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Designing a high-performance international regime for embedded emissions accounting

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Emma Aisbett
College of Law, Governance and Policy, Australian National University

Saule Burkitbayeva
College of Law, Governance and Policy, Australian National University

Abstract

The international regime of Embedded Emissions Accounting and Verification Frameworks (EEFs) unpins a range of domestic and trade-related climate policies, including carbon border adjustments, eco-certification, and Green Industrial Policy targetting. As such a high-performance (efficient and effective) regime is essential to support a range of economic and climate objectives. Yet the emerging regime is at risk of poor performance due to rapid and uncoordinated proliferation, and potential capture by vested interests. The current paper is designed to support academic and practical efforts to steer the evolution of a high-performance regime. To do this, it develops and applies a structured approach to understand and align key design elements in EEFs.

Keywords:
embedded emissions accounting; trade-related climate policy; carbon border adjustments; eco-certification; international regulatory regimes

JEL Classification:
F13; F18; K32; K33; Q58

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Address for Correspondence:
A/Prof. Emma Aisbett; ANU School of Law; 5 Fellows Rd, Acton, ACT, 2601, Australia.
Email: emma.aisbett@anu.edu.au

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Australian National University

Extended Abstract

Embedded emissions accounting and verification frameworks (EEFs) are documented approaches to generating facility-level, or even batch-level, information about emissions associated with product supply chains. EEFs are emerging in a variety of settings. Some are stand-alone instruments, designed to serve a variety of purposes. Other EEFs have emerged as an integral part of the initiative that they serve.

Taken as a whole, EEFs can now be considered to comprise an emerging international regulatory regime. Furthermore, concern about the problems arising from an uncoordinated global regime of EEFs is driving the dedication of substantial, and growing, governance resources towards coordination efforts.

The current paper seeks to inform architects of the emerging international EEF regime. These architects include public, private and non-government and multistakeholder designers of individual EEFs as well as international and transnational initiatives which seek to intervene at the regime level. Our paper aims to help these architects answer the question of how to design a high-performing EEF regime. We offer a structured approach to designing a high-performing global EEF system.

First, we introduce a conceptual framework, a top-down design pyramid, that organizes the EEF design process into successive layers of increasing detail and complexity. At the top of the pyramid are the broad Governance Objectives. The broad Governance Objectives we address in the current paper are Efficiency and Effectiveness. Identification of these objectives necessarily leads to the question: Efficient and effective at what? To date, no one has explicitly articulated the overarching objective of a global EEF regime. This paper addresses that gap by offering what we believe to be the first such articulation. The core purpose of an international EEF regime is to enable informed decision-making based on product-level embedded emissions data. Relevant decision-makers include governments, investors, producers, and consumers.

The second layer of the design pyramid comprises Overarching Principles for the EEF regime. We discuss how the general Governance Objectives of Effectiveness and Efficiency motivate three key Overarching Principles for the EEF regime: Relevance, Least Restrictive Means, and Non-Discrimination.

The third layer of the design pyramid comprises Supporting Principles, which act as practical guardrails that steer design choices in alignment with the Overarching Principles. Drawing from White et al's (2025) synthesis of principles in the trade law and carbon accounting literatures, we propose Accuracy, Conservativeness, Monotonicity, Subsidiarity, and Transparency. We additionally propose three further principles:

Comparability, Flexibility, and Interoperability. These additional principles reflect the regime-level considerations of the current paper.

The fourth layer of the design pyramid comprises Framework Structure. Here we identify which elements of EEF structure are of key importance for alignment with the previously identified principles. We also provide guidance on the choices for these elements that help align both individual EEFs and the global regime with the design principles. The key framework elements are we identify are:

- a modular approach to defining emissions accounting boundaries,
- identifying the covered products and production pathways,
- inclusion of all relevant greenhouse gases,
- determining necessary additional information layers,
- setting appropriate levels of temporal and spatial precision, and
- deciding on the time-scale for assessing global warming impact.

The final layer of the design pyramid that we consider in detail comprises Framework Rules. Key rules to consider include:

- emissions allocation among products, co-products, and wastes,
- treatment of carbon capture,
- approach to the use of counter-factuals, baselines, and additionality,
- selection and application of methods and default values for calculations, and
- choice of Global Warming Potential (GWP) factors to convert different greenhouse gases into CO_2 equivalents.

We summarize our discussion of these Framework Structure and Framework Rule design elements in Appendix Tables A1 and A2. Table A1 focusses on designing high-performance individual EEFs, and Table A2 takes a regime-level perspective. Both tables highlight priorities for consistency and (within or between EEFs) with reference to the principles and objectives of the upper layers of the Design Pyramid.

Overall, this paper aims to provide a structured approach to EEF design, including both individual and regime-level considerations. We hope that it will be a useful aid to both researchers and practitioners working on emerging global embedded emissions accounting regime.

Contents

1 Introduction

Today, many important approaches to the net zero transition require information about the greenhouse gas emissions resulting from product upstream supply chains, known as product “embedded emissions”. These approaches represent a shift in focus for climate mitigation initiatives: from addressing emissions associated with a certain place or territory; to addressing those associated with a certain product or supply chain. Examples of public policies which rely on product embedded emissions information include carbon border adjustment mechanisms (CBAMs) and targeting mechanisms for green industrial policies, including green investment taxonomies and procurement policies. Examples of private sector initiatives relying on this information include corporate Net Zero Scope 3 emissions commitments and product “eco” certification. Each of these initiatives relies on information about product embedded emissions of some sort.

Embedded emissions accounting and verification frameworks (EEFs) are documented approaches to generating facility-level, or even batch-level, information about product embedded emissions. EEFs allow reporting entities (usually private supply chain participants, especially producers) to report specified information, and use that information to generate standardized calculation of the greenhouse gas emissions associated with a specified portion of a product’s supply chain. The rapid growth in initiatives relying on embedded emissions information has seen a proliferation of EEFs in the last five years.

EEFs are emerging in a variety of settings. Some are stand-alone instruments, designed to serve a variety of purposes. Such examples include the Pathfinder Framework, Environmental Product Declarations (EPDs), or the Australian Government’s Guarantee of Origin Scheme. Other EEFs have emerged as an integral part of the initiative that they serve. Examples here include the European Union's Carbon Border Adjustment Mechanism (CBAM) accounting rules or the United States Inflation Reduction Act (IRA) subsidy accounting rules, as well as product certification schemes like Responsible Steel. While a positive indicator of climate action, the number and variety of EEFs currently emerging is also cause for concern.

The uncoordinated proliferation of EEFs poses serval problems. Producers and reporting entities face excess regulatory burden as they must not only decide which EEFs to engage with, but may also need to duplicate the effort of data collection, measurement and reporting for multiple EEFs. Lack of interoperability due to EEFs’ varied information requirements complicate our ability to combine measurements across different systems along value chains (Luers et al., 2022). Meanwhile, different methodologies and boundaries result in varying emissions intensity claims, even when applied to similar products (Biberman et al., 2022; Deconinck et al., 2025; Toledano et al., 2023; Velazquez Abad & Dodds, 2020; White et al., 2021a). The complexity and variety of EEFs, combined with the dramatically different emissions claims they support creates confusion for consumers and investors, and raises concerns of greenwashing.

Taken as a whole, EEFs can now be considered to comprise an emerging international regulatory regime. Furthermore, concern about the problems arising from an uncoordinated global regime of EEFs is driving the dedication of substantial, and growing, governance resources towards coordination efforts. Intergovernmental forums such as the OECD's Inclusive Forum on Carbon Mitigation Approaches, the Climate Club, and International Energy Agency are emerging to facilitate these efforts through inclusive dialogues, information sharing and mutual learning. Given the quantum of resources involved in these efforts, and the economic and environmental importance of their success, it is crucial that they are well-invested.

The current paper seeks to inform architects of the emerging international EEF regime. These architects include public, private and non-government and multistakeholder designers of individual EEFs as well as international and transnational initiatives which seek to intervene at the regime level. Our paper aims to help these architects answer the question of how to design a high-performing EEF regime.

To answer this question, in Section 2 we develop a conceptual framework in the form of a top-down design "pyramid" for EEFs. We then use this framework to address substantive questions at different levels. Beginning at the top of the pyramid, Section 3 motivates our choice of Governance objectives and their translation into Overarching Principles for the EEF regime. Section **Error! Reference source not found.** introduces Supporting Principles. These principles provide guardrails that help guide design choices towards the alignment with the Overarching Principles. Building on the work of White et al. (2024), we focus on Interoperability, Comparability, and Flexibility as key principles from a regime perspective.

Sections **Error! Reference source not found.** and 6 examine the implications of these principles for questions around the design and negotiation of EEFs. Focussing on the principles of Interoperability, Comparability, and Flexibility, it: introduces several design choices and explains why they are important; and argues for particular answers to these design choices. Acknowledging the inherent tension between the principles of Interoperability and Comparability on the one hand, and Flexibility on the other, it also recommends priorities for negotiating consistency within and across EEFs, and explains which choices can safely remain idiosyncratic.

2 Conceptual framework

We take a top-down approach to the question of EEF-regime design. Importantly, we are not arguing that a single, global entity should take a top-down approach to creation of the EEF regime. It is clear, and appropriate, that many actors - both public and private, transnational, international, national, and subnational – will contribute to the creation of the regime. However, no one to date has taken a global view. This means the participants in the regime's creation lack the information they require to optimally coordinate. The purpose of the current paper is to help provide that information to regime participants.

Figure 1 schematically represents our top-down approach as a layered pyramid, where each layer from top to bottom addresses increasingly detailed and specific aspects of EEF design.

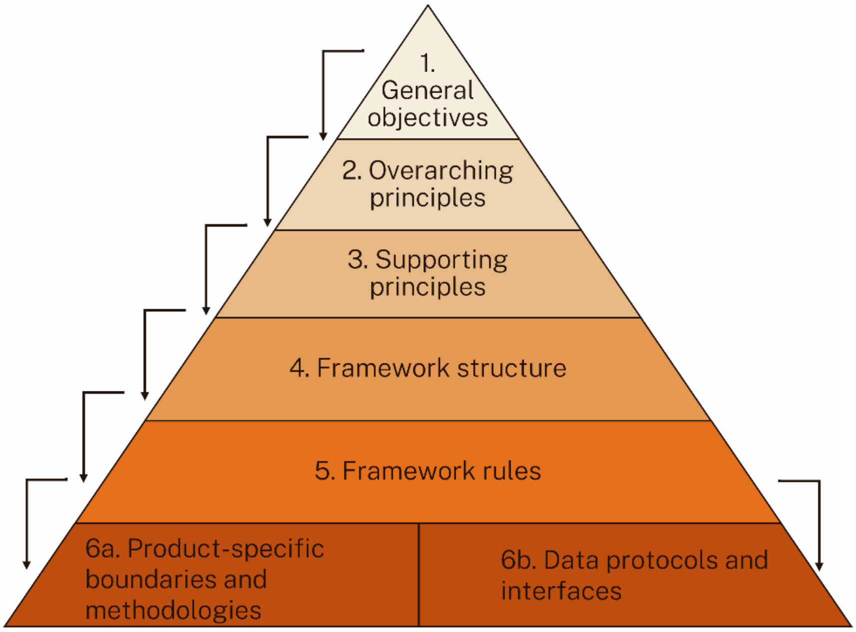

Figure 1: Schematic of top-down approach to EEF regime design

The top section of the pyramid (Levels 1-3) is aspirational, and principles based. The pinnacle of the pyramid represents General Objectives common to global regulatory regimes across a range of issue areas. "Effectiveness" is an example of a General Objective. Level 2 of the pyramid consists of Overarching Principles. These core principles represent the translation of general regulatory objectives into the context of the global EEF regime. "Non-discrimination" is an example Aspirational Principle. The third level consists of Supporting Principles. These more diverse and specific principles help align EEF design choices to achievement of the Overarching Principles. "Transparency" is an example of a Supporting Principle.

In contrast to the top levels, the middle section of the pyramid (Levels 4-5) is concrete, and rules based. Framework Structure (Level 4) includes choices around what elements comprise the EEF and the architecture of how these elements combine. Modular accounting boundaries is an example component of Framework Structure. Framework Rules (Level 5) are specific rules which apply across a given EEF, such as the approach to allocation of emissions among products, or determination of global warming potential of greenhouse gases. These design choices at Levels 4 & 5 should be consistent with the objectives and principles of Levels 1-3.

