Designing for Comparability: a foundational principle of analysis missing in carbon reporting systems.

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Designing for comparability: A foundational principle of analysis missing in carbon reporting systems

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Abstract

Market participants require comparability to make decisions, and policies aimed at using market mechanisms to address climate change rely on this ability. However, this paper shows that the commonly used greenhouse gas (GHG) emission metrics are suitable for trend analysis, continuous improvement, and target setting, but not fit-for-purpose in making comparative assertions between multiple entities. Therefore, relying on contemporary GHG emission metrics could limit policymaker's efficacy in using market forces to make climate change interventions. We identify that the problem arises in the merger of two incompatible metric systems – life cycle assessment and financial reporting. We propose three necessary conditions when combining metric systems which preserves the ability to make comparative assertions, which were developed from research on comparability across the accounting, engineering, and social science fields. As the scientific community continues to develop additional metric systems for biodiversity, nature, water, land use, and other environmental indicators, policy makers, regulators, and standard setters can use these necessary conditions to ensure that new non-financial metric systems are fit-for-purpose for decision-making in the financial sector.

Keywords: Carbon accounting, GHG Protocol, comparability, classification systems, life cycle assessment, Scope 1, 2, and 3, emissions

Executive Summary

This working paper explores the fundamental question: can greenhouse gas (GHG) emissions be used to compare corporate entities? If not, why not, and how can comparability be improved?

Market participants require comparability to make decisions, and policies aimed at using market mechanisms to address climate change rely on this ability. Comparability, considered by some financial researchers as the principal reason for the development of accounting standards, is the ability to tell apart similarities and differences between items.

This paper shows that the commonly used GHG emission metrics, largely relying on the GHG Protocol; while suitable for target setting; are not fit-for-purpose in making comparative assertions between multiple entities. Relying on contemporary GHG emission metrics could limit decision-makers' efficacy in using market forces in climate change interventions and risks the potential misallocation of trillions of dollars of capital.

The problem occurs due to differences between the underlying measurement systems – lifecycle assessment (LCA)-based methodologies to model the GHG Inventory (GHGI) and double-entry bookkeeping-based systems that underly financial reporting. GHG emission metrics can seem comparable on the surface, but upon closer scrutiny, fail to be comparable.

Comparability can be understood through the following analogy. If one asked, "Who was the best athlete at the Rio Olympics?" the default choice would be to compare who won the most gold medals. However, Michael Phelps competed in six events and won six medals while Alexander Lesun, a pentathlete, participated in five events (pistol, swimming, fencing, equestrian and cross country), yet was only awarded a single gold medal for his efforts. The medal count of the two athletes is therefore not comparable. More granular and accurate data, such as that Phelps swam the 200-meter butterfly in 1 minute 53.36 seconds, and that Lesun scored 268 points in fencing, does not improve comparability.

GHG inventories are reported using the Greenhouse Gas Protocol (GHGP) system of Scope 1, 2, and 3. Our study finds that GHGI lacks adherence to three necessary conditions of comparability from three fields of research:

- Accounting researchers use the 'similarity and difference facet' to tell whether a difference is due to an operational decision or a methodological choice. We find that Scope 1, 2, or 3 permits similar items to be reported differently and different items to be reported similarly.
- Engineering researchers, through dimensional analysis, state that only derived units that describe the same phenomenon can be compared. We find that the unit *metric tonnes of carbon dioxide equivalent* (MTCO2e) is not a derived unit, and not usable to make comparisons.

- Social scientists, who study categorisation as a form of information architecture, require metric systems to be a classification system, rather than a nomenclature, to make comparative assertions. We find that the GHGI categories is a nomenclature.

We propose a set of conditions necessary for a metric system to enable comparative assertions, as shown in Table ES.1.

Table ES.1 Necessary conditions for a metric system to enable comparative assertions

Condition 1: Similar items need to be reported similarly and different items need to be reported differently. **Analysis technique:** Similarity and difference facet	**Issue for GHGI:** Within the GHGI, it is not possible to tell whether a difference is due to an operational change or an accounting choice.	**Solution:** Separate out the accounting of activity data, which represent operational decisions, with emission factors, which are accounting choices.
Condition 2: Only derived units that represent the same phenomenon have additive and comparative properties. **Analysis technique:** Dimensional analysis	**Issue for GHGI:** The unit MTCO2e is not a derived unit and each category of Scope 1, 2, and 3 represent different phenomena.	**Solution:** Use only combustion emission factors, which maintain the requirement for being a derived unit. The use of LCA- and EEIO-based emission factors do not.
Condition 3: Only categories that belong to a classification system can be used to make comparative assertions. **Analysis technique:** Category Theory	**Issue for GHGI:** By definition, nomenclatures do not give the ability to compare. The GHGI system is a nomenclature because it does not follow the rules for a classification system.	**Solution**: Use an accrual-based system that has a spatio-temporal relationship between the categories.

Furthermore, our study found that Scope 1, 2, and 3, as models of emissions rather than measurements, have embedded assumptions within them that may not be readily apparent. One embedded assumption is that emission factors carry specific boundary conditions. Therefore, standardising the activity data boundary while enabling a free choice on emissions factors does not standardise the overall metric’s boundary. A second assumption is its treatment of time. GHGI is a flow-based accounting system, where all activities are ‘expensed’ in the time-period it occurred. This is incompatible to financial reporting which use an accrual-based system where some activities are capitalized, and others are expensed.

There are already dozens of quantitative measures used within ESG reporting taken from many different disciplines that can be vetted for comparability using our conditions. Further, the scientific community continues to develop additional metric systems for biodiversity, nature, water, land use, among other environmental indicators. Policy makers, regulators, and standard setters can use these necessary conditions to ensure that new non-financial metric systems are fit-for-purpose for decision making in the financial sector.

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List of acronyms and abbreviations

AD	Activity data
CDP	Climate Disclosure Project
CDSB	Climate Disclosure Standards Board
COGS	Costs of goods sold
DA	Dimensional analysis
DEBK	Double-entry bookkeeping
EEIO	Environmentally extended input-output
EF	Emission factor
ESG	Environment, social, and governance
EU ETS	European Union Emissions Trading System
GHG	Greenhouse gas
GHGI	Greenhouse gas inventory
GHGP	Greenhouse gas Protocol
GWP	Global warming potential
IAS	International Accounting Standards
IASB	International Accounting Standards Board
IFRS	International Financial Reporting Standards
IO	Input-output
IOSCO	International Organization of Securities Commissions
IPCC	Intergovernmental Panel on Climate Change
IR	Integrated Reporting
ISO	International Standards Organisation
ISO/TR	International Standards Organisation / Technical Report
ISSB	International Sustainability Standards Board
kWh	Kilowatt-hour
LCA	Life cycle assessment
LCI	Life cycle inventory
MFF	Mainstream financial filings
MTCO2e	Metric tonnes of CO_2 equivalent
MWh	Megawatt-hour
O-LCA	Organisational life cycle assessment
P&L	Profit and loss
PCAF	Partnership for Carbon Accounting Financials
SASB	Sustainable Accounting Standards Board
SETAC	Society of Environmental Toxicology and Chemistry

SI	The International System of Units
T&D	Transmission and distribution
TCFD	Task Force for Climate-Related Financial Disclosures
U.K BEIS	U.K. Department for Business, Energy & Industrial Strategy
U.S. EPA	U.S. Environment Protection Agency
U.S. SEC	U.S. Securities and Exchange Commission
VRF	Value Reporting Foundation
WBCSD	World Business Council for Sustainable Development
WEF	World Economic Forum
WRI	World Resources Institute

1. Introduction: Why comparability is important, yet lacking in GHG accounting

This working paper explores the fundamental question: can GHG emissions be used to compare corporate entities? If not, why not, and how can comparability be improved? This paper demonstrates that, based on current GHG accounting methods, entities cannot be compared by their GHG emissions and that existing approaches to fixing the problem are not sufficient.

The ability to consistently measure GHG emissions and compare across firms is the foundation for climate action by the financial sector, as well as more broadly. GHG inventories (GHGI) are now the core metric feeding into risk assessments, disclosure, capital allocation, transition plans and financial instrument design. Investors are routinely utilizing GHG emissions data to compare, rate, and benchmark companies for climate-related index funds (FTSE, 2018), making capital allocation decisions (Andrew & Cortese, 2011), determining credit risk (Moody's, 2019, 2021) and creating thematic investment vehicles (PRI, 2016). The amount of capital whose decisions depends on climate-related data is huge. The Glasgow Financial Alliance for Net Zero (GFANZ), representing over $130 trillion in assets, have committed to support for the goals of the Paris Agreement (GFANZ, 2022). These financial decisions, amongst many others, require comparisons between companies. If such comparisons do not meaningfully reflect real world impacts, then the ratings, indices, and investment vehicles may also be invalid. The result could be trillions of dollars of capital potentially misallocated (Chatterji et al., 2016).

GHG inventories are reported using the Greenhouse Gas Protocol (GHGP) system of Scope 1, 2, and 3. Briefly, Scope 1 are direct GHG emissions from assets owned by the reporting organisation, Scope 2 are indirect GHG emissions from the purchase of energy and Scope 3 are other indirect GHG emissions emitted as a consequence of the organisation's upstream and downstream activities (WRI/WBCSD, 2004). Major financial institutions have committed to using the system. The U.S. Securities and Exchange Commission (U.S. SEC) recently proposed rule changes to require companies to disclose climate-related metrics (U.S. SEC, 2022) and the International Sustainability Standards Board (ISSB) prototype framework for climate-related disclosures (ISSB, 2021b).

However, the GHGI system was designed to be *consistent*, or producing trends over time to track performance (WRI/WBCSD, 2004), not *comparable*, or the ability to identify the similarities and differences between two objects (IASB, 2018). Thus, GHGP may be valid for use in tracking progress and setting science-based target (SBTi, 2020) but may not be fit-for-purpose in making comparative assertions. In essence, today's system is not suited to handle decision-making that involves more than one company at a time.

A number of studies point out that existing methodologies to model environmental characteristics have low comparability across companies (Bini & Bellucci, 2020; Emblemsvåg & Bras, 1999). A study of GHG calculators found that different calculators offered different results for the same inputs (Harangozo & Szigeti, 2017). GHG emission reporting utilizes life cycle assessment (LCA) methodologies (BSI, 2019a; WRI/WBCSD, 2004) and the rules for drawing boundaries produces some of these challenges to comparability (Suh et al., 2004). The International Standards Organisation's (ISO) standards on LCA, known as ISO 14040, recommends drawing system boundaries such that all inputs and outputs are elementary flows, or material or energy entering or leaving the system being studied without previous human transformation (BSI, 2020a). However, these system boundaries are determined at the discretion of the reporting organisation, inevitably resulting in different boundaries being compared (Patterson et al., 2017).

The ISO methodologies for LCA recognizes its own limitations of comparability. ISO 14044 on the requirements for LCA, suggests that comparable procedures may not result in comparable outcomes (Rapf & Kranert, 2021). The standard also gives additional procedures if an analysis is to be used for comparative assertions between multiple products (BSI, 2020b). Comparing organisations using LCA is strictly forbidden. ISO 14072, the technical report that extends LCA to entire companies, explicitly states that organisational LCA (O-LCA) studies cannot be used for comparative assertions between different organisations (BSI, 2014).

However, a gap exists in the literature as no studies have analysed the comparability of GHG Inventory reporting.

