



CASInitiative.org

ICCA Perspectives

Boundaries for Product Carbon Footprint Assessments

Authors:¹

Fernando Penalva
IESE Business School, University of Navarra, ECGI
fpenalva@iese.edu

Benedikt Steiner
BMW Group, Catena-X
benedikt.steiner@bmw.de

September 2026

¹ This paper has benefited enormously from the guidance and suggestions of Stefan Reichelstein, whose feedback was instrumental in shaping the paper's structure and content. The authors are also grateful for comments from Nils Cremer, Jens Haubensak, Carolin Matuschke, and participants in the CASI workshops held in Frankfurt on December 4–5, 2025, and in Munich on May 11–12, 2026. Fernando Penalva acknowledges financial support from the Spanish Ministry of Science, Innovation and Universities, Grant PID2023-150744NB-C41 funded by MICIU/AEI/ 10.13039/501100011033. The authors acknowledge the use of GPT-5.5 to support grammar, style, clarity, flow, and the preparation of the Executive summary and the Scope and limitations sections. All AI-generated suggestions were reviewed, revised, and approved by the authors, who take full responsibility for the accuracy and integrity of the work.

Executive summary

This paper proposes a structured and auditable approach to setting system boundaries in assessing Product Carbon Footprints (PCFs). Boundary choices determine which emissions are included, how results can be compared across products and suppliers, and whether PCFs are suitable for third-party assurance and value-chain exchange. Drawing on international standards and leading industry frameworks, the paper recommends a cradle-to-gate, attributional PCF as the default boundary for reporting and data exchange, while allowing supplementary disclosures where decision-relevant. It further addresses the treatment of inventoriable emissions, long-lived assets, biomass, and recycled materials, and proposes a transition toward primary data exchange supported by integrated corporate carbon accounting systems. The framework is intended to inform regulators and organizations developing carbon measurement guidance, as well as companies seeking to calculate consistent and credible PCFs. The resulting framework seeks to balance methodological rigor with practicability and is designed to support scalable, comparable, and verifiable PCFs across global supply chains.

Boundaries for Product Carbon Footprints

1. Introduction

Companies, regulators, and value-chain partners increasingly use Product Carbon Footprints (PCFs) to understand, manage, and communicate the climate impacts of products. PCFs support a wide range of objectives, including internal decarbonization strategies, supplier engagement, customer reporting, regulatory compliance, and product comparison. Achieving these objectives, however, depends critically on how the system boundaries of the PCF are defined.

System boundaries determine which processes, emissions, and removals are considered in the life-cycle assessment of a product. Boundary definition is therefore a **necessary** element of the goal and scope of a PCF study and must be consistent with its intended application and audience (ISO 14044; ISO 14067). Because boundary choices govern what is included or excluded, they have a direct and often decisive influence on the resulting footprint, its comparability with other products, and the interpretation of the product's climate performance.

International standards and guidance documents recognize that boundary setting is not merely a technical detail, but a central determinant of credibility and usefulness (ISO 14040; ISO 14044; ISO 14067; GHG Protocol Product Standard; PAS 2050; EU PEF Method). While these frameworks differ in emphasis and level of prescription, they share a common objective: to ensure that PCFs are transparent, consistent, and fit for purpose.

The objective of this paper is to provide a framework for regulators and organizations developing carbon measurement guidance, as well as for companies seeking to calculate credible PCFs. The framework seeks to balance methodological rigor with practical implementability and is designed to support scalable, comparable, and verifiable PCFs across global supply chains. The paper does not aim to prescribe detailed calculation methods for each PCF category, which will be addressed by specific carbon accounting standards; nor does it replace applicable sector-specific product category rules or regulatory requirements.

1.1 Avoiding bias through consistent boundary definition

Boundary choices can introduce bias if they selectively include or exclude processes in a way that favors a particular outcome. ISO 14044 requires that the system boundary be clearly defined as part of the goal and scope of the study and that any exclusions be justified and consistent with the intended application. ISO 14067 similarly allows exclusions only where they do not materially affect the total carbon footprint and requires that such exclusions be documented.

An unbiased boundary does not imply that every conceivable process must be included. Rather, it requires that inclusions and exclusions follow predefined and transparent rules, grounded in materiality and applied consistently across comparable products or suppliers. When boundaries are adjusted ad hoc, without reference to such rules, PCFs risk becoming misleading or unsuitable for comparison.

1.2 Minimizing subjectivity through methodological hierarchies

Many boundary-related decisions, such as the treatment of shared processes, co-products, recycling, or long-lived assets, involve judgement. To limit subjectivity, international standards establish hierarchies and default approaches that guide practitioners toward the least arbitrary options.

ISO 14044 defines a clear hierarchy for dealing with multifunctional processes: allocation should be avoided where possible, for example by subdividing processes or applying system expansion; only if this is not feasible should allocation be applied, first using physical relationships and then, if necessary, other relationships such as economic value. This hierarchy is explicitly intended to reduce subjective choices and improve reproducibility. The GHG Protocol Product Standard adopts a similar logic, emphasizing consistent allocation rules within an attributional life-cycle perspective and requiring transparent justification of allocation choices.