There are two sections in the bottom level of the design pyramid: Product-specific Boundaries and Methodologies (Level 6a) and Data Protocols and Interfaces (6b). Both represent distinct categories of detailed design choices. They are situated on the same level, because neither determines the other from a "top-down" design perspective.

3 Governance Objectives and Overarching Principles

3.1 Governance objectives

The pinnacle of the pyramid contains Governance objectives common to global regulatory regimes across a range of issue areas. The literature contains a variety of suggested principles of good governance (van Doeveren, 2011). Many of these principles, such as "participatory" are related to process, and more broadly to governance rather than regulation. While they are important principles, the focus of the current paper is on performance of the EEF regulatory regime.

The General objectives at the top of our design pyramid comprise the two most widely accepted performance principles for governance: Effectiveness and Efficiency (Pomeranz & Stedman, 2020). In focussing on these two objectives to inform a principles-based approach to environmental regulatory design, we follow seminal work by (Gunningham & Sinclair, 1999). We are also acknowledge we are emphasizing priorities for good governance most advocated in the economics discipline (Addink, 2019).

In the current context, we define Efficiency as optimal use of resources, such as time, institutional capacity, funding, and human resources, to achieve regulatory goals. Efficiency focuses on how objectives are achieved, emphasizing cost minimization and resource optimization (Rhodes et al., 2021). Effectiveness refers to the ability of a regulatory regime to achieve its Governance objective. Intrinsic to effectiveness is, therefore, a clear statement of what the intended objectives of the regulation are (Addink, 2019). To the best of our knowledge, no one has attempted to articulate an objective for the global EEF regime. Developing such a statement is the first contribution of this paper to regime designers.

To determine an objective for the global EEF regime, we begin by considering statements of purpose available for existing individual EEFs. Though rarely explicitly stated as such, purpose can be implied from the websites associated with some stand-alone EEFs. For example:

- "The Pathfinder Framework and Network enable companies to better understand carbon emissions on a granular level, improving business decision-making and helping them meet their net zero targets" (WBCSD, 2023).
- "ResponsibleSteel certification …. gives buyers, investors, and other stakeholders the confidence that a steel site is working to implement some of the most rigorous social and environmental standards in the industry" (Responsible Steel, n.d.).
- "The objects of this Act are to: (a) improve transparency and provide trusted information about renewable electricity and emissions associated with products, to enable producers and consumers to make credible claims about the production and use of renewable electricity and products; and (b) encourage decarbonisation and investment in Australian industry, and accelerate the commerciality of low emissions products; and (c) support the development of markets for renewable electricity and low emissions products; and (d) support

> the achievement of Australia's greenhouse gas emissions reduction targets and the reduction of global greenhouse gas emissions in accordance with the Paris Agreement; and (e) give effect to certain obligations that Australia has as a party to the following: (i) the Climate Change Convention; (ii) the Kyoto Protocol; (iii) the Paris Agreement." (Future Made in Australia (Guarantee of Origin) Bill 2024, 2024)

For EEFs embedded in regulation, statements of purpose are only available for the regulation itself, for example:

- "The EU's Carbon Border Adjustment Mechanism (CBAM) is the EU's tool to put a fair price on the carbon emitted during the production of carbon intensive goods that are entering the EU, and to encourage cleaner industrial production in non-EU countries" (European Commission, n.d.).
- The Inflation Reduction ACT 2022 "provides targeted incentives to drive investment and create opportunity in communities across the country [...] encourages clean energy project developers to meet strong labor standards [...] will lower the costs of energy-saving property improvements and rooftop solar installation [...]" (U.S. Department of the Treasury, 2025).

Considering these stated and implied objectives of individual EEFs, **we propose the purpose of the international regime of EEFs is to support decision-making based on product embedded emissions information**. The actors whose decisions are supported include governments, investors, producers, and customers (both final consumers and downstream supply chain). The types of decisions that are supported by the regime are summarised in Table 1.

Table 1: Decisions that can be supported by the EEF regime

Actors	Decisions
Customers	• Choice of product (e.g. wood versus metal) • Choice of supplier of otherwise like product (e.g. renewable or fossil hydrogen)
Producers	• Product choices • Decarbonization pathways • Investments • Market opportunities
Governments	• Support targets • Taxation rates • Regulation • Procurement
Investors	• Support investment decisions • Risk assessment

3.2 Overarching Principles

Level 2 of the design pyramid consists of Overarching Principles. These principles represent the translation of general regulatory objectives into the context of the global EEF regime. To identify potential Overarching Principles, we draw on the work of White et al. (2024) who synthesized eight principles for EEF design from a survey of trade law and carbon accounting literature and practice. Of these eight, three stand out as Overarching Principles to map the general Governance objectives (Effectiveness & Efficiency) onto the EEF regime, they are: Relevance, Least Restrictive Means, and Non-discrimination. The mapping of Overarching Principles onto Governance objectives is illustrated in Figure 2: **Mapping of Overarching Principles onto the Governance objectives they underpin**.

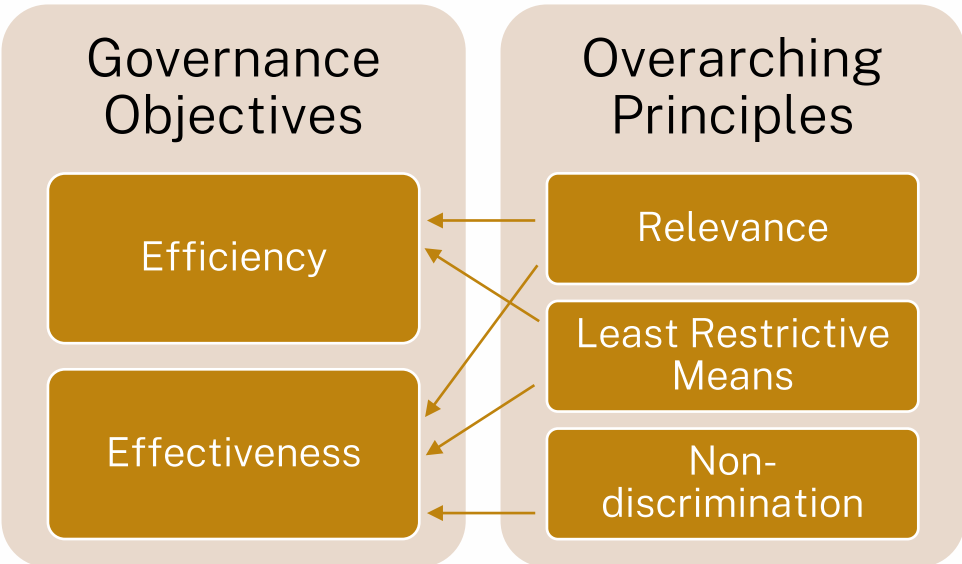

Figure 2: Mapping of Overarching Principles onto the Governance objectives they underpin

Relevance is a widely adopted principle of carbon accounting literature and practice. In the context of EEFs, the Relevance principle states that EEFs "should be designed to support the needs of the intended uses and users." (White et al., 2024, p.11). Considering governments, investors, and customers as intended users of EEFs, the Relevance principle relates to the attainment of the Governance objective of Effectiveness. White et al. also point out that reporting entities are among the users of EEFs. By encouraging EEF design to support the needs of reporting entities, the Relevance principle also relates to the attainment of the "Efficiency" Governance objective. Hence, the Relevance principle supports the Governance objectives of Effectiveness and Efficiency. Both these objectives are also supported by the principle of Least Restrictive Means (LRM).

LRM is a widely used principle in trade law. White et al.'s translation of this principle to the context of EEFs, says EEFs "should be designed to meet the requirements of their intended use in the least trade restrictive means possible." LRM, therefore, focuses on achieving Efficiency, while acknowledging this efficiency should not come at the expense of Effectiveness.

Arguably the central principle of trade law, Non-discrimination in this context means that EEFs "should not generate explicit or implicit advantage or disadvantage for like products, where "like" includes true emissions impacts." (White et al., 2024, p. 11). The inclusion by White et al.(2024) of reference to true emission impacts means that the principle of Non-discrimination supports the Effectiveness objective.

4 Supporting Principles

We view Supporting Principles as guardrails that help guide design choices towards the alignment with the Overarching Principles discussed above. To identify potential Supporting Principles, we once again turn to the work of White et al., (2024).

4.1 Accuracy, Conservativeness, Monotonicity, Subsidiarity, and Transparency

The eight core principles identified by these authors include our Overarching Principles (Relevance, Least Restrictive Means, and Non-discrimination) plus: Accuracy, Conservativeness, Monotonicity, Transparency, and Subsidiarity. We view these latter five as Supporting Principles. Their definitions are provided in Table 1.

Table 2. Definitions of Supporting Principles drawn from White et al. (2024)

Principle	Definition
Accuracy	True embedded emissions should neither be under-estimated or over-estimated.
Conservativeness	Where further accuracy cannot reasonably be achieved, assumptions, default values and alternative methods should be chosen such that the risk of reported emissions (removal) being an underestimate (overestimate) of the true values is minimized.
Monotonicity	Embedded emissions accounting frameworks should not allow actors to decrease their reported emissions in a way that may increase overall emissions.
Subsidiarity	Data collection and accounting should be conducted at the lowest level of aggregation and control that is consistent with meeting its intended use.

Transparency	Information should be provided sufficient to allow stakeholders to assess robustness and reliability.

All five of the principles in Table 2 support the Relevance and Effectiveness of EEFs. They guide the design towards the creation of high-integrity, trusted information that meets the needs of both public-and private-sector regulators, customers, and funders. As these principles are discussed at length in White et al. and pertain mainly to the design of individual EEFs, we do not discuss them further here.

While White et al. were interested in the question of how to design individual EEFs, our focus is at the regime level. That is, we are interested in the design of individual EEFs insofar as it effects their interactions with other EEFs and the regime as a whole. With this regime-level focus, we recommend the addition of three further Supporting Principles: Comparability, Flexibility, and Interoperability.

4.2 Comparability

Comparability is a principle that arises in both trade law and carbon accounting literature and practice. Although identified by White et al. (2024) it was not included in their synthesised list of eight principles because it was considered subsumed by the principle of Non-discrimination. In the current paper, we bring Comparability back in its own right, precisely because it supports Non-discrimination in the international regime. A variety of definitions of Comparability were identified by White et al. For clarity, we define Comparability in the current context to mean that –within reasonable bounds -differences across or within EEFs in the embedded emissions associated with a specified portion of a product's supply chain reflect actual differences in embedded emissions. In other words, if two different EEFs are used to calculate the embedded emissions of a given component of a given supply chain of a product which is made at a given facility in a given timeframe, the calculated embedded emissions should agree to within the bounds of the accuracy of the two frameworks. This is illustrated in

Figure 3.

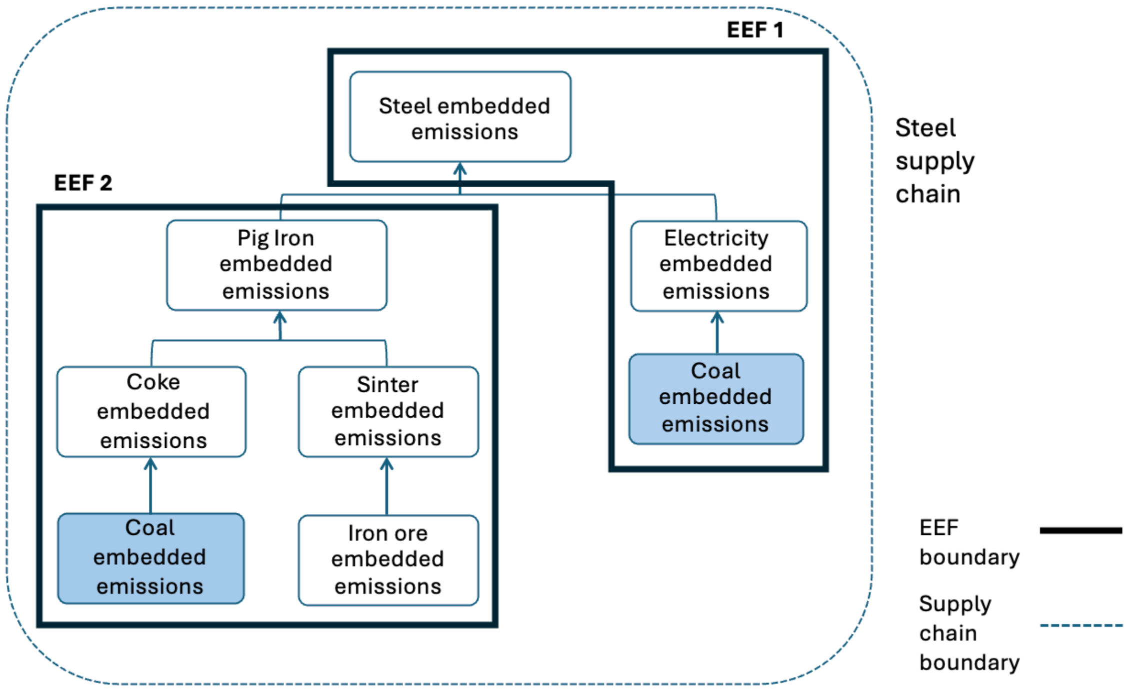

Figure 3: Comparability of Coal embedded emissions as part of steel supply chain

Similarly, if identical processes occur in the supply chains of two different products which are covered by a single EEF, the calculated emissions should be the same regardless of which product pathway is chosen. For example, the emissions allocated per kilogram of hydrogen from a steam methane reforming process should be the same, regardless of whether this process is part of the supply chain of steel or fertilizer. This is illustrated in Figure 4.