There is extensive literature regarding comparability within financial accounting. Comparability can be analysed based on inputs (Barlev & Haddad, 2007), outputs (De Franco et al., 2011), and the classification system used to make the comparison (Bowker & Star, 1999b). Input comparability is achieved through standardization of rules and classification systems (Pantić, 2016). Similarities and differences between companies can be revealed because the firms use similar inputs, follow similar procedures and use the same classification system of accounts (Barlev & Haddad, 2007). Input comparability in environmental accounting can be compromised when different emission standards use different boundaries and thresholds (Alvarez et al., 2016; Stanny, 2018). Output comparability helps decision-makers understand whether internal methodological choices differ within companies. These could include changes in accounting measurement rules, reporting standards, or adjustments (De Franco et al., 2011). When lacking output comparability, differences between firms may arise due to procedural variations rather than input differences. Output comparability in environmental accounting is challenged when a standard allows for the choice of multiple methodologies (Andrew & Cortese, 2011; Wegener et al., 2019) or permits significant variability in the mechanisms they use (Schönherr et al., 2022).

Within GHG accounting, current efforts have focused on improving input and output comparability. Researchers have suggested improving procedures (Yilmaz & Seyis, 2021), standardising boundary conditions (Wiedmann et al., 2009), standardising methodological approaches (Cort & Esty, 2020), and adopting a single standard (Andrew & Cortese, 2011; Pronobis & Venuti, 2021). Standard setters have asked companies to set ESG reporting boundary to be the same the entity's mainstream financial filing (CDSB, 2019; ISSB, 2021c; SASB, 2018e; TCFD, 2021b). However, the same standard setters also require entities to disclose their GHG inventory, which follow different boundary rules. Can the two boundary criteria co-exist? Additionally, the GHGP acknowledges that Scope 3 may not be comparable between entities (WRI/WBCSD, 2004). TCFD acknowledges this problem and asks entities to disclose only Scope 1 and 2.

This research contributes to the field by identifying necessary conditions that need to be met for GHGI to enable comparative assertions. We analyse GHGI with tools developed by accounting, social science, and engineering researchers. In doing so, we identify attributes of non-comparability beyond those already known.

Our paper is structured as follows. We first present our theoretical approach, based in category theory (Bowker & Star, 1999a), dimensional analysis (Sonin, 2001), and the similarity facet (Yip & Young, 2012). Next, we describe the methods used to analyse the categories, beginning from creating a map that traces the references among GHG emission standards, identifying different boundary assumptions of various methods being used simultaneously, and analysing the system for comparability. We present commentary of whether existing attempts to fix comparability addresses the core issues. We conclude with recommendations for design principles for a comparable GHG emissions accounting system.

2. Theoretical approach: Three methods

We analyse comparability with approaches used by accounting, social scientists, and engineering. Accounting researchers use the similarity and difference facet to evaluate comparability. Social scientists use category theory to determine whether systems are classification systems, a necessary condition in making comparative assertions. We also use dimensional analysis, an engineering tool, to understand if the unit of measure, metric tonnes of carbon dioxide equivalent (MTCO2e), has comparative properties. This section introduces the three approaches.

2.1. Evaluating comparability with the Similarity and Difference Facet

The accounting profession emphasizes comparability as a core principle of the financial reporting system. According to the International Accounting Standards (IAS), *comparability* is the ability to tell similarities and differences between two objects. Information from one entity can be compared with “Similar information about other entities and with similar information about the same entity for another period or another date,” (IASB, 2018). *Consistency*, on the other hand, is defined as “The presentation and classification of items in the financial statements shall be retained from one period to the next,” (IASB, 2017).

Although the Intergovernmental Panel on Climate Change (IPCC) defines comparability and consistency similarly to accountants (Eggleston et al., 2006b), within the environmental community, the two words are sometimes used interchangeably. For example, one paper defined comparability as the ability to “track performance over time” (Ranganathan, 1998), which financial accountants would define as consistency. The GHGP describes consistency as “Users of GHG information will want to track and compare GHG emissions information over time in order to identify trends and to assess the performance of the reporting company,” (WRI/WBCSD, 2004). ISO 14064-1, the standard for modelling GHG emissions defines consistency as “Enable meaningful comparisons in GHG-related information,” (BSI, 2019a).

Although the two concepts are similar and consistency is a necessary ingredient for comparability, it is not a sufficient condition (Barlev & Haddad, 2007). Consistency requires that the boundaries and assumptions of a single entity stay the same over time, thereby enabling evaluation of performance trends. Comparability, on the other hand, requires that boundaries and assumptions of multiple entities be the same at the same time. To achieve both consistency and comparability, multiple companies need to use the same boundary conditions over time. For clarity, this paper adopts the ISSB’s definition, where consistency refers to the use of the same approach over time and comparability as ability to evaluate information provided by different entities to understand similarities and differences amongst them (ISSB, 2021c).

Within financial reporting, there are two facets of improving comparability: the similarity facet, or “firms engaged in similar economic activities report similar accounting amounts” and the difference facet, or “firms engaged in different economic activities report dissimilar accounting amounts,” (Yip & Young, 2012). In essence, similar items should not look different and different items should not look alike. We use the similarity and difference facet to evaluate whether the GHG Inventory system of accounts creates the conditions necessary for comparability.

2.2. Introduction to category theory

Classification systems are a form of information infrastructure that communicate relationships among categories, informing data acquisition standards, support decision-making, among other activities. According to category theory, a classification system is a “Spatial, temporal or spatio-temporal segmentation of the world.” Importantly, properly designed classification systems create the conditions for comparability. Otherwise, the systems are known as nomenclatures, or an agreed-upon naming scheme without the ability to compare (Bowker & Star, 1999b).

An example of a spatial segmentation is zoning laws, which categorises land by usage, thereby affecting residents and neighbourhoods of the locale. An example of temporal segmentation is to categorize buildings by their age, historical era, or cause-and-effect such as wear and tear through usage. A spatio-temporal classification systems can be exemplified by a series of tasks that need to be completed in a specific order. As the tasks may need to occur in a different place, both the location and the time which the activities occur need to be classified.

Bowker & Star further observes three properties of an ideal classification system (Bowker & Star, 1999b):

(1) There are consistent, unique classificatory principles in operation.
(2) The system is complete.
(3) The categories are mutually exclusive.

Property 1 states that the categories are arranged in relation to one another. This ordering, whether spatial, temporal or spatio-temporal, determines the categories of what is being counted. Property 2 states that the ideal classification system provides total coverage of the world it describes. These two properties describe the boundary condition of how one draws the system – everything that is counted need to have a logical relationship to each other, and everything that falls into that relationship needs to be counted. Lastly, property 3 states that the categories within the system should be unique and fit into clearly demarcated bins. Everything is counted only once.

Systems that do not adhere to these three principles cannot be used to make comparisons. Some systems can systemically hide or exclude information, resulting in an undercount.

Excluded items are known as residuals which are effectively invisible from the system. For example, the cost of nurses in hospitals used to be categorized under the cost of the hospital room, and not as care that affected a patient's health. This hid the ability to query whether nursing care had a measurable effect on a patient's health. It was through the creation of a new classification system of nursing activities that contributed improvements in nursing care at hospitals. An example of undercounting within environmental accounting is that LCA-based environmental impacts have been found to have truncation errors as high as 50% (Suh et al., 2004), creating a severe undercount. Other systems can overcounting or miscount. Double counting is well documented within LCA models (Lenzen, 2008) and also can be found in assigning GHG emissions to certain firms (Caro et al., 2013). Overcounting can arise as a result of varying boundary definitions (Chen et al., 2020). The uncertainty of undercounting and overcounting within LCA therefore prohibits comparisons to be made.

We apply the principles of classification systems to the GHG Inventory to determine whether it is a classification system or a nomenclature. Does the GHG Inventory follow unique classificatory principles? Is the system a complete count of an entity's emissions? Finally, are all items counted only once?

2.3. Introduction to dimensional analysis

What items are being counted within GHG Inventories? With a myriad of environmental standards, do all GHG emission items being disclosed describe the same phenomenon? Rarely are GHG emissions measured directly. Rather, they are modelled based on various assumptions and calculated using databases and averages. Do the models use the same assumptions? If not, do the different assumptions affect consolidation into groupings and categories used to report GHG emissions? Before we can analyse the GHG classification system, we need to understand if the items being counted are the same or different.

We use dimensional analysis (DA) to understand what is being counted. Formally, DA is an engineering technique that depicts the similarity between two physical terms (Sonin, 2001). Practically, it is the study of units used in measurement and helps understand the phenomenon being described. It is able to track units of items being counted through the various calculations being performed. DA distinguishes between base units, or those that are physically measured, and derived units, or those that are modelled. For this study, DA gives us a technique to trace reported GHG emissions to their original measurement, separating out what is being counted, what is being modelled, and what are the assumptions of the models.

A *base unit* is the description of a physical property, such as distance, mass, and time. Base units for a measurement (such as distance) can be of different sizes (such as inches, centimetres, or furlong). The International System of Units (SI) defines seven base units for several physical properties, from which all other units and measures are derived from. The

SI system also defines the standard size, or unit that should be used for each physical property. These are shown in

Table 1.

Base quantities are physical measurements that describes how much one has of the base unit. Base quantities are defined by two mathematical operators, the comparison operation of determining if sample A and B are equal (A = B), and the addition operation that defines a sum (C = A + B). To make comparisons or additions, the base units need to be in the same size. In other words, one can only add inches to inches or compare meters to meters. It may be intuitive that one can't compare apples to oranges, but the reason behind it is that the unit of *apple* is a different base unit from the unit of *orange*. Adding inches to centimetres, even though both describe length, can be costly, as seen in the loss of the NASA Mars Climate Orbiter due to a failure to translate between metric and imperial units (NASA, 2019).

Table 1 Base units in SI system

Physical Property	Unit (abbreviation)
Time	second (s)
Length	metre (m)
Mass	kilogram (kg)
Electric Current	ampere (A)
Thermodynamic temperature	kelvin (K)
Amount of a substance	Mole (mol)
Luminous intensity	Candela (cd)

Derived units are those that are created through mathematical formulas and can be described by a power law with the following form:

$$Q = \alpha\, A^a B^b C^c \ldots$$ **Equation 1**

For example, in the SI system, energy, measured in Joules, is a derived unit because it uses base units of mass, distance and time in the following relationship:

$$energy = \frac{mass \times\ distance^2}{time^2} \quad with\ units \quad J = \frac{kg \cdot m^2}{s^2}$$ **Equation 2**

In power law form, the units are:

$$J = \ kg \cdot m^2 \cdot s^{-2}$$ **Equation 3**

Derived units retain their original properties of comparison and addition unless the derivation and the physical representation of the measurement is different. For example, all forms of energy, whether electrical, mechanical, chemical or others, are measured in Joules (J). These forms of energy can be added and compared. However, although torque is measured in the same base units as the Joule, it cannot be compared to energy. This is because, mathematically, energy is a scalar, calculated from a dot product of the terms whereas torque is a cross product between two vectors. To prevent confusion, torque is commonly represented in Newton-meter (N-m) while energy is represented in Joules (J).

There are many models used to calculate GHG inventories. We use dimensional analysis to understand whether the unit MTCO2e across these models represent the same phenomenon. If so, MTCO2e can be considered a derived unit that maintains comparative and additive properties. Otherwise, making comparisons by using MTCO2e may not be valid.

3. Methodology

A schematic of our research process is shown in Figure 1. We begin with document selection. ESG reporting is an emerging space with many competing standard setting bodies and disclosure requirements. There are also efforts to consolidate efforts to simplify reporting requirements. We started by tracing the GHG emission requirements within the Task Force on Climate-related Financial Disclosures (TCFD) and the General Reporting Initiative (GRI). This led us to a myriad of other ESG standards and disclosures, many of which cited the same references. After a broad review, we decided that the organisations which participated in the formation of the ISSB was a sufficient representation of ESG standards. These documents are listed in Table 2.

