWh)	29.8	21.3	47.6
Physical grid with CAs adjusted for exclusion of renewable generators	Electricity (MWh)	1,756	1,198	1,717
	Carbon (tC)	63.2	34.5	90.6
	PCI (kgC/MWh)	36.0	24.5	50.1
Solar 1-4	Electricity (MWh)	80	0.0	0.0
	Carbon (tC)	0.39	0.0	0.0
	PCI (kgC/MWh)	4.8	0	0
Wind 1-4	Electricity (MWh)	256	211.3	93.2
	Carbon (tC)	0.8	0.66	0.29
	PCI (kgC/MWh)	3.1	3.1	3.1
CA values of EACs (based on time of day of generation)	**Solar EACs total $(tC)_{ca}$**	**2.5**	**0.0**	**0.0**
	Wind EACs total $(tC)_{ca}$	**8.4**	**4.51**	**4.37**

Source: Sesame Sustainability.

For example, at Hour 12, the time period used in the case study scenarios, the CA value of the EACs was 2.5 tC_{ca} for solar and 8.4 tC_{ca} for wind. At other times of the day, the CA values of EACs associated with solar and wind generation are different based on the PCI of the residual grid (i.e., the generation mix absent solar or wind) at that time.

- At 2 a.m., total demand on the grid is low, no solar is generated, and the residual grid PCI is relatively low. So even though the wind generation level is higher than at noon, the carbon attribute value of the wind RECs is 4.51 tC_{ca}, below the carbon attribute value at noon.
- At 6 p.m., the total demand on the grid is the highest among the three examples, as is the residual grid PCI. Although the level of wind generation is lower than at noon, the carbon attribute value of total wind RECs only slightly decreases because the PCI of residual grid is high.

Once fixed, the CA value of EACs does not change depending on the time of retirement of the REC and its associated EAC. Consequently, time matching of the generation and retirement of the RECs is not required in order to assure that its value is maintained.

In the case study example, it is assumed for simplicity of presentation that the EACs are created and retired within the same accounting period, which in this case is hourly. The accounting framework, however, can accommodate creation and retirement across accounting time periods. Some states, for example, allow up to three years for retirement of EACs.

- By comparison, the current GHGP Scope 2 guidelines would allow the EAC of the REC to fully offset the carbon attribute value of an equivalent amount of generation at any time, regardless of the weighted average carbon intensity of the grid at that time. The proposed GHGP guidelines would attempt to achieve equality between the value of the EAC of the REC with the value of the carbon emissions reduction by the customer by severely restricting the time period in which the customer could claim (and thus retire) the REC, imposing a new policy constraint on the operation of the REC market.

V. Conclusions and Insights

This study analyzes the challenges of accounting for carbon in the power sector and demonstrates through case study scenarios how comprehensive, ledger-based carbon accounting can address these challenges. A particular focus of the study was on the accounting for the carbon attributes of energy attribute certificates, or EACs, a contractual instrument typically associated with renewable electricity generation, that can be purchased and sold separately from the underlying physical electrons generated.

The study does not advocate for contractual instruments such as EACs, nor does it recommend changes in current governmental policies establishing EACs. Rather, the case studies are policy agnostic, and seek to demonstrate how contractual instruments that exist in the market today can be adopted in carbon accounting, and incorporated into power sector PCIs.

The study process considered five different methodologies for accounting for the carbon attributes of EACs associated with renewable electricity generation. The case study adopted a methodology that assigns the value of the carbon attributes associated with an EAC based on value of average PCI of the electricity grid (without the renewable generators) that would otherwise be added to the grid in the absence of the low-carbon generators. This approach, compared to other possible approaches, requires further review and discussion.

The case study analyses provided a number of insights into how a ledger-based carbon accounting system that differentiates low-carbon attributes from the physical electrons required can be adopted in the power sector in a manner that meets the general principals of completeness, consistency, transparency, and verifiability. These insights include the following:

- Ledger-based carbon accounting that is grounded in carbon mass balances ensures that all carbon is recorded without gaps and overlaps across the entire electricity product value chain.
- Ledger-based carbon accounting for the power sector on the basis of transactions enables accounting to follow the temporal variation in the grid for changes in both demand and generation mix to the extent of the granularity in available data.
- The carbon accounting methodology applied to the case study establishes values for carbon attributes for energy attribute certificates, such as RECs, based on the magnitude of emissions reductions achieved at the time of generation.
- In contrast to current and proposed GHGP Scope 2 guidelines, the comprehensive carbon accounting system allows for reporting of electricity-related emissions in a manner that integrates the concepts of location-based and market-based

emissions tracking within a single ledger, with transparent crosswalks between the two types of GHGP reporting with no gaps or duplication.

- Fixing the value of the EAC carbon attributes at the time of generation allows for value-matching of the credit to its value when retired by the EAC buyer, avoiding the need for more complex and restrictive time-matching and location-matching approaches for achieving the same outcomes.
- Carbon accounting reduces the burden on end-use electricity customers in developing Scope 1, 2, and upstream Scope 3 inventories and reports by providing them with complete and disaggregated PCI metrics. It does, however, increase the needs of full participation of generators, grid operators and LSEs in managing their own carbon accounting ledgers. In addition, the proposed approach to accounting for carbon attributes of EACs associated with RECs, would require additional data collection and reporting by the generators of RECs to grid operators and current REC registries.

VI. Next Steps

The case study scenarios provide a simplified representation of grid operations for the purpose of illustrating the basic concepts of power sector carbon accounting. These represent a starting point for discussion, and substantial further work is needed to demonstrate the application of carbon accounting to the complex and dynamic conditions of power markets. These include:

Implications for customer choice: The emissions associated with electricity supply can represent a significant share of total supply chain emissions for manufacturers and large-scale corporate customers. Scenarios 2 and 3 in this study showed that, applying the terms of the contractual agreements, the accounting for the carbon attributes of EACs associated with RECs can result in additional carbon being allocated to other grid customers without their knowledge or prior consent. While this information can be disclosed by the grid operator to the customer, the larger policy issues require further discussion among stakeholders.