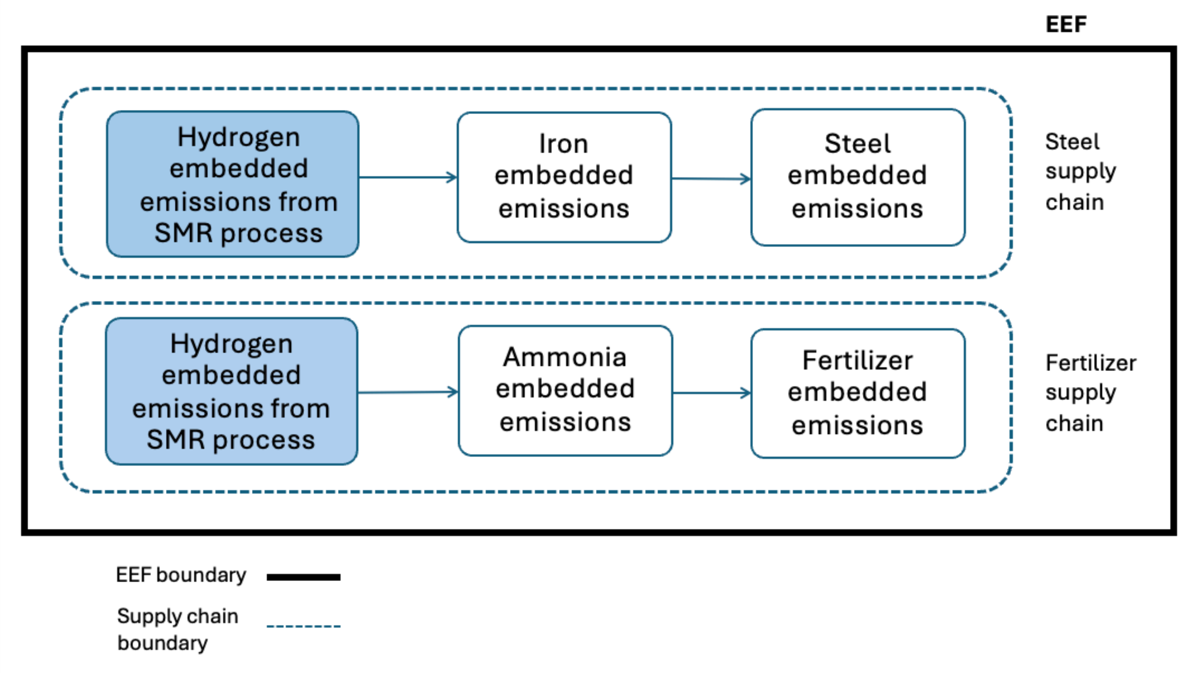

Figure 4: Comparability of embedded emissions from SMR hydrogen as part of steel and fertiliser supply chains.

4.3 Flexibility

Flexibility is another common principle in trade law. Although identified in the systematic review by White et al., Flexibility was not one of those authors' eight key principles because they considered it a "distributional" principle and therefore outside the scope of their synthesis exercise. Indeed, as it is defined and applied in trade law, Flexibility is aimed at allowing alternative approaches to trade liberalization for parties with lower capacity (cites taken from White et al. 2024, Supplementary Material: Table D2, p.33). In other words, traditionally in trade law, Flexibility refers to allowing different "means" to achieve the same (or similar) "ends".

An alternative definition of Flexibility is that a given "means" should be able to achieve multiple "ends". This understanding of Flexibility is the one used in the Australian Government's Principles for development of its Guarantee of Origin Scheme. They define flexibility in this context to mean "the scheme can align with evolving consumer needs, technology, and international market developments." (CER, 2023, p.5). Our meaning of Flexibility is similar. Specifically, we define Flexibility to mean "EEFs should be designed to maximise the number of uses and users for which they are relevant". The potential range of climate-related initiatives which can be underpinned by flexible EEFs is illustrated in Figure 5.

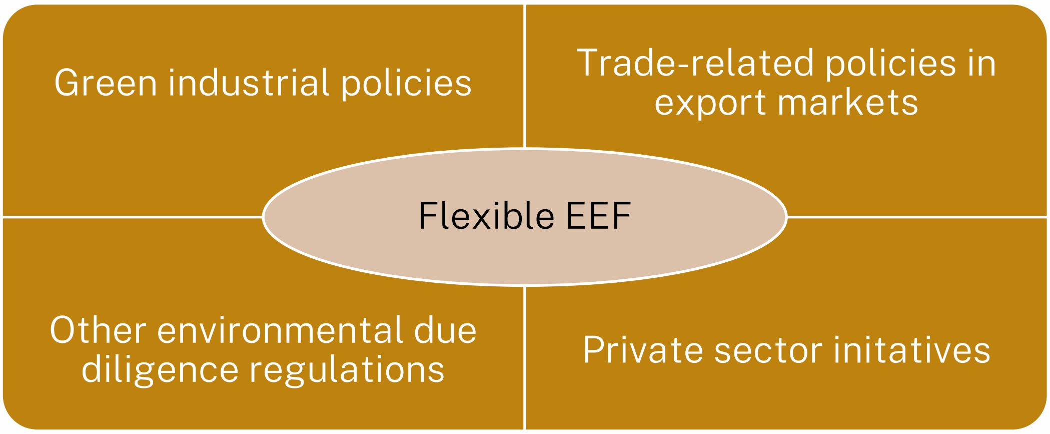

Figure 5: Illustrating the range of potential uses of a flexible EEF

Clearly, the above definition of Flexibility supports the Aspirational Principle of Relevance. Even more, this conception of Flexibility supports the Aspirational Principle of LRM. If an EEF can be used for multiple purposes, it lowers the overall regulatory burden for reporting entities. Where this reporting burden represents a trade cost, Flexibility lowers trade costs and thus supports a less restrictive means of regulating emissions embedded in trade. An example of a Flexible EEF is one which is designed to be compatible with – and hence potentially recognised by – the regulatory frameworks of one or more export markets.

4.4 Interoperability

In the literature and policy discourse on trade-impacting EEFs, interoperability is undoubtedly the most cited principle or desired attribute. Although rarely explicitly defined, interoperability is widely considered synonymous with a "good" EEF. The concept of interoperability is the subject of extensive literatures in both the fields of Regulation/Governance and Computing/Data Science. Some confusion in policy discourse on EEFs appears to arise from the fact that both conceptions of interoperability are relevant to EEFs. EEFs are, at heart, information instruments. They achieve policy and regulatory objectives using information systems.

Broadly speaking, interoperability means the ability to pass useful information from one system to another. Interoperability is an important feature of EEFs because they apply to supply chains, hence, information about the embedded emissions in one product is relevant to the embedded emissions of downstream products for which it is an input. Internal interoperability is required where multiple products and processes in the relevant supply chain are covered by a single EEF. External interoperability is required where different EEFs (e.g. from different jurisdictions) apply to different parts of the supply chain. Both types of information transfer are illustrated in Figure 6.

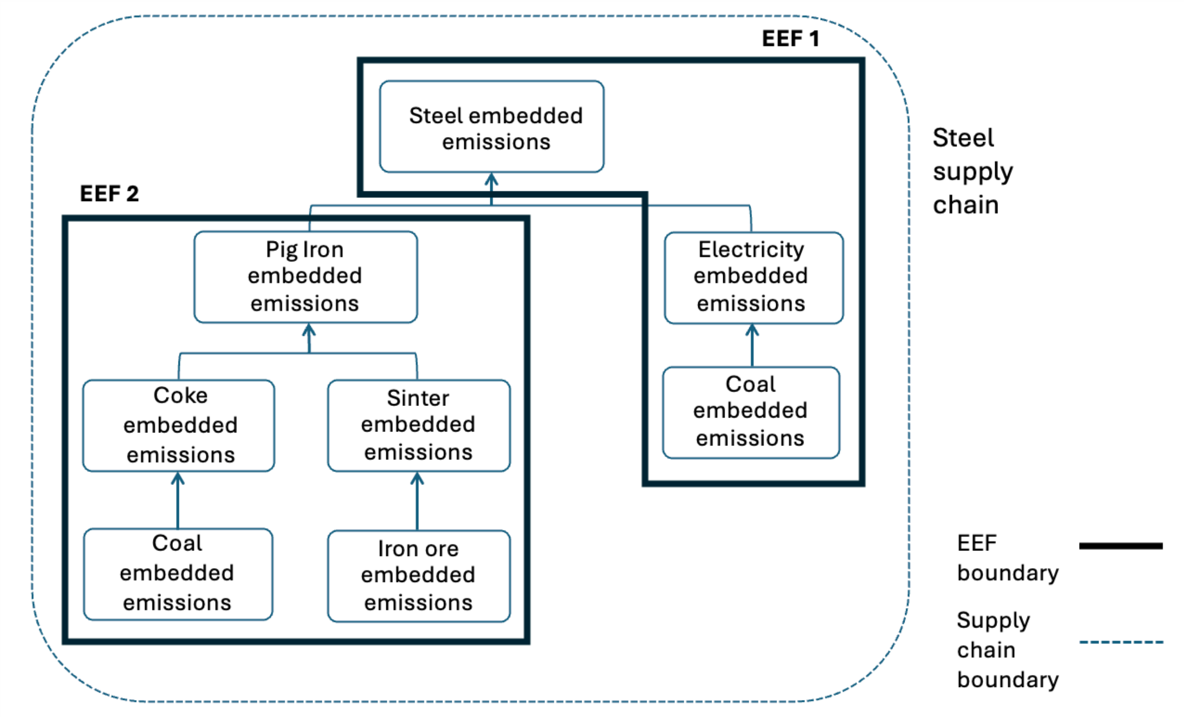

Figure 6: Embedded emissions information transfer between products within a single EEF as well as across EEFs for a hypothetical steel supply chain

Interoperability also supports the principles of Non-discrimination and LRM by ensuring fair treatment of different producers and minimizing trade barriers. For example, White et al. (2021) explain that hydrogen certification schemes covering the entire supply chain benefit producers located in the same jurisdiction as their end consumers. This EEF design approach violates non-discrimination and LRM principles, as it disadvantages certain exporters and hinders tradability for certain exporters in international markets. By enabling the comparison of 'like' products at different stages of the supply chain, Interoperability ensures that no producer is discriminated against. It also reduces regulatory burden and trade costs by allowing producers to comply with different certification schemes, rather than acquiring multiple certifications with varying supply chain boundaries separately.

Finally, we note that Interoperability and Flexibility principles are closely related. Interoperability essentially refers to the compatibility of an EEF with other EEFs, while Flexibility refers to the compatibility of an EEF with different regulatory initiatives. When the regulatory initiative in question has an embedded EEF, the two principles essentially overlap.

5 Framework Structure

Framework Structure (Pyramid Level 4) includes choices around what elements comprise the EEF and the architecture of how these elements combine. In this section we discuss the elements of framework structure that are most important to align EEFs with the principles identified in the previous sections: Accounting Boundaries, Covered Products and Production pathways, and Information Layers and Multidimensionality, Temporal and spatial precision, and the Time-scale of global warming impact.