1.3 Comparability as a core objective

Comparability is a central requirement for PCFs used in disclosure, benchmarking, procurement, or value-chain communication. Two PCFs can only be meaningfully compared if they are based on equivalent system boundaries, modelling assumptions, and data quality requirements.

The GHG Protocol Product Standard explicitly identifies comparability and consistency as core objectives of product life-cycle accounting. The EU PEF Method and PEFCR Guidance further state that results are only comparable when calculated using the same methodological rules and product environmental footprint category rules.

1.4 Practicality and ease of application

For PCFs to be widely adopted by companies, boundary definitions must also be practical and scalable. PAS 2050 explicitly excludes long-lived assets from PCF calculations unless supplementary requirements specify otherwise. ISO 14067 similarly allows the exclusion of processes, including long-lived assets, where their inclusion would not significantly affect the carbon footprint and where exclusions are transparently documented.

1.5 Attributional perspective and intended use

Most product-level carbon accounting frameworks converge on a predominantly attributional perspective for PCF reporting. This perspective takes the current production system as given and assigns (“attributes”) a portion of total emissions to one unit of product. ISO 14040 distinguishes attributional and consequential life-cycle assessment approaches (the latter approach tries to predict how markets or technologies would change if decisions were different), while the GHG Protocol Product Standard states explicitly that reported PCFs are attributional in nature. This paper follows this approach.

1.6 Verifiability and auditability of PCFs

For PCFs to be credible and useful beyond internal analysis, they must be verifiable and auditable. Verifiability requires that system boundaries, data sources, assumptions, exclusions, and calculation methods be defined in a manner that allows an independent third

party to reproduce the results within an acceptable margin of error. Clear and consistently applied boundary definitions are therefore a prerequisite for effective assurance.

International standards explicitly link boundary transparency to verification and review requirements. ISO 14067 requires comprehensive reporting of system boundaries, exclusions, data quality, and methodological choices to enable verification and informed interpretation. ISO 14044 further establishes the need for critical review when results are intended for external communication, including verification that system boundaries and methodological choices are consistent with the stated goal and scope.

From a corporate perspective, auditable PCFs support internal governance, risk management, and regulatory readiness. They enable companies to substantiate climate-related claims, respond to customer and regulatory scrutiny, and integrate product-level emissions data into broader sustainability reporting frameworks. Boundary choices that are weakly justified, inconsistently applied, or excessively complex undermine auditability and increase the risk of misinterpretation or challenge.

1.7 Intended level of assurance

Unless otherwise stated, PCFs prepared in accordance with the principles outlined in this paper are intended to be suitable for independent third-party assurance at a limited level of assurance. Where PCFs are used to support public comparative assertions, regulatory disclosures, or product claims, additional documentation, data quality controls, and critical review procedures consistent with ISO 14044 should be applied to support a higher level of assurance.

2. Life-Cycle Boundary Options in Product Carbon Footprints

2.1 Overview of life-cycle boundary types

Life-cycle assessment (LCA) provides a structured framework for quantifying the greenhouse gas (GHG) emissions associated with a product system. A fundamental design choice in any LCA—and therefore in any PCF—is the selection of the life-cycle boundary, which determines which stages of the product’s life are included in the assessment.

Two boundary configurations are most commonly applied in PCF practice:

- Cradle-to-gate, which includes all relevant processes from raw-material extraction (“cradle”) through manufacturing and upstream logistics, up to the point at which the product leaves the manufacturer’s control (“gate”).
- Cradle-to-grave, which extends the boundary beyond the factory gate to include the use phase and end-of-life treatment (reuse, recycling, energy recovery, or disposal).

Both approaches are recognized under ISO 14044 and ISO 14067, provided that the chosen boundary is consistent with the goal and scope of the study, clearly disclosed, and appropriately justified. The choice between them has significant implications for data requirements, uncertainty, comparability, and auditability.

2.2 Cradle-to-gate LCA

A cradle-to-gate PCF focuses exclusively on production-related emissions. It covers raw material extraction, upstream processing, transport, and manufacturing operations, including purchased energy and other attributable inputs.

Cradle-to-gate LCAs are particularly well suited to business-to-business (B2B) contexts and value-chain data exchange, where products often serve as inputs to downstream products rather than being used directly by end consumers. In such cases, the manufacturer has limited control over how, where, and for how long the product will be used, making use-phase modelling highly uncertain.

By limiting the system boundary to stages that are largely under the control or influence of the reporting company and its immediate suppliers, cradle-to-gate PCFs typically achieve:

- higher data quality,
- greater consistency across suppliers and regions,
- improved verifiability and auditability.