Defining the roles and responsibilities of the "grid operator": In this study, the grid operator is responsible for allocating carbon attributes to grid electricity and EACs and transferring them to LSEs and from there to end-use customers. This role would require access to data on transactions involving contractual instruments for the purchase and sale of EACs, and to the capability to integrate this data with data on physical flows of electricity. In regulated markets, a vertically integrated utility can perform this role in coordination with existing renewable energy certificate tracking systems. In deregulated markets, however, the supply chain involves a larger number of actors. ISOs manage a wholesale electricity market and associated transmission systems; generators owned by different entities bid into wholesale markets and dispatch when called upon; load-serving entities procure electricity for diverse customer groups; and end-use customers can enter into bilateral contracts with terms and conditions that may not be fully transparent to transmission and distribution system operators. In all cases the integrated utility, the ISO, and the LSE may not have full information on transactions of the carbon attributes of EACs. As a result, identifying and coordinating an entity to perform the grid operator function would be considerably complex.

Incorporation of electricity storage: The illustrative grid in this case study assumes an instantaneous grid, where all of the electricity is generated, transmitted, distributed, and consumed within the same time period. Electricity storage allows electricity to be generated and consumed across different time periods. Battery energy storage systems (BESS) are the fastest-growing power technology, with 108 GW of new battery storage deployed globally in 2025, a 40% increase from 2024.[18] Additional analysis is needed of how the carbon attributes should be tracked through charging, storage, losses, and discharge while maintaining carbon mass balance and avoiding double counting. For example, BESS systems co-located with renewable electricity generators could be incorporated into the carbon accounting ledger of the generator. BESS systems located within the transmission and distribution system pose more complicated sets of transactions for carbon accounting. Behind-the-meter storage systems directly affect patterns of energy demand and, consequently, indirectly affect the dispatch of the generation mix at any particular point in time.

Dynamic grid conditions: The case study scenarios do not address more complex dynamic changes, such as spinning reserves, requirements for voltage and frequency control, and adjustments to PCI values due to transmission and distribution losses. Additional scenarios reflecting the dynamic nature of power markets should be explored. Future analysis will need to address how such dynamics should be incorporated within the carbon mass balances and ledger-based carbon accounting systems.

Appendix A. Discussion of GHG Protocol Scope 2 Emissions Reporting

This appendix summarizes issues with the current Greenhouse Gas Protocol (GHGP) Scope 2 Guidance for reporting electricity-related emissions, shortcomings of the guidance relative to a comprehensive carbon accounting system, the growing use of contractual emissions as the basis for reporting market-based Scope 2 emissions, and the next steps toward a harmonized set of accounting rules.

Issues With the Current Scope 2 Methodology

The GHGP was designed as a disclosure mechanism for GHG emissions. The GHGP Scope 2 Guidance has been the principal methodology for quantifying and reporting electricity-related emissions since its release in 2015.

It is widely recognized that the current Scope 2 Guidance for preparing inventories and reporting electricity GHG emissions does not adequately address the challenges of the evolving power sector. Current guidance, for example:

- Places responsibility on customers to collect and collate the data from electricity suppliers, even though customers do not necessarily have complete visibility into the operation of the grid and the interplay between physical grid carbon characteristics and market-based contractual instruments.
- Allows customers to value the GHG emissions reduction benefits of energy attribute certificates, such as RECs, equally, regardless of the time and place where they were generated and the time and place where they were retired.
- Allows use of emissions factors based on averages of up to a year in duration, masking temporal variations in grid operations that can vary by the hour.
- Does not ensure complete offsetting balances in the generation and retirement of the carbon attributes associated with power purchase agreements and RECs, resulting in double counting of GHG emissions reduction benefits.

Under the current Scope 2 Guidance, organizations that purchase electricity in markets where contractual instruments are available are required to report their Scope 2 emissions using both “location-based” and “market-based” methods:

- **Location-based Scope 2** reflects the average emissions intensity of the physical electricity grid and assigns the same average grid emissions factor to all customers. It ignores differentiated procurement choices embodied in contractual instruments.
- **Market-based Scope 2** reflects emissions accounting for contractual instruments. Market-based methods allow industrial and commercial electricity customers to

report emissions based on the terms of contractual instruments that may or may not specify a physical pathway for delivery. This, in turn, impacts all other customers, in many cases unknowingly to them, since the residual carbon emissions intensity of the grid may not account for the assignment of certain low-carbon electricity to specific individual customers.

The use of two separate approaches poses several significant issues. The two approaches cannot be readily reconciled, because they both lack the underlying product-level carbon accounting that could allow for crosswalk between the two estimates. More importantly, the market-based approach can lead to double counting of emissions reductions, because a customer may claim the low-carbon attributes of a renewable generator through a certificate while the same low-carbon generation simultaneously reduces the grid-average emissions factor applied to all other customers. In some cases, companies may also be unable to report market-based Scope 2 emissions because of limited data availability, particularly the lack of reliable residual grid emissions factors that exclude contractual instruments.

Another complexity is that upstream emissions from electricity generation inputs and feedstocks are separated from Scope 2 and classified as GHGP Scope 3, Category 3: fuel and energy-related activities not included in Scope 1 or Scope 2 emissions. Reporting Scope 3 emissions is less common than reporting of Scope 1 and 2, and among companies that do report Scope 3, only about half provide a categorical breakdown.[19,20] Thus, the upstream emissions of electricity products are often overlooked by many organizations.

Finally, a fundamental issue has been raised regarding the basic rationale for a market-based approach to carbon accounting for electricity emissions. Proponents of market-based Scope 2 reporting argue that the market-based approach represents a swap between two different entities with different carbon attribute profiles.