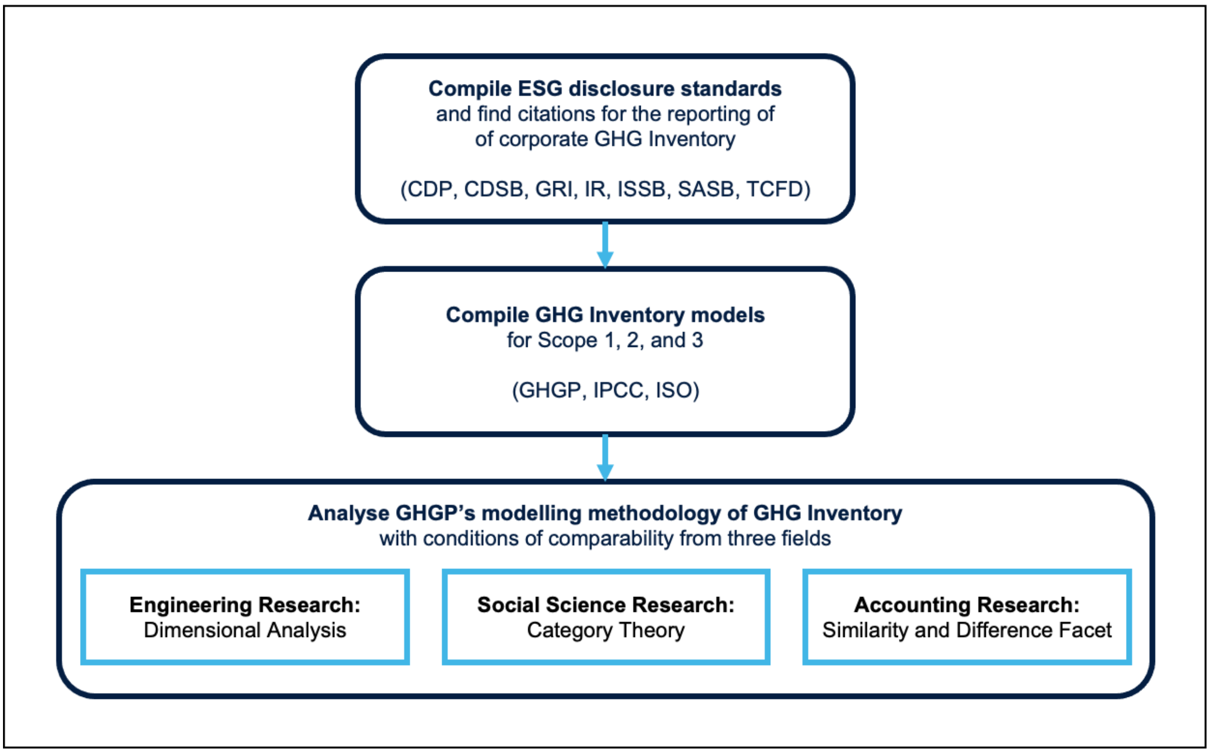

Figure 1 Schematic of our research process

The ISSB, announced at COP26 in Glasgow (IFRS, 2021), consolidated the Climate Disclosure Standards Board (CDSB) and the Value Reporting Foundation (VRF). The CDSB is an initiative of the Climate Disclosure Project (CDP) and the VRF combined the Integrated Reporting (IR) framework and the Sustainable Accounting Standards Board (SASB). Further, ISSB's creation was supported by the Task Force on Climate-related Financial Disclosures (TCFD), World Economic Forum (WEF), International Organization of Securities Commissions (IOSCO), and the International Accounting Standards Board (IASB). As the WEF, IOSCO and IASB do not produce ESG disclosure standards, their documentations were not included in the study.

Table 2 ESG disclosure standards analysed for this study.

<table>
<tr><th colspan="3">ESG disclosure standard</th><th>Documents analysed</th></tr>
<tr><td colspan="3">CDP</td><td>• CDP climate change 2021 questionnaire (CDP, 2021)</td></tr>
<tr><td colspan="3">TCFD</td><td>• Implementing the recommendations of the task force on climate-related financial disclosures (TCFD, 2021b)
• Guidance on metrics, targets, and transition plans (TCFD, 2021a)</td></tr>
<tr><td>IR</td><td rowspan="2">VRF</td><td rowspan="4">ISSB</td><td>• International <IR> framework (IIRC, 2021)</td></tr>
<tr><td>SASB</td><td>• Conceptual framework exposure draft (SASB, 2020a)
• SASB standards application guidance (SASB, 2018e)
• Industry standards (SASB, 2018a, 2018b, 2018c, 2018d)
• Implementation supplement: Greenhouse gas emissions and SASB standards (SASB, 2020b)</td></tr>
<tr><td colspan="2">CDSB</td><td>• Framework for reporting environmental & climate change information (CDSB, 2019)
• Application guidance for climate-related disclosures (CDSB, 2020)</td></tr>
<tr><td colspan="2"></td><td>• General requirements for disclosure of sustainability-related financial information prototype (ISSB, 2021c)
• Climate-related disclosures prototype (ISSB, 2021a)
• Climate-related disclosures prototype - Supplement: Technical protocols for disclosure requirements (ISSB, 2021b)</td></tr>
</table>

ESG standards require the disclosure of corporate GHG Inventories (GHGI), commonly reported in the form of Scope 1, 2, and 3. Three families of methodologies emerged, the GHGP, ISO and IPCC. The IPCC set the protocol for national greenhouse gas inventories with their 1996 publication, superseded by the 2006 version and amended in 2019 (Eggleston et al., 2006b; Garg & Weitz, 2019). Within the GHGP family, formulas can be found in the GHG protocol Scope 2 guidance (Sotos, 2015) and the technical guidance for calculating Scope 3 emissions (WRI/WBCSD, 2013). Within the ISO family, the models are described in ISO/TR 14069 (BSI, 2013). Table 3 lists the technical documents analysed for this study.

We then analysed the technical documents for methodologies to model GHGIs. We found that the GHGP and ISO systems are harmonised, and both are based on IPCC methods. For example, GHGP's Scope 1, 2, and 3 correlate to ISO's direct, energy indirect, and other indirect emissions (BSI, 2019a) categories. We therefore focus the bulk of our analysis on the GHGP system, as ISO would be subject to the same challenges.

We apply our three analytical techniques to the GHGP. First, we use category theory to examine relational logic between the Scope 1, 2, and 3 categories. Our analysis reveals that the GHGI system is derived from the LCA-based value-chain model. Thus, the GHGI system suffers from the same comparability challenges that are known to exist within the LCA system.

Table 3 GHG emission methodologies analysed

Emission methodology	Documents analysed
GHGP	• The greenhouse gas protocol: A corporate accounting and reporting standard, revised edition (WRI/WBCSD, 2004) • GHG protocol Scope 2 guidance: An amendment to the GHG protocol corporate standard (Sotos, 2015) • Corporate value chain (Scope 3) accounting and reporting standard: Supplement to the GHG protocol corporate accounting and reporting standard (WRI/WBCSD, 2011a) • Technical guidance for calculating Scope 3 emissions (version 1.0): Supplement to the corporate value chain (Scope 3) accounting & reporting standard (WRI/WBCSD, 2013) • Product life cycle accounting and reporting standard (WRI/WBCSD, 2011b)
IPCC	• 2006 IPCC guidelines for national greenhouse gas inventories (Eggleston et al., 2006a) • 2019 Refinement to the 2006 IPCC guidelines for national greenhouse gas inventories (Garg & Weitz, 2019)
ISO	**Quantification of GHG emissions** • ISO 14064-1 greenhouse gases part 1: Specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals (BSI, 2019a) • ISO 14064-2 greenhouse gases part 2: Specification with guidance at the project level for quantification, monitoring and reporting of greenhouse gas emission reductions or removal enhancements (BSI, 2019b) • ISO 14064-3 greenhouse gases Part 3: Specification with guidance for the verification and validation of greenhouse gas statements (BSI, 2019c) **Organizational reporting of GHG emissions** • ISO/TR 14069 Greenhouse gases — Quantification and reporting of greenhouse gas emissions for organizations — Guidance for the application of ISO 14064-1 (BSI, 2013) **Which uses**: • ISO 14067 Greenhouse gases – Carbon footprint of products - Requirements and guidelines for quantification (BSI, 2008) **Which relies on**: • ISO 14040 Life cycle assessment – Principles and framework (BSI, 2020a) • ISO 14001 Environmental management systems – Requirements with guidance for use (BSI, 2015) • ISO 14044 Life cycle assessment – Requirements and guidelines (BSI, 2020b)

Scope 1, 2, and 3 emissions are reported in *metric tons of CO_2 equivalent* (MTCO2e), a derived unit. In the second step of our analysis, we apply DA to the formulas to trace the model back to a physical quantity and separate out modelled assumptions. We examined the technical documentation to understand what the basic activity is being measured and counted. As a derived unit, does the unit MTCO2e retain the original properties of comparison and addition, or is the unit used to describe different physical phenomena? Our analysis shows that Scope 1, 2, and 3 describe different phenomena and the standard permits reporting entities to pick and choose which phenomenon to report.

Third, we use the similarity and difference facet demonstrate the noncomparability of entities based on their GHGI. We show that similar items can be reported differently, and different items can be reported similarly.

To fix the boundary ambiguity, some ESG disclosure standards require the entity to use mainstream financial filings (MFF) as their corporate boundary. However, the ESG disclosure standards still require entities to report their GHG inventory, which utilises different boundary assumptions. Further, there is a lack of guidance for the choice of emission factors, each having their own embedded boundary assumptions. This leaves unclear whether the GHG emissions of entities are being compared by their MFF boundary, their GHGI boundary, or emission factor choices.

In essence, we find that the current merged use of the financial and GHG metric systems is incompatible and current fixes do not address these fundamental challenges. In the next section, we identify how noncomparability enters the GHG inventory accounting system. This creates a set of design principles that are necessary for comparability.

4. Analysis

4.1. Creating a mapping of documents based on GHG metric citations

The purpose of mapping the citations of the documents is to make sense of what's being asked to be disclosed. Our analysis shows that all standards cite the GHGP either directly or indirectly. This implies that an analysis of the GHGP classification system is sufficient to understand the comparability challenges of the GHG emissions system. One key insight is that all GHG accounting is derived from LCA. The implication is that GHG emissions are subject to same comparability challenges as other environmental indicators modelled from LCA.

Table 4 maps ESG disclosure depicts the GHG emission metrics used to the references of where to find them. Two organisations, CDP and ISSB, require Scope 1, 2, and 3 disclosures. Two other organisations, TCFD and CDSB, require Scope 1 and 2 disclosures with Scope 3 deemed optional. SASB segments the market into 77 industries each with their own disclosure standards. Scope 1 are required for 22 sectors, topics related to Scope 2 are required for a further 33. Scope 3 emissions themselves are not required, but their related issues are included in many of the other industry standards. IR mentions emissions reporting as an environmental indicator but does not give guidance as to which metrics to report.

Because ESG disclosure standards do not instruct how to model Scope 1, 2, and 3, the standards also give references of where to obtain the metrics from. As depicted in Table 4 Column D.1, many of the ESG disclosure standards referenced other ESG disclosure standards as a source for emissions reporting, creating circular references. These circular references are visualized in Figure 2. An example of this is TCFD suggesting that a company's CDP report would fulfil emissions reporting while CDP suggests the same for TCFD.