As a result, cradle-to-gate is widely adopted as the default boundary in PCF frameworks aimed at scalable reporting and digital exchange (e.g. Together for Sustainability (TfS), Catena-X), and is fully compatible with the attributional perspective endorsed by the GHG Protocol Product Standard.

2.3 Cradle-to-grave LCA

Cradle-to-grave LCAs aim to capture the full life-cycle climate impact of a product, including emissions arising during use and at end of life. This approach is particularly relevant when:

- the use phase dominates total emissions (e.g. fuel- or energy-using products),
- the manufacturer has significant influence over use-phase performance (e.g. through product design or operating instructions), or
- the PCF is intended for consumer communication, eco-design analysis, or policy evaluation.

However, cradle-to-grave LCAs introduce additional sources of uncertainty and subjectivity. Use-phase emissions depend on assumptions about user behavior, maintenance, operating conditions, geographic context, and lifetime, while end-of-life modelling requires assumptions about disposal routes and recycling rates that may vary widely across regions and over time.

When such assumptions are embodied in the headline PCF value, they can dominate the result and obscure differences in production performance. For this reason, cradle-to-grave PCFs are more demanding to implement and more difficult to compare across products and suppliers, particularly in B2B settings.

2.4 Comparison of cradle-to-gate and cradle-to-grave approaches

The following table summarizes the main properties of both approaches:

Aspect	Cradle-to-Gate	Cradle-to-Grave
System boundary	Raw materials → manufacturing → factory gate	Full life cycle including use and end-of-life
Primary focus	Production-related emissions	Total life-cycle emissions
Data availability	Increasingly high; supplier and plant data	Often limited; relies on assumptions
Uncertainty	Relatively low	Higher (user behavior, lifetime, disposal)
Comparability	High across suppliers and regions	Lower; driven by modelling choices
Auditability	Strong; limited assumptions	More complex; extensive documentation needed
Best suited for	B2B reporting, procurement, supply-chain exchange	Consumer products, eco-design, policy analysis
Ease of implementation	High	Moderate to low
Default desirability for PCFs	High	Context-dependent

Note: This table was created using GPT-5.5 to summarize and complete a first draft, with subsequent modifications and review by the authors.

2.5 Rationale for recommending cradle-to-gate as the default

For the purposes of this paper, namely to support consistent, comparable, and auditable PCF reporting in corporate and value-chain contexts, a cradle-to-gate boundary is recommended as the default life-cycle approach. This recommendation is grounded in four key considerations:

1. **Comparability:** Cradle-to-gate PCFs isolate production-related emissions, enabling meaningful comparisons between suppliers, technologies, and regions without conflating differences in use patterns or disposal practices.
2. **Data quality and verifiability:** Production-stage emissions can increasingly be quantified using primary data. In contrast, use-phase and end-of-life emissions often rely on generic scenarios that are difficult to verify and audit.

3. **Scalability and interoperability:** Cradle-to-gate PCFs function as modular building blocks that can be exchanged digitally and aggregated downstream. This is essential for large, multi-tier supply chains.
4. **Alignment with existing frameworks:** Major PCF initiatives and sectoral guidelines designate cradle-to-gate as the default boundary, while allowing broader boundaries as optional or supplementary analyses.

For these reasons, cradle-to-gate provides the most robust balance between methodological rigor and practical applicability for mainstream PCF use.

2.6 Incorporating use-phase emissions in specific cases

Despite the advantages of the cradle-to-gate approach, excluding the use phase entirely may disadvantage products whose principal climate benefits arise during the use phase. This concern is particularly relevant for large, energy-using products, such as passenger cars, trucks, buses, aircraft, ships, and certain industrial equipment.

In these cases, recent technological developments significantly reduce the uncertainty traditionally associated with use-phase modelling. Modern vehicles and machines routinely generate and transmit large volumes of operational data (i.e., fuel or energy consumption, operating conditions, mileage, duty cycles, maintenance events, etc.) to manufacturers' cloud systems. These data are already used for safety analysis, parts design, predictive maintenance, and performance optimization.

As a result, for certain product categories it may be feasible to quantify use-phase emissions over a defined and representative time horizon (for example, three years) with relatively low uncertainty and minimal reliance on generic assumptions. Where such data are:

- based on large, representative fleets,
- measured rather than modelled,
- and transparently documented,

use-phase emissions may be reported alongside the cradle-to-gate PCF.

However, to preserve comparability and avoid conflating fundamentally different sources of uncertainty, this paper recommends that:

- the core PCF value remains cradle-to-gate, and
- any use-phase emissions should be disclosed separately, with clear specification of the time horizon, data sources, and assumptions applied.

This approach allows energy-efficient products to demonstrate their operational advantages without compromising the integrity and comparability of the production-stage PCF.

Recommendation 1:

Adopt cradle-to-gate as the default life-cycle boundary for product carbon footprints. Where reliable, measured use-phase data are available (e.g., large, cloud-connected products with well-characterized operating profiles) use-phase emissions may be disclosed as supplementary information, over a clearly defined time horizon, but should not be embodied in the core PCF value. For brevity, PCF hereafter refers to cradle-to-gate PCF.