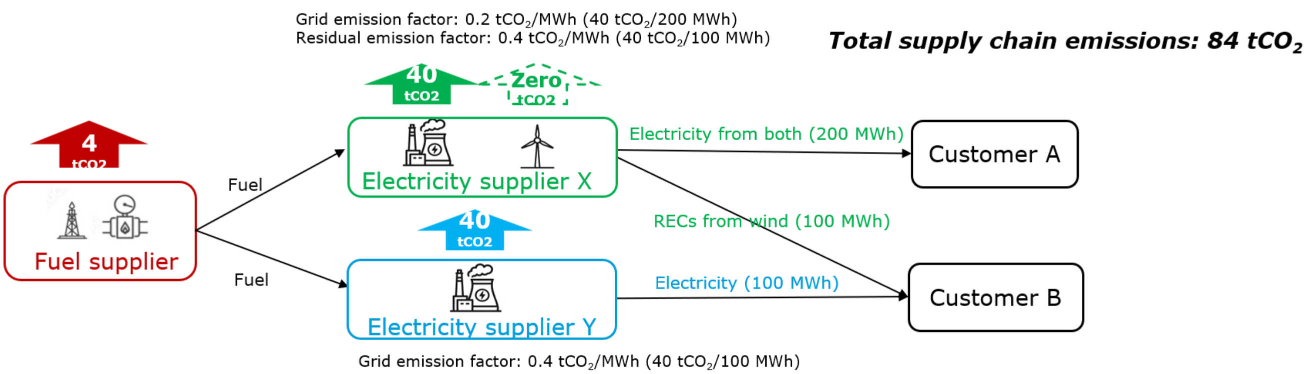
Some economists (Roston) argue that the market-based approach is fundamentally different from a financial market swap.[21] Roston and colleagues point out that these transactions are not true swaps because both parties do not mutually agree to exchange attributes. They note further that such transactions have no value because they do not generate any additional environmental gain even if both parties did consent.

Stakeholders have varied views on this "dual reporting" guideline, with some supporting location-based reporting only, some supporting market-based reporting only, and others preferring to maintain dual reporting.[22] In practice, however, many entities selectively report the more favorable metric. Numerous respondents to a GHG Protocol survey pointed out the selective reporting of more favorable Scope 2 emissions numbers as a significant concern.[23] A study of 102 European companies found that only half reported both location-based and market-based Scope 2 emissions in 2023.[24]

A Hypothetical Example of Differences in Scope 2 Reporting

A hypothetical example illustrated in Figure 7 highlights the challenges discussed above. This example assumes a supply chain consisting of one fuel supplier, two electricity suppliers, and two customers. The fuel supplier delivers fuels to each electricity supplier and emits 4 tons of carbon dioxide (tCO_2). Electricity Supplier X generates 200 MWh of electricity from two generators—one emitting 40 tCO_2 and the other carbon-free. Electricity Supplier Y generates 100 MWh of electricity from a single power plant, which emits 40 tCO_2. Electricity Supplier X sells all of its electricity to Customer A and separately sells 100 MWh of RECs to Customer B. Electricity Supplier Y sells all of its electricity to Customer B.

Figure 7. A hypothetical electricity supply chain for Scope 2 reporting



Source: EFI Foundation.

Under the Scope 2 Guidance, emissions associated with purchased electricity are calculated as shown in Table 9.

Table 9. Comparing emissions from purchased electricity

	Customer A's emissions from purchased electricity	Customer B's emissions from purchased electricity
Location-based Scope 2	**40 tCO_2** = 0.2 tCO_2/MWh (grid emission factor) * 200 MWh (purchased electricity)	**40 tCO_2** = 0.4 tCO_2/MWh (grid emission factor) * 100 MWh (purchased electricity)
Market-based Scope 2	**80 tCO_2** = 0.4 tCO_2/MWh (residual emission factor) * 200 MWh (purchased electricity)	**0 tCO_2** = 0 tCO_2/MWh (REC emission factor) * 100 MWh (purchased electricity)
Scope 3 Category 3	Estimated or not reported	Estimated or not reported

In an ideal world, both customers would report all categories of emissions and compare only within the same categories. However, in practice, it is common for Customer A to report only location-based Scope 2 emissions (40 tCO_2), because this is more favorable or the residual emission factor is unavailable.[h] Similarly, Customer B is likely to report only market-based Scope 2 emissions to highlight the use of 100% carbon-free electricity. It is also common for Scope 3 Category 3 emissions to be omitted by both customers.

As a result, in a worst-case scenario, only 40 tCO_2 out of the 84 tCO_2 of total emissions in this supply chain may be reported—namely, Customer A's location-based emissions (40 tCO_2) plus Customer B's market-based emissions (0 tCO_2). The remaining 44 tCO_2 are not reflected in reported Scope 2 emissions: 40 tCO_2 are unaccounted for because of double counting of environmental attributes associated with Electricity Supplier X's generation, and 4 tCO_2 of upstream emissions are excluded because Scope 2 does not cover upstream emissions. Consequently, the reported figures are not fully comparable.

The Growing Use of Contractual Instruments

At a time when there is growing criticism of the current Scope 2 Guidance, there also is increasing use of the Scope 2 market-based approach. Contractual instruments to allow entities to make carbon reduction claims have become critical tools to decarbonize reported electricity-related emissions.

Globally, corporations announced PPA deals totaling 56 GW of clean power in 2025, more than double the volume reported in 2020.[25] Roughly half of the 2025 capacity was contracted by hyperscalers, including Meta, Amazon, Google, and Microsoft.