5.1 Accounting boundaries

Accounting boundaries are an essential component of EEFs as they specify which greenhouse-gas-emitting processes are to be included. Not surprisingly, differences in boundaries are a major source of non-comparability between EEFs. A number of studies have identified differences in boundary definitions among EFFs for various products, including hydrogen (Velazquez Abad & Dodds, 2020; White et al., 2021b), steel (Biberman et al., 2022; Toledano et al., 2023), and agri-food products (Deconinck et al., 2025).

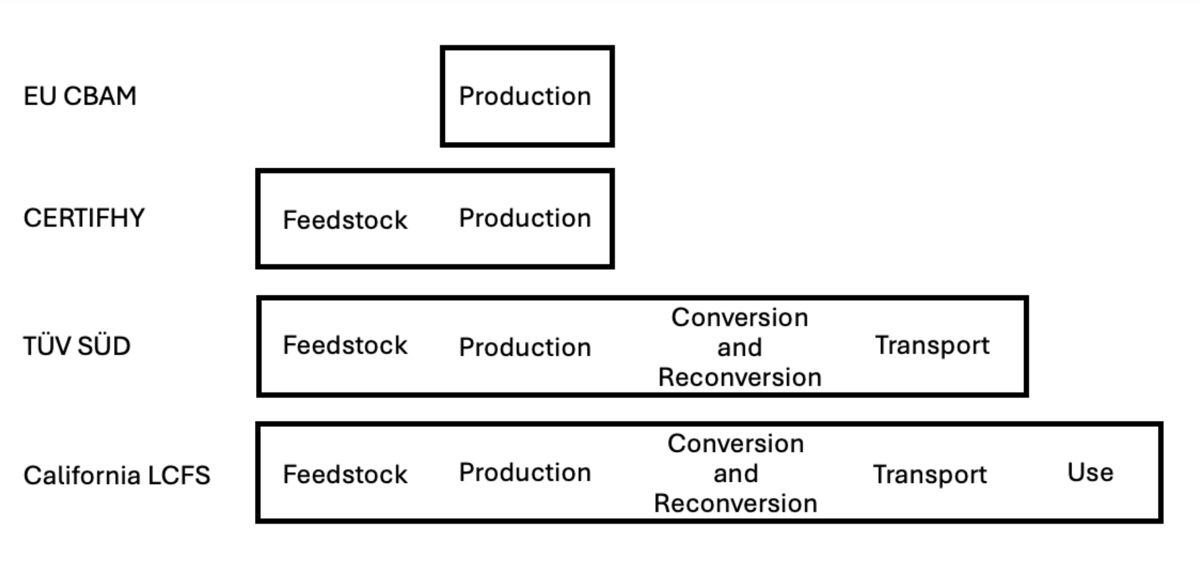

Figure 7: Example of boundary differences causing violation of the principle of Comparability between EEFs.

Figure 7 demonstrates how EEFs for hydrogen differ in terms of accounting boundaries and processes included. In the absence of modular accounting boundaries, these EEFs will fail the principle of Comparability.

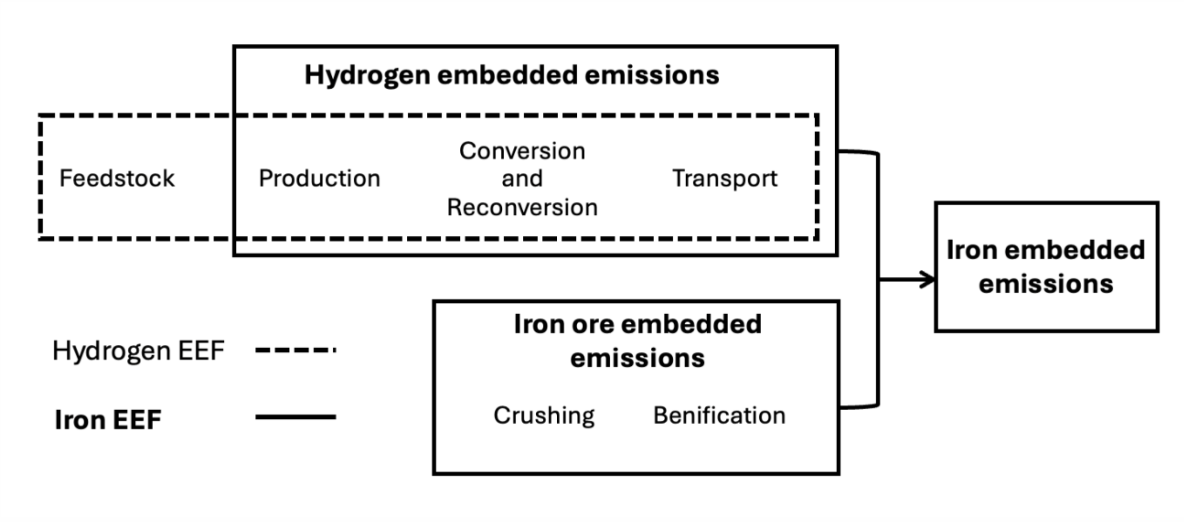

Figure 8 illustrates how misalignment of boundaries can seriously compromise Interoperability. In this example, a hydrogen EEF with a well to delivery gate boundary (in dash line) is trying to feed information into an iron EEF (in solid line), which has different requirements for hydrogen emissions information. In this example, the iron EEF requires production to deliver gate boundary only. This means that without modular accounting boundaries, the two EEFs are not interoperable.

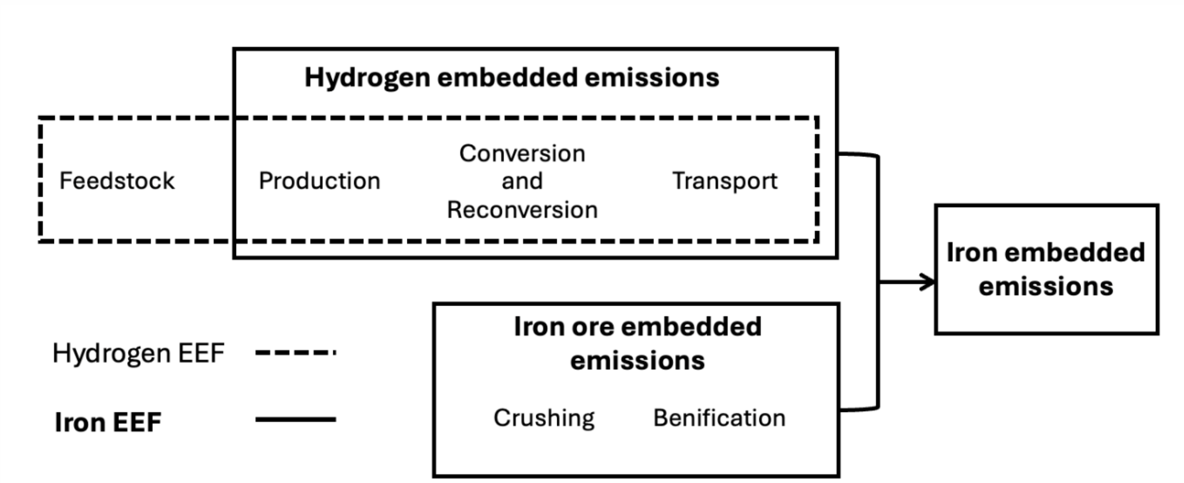

Figure 8: Example of misalignment of boundaries between different EEFs compromising Interoperability.

Lastly, the approach to boundary specification has a major impact on the Flexibility of EEFs and adherence to the principle of LRM. As mentioned previously, a Flexible EEF is one which is designed to be compatible with multiple regulatory frameworks, potentially across different export markets. However, regulatory frameworks may differ a lot in terms of boundary specifications (Figure 9).

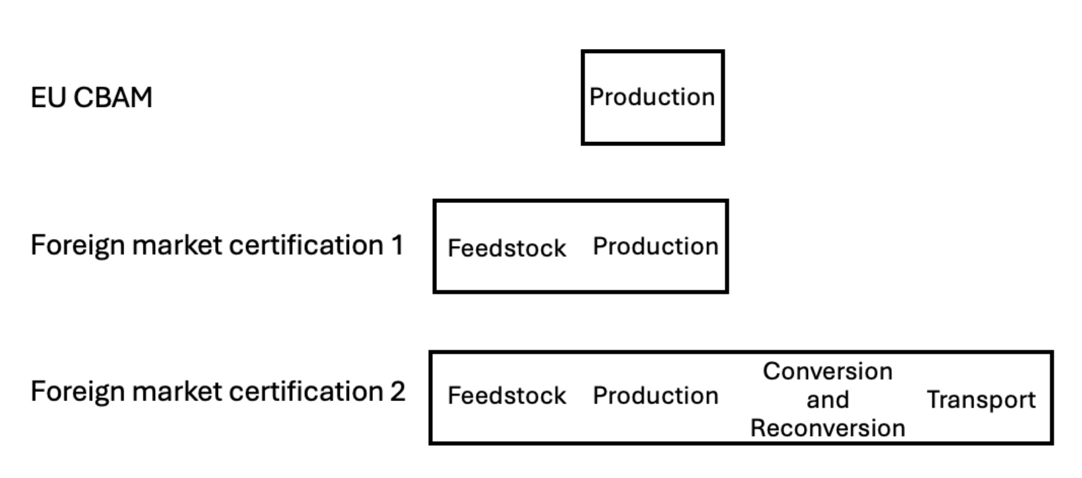

Figure 9: Different regulatory uses with different boundaries can pose challenges for Flexibility of EEFs.

5.1.1 Modular Accounting Boundaries for individual EEFs

A modular approach can help to address many of the issues that arise from misalignment of accounting boundaries, helping to achieve Comparability, Interoperability, and Flexibility (and by extension Relevance, LRM and Non-discrimination). Under this approach, each module defines an accounting boundary around a single, well-defined process (Reeve & Aisbett, 2022). The accounting boundary for a given product supply chain can then be specified by stipulating which modules comprise it. This means emissions for a given supply chain can be obtained by combining the emissions from the constituent modules (White et al., 2021b).

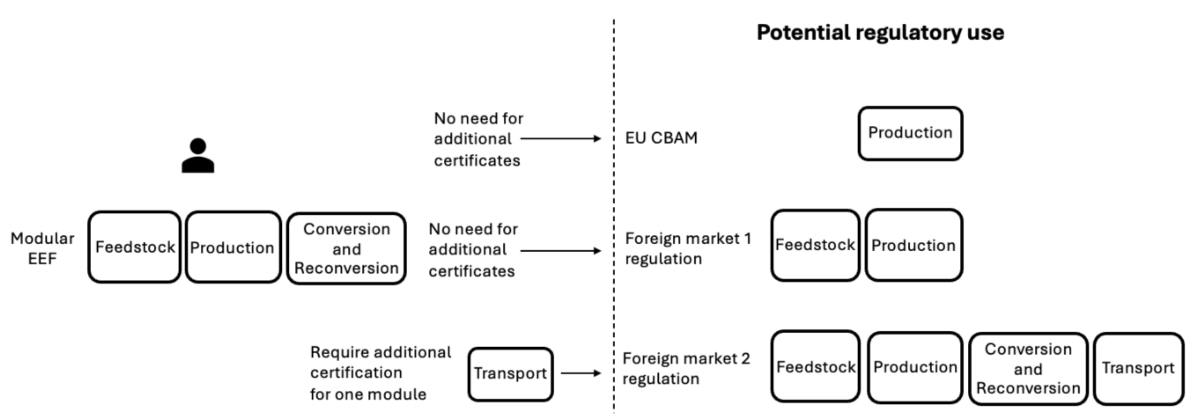

Figure 10: Modular EEF design can support Interoperability and Flexibility

Figure 10 illustrates how modular approach aligns with the principles of Interoperability and Flexibility, and by extension our Overarching Principles. On the left side of the dotted line is a hydrogen producer who has already provided relevant information required by a modular EEF (for example the Australian GO Scheme). On the right side of the dotted line are several regulatory schemes that this hydrogen producer must satisfy to gain access to foreign markets. For example, these regulations might be CBAMs or required product certifications. Importantly, the EEFs embedded in these regulations also take a modular approach to emissions boundaries. As long as the different EEFs in Figure 10 agree on the module boundaries of relevance, modularity enables Interoperability between the original domestic EEF and the EEFs embedded in foreign regulations. Depending on the requirements for various standards/schemes or jurisdictions, the hydrogen producer can present certificates for relevant modules. In our example, the only additional certification required would be for transport module (and only if they wished to access Foreign market 2). The domestic EEF in this example can be considered Flexible, as it allows the hydrogen producer to achieve multiple regulatory objectives. The Flexibility and Interoperability provided by modularity eases the regulatory burden and supports compatibility with the Overarching Principles of LRM and Non-discrimination (see Section **Error! Reference source not found.Error! Reference source not found.**).