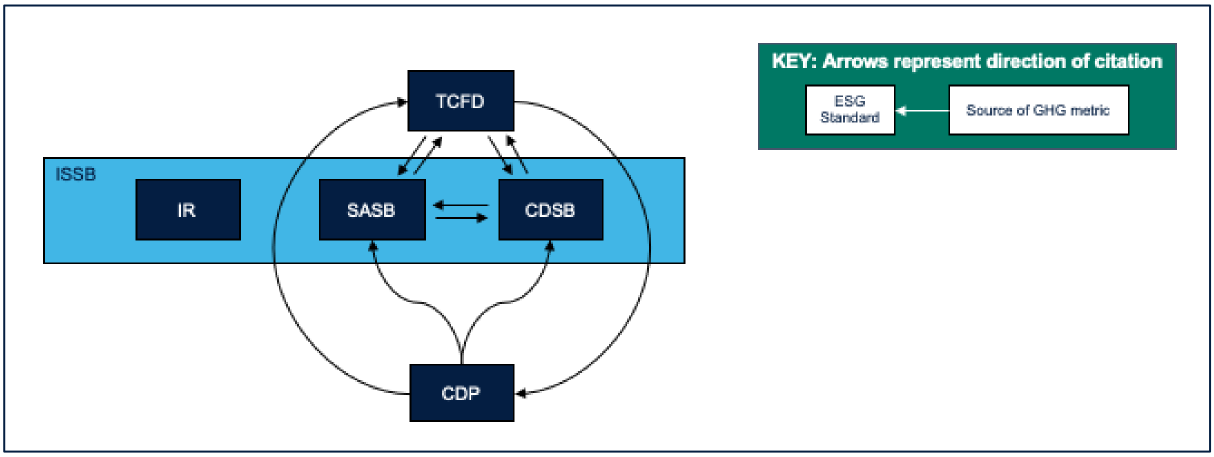

Figure 2 Disclosures referencing other disclosure for GHG emissions metrics. Arrows represent the direction of citation (i.e., CDP is cited by TCFD, SASB, and CDSB).

Table 4 Identifying GHG emission KPIs used in corporate disclosures and their technical documentation.

(A) ESG Disclosure Standard	(B) Reference	(C) GHG emission metric (in MTCO2e)	(D) References to acceptable GHG emission metrics									
			(D.1) In other disclosure standards					(D.2) In emission methodologies				
			CDP	CDSB	IR	SASB	TCFD	GHGP	IPCC 2006	ISO 14040	ISO 14064	Other
CDP climate change 2021 questionnaire (CDP, 2021)	Section C6	Scope 1 Scope 2 Scope 3					x	x	x	x	x	x
TCFD: Guidance on metrics, targets, and transition plans (TCFD, 2021a)	Table C1	Scope 1, Scope 2 (required) Scope 3 (optional)	x	x		x		x				
IR: International <IR> framework (IIRC, 2021)		Mentions emission reporting						x				
SASB: Implementation supplement: Greenhouse gas emissions and SASB standards (SASB, 2020b)	110a.1	Scope 1 (22 industries) Scope 2 (via energy) Scope 3 (Included in many industry standards)	x				x	x			x	
CDSB: Application guidance for climate-related disclosures (CDSB, 2020)	REQ-04	Scope 1 and 2	x			x	x	x				
ISSB: Climate-related Disclosures Prototype - Supplement: Technical protocols for disclosure requirements (ISSB, 2021b)	Paragraph 13	Scope 1, 2, and 3	x		x	x	x	x	x		x	

The ESG disclosure standards also reference technical guidance and methodologies on how to model emissions, as depicted in Table 4 Column D.2. All the disclosure standards analysed accept the GHGP, three of them accept ISO standards, and two the IPCC guidelines. CDP also permits GHG disclosures based on 67 other methodologies, such as US EPA, The Climate Registry, European Union Emissions Trading System, among others (CDP, 2021). We omitted methodologies only referenced by CDP. Figure 3 provides a visualisation of the relationship between ESG disclosures standards and GHG emission methodologies.

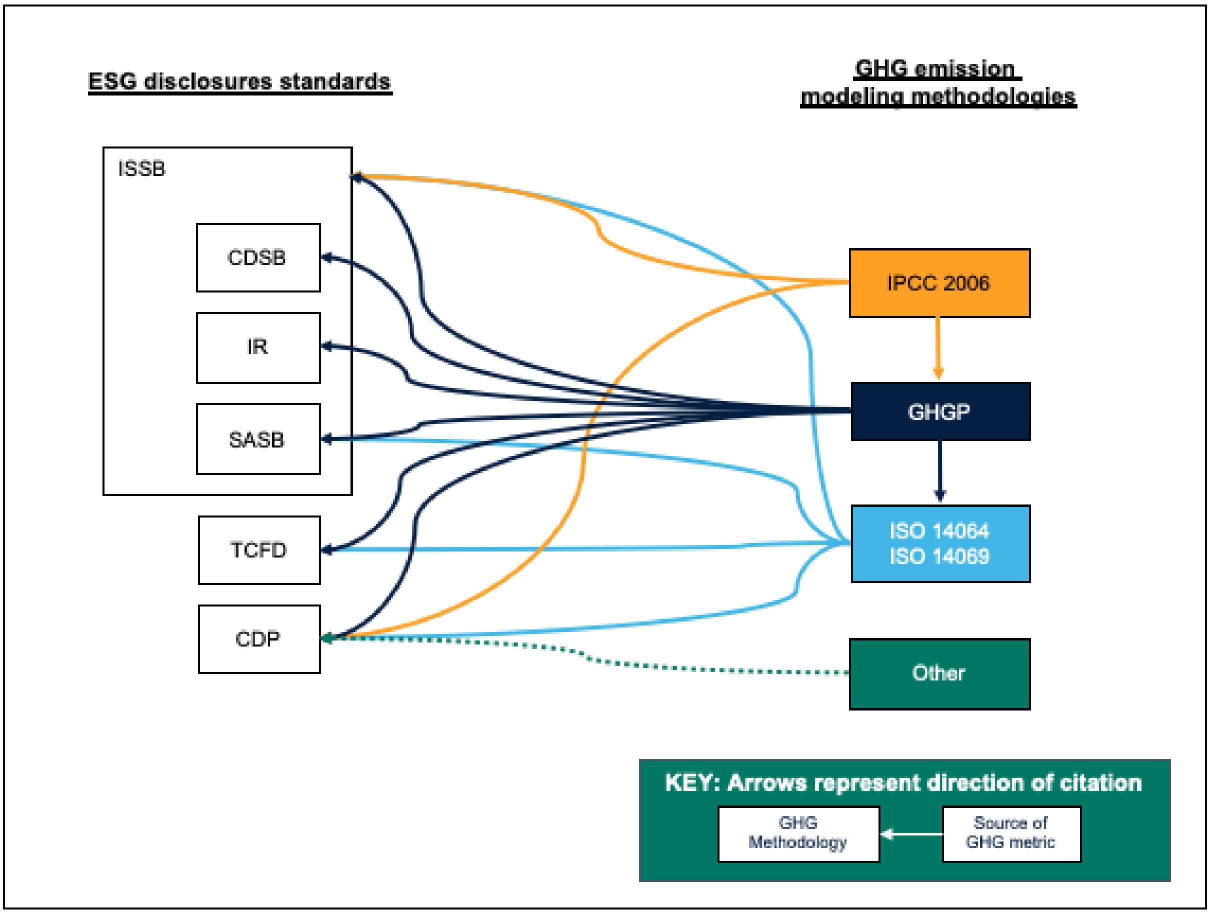

Figure 3 GHG emission modelling methodologies referenced by ESG disclosure standards. Arrows represent the direction of citation (i.e., IPCC2006 is cited by GHGP, ISSB and CDP).

The GHG emission methodologies are also interrelated. The GHGP is a joint effort by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD). GHGP claims their calculation tools are consistent with the IPCC methodology for modelling emissions. To do this, the GHGP adopts a life cycle approach, and the metrics reflect a reporting organisation's direct emissions as well as indirect emissions of the value chain as a consequence of the organisation's activities (WRI/WBCSD, 2004). The GHGP product life cycle standard is based on the ISO 14044 life cycle assessment standard.

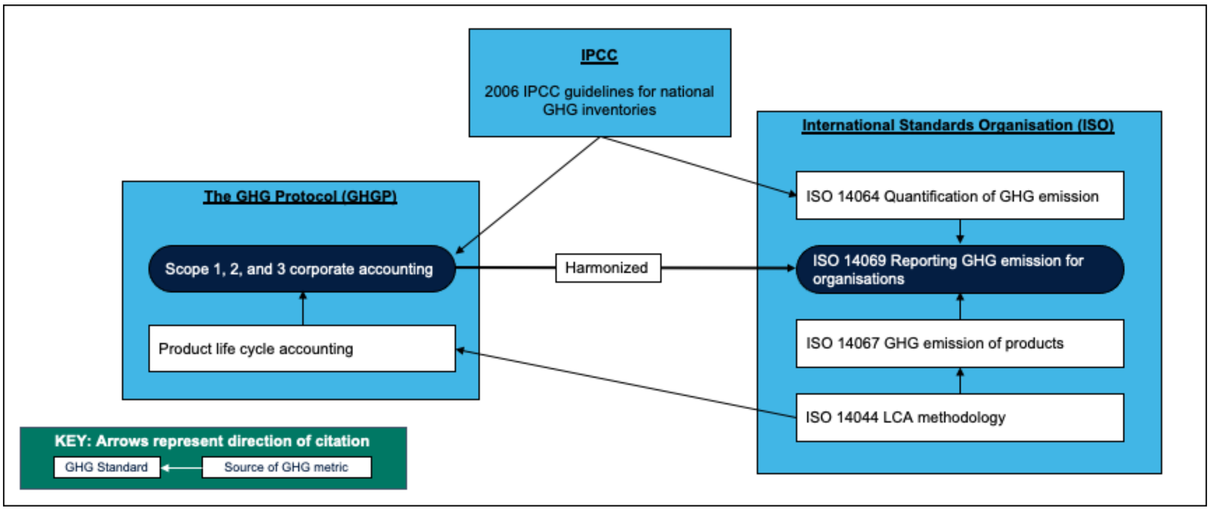

Figure 4 Referencing among modelling methodologies

The ISO 14000 family of standards covers environmental management and many of the standards reference other standards within the family. For example, ISO 14064-1 sets the foundation of quantifying GHG emissions for organisations while technical report ISO/TR 14069 gives guidance on how organisations should report their emission data. Both standards depend on LCA methodologies described in ISO 14040 and ISO 14044.

4.1.1. How GHGP and ISO standards are harmonised

The GHG emission models also reference each other, as depicted in Figure 4. GHGP defined Scope 1, 2, and 3 to give a reporting organisation visibility on GHG emissions due to corporate activities (WRI/WBCSD, 2004). Scope 1 is defined to be "Emissions from sources owned or controlled by the reporting organisation." However, as most entities do not own their own power plants or generate their own power, Scope 2 represents GHG emissions due to the consumption of electricity, steam, heating, or cooling purchased from a utility. Scope 3 to be all other indirect emissions that arise as a "Consequence of the activities of the company but occurred from sources not owned or controlled by the company." This captures both upstream and downstream value chain effects. The units of Scope 1, 2, and 3 are in MTCO2e.