The large gap between location-based and market-based Scope 2 emissions for leading hyperscalers, shown in Figure 8, underscores the importance of accounting for these instruments.[26] [27,28,29,30,31,32,33]

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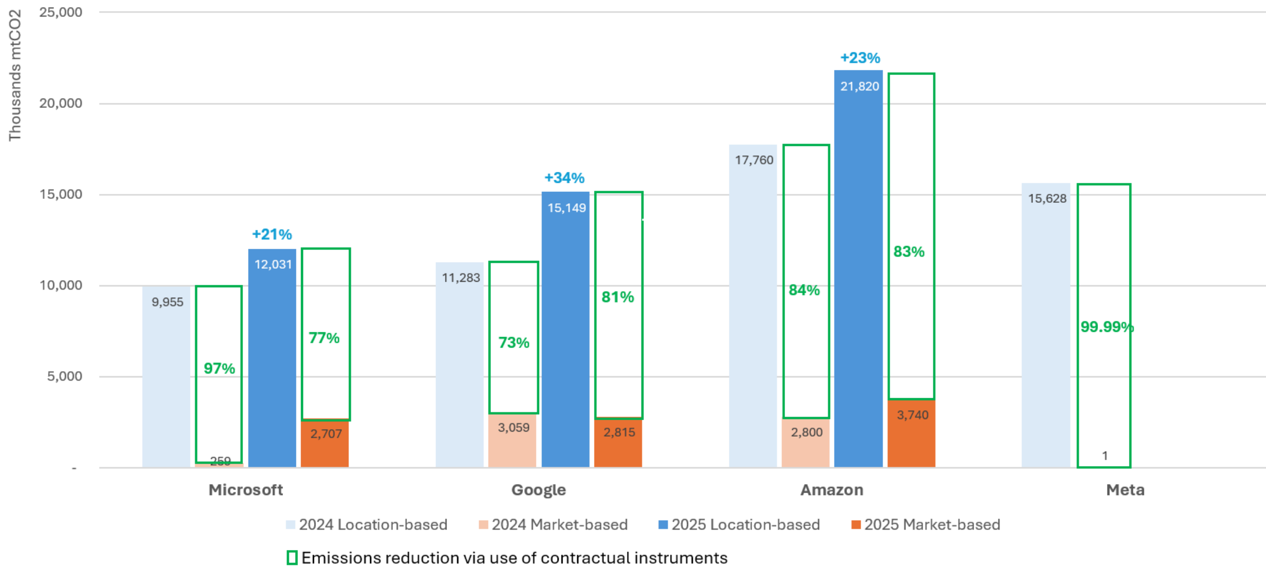
[h] In practice, residual mix emission factors are often unavailable and inconsistently applied. Many jurisdictions do not publish them, and those that do typically release them only on an annual basis. Such annual averages do not adequately capture the temporal and spatial dynamics of physical electricity flows, limiting their accuracy and relevance for rigorous carbon accounting.

Figure 8. Leading hyperscalers' Scope 2 emissions, 2024-2025



Note: Data are sourced from each company's sustainability report. Amazon did not publicly report location-based Scope 2 emissions; this information is derived from a third-party review report. Meta's 2025 data were not publicly available at the time of writing this report. $mtCO_2e$ = metric tons of carbon dioxide equivalent. Source: EFI Foundation.

Figure 8 shows that hyperscalers' electricity-related emissions are rapidly increasing, while contractual instruments are being used to reduce a substantial portion of these emissions. Compared with 2024, the location-based Scope 2 emissions of Microsoft, Google, and Amazon increased by 21%, 34%, and 23%, respectively, in 2025. These companies reduced their market-based Scope 2 emissions by 77%, 81%, and 83%, respectively, through the use of contractual instruments in 2025. Meta reduced nearly 100% of its Scope 2 emissions through contractual instruments in 2024. For these companies, investment in contractual instruments is a key strategy to manage the carbon footprint associated with the rapid growth in electricity requirements for expanding data center operations.

Differences in the contractual instruments used and the quality criteria applied to them can result in carbon information that is difficult to compare across companies. For example, Microsoft's decision to stop using nonadditional, unbundled RECs beginning in 2025 led to a 945% increase in its market-based Scope 2 emissions compared with 2024. This illustrates how a company's choice of contractual instruments and the quality criteria applied to them can substantially affect its reported emissions.

While the hyperscalers are the predominant force in the use of contractual instruments, participation rates in voluntary carbon markets have been increasing across the board in the private sector. In the United States, approximately 9.7 million customers procured about 319 million MWh of renewable energy certificates in 2023, representing roughly 44% of U.S. non-hydropower renewable energy generation.[34] The U.S. RECs market is expected to continue growing, with an analysis forecasting a 15.9% annual growth rate through 2033.[35]

With the growing use of contractual instruments, carbon accounting methodologies cannot provide a complete picture useful for decision-making unless they explicitly account for contractual instruments. Methodologies that rely solely on location-based emissions may overlook one of the most important corporate decarbonization strategies—contracting for low-carbon electricity. The issue, therefore, is not whether to account for contractual instruments, but how to estimate and represent them more accurately.

Next Steps

The GHGP Scope 2 Guidance is undergoing a major revision to reflect the recent developments in climate disclosure standards and related initiatives. Draft updates were released for public consultation between October 2025 and January 2026, with the final revised standard expected in 2027. The recently proposed updates to the Scope 2 Guidance retain the dual-reporting structure for location-based and market-based emissions but propose stricter rules for determining the scope of the market-based approach.[36] These proposed changes have triggered vigorous discussion and debate.

The GHG Protocol is also collaborating with the International Standards Organization (ISO) to better address the linkage between product-level and entity-level emissions reporting. Resolution of these and other issues ultimately will require adoption of product-level carbon accounting that can be fully integrated with entity-level emissions accounting, with the stated purpose of applying financial accounting principles.

The comprehensive product- and entity-level carbon accounting system, as applied to the power sector in this case study report, could provide a path forward for harmonizing the current varied approaches.