Figure 11 illustrates how modular boundaries support the principle of Comparability. Here on the left-hand side, producers have each complied with the requirements of their domestic, modular, EEFs. Although the overall boundaries for the different producer schemes vary, the modular approach allows comparability across their products for the purposes of the Foreign market regulation on the left-hand side of the diagram.

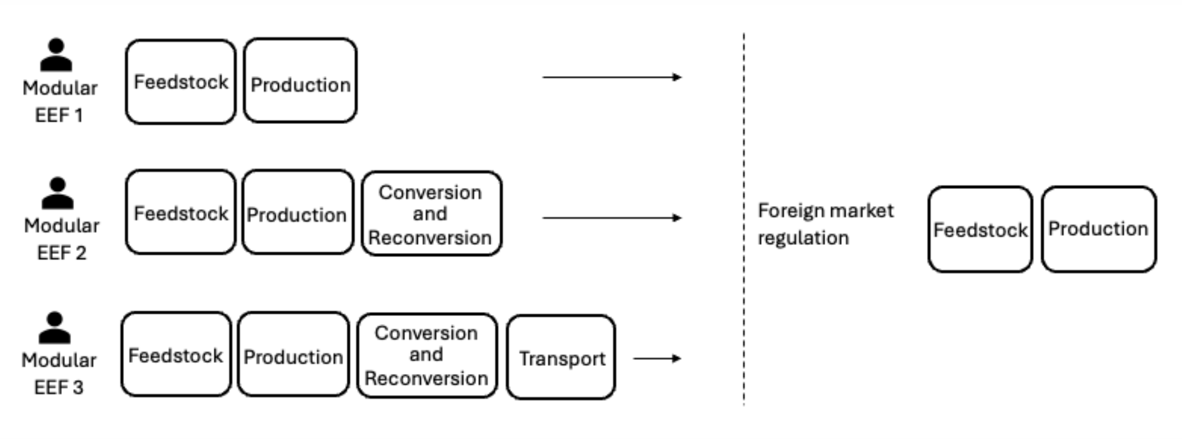

Figure 11: Modular boundaries support the principle of Comparability

Finally, modularity also supports the principle of Subsidiarity if each supply chain component is responsible for providing the information for the modules relevant to the components of the supply chain under their direct control.

Overall, modular accounting boundaries are an essential design element for principles-based EEFs. Adopting the modular approach should be a priority for both EEF-level designers and regime-level negotiators and interlopers.

5.1.2 Regime-level considerations for modular accounting boundaries

Although constituent EEFs having modular accounting boundaries is necessary, it is not sufficient. To support Interoperability, Flexibility, and Comparability, in the regime it is also necessary for the boundary definitions of the modules to align. Although an easier task than aligning overall accounting boundaries, this task still requires negotiation resources. It is recommended, therefore, that negotiators identify for initial focus a product supply chains which are key to Interoperability, Flexibility and Comparability of the regime. Transparent approaches to this product prioritization task include multi-criteria analysis as demonstrated by Jackson & Aisbett (2025) for the case of the Australian GO scheme.

While agreement on component module boundaries is important, agreement on the overall supply chain boundary for a given product (i.e. which modules to include) is not necessary for Interoperability. Indeed, as discussed above, forcing agreement on the necessary modules may be counter to the principle of Flexibility because different jurisdictions or regulatory applications may require information on different components of the product life cycle.

The following example illustrates how agreement on module boundaries is important, while agreement on which modules to include is not necessary for Interoperability and could compromise Flexibility. In accordance with the principle of Non-discrimination (specifically WTO National Treatment rules) the EU's CBAM accounting rules align with those under their Emissions Trading Scheme. For hydrogen, this means the accounting boundary does not include fugitive emissions from gas extraction. Meanwhile, in the interests of non-discrimination (level playing field) for renewable and fossil-based hydrogen, the Australian Government's Guarantee of Origin (GO) Scheme does include fugitive emissions in their "well-to-gate" boundary. An interoperable, modular, approach for these two EEFs would mean that Australian hydrogen producers could comply with the EU CBAM accounting rules by providing information from the subset of relevant modules for which they already calculate emissions for the Australian GO. This would require agreement between the EU CBAM and Australian GO on module boundaries for overlapping modules, but not on which modules need to be included in the overall accounting boundary.

It is important to note that the need for Comparability in certain situations limits when it is appropriate to take a flexible approach to selecting which modules are included in each supply chain accounting boundary. There are two broad situations in which Comparability requirements dictate the need to align overall boundaries. Firstly, for a given regulatory objective by a given regulator, it is important to compare "apples with apples". For example, if EEFs from different exporting jurisdictions are being used to calculate a carbon border adjustment for an importer, they must all cover the modules specified by the importer. Secondly, if mutual recognition of product-level emissions values (as opposed to module-level) is desired, the modules included must be the same. For example, if two countries seek to mutually recognize each other's emissions calculations from their respective "clean aluminium" certification schemes, the definition of the proportion of the aluminium supply chain covered must align.

5.2 Covered products and production pathways

Design, development and implementation of high-performance EEFs is not a trivial undertaking. Each additional product or production pathways adds to the task and increases the complexity of efforts to maintain Comparability and Interoperability. The choice of product and production pathways is therefore an important determinant of the Efficiency and Effectiveness of an EEF.

Products whose embedded emissions can be reported by an EEF are referred to as Accounting Products. An Accounting Product can be an intermediate product which is an input to a final product. As such, the choice of Accounting Products can be understood as a choice about which parts of the supply chains of final products are to be included.

For each Accounting Product, there will usually be more than one possible production pathway. Different production pathways involve different processes and/or technologies.

5.2.1 EEF-level considerations for products and production pathways

The best approach to selecting products for coverage will depend on the primary purpose of the EEF. For EEFs underpinning product certification schemes, such as CertifHy, the choice is relatively constrained. For them the question comes down to the choice of accounting boundary, and which alternative production pathways to include. Product choice is also less of a concern for EEFs, such as the Pathfinder Framework, which seek to cover essentially any product.

Product choice is a particularly important consideration for public EEFs, whose development requires investment of government revenues and which may be compulsory (at least for firms wishing to access government support schemes). The question of product prioritization for public EEFs has been taken up by Jackson & Aisbett (2025). They recommend use of multi-criteria analysis (MCA) as a transparent and robust approach to supporting product choices in the presence of a combination of economic, environmental and policy considerations. These same methods could also be used to inform production pathway choices. Transparent approaches such as MCA are a good means to align with the principle of Non-discrimination by ensuring that novel processes are not unfairly excluded.

Irrespective of the initial choice of products and production pathways, EEF designers should keep the principle of Flexibility in mind. Design choices should be made with a view to enabling Interoperability and Comparability between products and pathways for a wider range of supply chains that may be incorporated at a later stage. For example, even if an EEF will only cover manufacturing and extractive products initially, design choices which are compatible with accounting approaches for agricultural products will enable later addition of these products as appropriate.

5.3 Inclusion of relevant greenhouse gases

Inclusion of all relevant greenhouse gases in essential to the principle of Accuracy.[1] Currently, different frameworks exhibit varying levels of greenhouse gas coverage. For example, in Australia, the National Greenhouse and Energy Reporting (NGER) Scheme is designed to encompass all relevant greenhouse gases, including carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), sulphur hexafluoride (SF6), and specified kinds of hydrofluorocarbons and perfluorocarbons (CER, 2025). This broad coverage a Complete and Accurate accounting of emissions. In contrast, the European Union's Emissions Trading System (EU ETS), which influences mechanisms like the Carbon Border Adjustment Mechanism (CBAM), has a more limited scope regarding GHG coverage. The EU ETS primarily covers carbon dioxide (CO2), nitrous oxide (N2O) and perfluorocarbons (PFCs) (European Commission, n.d). Notably, methane (CH4) is not explicitly listed among the gases covered by the EU ETS.

5.3.1 EEF-level considerations for choice of greenhouse gases

There is no strict need for consistency across all products within one EEF regarding the exact set of gases covered. The specific greenhouse gases covered can vary for different accounting products within a single EEF based on their relevance to GHG sources and sinks in that product's supply chain. For instance, methane is an especially important gas for agricultural products. To ensure Relevance is balanced against Accuracy and Comparability, EEF designers should ideally have consistent approaches to determining which greenhouse gases are considered in the accounting for each product.

5.3.2 Regime-level considerations for choice of greenhouse gases

Because different GHGs may be relevant to different modules in a product supply chain, full alignment of GHGs included may not be necessary to support Interoperability. However, Interoperability does require transparency about the GHGs included and sufficiently consistent approaches to determining which are included. Agreement on greenhouse gases which are relevant to a given accounting module is necessary to achieve full Comparability. If the included gases vary across EEFs, conditional Comparability may be achieved by ensuring that emissions for each GHG are separately reported.

5.4 Information layers and multidimensionality

EEFs are a form of information system. As such, the choice of what categories information they generate and convey is an important design consideration. To qualify as an EEF, the

[1] Here we follow White et al. (2024) who note that IPCC and GHG Protocol guidelines and ISO standards all include "Completeness" as a key principle. Like White et al (p. 199), we do not include Completeness as a separate principle because "In our interpretation, Accuracy includes Completeness (described by the IPCC as reporting estimates for all relevant categories of sources and sinks), because incomplete accounting will underestimate true emissions within the specified boundary."

unit value of greenhouse gas emissions (for example in 100-yr carbon equivalent per kg product) associated with some portion of a product supply chain is a required layer of information. Additional layers can include among others: the technologies used in the supply chain, time & date of emissions-relevant activity, and location of emissions-relevant activity.

Some EEFs - such as those underpinning eco-certification schemes - may also carry information about additional dimensions or attributes that are not directly related to embedded emissions. These dimensions could relate to other environmental attributes, such as biodiversity or water use. They may also relate to social attributes such as free prior informed consent (FPIC), or compliance with labour laws.

5.4.1 EEF-level considerations for information layers

The relevant information layers may vary between EEFs for a particular accounting product, or within an EEF for different accounting products. For example, layers associated with indigenous rights, or water use will be relevant information for some products in some locations, but not all.

5.4.2 Regime-level considerations for information layers

Principles-based design and negotiation of information layers requires a similar approach to the definition of accounting boundaries discussed above. To be Comparable and Interoperable regarding a specific information layer, EEFs must agree on the definition of that layer. Similarly, Interoperability does not require that EEFs have all the same layers, and requiring agreement on all layers would violate the principles of Flexibility and LRM. Also similarly to the boundary case, Comparability takes precedence over Flexibility in some cases - requiring agreement on which information layers are necessary. For example, where mutual recognition of a product eco-certification is desired (e.g. “certified low-carbon fuel”), both EEFs will need to cover any required layers of information for the other’s respective scheme. Similarly, if a country is offering subsidies for “green steel” which require proof of adherence to certain labour standards along the full supply chain, Comparability requires all relevant modules for all involved EEFs will need to include this layer of information.

5.5 Temporal and spatial precision

There currently exist a range of understandings about what it means to calculate “embedded emissions”, especially in a trade context. Traditionally, the both academic and grey literature referring to calculation of embedded emissions in trade have been based on environmentally extended input-output tables. These tables have drawn their information predominantly from National Greenhouse Accounts. As such, they usually provide estimates of embedded emissions averaged at the country-year level. This level represents high spatial and temporal aggregation (and correspondingly low precision).

The regulatory objectives driving recent developments in EEFs require embedded emissions calculations at lower levels of aggregation than can be achieved from input-output tables. In the context of EEFs, the required spatial precision is usually the facility level, but it may be lower. For example, a facility may produce both “blue” and “green” hydrogen. In this case, it is appropriate to calculate the embedded emissions separately for each process line within the facility.