Scope 3 is further refined into 15 categories, each representing a source of value chain emission. Some categories are upstream, such as *Category 1: Purchased goods and services*. Others are downstream, like *Category 13: Downstream leased assets*. Some Scope 3 categories have further subcategories. For example, *Category 9: Downstream transportation and distribution* is further divided into emissions due to the transport of products and emissions due to storage of products at distribution warehouses (WRI/WBCSD, 2013).

The GHGP permits industry organisations to adapt the protocol to their own sectors. These sectorial guidances, modelling tools, and reporting programmes can earn a "Built on GHG

Protocol" mark to recognize adherence to the standard (WRI/WBCSD, 2021). For example, the Partnership for Carbon Accounting Financials (PCAF) has published further guidance on the disclosure of *Category 15 Investments* for financial institutions (PCAF, 2020). It expands on the original three subcategories in Category 15 into six: (1) listed equities and corporate bonds, (2) business loans and unlisted equity, (3) project finance, (4) commercial real estate, (5) mortgages, and (6) motor vehicle loans. The Innovation Center for U.S. Dairy has also published a GHG inventory guidance on how the dairy sector should manage Scope 1 and 2 emissions (U.S. Dairy, 2019), while the International Aerospace Environmental Group published an approved method for the aerospace industry (IAEG, 2019).

ISO 14064-1 defines seven GHG emission inventory categories amongst direct and indirect sources. Direct emissions are those from sources owned or controlled by the organisation. Indirect emissions are those that arise as a consequence of the organisation's operations and activities from sources not owned or controlled by the organisation (BSI, 2019a). Indirect emissions are further separated out into energy indirect, or energy purchased from a utility, indirect from transportation, from products used by an organisation, from services used by an organisation, from emissions associated with use of a product, and from emissions from other sources. ISO/TR 14069 further refines this list into 23 categories for organisational reporting which are harmonized with the categories of GHGP. Table 5 depicts the harmonization of the categories amongst the three standards.

There are some small differences in the categorizations. First, ISO 14069 makes a distinction between different sources of direct emissions (Category 1 to 4) and adds a category for land use changes, something not explicitly mentioned in the GHGP. ISO 14069 also makes a distinction in energy indirect emission between fuel consumed for supplying electricity and fuel consumed for supplying steam, heating, and cooling (Category 6 and 7) while GHGP considers both within Scope 2. Within other indirect emissions, ISO 14069, Category 18 Use Stage of Product, combines two GHGP Scope 3 categories (Category 10 Processing of Sold Products and Category 11 Usage of Sold Products). ISO 14069 further has two categories that do not have GHGP counterparts (Category 16 and 23).

Table 5 Harmonization of emission categories between GHGP, ISO/TR 14069 and ISO 14064-1

<table>
<tr><th>(A) GHGP</th><th>(B) ISO/TR 14069</th><th>(C) ISO 14064-1</th></tr>
<tr><td rowspan="4">Scope 1 - GHG emissions from sources they own or control. This includes stationary sources, mobile sources, physical or chemical processing and fugitive emissions</td><td>Category 1 - Direct emissions from stationary combustion</td><td rowspan="5">Direct emissions</td></tr>
<tr><td>Category 2 - Direct emissions from mobile combustion</td></tr>
<tr><td>Category 3 - Direct process related emissions</td></tr>
<tr><td>Category 4 - Direct fugitive emissions</td></tr>
<tr><td>N/A</td><td>Category 5 - Direct emissions and removals from land use, land use change and forestry (LULUCF)</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td rowspan="2">Scope 2 - Emissions from generation of acquired and consumed electricity, steam, heat, or cooling (collectively referred to as "electricity")</td><td>Category 6 - Indirect emissions from imported electricity consumed</td><td rowspan="2">Energy indirect emissions</td></tr>
<tr><td>Category 7 Indirect emissions from (steam, heating, cooling, compressed air) excluding electricity</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td>Scope 3 - Category 1 Purchased goods and services</td><td>Category 9 - Purchased products</td><td rowspan="17">Other indirect emissions</td></tr>
<tr><td>Scope 3 - Category 2 Capital goods</td><td>Category 10 - Capital equipment</td></tr>
<tr><td>Scope 3 - Category 3 Energy-related activities not included in scope 1 or scope 2
a) Fuel
b) Electricity
c) T&D Losses
d) Electricity pass-through</td><td>Category 8 - Energy-related activities not included in direct and energy indirect</td></tr>
<tr><td>Scope 3 - Category 4 Upstream transportation and distribution
a) Transportation
b) Distribution</td><td>Category 12 - Upstream transport and distribution</td></tr>
<tr><td>Scope 3 - Category 5 Waste generated in operations</td><td>Category 11 - Waste generated from organizational activities</td></tr>
<tr><td>Scope 3 - Category 6 Business travel</td><td>Category 13 - Business travel</td></tr>
<tr><td>Scope 3 - Category 7 Employee commuting</td><td>Category 22 - Employee commuting</td></tr>
<tr><td>Scope 3 - Category 8 Upstream leased assets</td><td>Category 14 - Upstream leased assets</td></tr>
<tr><td>Scope 3 - Category 9 Downstream transportation and distribution
a) Transportation
b) Distribution</td><td>Category 17 - Downstream transport and distribution</td></tr>
<tr><td>Scope 3 - Category 10 Processing of sold products</td><td rowspan="2">Category 18 - Use stage of the product</td></tr>
<tr><td>Scope 3 - Category 11 Use of sold products
a) Direct energy consumed by products
b) Fuel and feedstock as products
c) Fugitive emissions of product use
d) Indirect energy consumed of final products
e) Indirect energy of intermediate product</td></tr>
<tr><td>Scope 3 - Category 12 End-of-life treatment of sold products</td><td>Category 19 - End of life of the product</td></tr>
<tr><td>Scope 3 - Category 13 Downstream leased assets</td><td>Category 21 - Downstream leased assets</td></tr>
<tr><td>Scope 3 - Category 14 Franchises</td><td>Category 20 - Downstream franchises</td></tr>
<tr><td>Scope 3 - Category 15 Investments
a) Equity investments
b) Project finance and debt
c) Total projected lifetime emissions</td><td>Category 15 - Investments</td></tr>
<tr><td rowspan="2">N/A</td><td>Category 16 - Client and visitor transport</td></tr>
<tr><td>Category 23 - Other indirect emissions or removals not included in the other 22 categories</td></tr>
</table>

4.1.2. Insights from the mapping analysis

In summary, the mapping shows that all the standards reference the GHGP for GHG emissions, whether directly (such as Scope 1, 2, and 3) or indirectly (such as via ISO). ISO and GHGP utilise the same classification system with minor differences. Thus, an analysis of GHGP is sufficient to demonstrate comparability challenges of both systems. Further, as GHGP is based on LCA, it will also be subject to the comparability challenges of the LCA methodology. Finally, as shown in Table 4 Column C, all GHG emissions are modelled in unites of MTCO2e.

4.2. Using Category Theory to determine the relational logic between GHGI categories

This section will show that a GHG inventory (GHGI) uses the LCA methodology for boundary setting. As a derivative of LCA, the GHGI is subject to similar comparability challenges.

LCA has its roots as far back as the 1960's where there was an interest in calculating the energy requirements of extended production systems in the chemical sector (Fava et al., 1991). By the early 1990's, the Society of Environmental Toxicology and Chemistry (SETAC) had developed early versions of the modern-day LCA methodology (James et al., 1993). LCA It is an analytical technique that helps understand resource consumption and environmental burdens from acquisition of raw materials to final disposition. Importantly, the early authors recognized that cause-and-effect relationships are difficult, if not impossible, to prove (James et al., 1993).

LCA is a relative approach and boundary setting depend on the *functional unit* and the *system boundary* (BSI, 2020a). The functional unit is the object being studied, such as the mug, the couch, or the whole organisation. The functional unit will consume resources, produce goods, or both. The *system boundary* incorporates processes related to the functional unit that are relevant to the environmental footprint. Ideally, the system boundary is drawn such that only *elementary flows*, defined as material and energy entering the system prior to human transformation, is present. This includes capturing both upstream and downstream impacts of the functional unit. A *life cycle inventory* (LCI) is the inventory of emission within the system boundaries that are related to the functional unit.

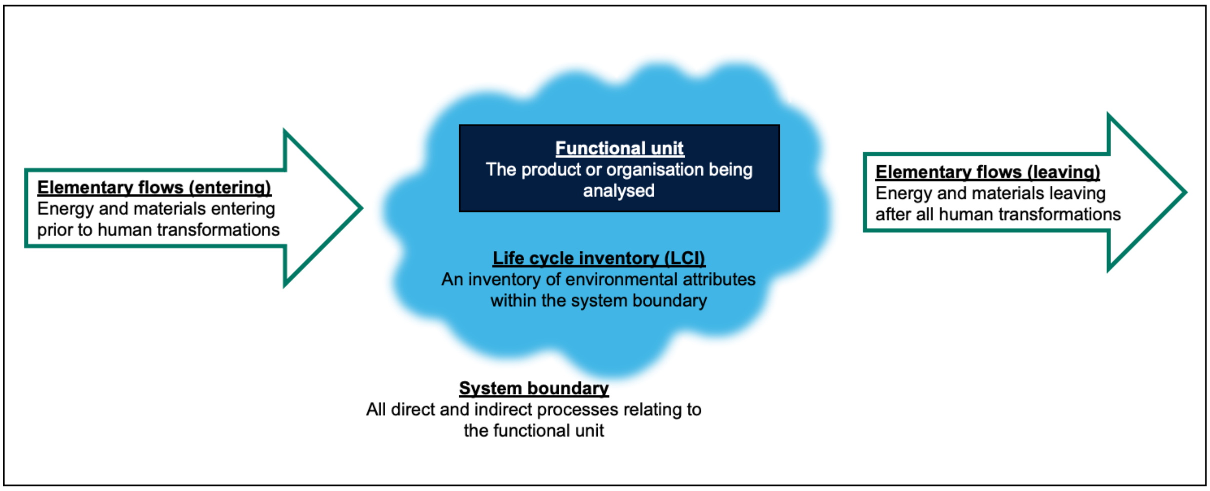

Figure 5 is a schematic that depicts the relationship between the functional unit and the system boundary.

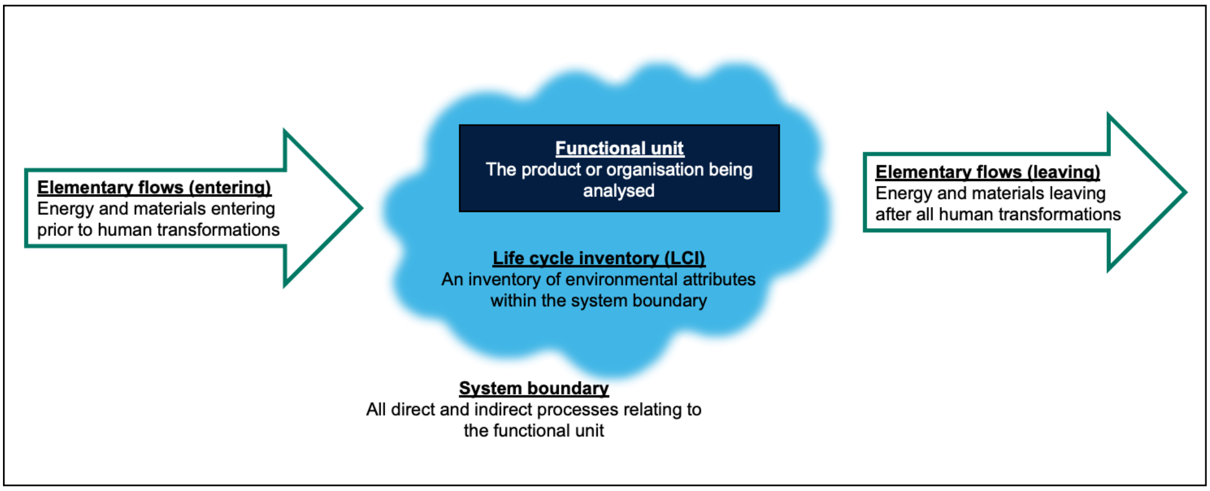

Figure 5 Depiction of generic LCA boundary setting

Both GHGP (WRI/WBCSD, 2004) and ISO 14064-1(BSI, 2019a) adopt the functional unit and system boundary approach to accounting for organisational GHG inventory boundaries. *Organisational boundaries* are the functional units. These are defined as the organisation being measured. As organisations can be complex, both protocols offer three methodologies to consolidate GHG emissions. Using an equity share approach, entities account for a fraction of an entity's emissions based on percentage ownership. Under a financial control approach, the reporting organisation accounts for 100% of GHG emissions if it can direct financial policies. Similarly, in the operational control approach, the reporting organisation accounts for 100% of GHG emissions if it can direct operational policies.