Appendix B. Data and Methods

Sesame Modeling Engine

This case study draws data from Sesame One, an industrial decarbonization platform from Sesame Sustainability that combines emissions modeling based on life cycle analysis, techno-economic analysis, and system optimization into a single, consistent framework. It provides the analytical foundation for both the generator-level and grid-level carbon accounting through two integrated modeling components:

- **Mass and energy balance resolution**: For each thermal generator, Sesame One resolves the fundamental mass and energy balance relationships that determine emissions from fuel inputs. The model calculates fuel consumption based on plant heat rate and electrical output, tracks the conversion of fuel carbon to CO_2 and other emissions species through combustion, and verifies that the carbon mass balance closes—that total carbon in fuel equals total carbon in emissions plus any unconverted residuals. This first-principles approach ensures that direct emissions are calculated from actual process chemistry rather than estimated from aggregate emissions factors.

  For renewable and nuclear generators, the mass and energy balance is simpler since there are no fuel-related carbon flows during operation, but the model still tracks the depreciation of attributed emissions in plant, property, and equipment (PPE) over the facility's lifetime production.

- **Power system modeling**: Sesame One also incorporates power system modeling capabilities. Its flagship model conducts a single-node dispatch or capacity expansion analysis, using an hourly resolution over a full year. This analysis minimizes total operating cost to determine the optimal capacity deployment and resulting hourly generation profiles for each generator.

  The model's input data integrates the generators' carbon data with operational parameters such as heat rates, ramp rates, and minimum stable level; financial parameters including financing costs, capital costs, and operational costs; and renewable generation profiles for wind and solar resources obtained from a global dataset.

Once the model is optimized and the dispatch schedule is obtained, the production and carbon data for each generator yield the hourly emissions profile in the system. These profiles, combined with hourly customer data and contractual agreements, provide all necessary data to perform the carbon accounting analysis for the power sector.

Case Study Inputs and Assumptions

Upstream Carbon and Emissions

Feedstock carbon intensities

Thermal generators procure fuel from upstream suppliers, each of which transfers attributed emissions to the generator's ledger alongside the physical fuel delivery, consistent with the free on delivery (FOD) framework.[i]

Natural gas attributed emissions are adopted from the Argonne National Laboratory GREET 2024 well-to-gate pathway for conventional natural gas, including upstream extraction, processing, and delivery up to a transmission pipeline. Emissions from transportation account for natural gas and grid electricity consumed to power the compressors along the route, as well as methane leakage rate.

Nuclear fuel cycle emissions—covering uranium mining, milling, conversion, enrichment, and fuel fabrication—are adopted from GREET. Where upstream processes require grid electricity, the carbon intensity is based on New York-specific grid emissions factors derived from the U.S. Energy Information Administration's Annual Energy Outlook for the North American Electric Reliability Corporation (NERC) Northeast Power Coordinating Council (NPCC) region. Table 10 summarizes the feedstock carbon intensities.

Table 10. Feedstock and transportation emissions intensities

Feedstock	Product CI	Source	Details
Natural gas	• 4.53 gCO_2/MJ • 0.11 gCH_4/MJ • 0.01 gCO/MJ • 0.01 gVOC/MJ	Argonne GREET Model, 2024[37]	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.
Natural gas pipeline	• 27.6 $kgCO_2$/ton • 1.4 gCH_4/ton • 348 gCO/ton • 68 gVOC/ton	Argonne GREET Model, 2024	Pipeline energy intensity and leakage rate consistent with GREET default (Argonne GREET Model, 2024).
Uranium	• 1,118 $kgCO_2$/kgU	*Internal Report: Analysis of Nuclear Fuel Cycle Data,* Argonne GREET, 2023[38]	Value for enriched Uranium. Corresponds to ~2.9 $kgCO_2$/MWh.
Electricity	• 60,568 gCO_2/mmBtu • 150.543 gCH_4/mmBtu	Argonne GREET Model, 2024	NERC region, 2024; NPCC region. AEO 2023 Reference Case.

[i] 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.

	• 64.031 gCO/mmBtu • 16.77 gVOC/mmBtu		

Note: CH_4 = methane, CO = carbon monoxide, VOC = volatile organic compounds, MJ = megajoule, kgU = kilogram of uranium, mmBtu = 1 million British thermal units.

Attributed emissions in plant, property, and equipment

All generators carry emissions from manufacturing, construction, and installation, recorded as plant, property, and equipment (PPE) in the carbon ledger. Because these emissions are incurred up front while electricity production spans decades, they must be systematically allocated to generation output over the facility's lifetime.

This case study adopts one illustrative approach for PPE depreciation, though other methods could be applied within the ledger framework. The approach works in three steps: (1) total embodied emissions are divided evenly across the generator's expected operational lifetime in years; (2) an average annual capacity factor yields a projected annual production in MWh; and (3) annual PPE emissions are divided by projected production to yield an emissions intensity ($kgCO_2$/MWh) applied to each MWh generated. If actual production in a given year diverges from the projection, the difference is rolled forward to subsequent years, ensuring total PPE emissions are fully allocated over the facility's lifetime.

PPE source data and assumed lifetimes for each generator type are summarized in Table 11.[39,40,41] For simplicity, all CO_2-equivalent emissions from source databases are treated as CO_2 in this case study, and maintenance and end-of-life disposal emissions are excluded for all generators.

Table 11. Emissions from plant, property, and equipment

Technology	PPE emissions	Lifetime	Notes & source
Nuclear	0.6 $kgCO_2$/MWh	-	Life cycle assessment of nuclear power in France: Électricité de France case study.
Natural gas combined cycle	1.86 $kgCO_2$/MWh	40	Derived from Ecoinvent data, assuming a 90% capacity factor and 400 MW power plant size.
Combustion turbine	0.93 $kgCO_2$/MWh	40	Derived from Ecoinvent data, assuming a 20% capacity factor and 300 MW power plant size.
Wind	11.4 $kgCO_2$/MWh	20	Derived from Ecoinvent data, assuming a 30% capacity factor and 2.3 MW turbine size.
Solar	17.7 $kgCO_2$/MWh	30	Panel size: 1 kW. Derived from NREL data, assuming a 20% capacity factor.