Temporally, annual data is also too imprecise to support the regulatory objectives underpinning most EEFs. Ideally, where production occurs in batches, the embedded emissions are calculated for each specific batch. In an agricultural setting, this would mean for a given crop harvested from a given field at a given time. For continuous processes, ideally embedded emissions would be calculated for the specific batch leaving the production gate (e.g. a tanker of gas).

5.5.1 EEF-level considerations for spatial and temporal precision

The appropriate level of temporal and spatial precision for any given module in an EEF represents a trade-off between the principles of Accuracy and Relevance on the one hand, and Non-Discrimination and LRM on the other. The appropriate trade off depends on the requirements of the regulatory purposes, the cost of extra precision, and the capacity of the reporting entity to meet these costs. These costs, in turn, depend on how the EEF is set up. If calculations can be largely automated, high levels of temporal precision need not have high marginal cost for the reporting entities.

Unlike most of the rules discussed here, we do not recommend a strong emphasis on alignment of temporal and spatial precision across products within an EEF. There may be meaningful differences across products in time-scale of production processes, regulatory objectives, and the cost of monitoring and reporting. Particularly when products come from different sectors (e.g. agriculture versus manufacturing), these differences may preclude alignment of temporal and/or spatial resolutions.

While differing resolution across products to does not inherently compromise the principle of Comparability, it does have implications for Interoperability. Where a given product supply chain includes accounting modules with differing resolutions, the resolution of the product-level calculation may need to drop to the lowest resolution of the constituent modules. The extent to which module being at a lower resolution than the rest of the modules in the supply chain affects the overall resolution will depend on the impact it has on the precision of the overall calculation. The resolution of the supply chain overall may be considered unaffected either if the emissions from the low resolution on modules do not vary substantially over the relevant dimension (of space or time) or if the affected modules contribute only a small fraction of the overall embedded emissions.

5.5.2 Regime-level considerations for temporal and spatial resolution

The same arguments as above suggest that the principles of Comparability and Interoperability do not dictate a need for alignment of temporal and spatial precision across EEFs. The principle of Flexibility, however, does have implications for efforts to align spatial resolution across EEFs.

The Flexibility principle suggests that the resolution of all constituent modules should be chosen to meet the minimum resolution requirement of any regulatory purpose they aim to serve, even if that regulation is determined by a different jurisdiction. An example of this approach to achieving Flexibility and Relevance is provided by the Australian Government's Guarantee of Origin (AusGO) Scheme which has been designed to allow it the flexibility to match the temporal and spatial resolution requirements of the EU's Renewable Energy Directive II (Li et al., 2025). Specifically, renewable energy certificates under the AusGO have been designed such that they provide the information that would be needed for hydrogen produced by electrolysis to be certifiable under the Europe's CertifHy scheme.

5.6 Time-scale for global warming impact

The global warming impact of emissions depends on the greenhouse gases involved and the timeframe over which the impact is considered. To facilitate fair comparison, emissions are reported in carbon dioxide equivalents (CO2e). Because different gases behave differently in the atmosphere and have different atmospheric lifetimes, their impact relative to carbon dioxide, and hence their CO2e, depends on the timeframe over which impact is being calculated.

The standard approach for reporting CO2 equivalents is to use the 100-year Global Warming Potential (GWP100). There are, however, growing calls for using other time horizons (for example 20, 500 year) (Lynch et al., 2021; Rypdal et al., 2005; Shine, 2009), or even for the simultaneous use of multiple metrics (both 20 and 100 years) to explicitly highlight the differing climate impacts associated with each time scale (Ocko et al., 2017). A twenty-year horizon is considered particularly appropriate for methane and is hence relevant for products for which methane comprises a substantial component of emissions.

5.6.1 EEF-level considerations for time-scale of global warming impact

The principle of Flexibility suggests that the chosen timescale (20- or 100-year) should vary in line with the emissions profile of the module or product. The principles of Comparability and Interoperability, however, demand that different modules and products be compared on the same basis. One approach which resolves the tension between these two principles is to report both timescales. This approach should not substantively increase costs for reporting entities as it does not change add to information gathering requirements. Rather, it involves rerunning calculations on the same information using a different GWP value. As such, the dual reporting approach does not conflict with the LRM principle.

5.6.2 Regime-level considerations for time-scale of global warming impact

Regime-level considerations for timescale of global warming impact closely mirror those for EEF level. Negotiators should therefore encourage EEFs to adopt a dual reporting approach encompassing both 20-year and 100-year scales.

6 Framework Rules

Framework Rules are specific rules and approaches which apply across a given EEF, such as the approach to allocation of emissions among products, or determination of global warming potential of greenhouse gases.

6.1 Emissions allocation rules

Product embedded emissions accounting entails some complications which are not encountered in traditional place-based (e.g. establishment-level) emissions accounting. Primary among these complications is the allocation of emissions across process outputs. For example, sheep husbandry may have outputs of wool and lamb meat. Wheat crops may produce grain and stubble. Steam methane reforming may produce hydrogen and heat. Emissions allocation rules specify which portion of emissions from which processes should be attributed to each output.

6.1.1 EEF-level considerations for allocation rules

Best-practice EEF design involves the specification of a consistent approach to emissions allocation across all products in the framework. This approach can be contrasted with the alternative of specifying ad hoc rules for each product. A consistent approach avoids potential violation of the principle of Comparability (across products within a given EEF). A consistent approach can, however, be challenging given differing norms across sectors – many of which arise from fundamental differences in trade-offs inherent in different allocation rules.

Given that there is no perfect allocation rule, it is widely agreed that the best approach is to avoid allocation as far as possible. This approach, called subdivision, entails drawing the boundaries of accounting modules as far as possible around individual processes, allowing more careful specification of which processes relate to which outputs. For example, in an integrated steel plant, intermediate products like coke, sinter, and pellets are produced before final steelmaking. Subdivision is most easily applied to such intermediate products, as their production processes are clearly defined (Wright et al., 2023). This is another benefit of a modular approach to accounting boundaries.

Coke production illustrates this well. It includes distinct steps: coal pre-treatment, charging, coking, quenching, and handling, representing a separate and well-bounded process within the plant. Because these boundaries are discrete, emissions and energy use can be directly attributed to coke, avoiding allocation across the wider steelmaking system. This makes emissions accounting more accurate and transparent. This is another benefit of a modular approach to accounting boundaries

For many processes, however, allocation is unavoidable. For this reason, some EEFs take a hybrid approach of specifying general allocation hierarchy - beginning with splitting to avoid allocation where possible - but also including ad hoc rules for certain products. The Pathfinder Framework provides an example of this hybrid approach in Figure 12.

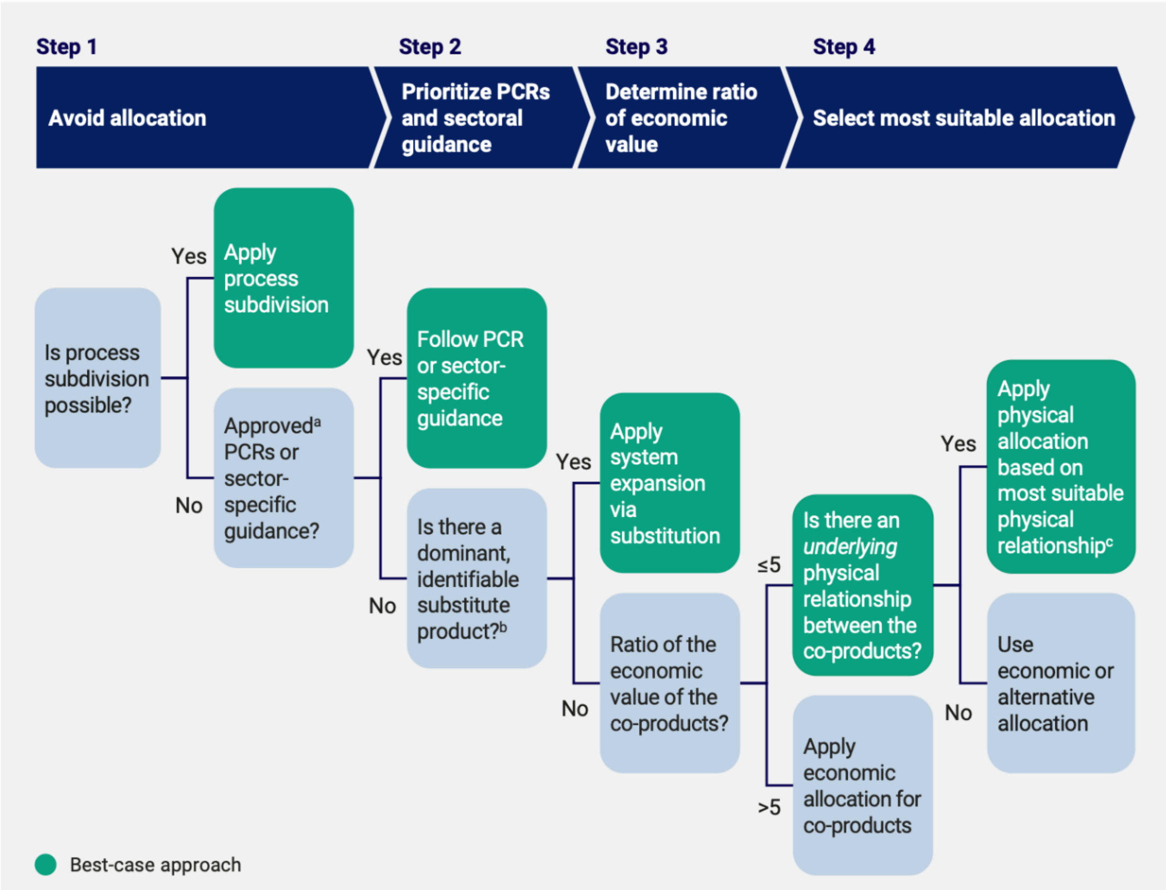

Figure 12: Pathfinder Framework decision-making tree for emissions allocation rules (WBCSD, 2023)

In Figure 13, we provide an example of the co-production of wool and meat and how to find the appropriate allocation rule.

Example: An Australian dual-purpose farm produces two products: wool and lamb meat. Because the co-production of wool and meat is complex, the system cannot be subdivided. Let's assume the following: the protein content of greasy wool is 60% and of meat is 20%; the economic value of greasy wool is $7 per kg and the economic value of meat is $2 per kg; the total GHG emissions from the sheep is 100 kgCO2e; and one sheep produces 3 kg of greasy wool and 5 kg of meat.

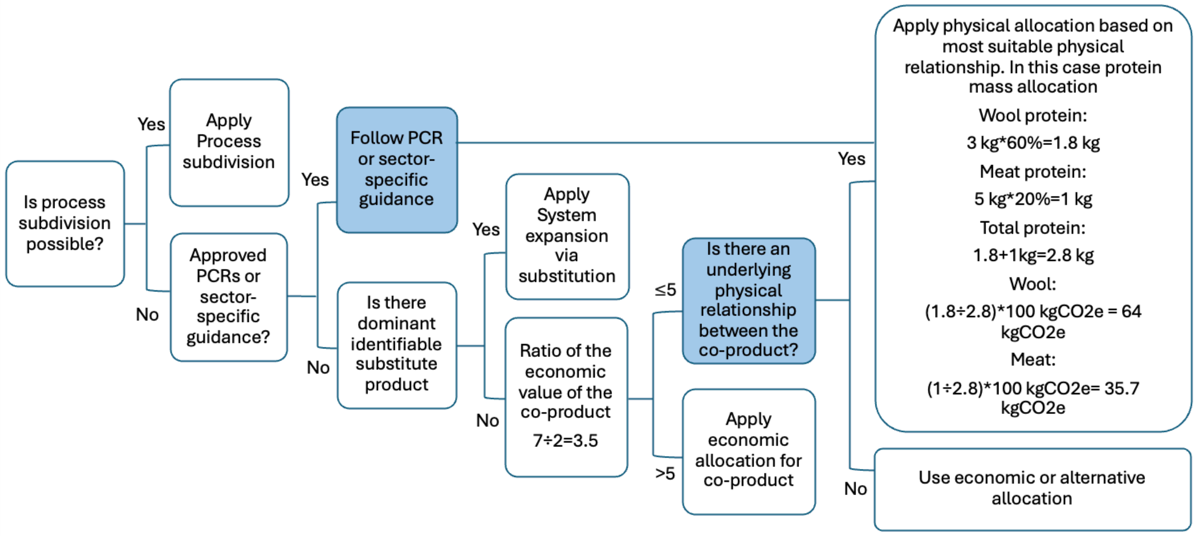

Figure 13: Example a of physical allocation based on protein mass for wool and lamb meat

Australia's sector specific guidance recommends protein mass allocation for wool and meat (Sevenster et al., 2023 with reference to Wiedemann et al., 2015). But, even without this sector specific guidance, the decision tree would have required us to use the physical allocation rule, which would have led us to the same results. These decision nodes are highlighted in blue.