Operational boundaries are the system boundaries. The operational boundary includes emissions directly emitted from assets owned or controlled by and those indirectly generated as a consequence of the reporting organisation's activity. A GHG Inventory is thus analogous to the LCI. It is an inventory of all GHG activities within the operational boundaries. The GHGI includes upstream and downstream value chain activity.

Figure 6 depicts the boundaries of disclosures and emission methodologies.

GHGP recommends that reporting organisations should apply the same consolidation rules for GHG accounting as they use for financial reporting (WRI/WBCSD, 2004) and ESG disclosure standards, such as TCFD and ISSB, require entities to use their mainstream financial filings as their organisational boundary. This implies that the mainstream financial filings are being treated as the functional unit. However, the reporting entity still has the flexibility on how to draw their operational boundary. Since Scope 1, 2, and 3 are determined by the operational boundary, standardizing the organisational boundary doesn't actually standardize the boundaries of GHG emission reporting.

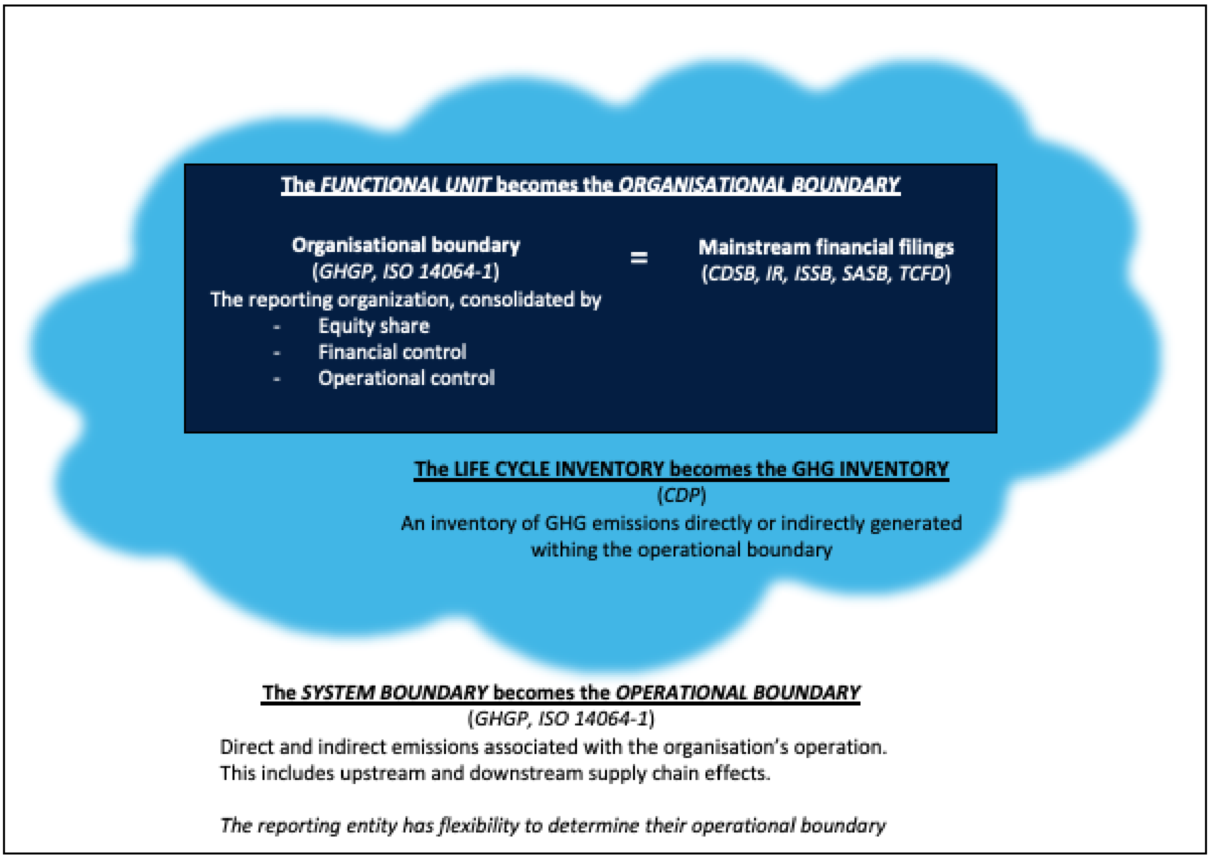

Figure 6 GHG inventory boundary

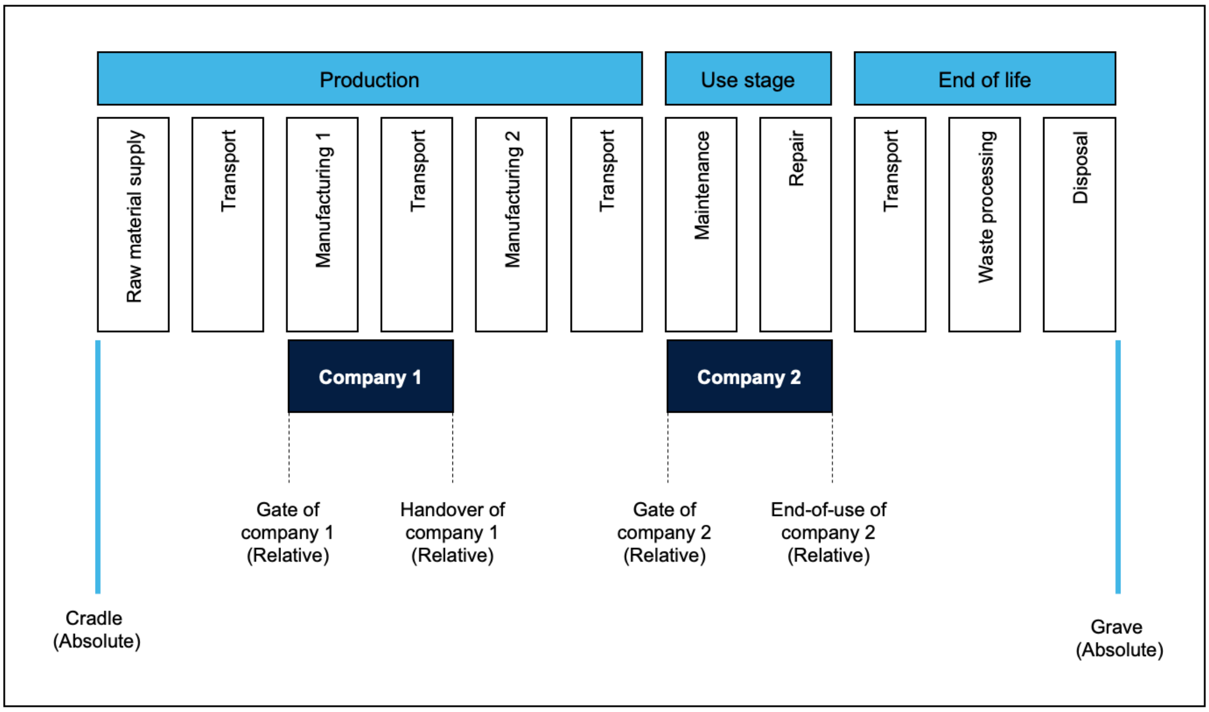

Figure 7 Stage names within the value chain for LCA studies. Adopted from (Balouktsi & Lützkendorf, 2016)

The steps within the system boundary are referred to as the value chain, as shown in

Figure 7. *Cradle* is defined as the beginning of the value chain, starting with raw material production. *Grave* denotes the end of the value chain, or how one disposes of materials. These two points are fixed, absolute points.

The stages in between cradle and grave are defined relative to the functional unit. For example, *gate* refers to the point when materials transfer into a company, regardless of where they reside in the value chain. When goods and materials exit a company, but is destined to another business, that stage is known as a *handover*. When goods and materials leave the final user of the material, that stage is known as the *end-of-use*. A full LCA is a cradle to grave inventory of emissions. A partial LCA represents a subset of the value chain, such as cradle to gate, gate to gate, or end-of-use to grave (BSI, 2020b).

Because of the flexibility of setting system boundaries in LCA, comparative studies need to follow additional steps, including using the same functional unit and using the same methodological considerations, including the same system boundaries (BSI, 2020b). The LCA methodology can also be applied to entire organisations to model environmental footprints. However, ISO 14072, the standard that applies LCA to organisations explicitly forbids comparative assertions. Section 5.2.1 requires any organisational LCA must unambiguously include “a statement that the results are not intended to be used in comparative assertions intended to be disclosed to the public,”(BSI, 2014). As some researchers have noted, the flexibility gained to customize LCA implementation for individual companies ruins the ability to compare them to their peers (Emblemsvåg & Bras, 1999).

4.2.1. Insights from the GHGI relational logic

In summary, LCA categories are spatially defined, relative to an entity's position in the value chain. A full LCA is a summation of environmental impacts across all time (past, present, and future) while a partial LCA accounts for only historic impacts. The aggregation across time means that not all of emissions actually exist, and differences in temporal assumptions can create different results (Yuan et al., 2015).

For these reasons, LCA studies intended for comparative assertions must take care to define the system boundary – including temporal boundary (BSI, 2020b). However, the standard for applying LCA to organisations acknowledges that the boundary setting is too complex for comparative assertions to be made. Studies of organisational LCA must include a statement that the results are not to be used to make comparative assertions (BSI, 2014).

As GHGI is defined based on LCA principles, its categories are also spatially defined rather than temporally defined. As such, it is subject to the same comparability challenges as with LCA. Since corporate GHGI is a footprint of the organisation, its result also cannot be used to make comparative assertions.

4.3. Dimensional analysis of MTCO2e

We use dimensional analysis to trace and separate out what is being measured and what is being modelled when estimating GHG emissions. This enables us to determine whether the unit MTCO2e is being used to describe the same physical phenomenon or different phenomena. We find that Scope 1 describes the consumption of fossil fuel and Scope 2 describes an allocation of a utility's consumption of fossil fuel. The fifteen categories of Scope 3 are each an accounting system that describes a different phenomenon. The boundary challenges of LCA are due to the assumptions embedded within the emission factors (EF) themselves. Further, databases of EFs will make different boundary assumptions, complicating the matter further.

In this section, we begin by examining the IPCC methodology. We then analyse GHGP in detail, tracing the basic units through Scope 1, 2, and the fifteen categories that make up Scope 3. We then perform DA on emission factors generated by LCA and environmentally extended input-output (EEIO) methodologies.