3. Inventoriable Emissions within the Cradle-to-Gate Boundary

3.1 Concept of inventoriable emissions

Within a cradle-to-gate PCF, all production-related greenhouse gas emissions that are inventoriable must be included. Inventoriable emissions are those that can be causally and systematically attributed to the production of a specific product, up to the point at which it leaves the manufacturer's facility.

This principle is firmly grounded in international standards. ISO 14067 requires that all relevant emissions within the defined system boundary be identified and included unless their exclusion can be shown not to materially affect the result. Similarly, ISO 14044 requires the system boundary to identify the unit processes included in the LCA, with omissions permitted only where they do not significantly change the result. The GHG Protocol Product Standard adopts the same logic, requiring inclusion of all attributable processes within the chosen boundary in order to ensure completeness and consistency of reported PCFs.

The purpose of this requirement is straightforward: excluding inventoriable emissions undermines the accuracy, comparability, and credibility of PCFs, particularly when results are exchanged along supply chains or used for benchmarking.

3.2 Alignment with financial accounting logic

A useful way to clarify what constitutes an inventoriable emission is to draw an analogy with financial accounting, particularly inventory accounting under IAS 2 and FASB ASC 330. In financial statements, costs are classified into:

- **inventoriable costs**, which are capitalized into the cost of goods produced because they are directly or indirectly attributable to production, and
- **period costs**, such as selling, general, and administrative (SG&A) expenses, which are expensed in the period in which they are incurred.

Applying this logic to PCFs implies that:

- emissions that are causally linked to the production process are inventoriable and belong in the PCF, whereas
- emissions associated with corporate overheads, marketing, sales activities, or general administration are period emissions and should not be allocated to individual products.

The term “inventoriable emissions” is not used by most PCF standards. However, it corresponds closely to the concepts of “attributable processes” in the GHG Protocol Product Standard and product-related or production-system emissions in Catena-X and TfL. These frameworks require cradle-to-gate PCFs to include emissions attributable to the product system while excluding non-product-related activities such as corporate administration, sales, business travel, commuting, and, in current practice, long-lived assets. The concept is also consistent with the ISO 14044 requirement that the system boundary include the relevant unit processes necessary to represent the product system.

This distinction is not explicitly mandated in carbon accounting standards, but it is fully consistent with their intent. Both ISO 14067 and the GHG Protocol Product Standard

emphasize causal attribution and avoidance of arbitrary allocation. By following an accounting-style distinction between inventoriable and period emissions, PCFs can be constructed in a way that is objective, auditable, and resistant to manipulation.

3.3 Scope of inventoriable emissions

Within a cradle-to-gate boundary, inventoriable emissions include all direct and indirect GHG emissions required to manufacture the product and deliver it to the factory gate, provided that these emissions can be attributed to the product system. At a minimum, this includes the following categories:

a) **Raw-material extraction and upstream supply chain:** All emissions arising from the extraction, cultivation, or production of raw materials and intermediate inputs must be included. This covers:

- mining, quarrying, and agricultural production;
- refining, smelting, chemical processing, and other transformation steps;
- production of semi-finished goods and intermediates; and
- all upstream transport and logistics between these stages.

These emissions typically represent a substantial share of the cradle-to-gate PCF and are therefore critical for accuracy and comparability.

b) **Manufacturing and on-site operations:** All emissions arising from on-site production activities must be accounted for, including:

- direct fuel combustion;
- process emissions (e.g. chemical reactions);
- fugitive emissions (e.g. refrigerants, leaks);
- all purchased energy, such as electricity, steam, heat, and cooling.

This treatment aligns with both ISO and GHG Protocol requirements to include Scope 1 and relevant Scope 2 emissions within the product system boundary.

c) **Upstream waste handling:** Where waste is generated before acquisition of the product by the customer and their treatment or disposal can be attributed to the product system, the associated emissions must also be included. This includes, for example, treatment of production scrap, rejects, or process waste. Including upstream waste handling avoids systematically understating production emissions and ensures consistency across products and facilities.

d) **Materiality and cut-off criteria:** The PCF calculation should cover all relevant emission sources within the product system boundary. Any exclusions should be justified, documented, and assessed against the applicable materiality or cut-off criteria. Frameworks such as TfS and Catena-X generally require coverage of at least 95% of expected cradle-to-gate emissions, ensuring that omitted sources do not materially affect the reported PCF.

3.4 Exclusions and boundary discipline

While inventoriable emissions must be included, not all emissions occurring within an organization are inventoriable. Emissions associated with:

- corporate offices,
- sales and marketing activities,
- research and development not directly attributable to a specific product,
- employee commuting and business travel,

are generally considered period emissions and should be excluded from the PCF, provided this exclusion is clearly documented and justified. This approach is consistent with ISO 14067's materiality principle and with the practical guidance in PAS 2050, Catena-X, and TfS. Maintaining a clear distinction between inventoriable and non-inventoriable emissions is essential to prevent boundary creep and to ensure that PCFs remain comparable across companies with different organizational structures. Period emissions are reported in the company's net CO₂ contribution.