6.1.2 Regime-level consideration for emissions allocation rules

Alignment of emissions allocation rules is essential for Interoperability and Comparability of EEFs. This is because the choice of allocation rule significantly affects the emissions embedded in each co-product (Sunar & Plambeck, 2016; Wardenaar et al., 2012; Wiedemann et al., 2015). Let's consider a simplified example of a co-production system with the following assumptions: a steel mill produces two products: crude steel and blast furnace slag at a ten-to-three ratio; the unit price of crude steel is $600 per tonne and the mass is 10 tonnes; the unit price of slag is $20 per tonne and the mass is 3 tonne; the embedded emissions of a substitute product for slag is 500 tonnes of CO2 per tonne of that product; and a total of 1000 tCO2e need to be allocated. Table 3 shows how different allocation rules result in different emission allocated to crude steel.

Table 3: Emissions embedded in crude steel under different allocation methods

Allocation rule	Rule description	Emissions embedded in crude steel (tCO2e)
Physical allocation	embedded emissions in proportion to the mass ratio	$1000 \times \frac{10}{10+3} = 769$
Economic allocation	embedded emissions in proportion to the revenue ratio	$1000 \times \frac{(600 \times 10)}{(600 \times 10 + 20 \times 3)} = 990$
Other relationships	subtracts the substitute embedded emissions for slag from the supplier's emissions intensity	$1000 - 500 = 500$

Source: adopted from Sunar (2016)

Regime designers should encourage consistent, best-practice approaches to EEF-wide allocation rules as described here. Negotiators also need to ensure consistency in the application of these rules for specific products for which Interoperability and Comparability are paramount. This includes agreement on ad hoc allocation rules for certain products where necessary. Lack of agreement on these points would seriously compromise the principles of Accuracy, Completeness and Monotonicity for any emissions calculation derived from a combination of the two "interoperable" EEFs.

6.1.3 Accounting Products, Co-products and Wastes

Emissions allocation rules in EEFs are often written in terms of Accounting Products, Co-products and Wastes. "Accounting products" of an EEF are those whose embedded emissions it is designed to report. "Co-products" are products which do not constitute an accounting product in their own right, but for which the EEF allows some emissions to be allocated. "Wastes" are outputs or results of activities for which the EEF does not allow emissions to be allocated.

To support Interoperability and Comparability, agreement between EEFs about definitions of accounting products, co-products, and wastes is not strictly necessary in its own right. For example, one EEF might label wheat stubble a waste, while another labels it a co-product. The key for Interoperability and Comparability is agreement about the emissions allocation as described above. However, semantic interoperability in the form of agreement on the definition of Accounting Products, Co-products and Wastes may be helpful insofar as the allocation rules for each EEF are specified with reference to these concepts.

6.2 Carbon capture

Carbon capture is an increasingly important element of low carbon products. This means that, although challenging, EEFs will need to be clear about how they treat captured carbon. Part of the complexity arises because carbon capture can take many forms, with very different emissions accounting implications. Key dimensions and alternatives for carbon capture are summarised in Table 4: Carbon capture varieties.

Table 4: Carbon capture varieties

Dimension	Options	Examples
Source	Industrial	Power plant emissions
	Atmospheric	Tree growth
Process	Natural/biological	Crop growth
	Manmade/chemical/physical	Direct air capture
End use	Storage	Geological storage
	Direct utilization (incorporation in product)	Low-carbon cement
	Indirect utilization	Enhanced oil recovery
Duration	Geological scale	Geological storage
	Moderate	Wood
	Short term	eFuels
Physical link to accounting product	Inseparable	Plantation tree growth where wood is the accounting product
	Moderately separable	On-farm tree growth where beef is the accounting product.
	Fully separable	Tree growth where air travel is the accounting product.
Legal/economic link to accounting product	Same establishment	On-site tree planting
	Trade or purchase	Third-party tree planting (Offsets)

6.2.1 EEF-level considerations for carbon capture rules

EEFs must have a consistent approach to the treatment of carbon capture across accounting products. They should also ensure logical consistency in their rules to ensure perverse incentives are not created. For example, major carbon footprint certification schemes (such as GHG Protocol, ISO 14067, PAS 2011, PEF) do not allow offsets to be counted against the product. The EU (2023), meanwhile, has officially banned using offsets to count against product emissions but are not clear on how to account for emissions sequestered on farms (e.g. through tree planting). Offsets are carbon reductions or removals that occur in locations other than the source of emissions. Therefore, carbon sequestered directly on a farm does not technically qualify as an offset. However, counting on-farm carbon sequestration against farm product emissions creates inconsistencies when comparing across different sectors. For instance, a steel plant might argue that trees planted around its facility should also be allowed to offset its product emissions. If permitted, this could incentivize polluting industries to set up or expand operations in areas with high potential for biological carbon sequestration.

6.2.2 Regime-level considerations for carbon capture rules

Unsurprisingly, the variety of forms of carbon capture that arise from different combinations of the dimensions in Table 4 has created a confusing and inconsistent array of terminology in literature and practice (Olfe-Kräutlein et al., 2022; Tanzer & Ramírez, 2019). This array poses substantial challenges for semantic interoperability between EEFs. Lack of clear agreement between EEFs on this point also has substantial potential to create emissions loopholes and greenwashing opportunities. Semantic interoperability regarding carbon capture should be a priority for negotiators so that any inconsistencies in practice are transparent and can be resolved.

6.3 Counter-factuals and additionality

Debates about counter-factuals, baselines, and additionality have been central to carbon accounting for the last quarter century. These concepts have been a focal point for two reasons. Firstly, national commitments in international climate agreements have been couched in terms of pledges about emissions reductions. This framing has had flow-on effects to policy thinking and analysis, where policy effectiveness was primarily measured in terms of improvements relative to business as usual. Especially for dynamic systems such as biological systems, baselines have been essential to help establish the counter-factual of what would have been "but for" the policy intervention or abatement effort. The second reason counter-factuals, baselines and additionality have had so much attention is that they are notoriously controversial and difficult to satisfactorily establish.

6.3.1 EEF-level considerations regarding counter-factuals and additionality

Embedded emissions accounting provides an opportunity to do away with counter-factual based accounting and its corresponding uncertainties. Avoiding the use of these concepts can help EEFs align with the principle of Accuracy. This shift away from counter-factual based accounting is in line with the emphasis in international climate mitigation efforts now shifting towards commitments in absolute terms – most commonly net zero by mid-century. Furthermore, when purchasing a product, concerned consumers do not care how much less emissions it produced relative to the historical norm in its country of production, they only care about how many emissions were released to the atmosphere as a direct result of its production.

In practice, most EEFs for industrial products currently eschew reference to counter-factuals and additionality. As discussed in section **Error! Reference source not found.**, leading EEFs are excluding the use of offsets. Since offsets frequently are generated through consideration of counter-factuals and additionality, this exclusion represents an acknowledgement of the danger they pose to the principle of Accuracy. It also represents acknowledgement that allowing counter-factual and additionality-based accounting reduces trustworthiness and perceived integrity of EEFs.

Baselines and additionality become harder concepts to avoid when production processes are part of systems which are open from the perspective of the production facility. The two main types of open system of relevance to EEFs are electricity networks and biological/earth systems. For example, additionality considerations remain difficult to avoid when accounting for emissions embedded in electricity. Similarly, baselines and counterfactuals are concepts that are difficult to entirely avoid in accounting for most agricultural and forestry products. To avoid compromising the integrity of EEFs, where baselines, additionality and counter-factual are unavoidable, it is essential to adopt leading-edge approaches to these issues.

6.3.2 Regime-level considerations regarding counter-factuals and additionality

Counterfactuals and additionality rules can have substantial implications for product embedded emissions calculations. It is important that negotiators and regime designers seek to minimize reliance on these concepts. Where they are unavoidable, as in the case of electricity and some agricultural products, agreement on both semantics and substantive rules should be sought in order to support Interoperability and Comparability.

6.4 Methods and Default Values

Methods include formulas, measurement techniques, and default values that are used to measure, calculate or estimate embedded emissions for a given accounting module.

Emissions accounting methods can be categorised according to their temporal or spatial resolution using the tier system developed by the UNFCCC. Tier 1 methodologies are simply default values that represent global averages. Tier 2 methodologies are country or region-specific default values. Tier 3 methodologies are formulas for a given process into which known values from a particular site at a particular time are entered. “Tier 4” is often used to describe direct measurement of emissions.

6.4.1 EEF-level considerations on choice of methods

As discussed in Section **Error! Reference source not found.**, regulations often require embedded emissions information with high levels of temporal and spatial resolution. For example, Condon & Ignaciuk (2013) has argued that to be compatible with WTO Law, CBAM calculations should be based on batch-specific data. The Relevance principle therefore suggests Tier 3 and 4 methodologies should dominate in EEFs. However, the choice of Tier has substantial impacts on the costs faced by reporting entities. Consequentially, where Tier 1 or 2 methodologies are sufficient for the regulatory purpose, their use may be justified by the principles of LRM and Non-discrimination.

6.4.2 Regime-level considerations on choice of methods

Different EEFs may use different methods for the same module for two main reasons. Firstly, because the appropriate Tier varies due to differences in regulatory purposes and/or ability to meet compliance costs. Secondly, for idiosyncratic reasons.

In light with the discussion in Section **Error! Reference source not found.**, the degree of alignment on Tiers represents a trade-off between the principles of Accuracy, Comparability & Interoperability on the one hand, and Non-discrimination and LRM on the other. Alignment of methodologies within a given Tier represents less of a trade-off.

There are few arguments against aligning Tier 3/4 methodologies. For a given module, efforts should be made to identify and agree on the best Tier 3 or 4 methodology – in terms of cost and accuracy across a wide range of settings where that module is found. This is highly technical work. Thankfully, much of this work has already been done via the program of development of UNFCCC Emissions Accounting Guidelines. Many of the methodologies developed as part of these guidelines can be readily translated into module boundaries (Reeve & Aisbett, 2022). Where possible, efforts should be made to align EEF methodologies with these established guidelines.

Tier 1 & 2 methods (i.e. default values) should be consistent with each other and with latest science. Although Tier 2 defaults will vary by location of production (and hence EEF), the reasons for this variation should be based on actual differences between locations, and not on methods used to establish default values.

6.5 Global Warming Potential factors

Carbon accounting involves processes that convert emissions from gases other than carbon dioxide into carbon dioxide equivalents (CO2e). This allows for the total impact of all gases to be assessed, despite their varying atmospheric lifespans and effects on solar forcing. This is done using Global Warming Potential (GWP) factors. For products whose supply chains emit substantial amounts of methane or other greenhouse gases than carbon dioxide, the choice of GWP can have substantial impacts on embedded emissions estimates.

The International Panel on Climate Change (IPCC) estimates GWPs for all climate-relevant greenhouse gases. IPCC processes mean these GWPs represent the best compromise between leading experts from around the world. Although the IPCC regularly updates GWPs, with the most recent revisions published in 2019, there is frequently a delay between the publication of these updates and their adoption by individual countries and practical accounting tools. This lag can affect the consistency and accuracy of emissions reporting and carbon accounting practices across different jurisdictions. For example, Reeve & Aisbett (2022) found significant variation in the pace at which countries adopt updated IPCC GWP factors, with some continuing to use outdated values. Their analysis indicated that reliance on outdated GWPs can result in persistent underestimation of embedded emissions, particularly leading to substantial discrepancies in methane emissions, potentially as high as 25%.

6.5.1 EEF-level consideration for GWPs

In the interests of Accuracy, EEFs should calculate CO2 equivalent embedded emissions based on the latest Global Warming Potentials (GWPs) advised by IPCC. Regular updating of GWPs does not lead to comparability issues for EEFs because – unlike National Greenhouse Accounts – their purpose is not to show progress over time. Rather, the purpose of EEFs is to provide the best possible comparison between products at a given time. Furthermore, since the choice of GWP has no implications for regulatory burden on reporting entities, there is no argument against regular updating based on the principle of LRM.