4.3.1. GHG emissions for national inventories: IPCC

The IPCC developed GHG emissions reporting for nation-states for four main sectors – energy, industrial processes, agriculture and land use, and waste. This paper focuses on energy-related emissions, as according to the World Resource Institute, such emissions have grown from 71% in 1991 to 76% in 2019 (ClimateWatch, 2022). There are six GHGs as defined by the original Kyoto Protocol – CO_2, CH_4, N_2O, HFCs, PFCs and SF_6 – with a seventh, NF_3, being added later (WRI/WBCSD, 2013).

According to the IPCC methodology, the first step is to calculate the mass of gas emitted for each GHG. It is derived by multiplying an activity data (AD) with an emission factor (EF) (Eggleston et al., 2006b).

$$emissions\ of\ a\ gas\ (by\ mass) = activity\ data \times emissions\ factor \qquad \textbf{Equation 4}$$

The AD represents a unit of human activity and can be measured in gallons of liquid fuels or weight of solid fuels, for example. This EF, also known as the *combustion EF*, can be considered as a conversion ratio that relates a quantity of fuel to an expected quantity of GHG emitted. Combustion EFs are measured scientifically and are specific to the fuel, the technology being used, and the GHG being emitted. Table 6(A) depicts common combustion EFs for gases emitted by burning various fuels.

Each GHG has a different effect on the climate, due to its radiative effect and duration it lasts in the atmosphere. To compare between the gases, one can calculate the quantity of CO_2 that would need to be emitted to have the equivalent effect of the emissions of another GHG. By definition, CO_2 has a GWP-100 of 1 and Table 6(B) gives GWP-100 for a small list of GHGs.

The resulting unit, *metric tons of CO_2 equivalent* (MTCO2e), follows a power law and is thus a derived unit. As shown in

Figure 8, the formula also carries the form of a unit conversion. The fuel consumption is converted to emissions via a combustion EF and a GWP-100. The end result is a derived unit that has equivalence to fuel consumed and maintains properties of comparability and equivalence (Equation 1). In essence, in this method, the activity data is a measurement of energy and emission factors converts the energy metric into a carbon equivalent.

Table 6 Exemplary combustion emission factors and GWP-100 values from the IPCC

(A) Default emission factors for stationary combustion in the energy industries (in kg of GHG per TJ on a net calorific basis) (Gómez et al., 2006)

Fuel	CO_2	CH_4	NO_2
Crude oil	73,300	3	0.6
Jet kerosene	71,500	3	0.6
Natural gas	56,100	1	0.1
Anthracite coal	98,300	3	1.5

(B) The 100-year global warming potential of select greenhouse gases (P. Forster et al., 2021)

	CO_2	CH_4-Fossil	N_2O
GWP-100 (kg CO2 / kg GHG)	1.000	29.8	273

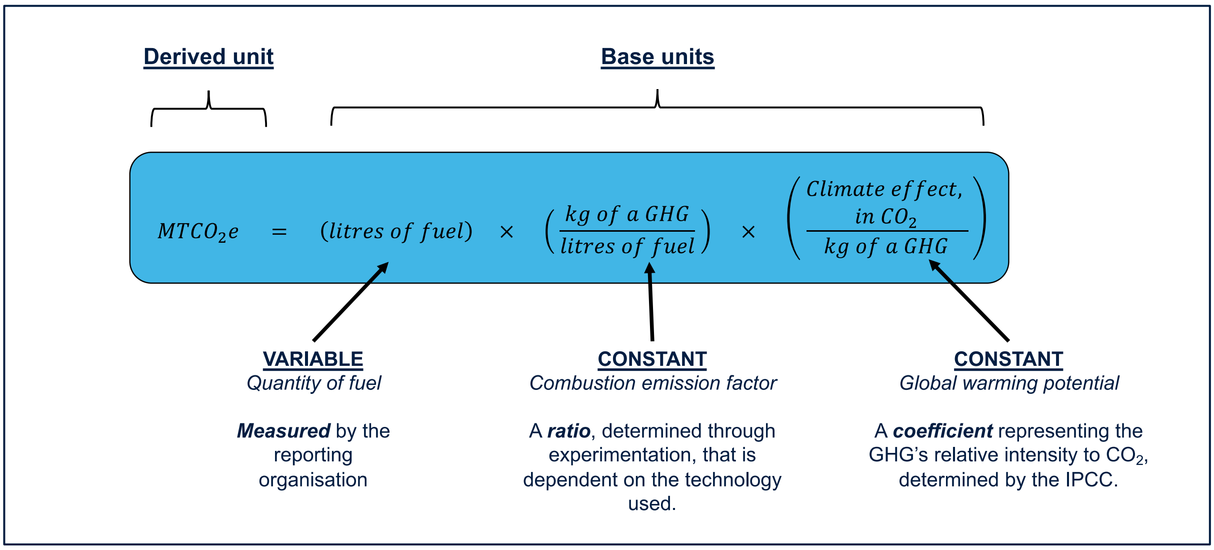

Figure 8 Unit analysis of GHG models

4.3.2. Dimensional analysis of Scope 1 and Scope 2

The GHGP acknowledges that although direct measurement of GHG emissions is the best, the most common approach is to model emissions based on an activity data, emission factor, and GWP. GHGP recommend the usage of GWP-100 numbers for the calculation of all Scopes (WRI/WBCSD, 2011a). Table 7 summarises the AD and EF used to model Scope 1 and 2.

Table 7 AD and EF used in Scope 1 and Scope 2

Category	Activity Data ×	Emission Factor
Scope 1: Direct Emissions	Energy (Quantities of fuel)	Combustion EF
Scope 2: Location-based	Electricity (MWh)	Location-based EF
Scope 2: Market-based	Electricity (MWh)	Market-based EF

The Scope 1 equation is the same formula as described in

Figure 8. Scope 1 can be considered a measure of the quantity of fuel with a unit conversion into MTCO2e.

Scope 2, modelling emissions from electricity, uses MWh of electricity consumed as the activity data and gives two options for EF – location-based and market-based. A location-based EF uses the local utility's average emissions per kWh consumed. On the other hand, some reporting entities enter long term contracts with specific suppliers for electricity, commonly from a renewable source. Although the electricity is still delivered via the local grid, the reporting organisation can use the emission factor of their contracted electricity rather than the grid average. This is known as the market-based approach. There are critics of the market-based approach, as described by (Brander et al., 2015).

A location-based EF has the units of MTCO2e / kWh and both the U.K. BEIS and the U.S. EPA take the same approach to model it. To find the numerator, the utility calculates how much fuel was burned at their power plants in a calendar year and multiply it by the appropriate combustion EF. To calculate the denominator, the utility measures how much electric energy was generated across their power plants in the same year (Hill et al., 2020; U.S. EPA, 2021). The final equation takes the following form:

$$location\ based\ EF\ =\frac{liters\ of\ fuel\ \times\ combustion\ EF\ \times\ GWP100}{annual\ electric\ energy\ produced\ (kWh)}$$

Equation 5

Market-based EF uses a similar equation. Rather than use the AD and EF of the local utility, one would use the AD and EF of power plants contracted to supply electric energy.

Figure 9 takes Equation 5 and rearranges the terms. The AD can be considered the variable being measured and the EF is a constant used for unit conversion. The first term is the ratio of electricity consumed by the reporting organisation to the total electricity generated by the utility. The second term is the annual emissions produced, found in Equation 4. Thus Scope 2 can be interpreted to be an allocation of fossil fuels burned based on the consumption statistics of the reporting organisation and the production statistics of the local utility.

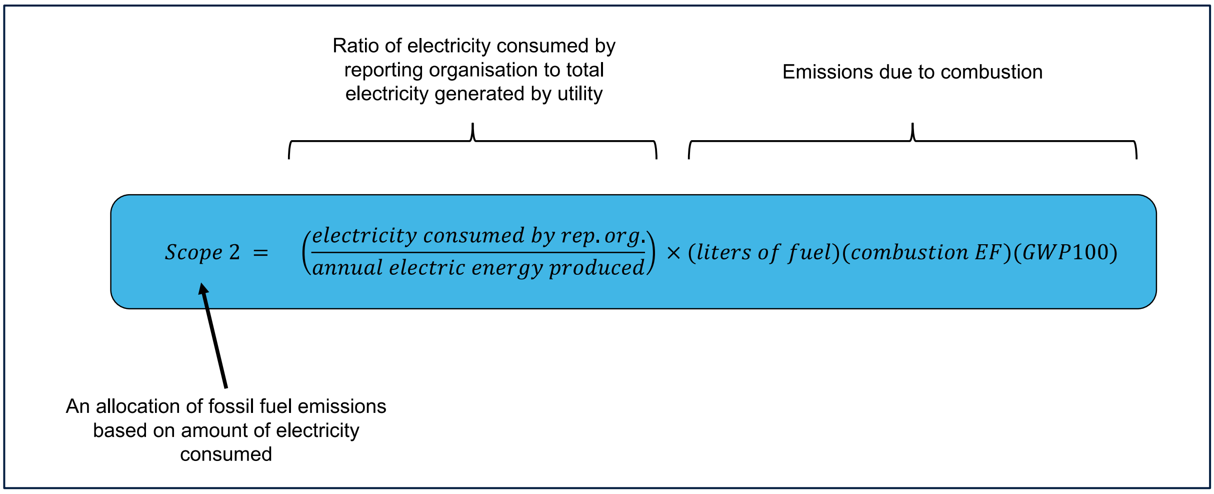

Figure 9 Scope 2 is an allocation of a utility's fossil fuel consumption based on the reporting organisation's consumption

4.3.3. Dimensional analysis of Scope 3

Scope 3 extends activity data from a fuel metric to any quantity that measures the extent to which human activity takes place (BSI, 2019a; Eggleston et al., 2006b). Example ADs include floorspace for rentals, weights or volume of products sold, distance travelled in a type of vehicle, or monetary based on expenditures or revenue.

The variety of AD require a variety of EFs, as listed in Table 8. If the AD metric is in emissions, fuel, or electric energy, one can use the same EF methodology as described for Scope 1 and 2. If the AD is a physical measurement, such as area, volume, mass, and so on, one uses LCA to calculate EFs. For some activities that are purely monetary in nature, one can use an environmentally extended input-output (EEIO) table. We will perform dimensional analysis on LCA and EEIO EFs separately.

4.3.4. Dimensional analysis of EFs derived through LCA

LCA-based emissions factors are models of emissions per activity and is commonly found by dividing the annual emissions generated by the activity with the annual activity. This can be expressed:

$$emission\ factor = \frac{annual\ emissions}{annual\ activity} \qquad \textbf{Equation 6}$$

Figure 10 rearranges the variables in the Scope 3 models into two terms, a ratio, and the sum of emissions. Scope 3 can be understood as an allocation of emissions to the reporting organisation based on activities, such as a producer or consumer. These emissions, which represent sub-activities, are modelled via LCA.

LCA is a methodology to quantify the environmental attributes, including GHG emissions, of products and services. It is a ground-up approach which attempts to take inventory of all individual components of a process, from raw sourcing of the material to the end of life of the resource. For example, energy itself requires energy to deliver. Upstream EF is defined as the emissions from extraction, production, and processing of fuels prior to the combustion EF while a fuel's lifecycle EF is the upstream EF plus combustion EF. The LCA approach to find EFs can be applied to any physical measurement, such as area, volume, weights, or costs. The primary standard for LCA is ISO 14044 (WRI/WBCSD, 2013).