3.5 Primary data exchange, supply-chain responsibility, and integrated corporate carbon accounting

Including all inventoriable emissions within a cradle-to-gate boundary raises a fundamental implementation question: how upstream emissions data should be generated, maintained, and exchanged at scale. A system in which each company independently “reaches into” its supply chain to conduct comprehensive life-cycle assessments of upstream processes is neither scalable nor robust. Such an approach inevitably leads to inconsistent modelling assumptions, excessive reliance on generic databases, duplication of effort, and diminished auditability.

To address these challenges, this paper advocates a progressive transition toward primary data exchange along the supply chain, supported by an integrated corporate carbon accounting (ICCA) system at the company level. ICCA refers to the company-level system used to measure, allocate, and report emissions consistently across operations and products. Under this approach, each company is responsible for quantifying and managing the greenhouse gas emissions associated with its own operations and products, using primary activity data wherever available. PCFs derived from this internal accounting system are then communicated downstream as carbon tags associated with intermediate goods and materials.

The foundations of ICCA are set out in CASI Whitepaper No. 1 and further developed through the double-entry bookkeeping architecture for CO₂ statements presented in CASI Whitepaper No. 2. This architecture mirrors well-established financial reporting practices. Just as companies maintain internal accounting systems to calculate and report costs, revenues, and inventories, they should increasingly maintain ICCA systems capable of producing consistent, auditable carbon information. Downstream actors can then rely on upstream disclosures rather than reconstructing emissions inventories themselves.

The advantages of this approach are significant. First, it aligns responsibility for data quality with operational control, ensuring that emissions are quantified by the entities that generate them. Second, it reduces dependence on generic secondary datasets, improving accuracy, comparability, and verifiability. Third, it enables scalable digital implementation across multi-tier supply chains, supporting interoperability with emerging data-exchange infrastructures.

Finally, it provides a clear audit trail, as each PCF can be traced back to a supplier's internal carbon accounting system.

Over time, widespread adoption of ICCA systems implies that every material input to a production process is accompanied by a verifiable product-level carbon footprint, calculated by the upstream supplier and suitable for aggregation downstream. This evolution is essential for credible cradle-to-gate PCFs and for the long-term integration of product-level carbon information into corporate decision-making.

Recommendation 2:

Include in the PCF only inventoriable emissions, that is, emissions attributable to the product system within the cradle-to-gate boundary. Period emissions should be excluded from the PCF and reported separately in the company's net CO₂ contribution. To obtain upstream emissions data, avoid a system in which each company independently models its entire supply chain. Instead, promote a transition to primary PCF data exchange, underpinned by an ICCA system at the company level. Each company should calculate PCFs for its own products using primary data and disclose these as verified carbon tags. Ultimately, all material inputs to a production process should carry an associated, audited and certified PCF, enabling accurate, scalable, and comparable cradle-to-gate PCFs.

4. Long-Lived Operating Assets, Embodied Emissions, and Integrated Corporate Carbon Accounting

4.1 Long-lived operating assets in current PCF practice

Long-lived assets, such as machinery, production lines, buildings, and infrastructure, are used to manufacture products over extended periods. Although life-cycle assessment in principle encompasses all processes required to produce a product, most existing PCF frameworks exclude emissions embodied in such assets, typically referring to them as capital goods.

In particular, ISO 14067, the GHG Protocol Product Standard, Catena-X, and TfS all permit or recommend the exclusion of long-lived assets from PCFs. The primary rationale for this exclusion is pragmatic: to avoid potentially subjective allocation choices and to preserve comparability across products and organizations with differing capital structures.

While this approach is defensible for reporting-oriented PCFs, it also means that emissions embodied in production assets are treated as structurally invisible at the product level, even where they may be significant in capital-intensive industries or in the evaluation of alternative production technologies.

4.2 The prerequisite problem: measuring embodied emissions

Before emissions embodied in long-lived assets can be allocated to products, they must first be measured or estimated. This prerequisite is often understated in discussions of capital-goods inclusion but is central to the debate.

In an ideal system, long-lived assets would enter the product system with verified product-level carbon footprints, supplied by their manufacturers as primary data. In such a case,

embodied emissions could be treated analogously to any other upstream input and allocated downstream using transparent rules based on well-established financial account rules.

However, this condition is rarely met today. Long-lived assets seldom come with supplier-provided PCFs, and attempts to quantify their embodied emissions typically rely on generic life-cycle factor databases. This reliance contradicts the primary-data philosophy underlying major PCF initiatives and sectoral guidelines and risks introducing inconsistencies and unverifiable assumptions. This measurement gap, not the allocation logic per se, is the primary obstacle to systematic inclusion of embodied emissions in long-lived assets in PCFs.