6.5.2 Regime-level considerations for GWPs

Alignment of GWPs is essential to support Non-discrimination, Comparability and Interoperability. Failing to do so, and using different GWPs, may encourage firms to relocate processes to countries with lower GWP factors, undermining efforts to prevent emissions leakage that trade-related climate policies aim to address (Reeve & Aisbett, 2022). Furthermore, as above, the principle of and LRM is not a consideration for choice of GWPs.

7 Conclusion

Embedded emissions accounting frameworks are emerging as a key component of the climate regime. Aimed at solving information failures, they underpin a variety of policies essential to successful scale-up of climate mitigation action. Their current proliferation is testimony to their importance, and together these frameworks can be considered to constitute an emerging global governance regime.

The environmental and economic objectives of the emerging EEF regime will only be met if it is high-performing. Poor and uncoordinated design choices will lead to confusion, greenwashing, excess regulatory burden and non-tariff barriers to trade. This paper has sought to provide a structured and principles-based approach to develop design recommendations for an efficient and effective global EEF regime.

The top-down design approach of the paper reflects its global, regime-level objectives and perspective. Beginning with the regulatory objectives of efficiency and effectiveness, we sequentially identify recommendations for design elements ranging from: Overarching Principles, through Supporting Principles, to Framework Structure and Framework Rules. Our recommendations identify which elements are important for designers of individual EEFs and for negotiators of alignment between EEFs. They also explain the benefits of certain choices about these design elements from both EEF and regime-level considerations.

As the regime develops, there will no doubt be important learnings about not only the design elements discussed here, but also others whose centrality we have failed to discern. We hope that the research and practitioner communities work together to develop and share these learnings. For now, we hope that this paper provides a useful starting point for collaborative efforts towards creating a high-performance EEF regime.

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Appendix

Table A1a: EEF-level considerations for Framework Structure design elements

	Design choice	Need for consistency across products within an EEF	Brief Description and link to Principles and Objectives	Prioritisation Status for Designers of EEFs
Framework structure	**Accounting Boundaries (Module Definitions)**	**Yes**	Boundary definitions of the individual modules that make up the accounting boundary is broadly important to support principles like Interoperability and Comparability. For individual EEFs to effectively participate in a regime or enable comparison, their constituent module definitions should align with those used elsewhere.	**High Priority (Necessary Alignment, Initial Focus)**
	Accounting Boundaries (Overall Supply Chain)	No	Consistency of overall boundaries (which modules are included) across all products within a single EEF is not strictly required for Interoperability. Flexibility suggests that an EEF should be able to accommodate different overall boundaries for different product types rather than requiring a single, consistent accounting boundary definition for all.	Low Priority (Prioritize Flexibility)
	Covered products and production pathways	No	Design choices should prioritize Flexibility and compatibility with different product types and sectors (e.g., agriculture vs. manufacturing) for potential future inclusion, rather than requiring initial consistency in which products or pathways are covered across the entire EEF.	Low Priority (Prioritize Flexibility)
	Information layers and multidimensionality	No	The relevant information layers may vary within an EEF for different accounting products. For example, layers related to indigenous rights or water use might only be relevant for certain products or locations, not all products within the EEF.	Low Priority (Not dictated by Comparability & Interoperability)
	Temporal and spatial precision	No	We do not recommend a strong emphasis on alignment of temporal and spatial precision across products within an EEF. This is due to potential meaningful differences in production processes, regulatory objectives, and monitoring/reporting costs across different products, particularly from different sectors.	Low Priority (Not dictated by Comparability & Interoperability)
	Choice of GHGs	No	The Accuracy principle requires that all relevant GHGs be included. The relevant information layers, including the specific greenhouse gases covered, may vary for different accounting products or within a particular EEF based on their relevance. There is no strict requirement for consistency in the information layers, and therefore the specific gases covered, across all products within a single EEF.	**Medium Priority (Develop consistent approach to determining "relevant" GHGs for each module/product)**
	Time-scale of global warming impact	**Yes**	To resolve the tension between Flexibility and Comparability/Interoperability, a dual reporting approach (both 20-year and 100-year scales) is recommended for all relevant modules and products within the EEF. This ensures a consistent method of reporting timescales, allowing comparison on a like-for-like basis for both time horizons, rather than requiring consistency in using only one single timescale. This also aligns with the LRM principle as it reuses existing data.	**Medium Priority (Encourage Dual Reporting Approach)**

Table A1b: EEF-level considerations for Framework Rule design elements

	Design choice	Need for consistency across products within an EEF	Brief Description and link to Principles and Objectives	Prioritisation Status for Designers of EEFs
Framework rules	**Emissions allocation rules**	**Yes**	Best-practice EEF design involves the specification of a consistent approach to emissions allocation across all products. This is necessary to avoid potential violation of the principle of Comparability across products within the EEF. Avoiding allocation as far as possible through subdivision is considered the best approach.	**High Priority (Essential Alignment)**
	Accounting Products, Co-products, Wastes	No, but helpful for allocation rules	Within an EEF, while semantic interoperability in definitions may be helpful if allocation rules reference these concepts, the key requirement is agreement about the emissions allocation itself, which must be consistent.	**Low Priority (Helpful but not essential)**
	Carbon capture rules	**Yes**	EEFs must have a consistent approach to the treatment of carbon capture across accounting products. Consistency in rules should also be ensured to avoid creating perverse incentives.	**High Priority (Priority for consistency in rules)**
	Counter-factuals and additionality	No	Embedded emissions accounting provides an opportunity to do away with these concepts to improve Accuracy. Most EEFs for industrial products eschew reference to them. They are harder to avoid for open systems like electricity networks and biological systems. The focus is on minimizing reliance and adopting leading-edge approaches where unavoidable. Consistency in whether these are used is not mandated across all product types if some inherently require them while others do not.	Low Priority (Minimize reliance)
	Methods and default Values (Tiers)	No	The choice of Tier (1-4) can vary within an EEF based on regulatory purpose, compliance costs, and the specific module. Consistency of the Tier level across all products or modules is not strictly required. However, for a given module, efforts should be made to identify and agree on the best Tier 3 or 4 methodology. Tier 1 & 2 default values should be consistent with each other and the latest science.	Low Priority (Not dictated by Comparability & Interoperability)
	Global Warming Potential (GWP) Factors	**Yes**	In the interests of Accuracy, EEFs should calculate CO2 equivalent emissions based on the latest GWPs advised by IPCC. This implies that within a single EEF, the same, latest GWPs should be applied consistently to all relevant emissions across all products.	**High Priority (Essential Alignment)**

Table A2a: Regime-level considerations for Framework Structure design elements

	Design Choice	Need for Consistency Across EEFs	Brief Description and link to Principles and Objectives	Prioritisation Status for Negotiators/Designers of EEFs
Framework structure	**Accounting Boundaries (Module Definitions)**	**Yes**	To support Interoperability, Flexibility, and Comparability at the regime level, it is necessary for the boundary definitions of the modules to align across EEFs.	**High Priority (Necessary Alignment, Initial Focus on key product supply chains)**
	Accounting Boundaries (Overall Supply Chain)	**Yes, in certain situations for Comparability**	Agreement on the overall supply chain boundary (which modules are included) is not necessary for Interoperability. However, Comparability does require aligning overall supply chain boundaries across EEFs in specific cases: when calculating a carbon border adjustment (must cover modules specified by the importer) or if mutual recognition of product-level values is desired (the modules included must be the same).	**Conditional Priority (Required for specific Comparability/Recognition goals, not for Interoperability alone)**
	Covered products and production pathways	No	EEFs do not have to cover the same specific set of products and production pathways for Interoperability or Comparability. The focus is on designing EEFs to be compatible with diverse product types for future inclusion, rather than requiring initial identical coverage across all EEFs.	Low Priority (Not dictated by Comparability & Interoperability)
	Information layers and multidimensionality	**Yes, for specific layers/sets of layers in some cases**	To be Comparable and Interoperable regarding a specific information layer, EEFs must agree on the definition of that layer. For Comparability in some cases, agreement is also required on which information layers are necessary, such as layers required for mutual recognition of an eco-certification or layers needed for a subsidy scheme. However, Interoperability does not require EEFs to have all the same layers.	**Conditional Priority (Agreement required for specific Comparability/Recognition goals)**
	Temporal and spatial precision	No	The principles of Comparability and Interoperability do not dictate a need for alignment of temporal and spatial precision across EEFs. This is because meaningful differences across products and sectors may preclude such alignment.	Low Priority (Not dictated by Comparability & Interoperability)
	Time-scale of global warming impact	**Yes, consistent reporting approach recommended (dual reporting)**	To enable comparison of different modules and products across EEFs on the same basis for Comparability and Interoperability, negotiators should encourage EEFs to adopt a dual reporting approach encompassing both 20-year and 100-year scales. This provides a consistent method of reporting timescales across EEFs, allowing like-for-like comparison for both time horizons.	**Medium Priority (Encourage Dual Reporting Approach)**
	Choice of GHGs	**Yes**	To ensure Comparability, EEFs must agree on the definition of that specific information layer, which includes the gases considered.	**High Priority (Essential Alignment on relevant gases for specific product types)**

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Table A2b: Regime-level considerations for Framework Rules design elements.

	Design Choice	Need for Consistency Across EEFs	Brief Description and link to Principles and Objectives	Prioritisation Status for Negotiators/Designers of EEFs
Framework rules	**Emissions Allocation Rules**	**Yes**	Alignment of emissions allocation rules is essential for Interoperability and Comparability of EEFs. Negotiators need to ensure consistency in the application of these rules for specific products where Interoperability and Comparability are paramount. Lack of agreement on these rules would seriously compromise the principles of Accuracy, Completeness, and Monotonicity for any emissions calculation derived from a combination of two EEFs.	**High Priority (Essential Alignment)**
	Accounting Products, Co-products, Wastes	Not strictly necessary for definitions, but semantic interoperability can be helpful.	Agreement between EEFs about definitions of accounting products, co-products, and wastes is not strictly necessary in its own right to support Interoperability and Comparability. However, semantic interoperability in definitions may be helpful insofar as the allocation rules for each EEF are specified with reference to these concepts.	Low Priority (Helpful but not essential)
	Carbon Capture Rules	**Yes, semantic interoperability should be a priority.**	Lack of clear agreement between EEFs on how carbon capture is treated has substantial potential to create emissions loopholes and greenwashing opportunities. Semantic interoperability regarding carbon capture should be a priority for negotiators so that any inconsistencies in practice are transparent and can be resolved.	**High Priority (Priority for Semantic Interoperability)**
	Counter-factuals and Additionality	**Yes, where unavoidable (e.g., agriculture/forestry).**	Embedded emissions accounting provides an opportunity to avoid these concepts to improve Accuracy. Negotiators/designers should seek to minimize reliance on these concepts as embedded emissions accounting can avoid them for Accuracy. Where unavoidable (e.g., electricity, some agriculture/forestry), agreement on both semantics and substantive rules should be sought for Interoperability and Comparability.	**High Priority (Minimize reliance, seek agreement where unavoidable)**
	Methods and Default Values (Tiers)	No, not strict consistency on Tier level; **Yes, for methodologies within Tiers and basis for defaults.**	Different EEFs may use different method Tiers (1-4) for the same module due to differences in regulatory purposes or ability to meet compliance costs. Alignment of the Tier level across EEFs represents a trade-off between Accuracy, Comparability & Interoperability and Non-discrimination & LRM. Alignment of methodologies within a given Tier represents less of a trade-off. For a given module, efforts should be made to identify and agree on the best Tier 3 or 4 methodology. Tier 1 & 2 default values should be consistent with each other and latest science.	**Medium/High Priority (Seek agreement on best methodology, Ensure consistency)**
	Global Warming Potential (GWP) Factors	**Yes**	Alignment of GWPs is essential to support Non-discrimination, Comparability and Interoperability. Using different GWPs may encourage firms to relocate processes to countries with lower GWP factors, undermining efforts to prevent emissions leakage that trade-related climate policies aim to address. The principle of LRM is not a consideration for choice of GWPs.	**High Priority (Essential Alignment)**