Physical carbon content

Unlike fuels, where physical carbon content travels with the product to the customer, electricity is a carbon-free energy carrier. All carbon entering a thermal generator as fuel exits as emissions—primarily CO_2 from combustion, with smaller quantities of CH_4, CO, and VOCs. The carbon mass balance for each generator therefore closes entirely on the emissions side: Total carbon in fuel equals total carbon emitted across all species. Physical carbon content of fuels is tracked within each generator's ledger to verify this closure, but no carbon content is transferred to the utility or its customers with delivered electricity.

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 plus emissions across all species).

Generator parameters and production models

Among the generators, only natural gas-fired plants generate emissions on-site via fuel combustion. All physical carbon content in the fuel entering the facility is converted into CO_2 during combustion, with additional CO, some uncombusted CH_4, and traces of pollutants such as NOx and VOCs. A bottom-up carbon balance on the plant computes the release of these pollutants according to a model provided by Argonne National Laboratory, which is derived from U.S. plant data. It is assumed that the plant loading does not affect the efficiency, meaning that the heat rate stays constant throughout the operation.

Nuclear plants do not generate emissions on-site. Most of their emissions come from attributed emissions in uranium and PPE. For simplicity, disposal emissions are not accounted for. Overall, the nuclear plant has the lowest emissions intensity per MWh, consistent with the literature. Similarly, wind and solar generators do not generate on-site emissions. In this analysis, their attributed emissions in PPE are accounted for. For simplicity, maintenance and disposal emissions are excluded.

Table 12 consolidates the key technical and emissions parameters for all 12 generators. For thermal plants, efficiency determines the heat rate and thus direct emissions per MWh; for all generators, the capacity factor determines how PPE emissions are distributed across production.

Table 12. Technical and emissions parameters for all generators

Generator	Nuclear	NGCC1	NGCC 2	CT	Wind 1-4	Solar 1-4
Type	Nuclear	Combined cycle	Combined cycle	Combustion turbine	Onshore wind	Solar PV
Capacity (MW)	1,000	500	600	200	1: 100, 2: 200, 3: 150, 4: 100	1: 50, 2: 100, 3: 20, 4: 80
Capacity factor	99%	70.50%	49.21%	8.26%	1: 19%, 2: 30%, 3: 15%. 4: 14%	13%
Heat rates (mBtu/MWh)	-	6.61	6.82	10.37	-	-
Efficiency (η, LHV)	-	η =51.9%	η =50%	η =32.9%	-	-
Attributed emissions intensity (tC/MWh)	0.00086	0.00995	0.01027	0.01561	0	0
Direct emissions intensity (tC/MWh)	0	0.10686	0.11027	0.16759	0	0
PPE intensity (tC/MWh)	0.00016	0.00051	0.00051	0.00025	0.00313	0.00483
Total PCF (tC/MWh)	0.00102	0.11732	0.12105	0.18345	0.00313	0.00483
Total PCF (tCO_2e/MWh)	0.0037	0.426	0.440	0.668	0.0115	0.0177

Note: Direct emissions intensity for thermal plants is based on fuel carbon content and plant efficiency. PPE intensity reflects depreciated emissions from construction and manufacturing. Efficiency (η, LHV) = efficiency calculated on a lower heating value (LHV) basis

Transmission and distribution losses

To simplify the ledger demonstration, transmission and distribution losses are excluded in this analysis; it is assumed that LSEs contract enough electricity to cover the losses associated with the grid operation. Upon implementation, the ledger should account for mechanisms that help quantify and attribute losses such as location loss factors and ex-post settlement processes.

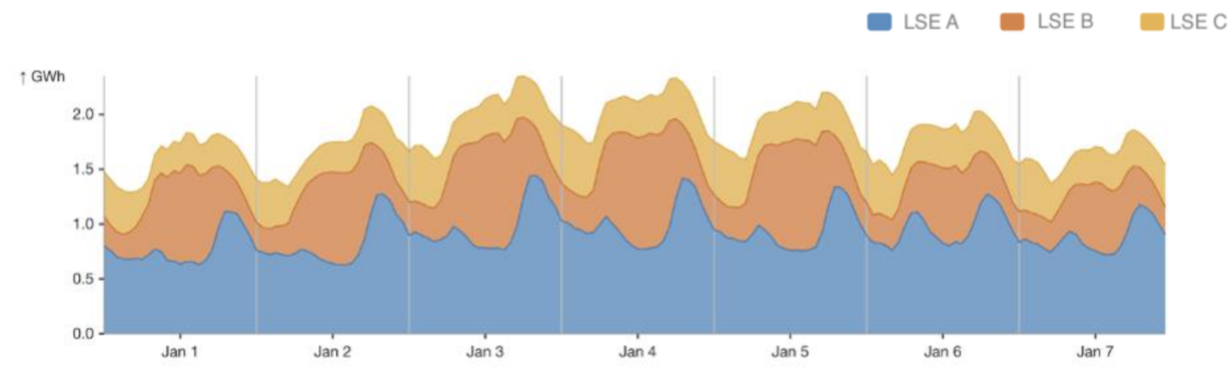
Demand data

Hourly load profiles are derived from NREL's study of NYISO demand patterns, scaled from 163.5 terawatt-hours per year (TWh/year) to 15.29 TWh/year to match the capacity of the 12-generator system.[42] Total demand is disaggregated into LSEs such that LSE A serves 50% of the monthly generation, while LSE B serves 30%, and LSE A serves 20%. The total hourly load profile was disaggregated to provide each LSE with their respective hourly demand.