4.3 Operational energy flows are necessary but not sufficient

An alternative proposal suggests focusing on actual Scope 1 and Scope 2 energy flows associated with operating long-lived assets while producing the product subject to the PCF. This approach is sound and already embodied in most PCF calculations.

Operational energy use:

- is typically well measured,
- is attributable to production activity,
- and is auditable using existing systems.

However, focusing exclusively on operational energy flows does not address embodied emissions arising from the manufacture, installation, and end-of-life of long-lived assets. From a life-cycle perspective, this approach implicitly assumes that such emissions are negligible or irrelevant, which may not hold for capital-intensive processes or long-lived assets. Therefore, while inclusion of operational energy flows is essential, it cannot replace a systematic approach to embodied emissions.

4.4 Alignment with financial accounting and the role of ICCA

To resolve both measurement and allocation challenges, this paper proposes embodying the treatment of long-lived assets within ICCA systems, explicitly aligned with financial accounting. In financial accounting, particularly under IAS 2 and ASC 330, the cost of producing a product includes a systematic allocation of indirect production overheads such as depreciation and maintenance of machinery and factory buildings. These allocations:

- are based on objective, well-defined rules,
- are applied consistently over time,
- are subject to audit and external review,
- and are widely accepted precisely because they prevent arbitrary manipulation.

An ICCA system extends this logic to carbon accounting. Within such a system:

- emissions associated with long-lived assets are quantified at the corporate level as part of the organization's internal carbon inventory;
- where embodied emissions can be estimated with sufficient reliability, they are capitalized within the ICCA system;

- allocation of these emissions to products follows the same allocation keys used for financial depreciation and overhead allocation (e.g. machine hours, throughput, or capacity utilization).

This approach does not require perfect data. Rather, it ensures that uncertainty is handled consistently and transparently, within a governance framework already accepted by auditors and regulators.

4.5 A phased, ICCA-enabled transition

Recognizing current data constraints, this paper advocates a phased approach explicitly tied to ICCA maturity:

- **Short term:** Long-lived assets may be excluded from PCFs where embodied emissions cannot be estimated without excessive reliance on generic data. Operational Scope 1 and Scope 2 emissions associated with long-lived assets remain fully included.
- **Medium term:** As ICCA systems mature, companies develop internal estimates of embodied emissions for major capital assets, using best available data and consistent accounting rules.
- **Long term:** With widespread adoption of ICCA and supplier-provided certified PCFs for long-lived assets, embodied emissions enter product systems as verifiable upstream inputs and are allocated systematically and auditable across products.

This pathway preserves short-term comparability while enabling long-term methodological completeness. Any embodied emissions not included in PCFs should be reported as part of the firm's current net CO₂ contribution.

Recommendation 3:

Include embodied emissions from long-lived assets in PCFs where reliable estimates are available, using the same systematic allocation rules applied in financial accounting (e.g. depreciation and overhead allocation under IAS 2 or ASC 330), and within the framework of an ICCA system. Where embodied emissions cannot yet be estimated without undue reliance on generic data, long-lived assets may be excluded temporarily, provided that:

- all operational Scope 1 and Scope 2 emissions associated with long-lived assets are fully included,
- the exclusion of embodied emissions is transparently disclosed, and
- the treatment is revisited as ICCA systems and upstream data availability improve.

The perspective and suggestions underlying Recommendation 3 have already been developed in detail in CASI (2026) Whitepaper No. 4, *Carbon Accounting for Long-Lived Operating Assets*.

5. Biomass and Biogenic Carbon within PCF Boundaries

5.1 Biogenic carbon in biomass-based production

Biomass is defined in ISO 14067 as material of biological origin, excluding fossil materials. It contains biogenic carbon that has been recently removed from the atmosphere through photosynthesis during plant growth. When biomass or biomass-derived products are

combusted or otherwise oxidized, this carbon is released back to the atmosphere as carbon dioxide (CO₂).

From a life-cycle accounting perspective, this creates a fundamental distinction between:

- biogenic CO₂, which participates in short-term biological carbon cycles, and
- fossil CO₂, which represents a net transfer of carbon from long-term geological storage to the atmosphere.

This distinction underpins the treatment of biomass in PCFs under ISO 14067 and the GHG Protocol Product Standard.

5.2 Treatment of biogenic CO₂ under current standards

Under current PCF practice, CO₂ emissions from biomass combustion are reported separately as biogenic CO₂ and are not included in the aggregated PCF total. This convention reflects the fact that the emitted carbon was previously absorbed from the atmosphere during biomass growth. When uptake and release are accounted for consistently within the system boundary, biogenic CO₂ is therefore not counted as a net increase in atmospheric CO₂.