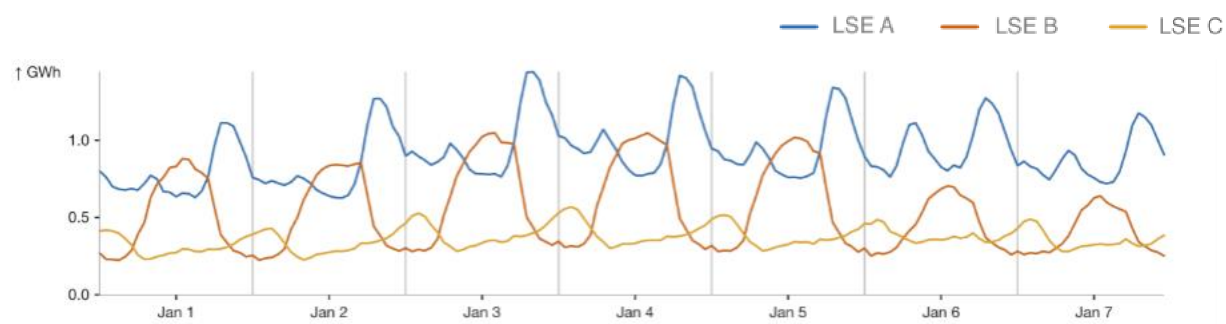
The resulting demand profiles are illustrated in Figure 9a and 9b.

Figure 9. Hourly electricity demand by LSE, January 1–7

a) Disaggregated utility load



b) Individual customer load profiles



Source: Sesame Sustainability.

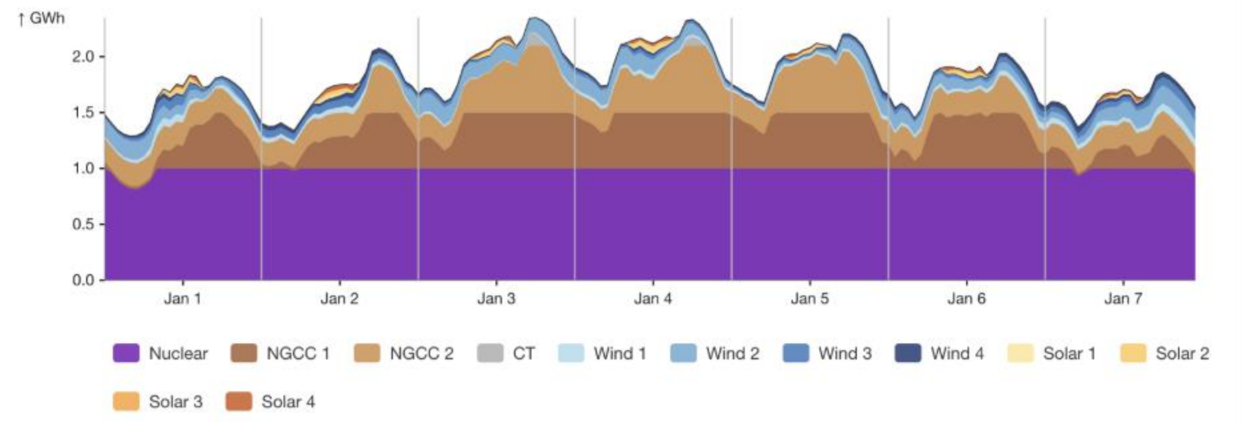
Dispatch model

The utility's operations are modeled using a single-node economic dispatch model that determines the hourly generation schedule for all 12 generators over a full calendar year. The model takes as inputs hourly demand profiles, generator technical parameters (capacity, heat rate, minimum stable level, ramp rates), variable operating costs, and renewable generation profiles based on regional wind and solar resource data.

The dispatch model minimizes total system operating cost at each hour subject to the constraint that total generation equals total demand. The resulting hourly generation schedule provides the production data for each generator that, combined with the generator-level carbon intensities, determines the hourly emissions profile of the entire system.

The dispatch model operates as a single-node system without transmission constraints, meaning all generators can serve all demand without congestion. This is a simplifying assumption. In practice, transmission constraints can affect which generators operate at any given hour and thus influence the locational emissions intensity of electricity. The resulting dispatch for a week in January is displayed in Figure 10.

Figure 10. Hourly dispatch stacked by generator

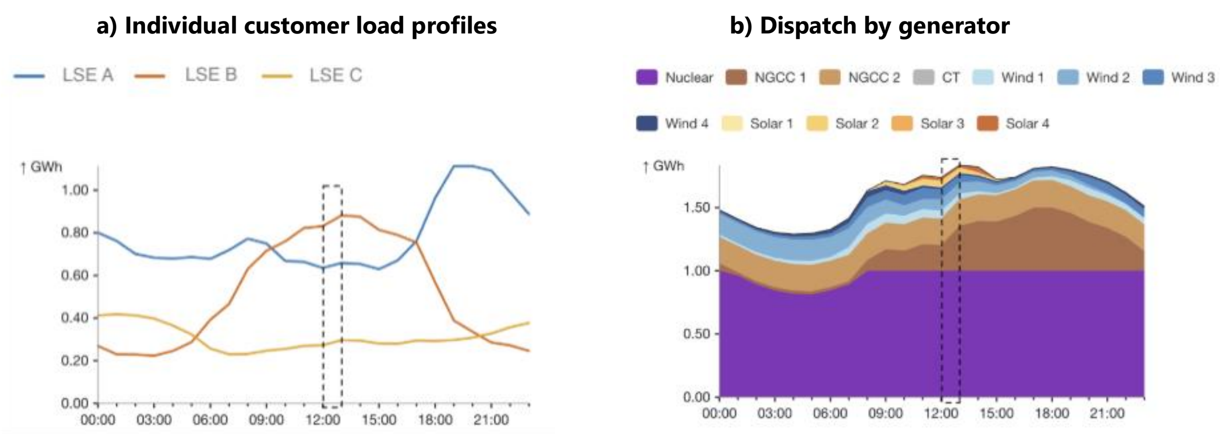


Source: Sesame Sustainability.