ISO 14067:2018, Annex E.3 clarifies this treatment by explicitly linking carbon storage and release to the system boundary. Where carbon removal during plant growth is included within the system boundary and biogenic carbon is subsequently released during use or at end of life, inflows and outflows of biogenic carbon cancel out, resulting in a zero net contribution to the PCF. This also applies where biomass-derived products are reused or recycled and biogenic carbon flows are transferred to subsequent product systems. In all cases, this neutrality applies only to biogenic CO₂, and any portion of biogenic carbon converted to methane must still be included. This clarification reinforces that neutrality is not an inherent property of biomass, but a consequence of boundary-consistent carbon-flow accounting.

5.3 Inclusion of non-CO₂ greenhouse gases

While biogenic CO₂ is treated separately, all other greenhouse gases emitted during biomass combustion must be included in the PCF total. This includes methane (CH₄) and nitrous oxide (N₂O), which contribute to climate change regardless of whether their carbon content is biogenic or fossil. The inclusion of non-CO₂ gases is required under the GHG Protocol Product Standard and TfS guidance and is essential to avoid systematically understating the climate impact of biomass-based energy or feedstocks.

5.4 Upstream emissions in biomass supply chains

In addition to combustion-related emissions, all upstream emissions associated with the biomass supply chain must be fully included in the PCF. These include emissions arising from:

- cultivation or growth,
- harvesting and collection,
- processing and pre-treatment,
- transport and storage.

ISO 14067 and Catena-X explicitly require inclusion of such upstream emissions within a cradle-to-gate PCF. Excluding them would bias results in favor of biomass and undermine comparability with fossil or alternative feedstocks.

5.5 Treatment of CO₂ removals and negative emissions

The treatment of CO₂ removals, often referred to as negative emissions, is a critical aspect of PCF boundary definition. These removals may arise from biogenic carbon uptake, carbon capture and storage (CCS), direct air capture, or nature-based solutions. Their treatment in a PCF depends fundamentally on whether they occur within the defined system boundary of the product. A clear distinction must be made between two cases.

First, where CO₂ removals occur within the system boundary, they should be included in the PCF. Examples include carbon uptake during biomass growth, CO₂ captured and permanently stored at the production facility, or carbon stored in long-lived products. In these cases, removals represent physical carbon flows within the product system and may offset emissions, subject to consistent boundary definition. This treatment is consistent with ISO 14067, which allows biogenic carbon uptake and release within the same system boundary to result in a net zero contribution.

Second, where removals occur outside the system boundary, they should not be used to reduce the PCF value. Examples include the purchase of carbon offsets, investments in external CCS projects, or participation in voluntary carbon markets. While such mechanisms may play an important role in broader climate strategies, they do not alter the physical emissions associated with producing the product. Including them in the PCF would introduce subjectivity, reduce comparability, and risk double counting across product systems. Accordingly, such removals should be reported separately from the PCF, as supplementary information.

From a methodological perspective, PCFs should reflect physical carbon flows within the product system, rather than external compensation mechanisms. This distinction is essential to preserve the integrity, comparability, and auditability of PCFs.

5.6 Illustration: biofuels and negative PCFs

This distinction is particularly important for biofuels, such as biodiesel. Biodiesel may have a negative biogenic carbon component because its biomass feedstock removes CO₂ from the atmosphere during growth. However, the overall PCF must also include all upstream and production emissions associated with growing, collecting, transporting, and processing the feedstock. If combustion is included within the system boundary, the later release of biogenic CO₂ normally offsets the earlier uptake, resulting in a net zero contribution for biogenic CO₂, while non-CO₂ combustion gases and upstream emissions remain included in the PCF total. Biofuels may therefore have a low, or in specific boundary conditions even negative, reported footprint, but they should not be assumed to have a negative PCF by default.

Recommendation 4:

Account explicitly for both sides of the biogenic carbon cycle in the PCF: recognize CO₂ uptake during biomass growth as a negative flow and biogenic CO₂ release during combustion as a positive flow. When both occur within the same system boundary, they net to zero. The PCF must still include upstream biomass emissions, production emissions, and combustion-related non-CO₂ gases such as CH₄ and N₂O.

6. Recycling and Recycled Materials within PCF Boundaries

6.1 Recycling as a boundary and allocation challenge

When a product incorporates recycled materials, the PCF must address a fundamental boundary question: how to treat emissions associated with the previous life cycle of the material. Without clear rules, recycling can lead to double counting of emissions or to inconsistent attribution of environmental benefits across products and supply chains. To avoid these issues, most reporting-oriented PCF frameworks adopt a clear and conservative boundary convention for recycled materials, ensuring consistency, comparability, and auditability.

6.2 The cut-off (recycled-content) approach

Both Catena-X and TfS adopt the cut-off approach (also referred to as the recycled-content approach) as the standard rule for recycling in PCFs. Under this approach:

- when a product is manufactured using recycled raw materials, its carbon footprint starts at the point where waste becomes a usable secondary resource;
- the recycled material enters the new product system burden-free, meaning it carries no historical emissions from its previous life cycle;
- emissions associated with producing the original product from which the recycled material originates are not counted again; and
- the PCF of the new product includes:
 - emissions from the recycling processes that transform waste into a secondary material, and
 - emissions from manufacturing the new product itself.

This boundary convention ensures that each unit of emissions is accounted for once and only once, thereby preventing double counting across product systems.

6.3 Inclusion of recycling processes

While recycled materials enter the new product system burden-free, recycling processes themselves are fully included in the PCF. This includes emissions from:

- collection and sorting,
- cleaning and pre-treatment,
- reprocessing or remanufacturing into secondary raw materials, and
- any associated transport and energy use.

Including recycling-process emissions ensures that PCFs reflect the actual environmental effort required to make recycled materials usable, while still avoiding the reallocation of historical emissions from previous product systems.

6.4 Transparency and supplementary information

Some frameworks, including TfS, recognize that companies may wish to communicate additional information about:

- the avoided use of virgin materials, or
- the expected end-of-life benefits of products designed for recyclability.

Such information can be valuable for internal decision-making, eco-design, or sustainability communication. However, to preserve comparability and avoid conflating fundamentally different modelling assumptions, this information must be:

- reported separately from the core PCF value, and
- clearly identified as supplementary or informative, rather than as part of the PCF itself.

Embedding avoided-burden credits or speculative end-of-life benefits directly into the main PCF value would introduce subjectivity and reduce consistency across products and supply chains.

Recommendation 5:

When a product uses recycled materials, the recycled material should enter the new product system burden-free, carrying no historical emissions from its previous life cycle. The PCF should include:

- emissions from recycling processes that convert waste into secondary materials, and
- emissions from manufacturing the new product.

Any information on avoided virgin material production or expected end-of-life benefits should be disclosed separately and should not be included in the core PCF value. This approach ensures transparent, comparable, and auditable treatment of recycled materials and supports consistent PCF exchange across value chains.

7. Scope and limitations

This paper focuses on the definition of system boundaries for PCFs intended for reporting, supply-chain communication, and corporate decision-making. It adopts an attributional life-cycle perspective and recommends cradle-to-gate boundaries as the default for PCF calculation. The paper does not aim to prescribe detailed calculation methods for each PCF category, which will be the object of specific carbon accounting standards; nor does it replace sector-specific product category rules or regulatory requirements where these apply. The framework is intended to inform regulators and organizations developing carbon measurement guidance, as well as companies seeking to calculate consistent and credible PCFs.

While the framework allows for supplementary disclosures such as use-phase emissions, avoided burdens, or long-term carbon storage, these are treated as complementary information and are not included in the core cradle-to-gate PCF value unless explicitly required. The recommendations are designed to support comparability and auditability under current data availability and are expected to evolve as primary data exchange and integrated corporate carbon accounting systems mature.

Appendix: References

1. Catena-X (2025), Product Carbon Footprint Rulebook, v4.0.
2. CASI (2025), CASI Whitepaper No.1: Foundations of Integrated Corporate Carbon. Carbon Accounting Standards Initiative. <https://casinitiative.org/#casi>.

3. CASI (2026), CASI Whitepaper No.2: CO2-Statements: Double-Entry Bookkeeping for Integrated Corporate Carbon Accounting. Carbon Accounting Standards Initiative. Available at <https://casinitiative.org>.
4. CASI (2026), CASI Whitepaper No.4: Carbon Accounting for Long-Lived Operating Assets. Carbon Accounting Standards Initiative. <https://casinitiative.org/#casi>.
5. European Commission (2021), Product Environmental Footprint (PEF) Method, Commission Recommendation (EU) 2021/2279.
6. European Commission (2017). PEFCR Guidance Document – Guidance for the Development of Product Environmental Footprint Category Rules (PEFCRs), Version 6.3.
7. Financial Accounting Standards Board (FASB) (2009). Accounting Standards Codification (ASC) Topic 330 — Inventory.
8. GHG Protocol (2011). Product Life Cycle Accounting and Reporting Standard (commonly referred to as the GHG Protocol Product Standard).
9. GHG Protocol Scope 2 Guidance (2015).
10. International Accounting Standards Board (IASB) (2003). IAS 2 — Inventories.
11. ISO 14040:2006. Environmental management — Life cycle assessment — Principles and framework.
12. ISO 14044:2006. Environmental management — Life cycle assessment — Requirements and guidelines.
13. ISO 14067:2018. Greenhouse gases — Carbon footprint of products — Requirements and guidelines.
14. PAS 2050:2011. Specification for the assessment of the life cycle greenhouse gas emissions of goods and services.
15. TfS (Together for Sustainability) (2024), Product Carbon Footprint Guideline for the Chemical Industry, v3.0.

About CASI

The Carbon Accounting Standards Initiative (CASI) advances the practice of corporate carbon accounting and reporting. CASI brings together academic scholars and practitioners to develop standards for integrated corporate- and product-level carbon accounting. Building on established financial accounting frameworks, the resulting carbon metrics provide comprehensive, reliable and decision-useful information about a company's carbon emissions performance.