Sample one-hour operation: 12 p.m. on January 1

This case study evaluates emissions accounting at an hourly level. To showcase the ledger transactions, an arbitrary hour (January 1, 11 a.m.-12 p.m.) is singled out. This corresponds to a midday hour with relatively high solar and wind production, with regular fossil-fired and nuclear production. Each LSE load and generator production are highlighted in Figure 11. This report highlights ledger transactions at that hour. These transactions are recorded at each hour and are compiled to generate summaries of account balances, product carbon intensity statements, and entity-level carbon emissions statements, all of which are illustrated in this study for the month of January.

Figure 11. Individual LSE load profiles and dispatch by generator, focusing on Hour 12, January 1



Source: Sesame Sustainability.

Additional assumptions

The following additional assumptions apply:

- Generators operate without beginning fuel inventory or work-in-process considerations.
- Grid infrastructure (T&D) PPE emissions are excluded.
- The analysis covers one calendar year with monthly reporting periods and hourly underlying data.
- Each thermal plant is served by a single gas utility under FOD terms.
- No electricity imports, exports, or storage facilities are modeled.
- Generation and emissions from power plants providing services such as operating reserves are excluded.

Appendix C. Glossary of Terms

Attributed emissions: Emissions from the production and processing of raw materials and energy inputs upstream of the entity's accounting boundary that are transferred to the entity's carbon ledger along with the goods and services provided by suppliers at the entry gate.

Bundled carbon attributes: Carbon attributes traded together with the underlying electricity.

Carbon attributes: Quantifiable characteristics describing the carbon associated with a unit of electricity generation. Under a carbon accounting framework, every unit of electricity generation has associated carbon attributes.

Carbon ledger: The foundational record of an entity's carbon-related transactions. It utilizes a chart of accounts to categorize, track, and balance carbon stocks and flows. The chart is divided into two sections, one for stock accounts and one for flow accounts. Each section includes specific accounts to track different forms of carbon. The stock accounts record carbon remaining within the entity and the flow accounts record carbon entering and exiting the entity. The changes in stocks always equal changes in flows.

Carbon mass balance: A material balance applied specifically to carbon in all chemical forms within a defined system. It ensures that all carbon entering, leaving, and accumulating in the system is quantitatively accounted for, based on the law of conservation of mass.

Comprehensive carbon accounting system: A definitive set of principles, conventions and rules for quantifying, organizing, and recording transactions affecting carbon emissions from all activities contributing to the manufacture of products under the ownership and control of the entity doing the accounting.

Contractual instruments: Any type of contract between two parties for the sale and purchase of energy bundled with carbon attributes, or for unbundled carbon attributes. They include energy attribute certificates (EACs) and direct contracts, including power purchase agreements (PPAs).

Depreciated emissions: Depreciated emissions represent a portion of emissions allocated over time across an asset's useful life, rather than being counted entirely in the period they occur.

Direct emissions: Emissions generated from activities within an entity's accounting boundaries.

EAC/REC registry: A system in which energy attribute certificates (EACs) or renewable energy certificates (RECs) are registered and tracked so that their attributes can be transferred, sold, and retired.

Energy Attribute Certificates (EACs): A category of contractual instruments used in the energy sector to convey information about energy generation to other entities involved in the sale, distribution, consumption, or regulation of electricity. This category includes Renewable Energy Certificates (RECs), Guarantees of Origin (GOs), and Zero-Emission Credits (ZECs).

Gate to gate: A carbon accounting boundary that spans from the point where inputs enter a company's custody and control (entry gate) to the point where the final product is transferred to the custody and control of the customer (exit gate).

Grid electricity: Electricity physically generated within a specific grid, reflecting the underlying generation mix, before accounting for carbon attributes conveyed through contractual instruments.

Grid operator: The entity responsible, for purposes of this study, for allocating carbon attributes to grid electricity and EACs, and transferring them to LSE and EAC registries. The entity performing this function may differ depending on the structure of the electricity market.

Independent system operator (ISO): An organization responsible for coordinating, controlling, and monitoring the operation of an electricity grid within a defined geographic area, including coordinating electricity supply and demand and maintaining reliable grid operations.

Load-serving entity (LSE): An entity that procures and provides electricity for end-use customers. Different types of LSEs exist depending on ownership, governance, and regulatory structure. The major types of LSEs include investor-owned utilities (IOUs), public power utilities (federal, state, and municipal entities), electric cooperatives, competitive retail electricity suppliers, and community choice aggregators.

Location matching: A requirement that contractual instruments demonstrate physical deliverability within the same regional grid where the electricity is consumed.

Power purchase agreement (PPA): A type of contract that allows an LSE or an end-use consumer, typically a large industrial or commercial entity, to form an agreement with a specific energy generating unit. PPAs may be **physical**, in which electricity and its associated carbon attributes are transferred to the buyer, or **virtual (financial)**, in which the buyer receives the contractual rights to the associated carbon attributes through financial settlement without taking physical delivery of the electricity.

Product carbon intensity (PCI): A metric defined as share of carbon emissions per unit of product, enabling the tracking of these emissions across complex supply chains.

Regional transmission organization (RTO): An organization responsible for coordinating and managing the operation of a regional electricity transmission system, including overseeing wholesale electricity markets and ensuring reliable and nondiscriminatory access to the transmission network.

Residual grid electricity: Electricity remaining after carbon attributes conveyed through contractual instruments have been allocated to other parties, together with the carbon attributes associated with the remaining electricity.

Time matching (hourly matching): A requirement to match every hour of electricity consumption with generation from renewable sources. Under this requirement, if a company claims the use of renewable electricity at any specific hour, it must show that an equivalent quantity of renewable electricity was generated and attributable to its load at that same hour.

Unbundled carbon attributes: Carbon attributes traded separately from the underlying electricity.

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