Let us use an example. Assume a hotel has purchased 100 couches and would like to know the GHG emissions associated with that purchase. The AD would be 100 couches. The hotel could request a supplier-specific EF from the couch manufacturer based on what the producer emitted to construct the couches. This EF would be in units of MTCO2e /couch. The denominator would be the number of couches produced by the factory in a year and the numerator would be the emissions produced by the factory in the same year.

Table 8 Emission factors used in Scope 3 models

AD options		EF options	EF determined by
If AD metric is emissions (MTCO2e)		None needed	N/A
If AD metric is energy	***Fuel (Litres)***	Combustion EF	IPCC tables
		Fuel EF	IPCC tables
		Cradle to gate of fuel	LCA
		Upstream EF	LCA
		Lifecycle EF	LCA
	Electric energy (kWh)	Supplier specific EF	Utility data
		Grid average EF	Utility data
		Electricity EF (Location- or market-based)	Utility data
		Upstream EF	Utility data
If AD metric is a physical measurement (#, kg, m^2, m^3, km)		Per unit or use	LCA
		By weight	LCA
		Area	LCA
		Volume	LCA
		Vehicle-Distance	LCA
		Other	LCA
if AD metric is a monetary value ($ revenue, $ cost)		Monetary EF	LCA
		Environmentally extended input-output (EEIO) tables	EEIO

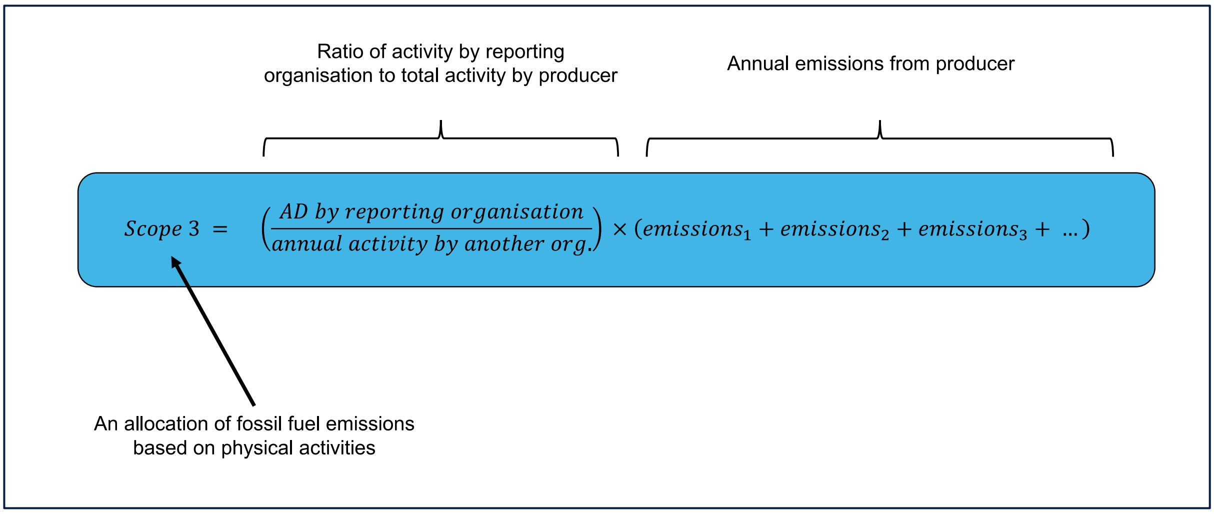

Figure 10 Scope 3 is an allocation of supply chain emissions

The couch factory could use LCA to calculate total emissions due to couches. It would first determine a set of activity data. Let us assume the couches are constructed from wood, steel, and electricity to run the shop. The activity data would therefore be kg of wood, kg of steel and kWh of electricity. Each of these AD would require an EF. The electricity EF is based on fuel consumption, as shown in the previous section. The EF for the wood and steel would be the emissions associated with the wood and steel. The couch factory will repeat the process by going to their suppliers and request an EF for emissions related to the materials, such as steel. The steel factory would then use another iteration of LCA to determine the emissions of the steel, using raw ore and energy as inputs. This iterative process, between different value chain stakeholders, would continue until one reaches *elementary flows* or material and energy entering the system prior to human transformation (BSI, 2020b). Figure 11 diagrams the nested iterations of LCA needed to derive an EF.

The LCA methodology can also be applied to a monetary metric. For instance, if the distance of flights is unknown, one can estimate emissions based on how much was spent on flights. When using monetary values for LCA, market values are used rather than actual price paid. For instance, one might have purchased a discounted flight as during a promotion. However, when accounting for GHG, one should use the market value of the flight rather than the discount paid. Using the discounted amount could result in an undercount of the GHG emissions caused by the travel.

There are two observations from EFs derived from LCA. First, all emissions are generated from the combustion of fuel. The iterative process of LCA merely reveals how much fuel was combusted at each layer. In the couch example, energy is used to manufacture the couch, but energy is also embedded in the processing of wood and steel components. Thus, if energy is not explicitly in the AD, it is estimated in the EF.

Second, EFs derived from LCA are not a derived unit. Derived units must follow the power law of Equation 1 and the terms need to be related by multiplication. However, after a rearrangement of terms, Figure 10 demonstrates that the terms within LCA-based EFs are related by addition. LCA-based EFs can be considered as accounting systems of activities. They do not retain comparative nor additive properties of a derived unit.

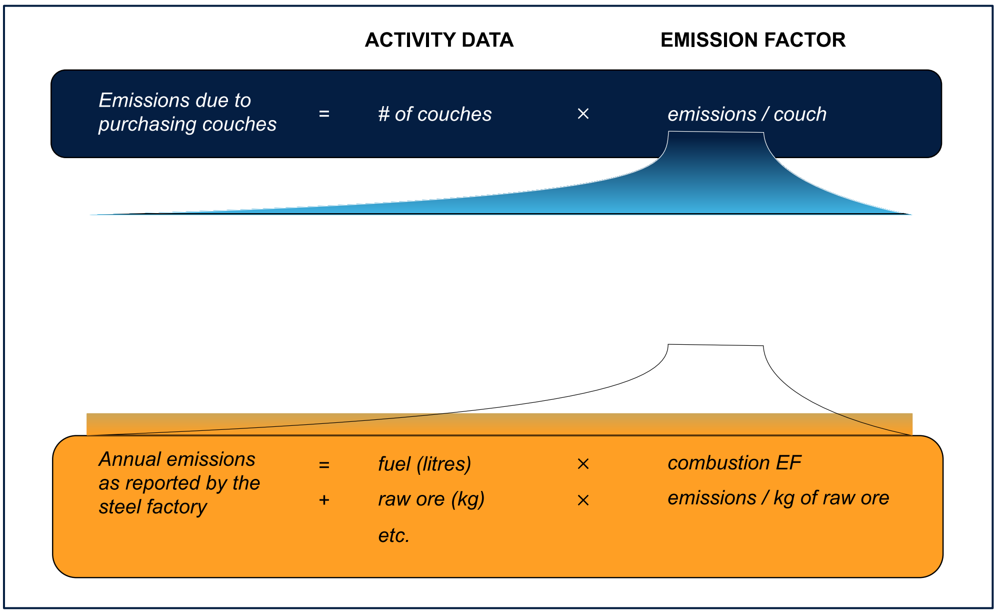

Figure 11 An example of the layered nature of emission factors

4.3.5. Dimensional analysis of EFs derived through EEIO

Environmentally extended input output (EEIO) tables are a top-down, economy-wide estimate of environmental impact that uses nation- or region-wide statistics and estimates corporate impact based on revenue or costs. Based on the input-output (IO) analysis developed by Wassily Leontief in the 1940s, the method helps understand the effects of monetary flow within the structure of the economy. Whereas LCA requires the tracing of physical quantities, EEIO allocates national environmental footprints based on economic flows. LCA is suited to primary sectors, such as manufacturing, while EEIO can help understand secondary sectors, such as hospitals and service sectors (Yang et al., 2017).

Monetary IO analysis relates total industry output ***x*** with the amount available for final consumption ***y***. Assuming *n* number of industries, matrix ***A*** is an $n \times n$ table defining intermediate industry's input and output. Matrix ***A*** is commonly referred to as the technology matrix (Tukker et al., 2006). The IO relationship is written in the following form, with ***I*** being an $n \times n$ identity matrix.

$$x = (I - A)^{-1} y$$ **Equation 7**

To extend monetary IO for environmental purposes, one defines a new $q \times n$ matrix ***B*** with q being the number of pollutants and environmental factors being tracked. The resulting matrix ***M*** is the environmental interventions per monetary unit of production for each environmental factor. EEIO analysis can be interpreted as reallocating responsibility from producer-orientation to consumer-orientation (Kitzes, 2013).

$$M = B(I - A)^{-1}y$$ **Equation 8**

Both the technology matrix ***A*** and the environmental matrix ***B*** are developed from national statistics. For example, in USEEIO, the IO tables are developed by the Bureau of Economic Analysis within the U.S. Department of Commerce. The GHG emissions source for matrix ***B*** is from the US GHG Inventory published by the U.S. EPA (Yang et al., 2017). The US GHG Inventory itself is calculated based on the IPCC guidelines for modelling emissions by using quantities of fuel and combustion EF (US EPA, 2015).

There are several observations. First, EFs derived from EEIO are national averages of quantities of fuel consumed per sector. The base unit is still fuel. Second, Scope 3 modelled by EEIO is an allocation of emissions based on econometrics rather than by physical activities. This is merely a variation of the LCA-based approach to find EFs. Lastly, Scope 3 modelled by EEIO is also not a derived unit. It includes the count of emissions across all economic activities associated with the production of monetary value.

4.3.6. Insights from dimensional analysis of MTCO2e

In summary, although Scope 1, 2, and 3 are all presented in the unit MTCO2e, the unit is not a derived unit because each represent different phenomenon. The MTCO2e in Scope 1 is a derived unit that models direct GHG emissions by using a combustion EF. This process can be thought of as a unit conversion from volume of fuel to mass of GHG emissions. The MTCO2e in Scope 2 is a derived unit that allocates GHG emissions from fossil fuel consumption based on electric energy consumed. The MTCO2e in Scope 3 is ***not*** a derived unit. Rather, each Scope 3 category is an accounting system that represents a different summation of items in the value chain. Each reporting entity has the freedom and flexibility to determine the boundary of their value chain.

By definition, it is invalid to add the three together into a single emission metric nor compare their values with each other because MTCO2e is not a derived unit. Further, because every entity has discretion to choose which emission factor they wish to use, measurements made in MTCO2e cannot be used to compare between entities.

The nuance can be understood with a sporting analogy. Although gold medals at an Olympic game is a standard metric of wins, it does not enable the ranking of athletic ability among sporting events. The unit “gold medal” could represent a team effort in one event, such as in basketball, a team effort in a collection of events, such as team gymnastic all-around, a single person's accomplishment in a single event, such as in the marathon, or a single person's accomplishment in multiple events, such as the pentathlon. In essence, adding and comparing based on gold medals is invalid to decide who is the better athlete.

The challenges within Scope 3 arises because LCA- and EEIO-based emission factors are different summations of items. This means that each EF carries with it different boundary assumptions. To further complicate matters, different databases of EF values are maintained by various universities, national governments, think tanks, and global institutions (WRI/WBCSD, n.d.). These databases will produce different results. This has caused some industries recommend that organisations should use the same data provider due to variability of methodologies between databases (PCAF, 2020). EEIO tables enables comparisons of industry sectors within an economy, but two economics, such as two nations, might have different IO tables, rendering them unable to be compared (Tukker et al., 2006). To continue with the sporting analogy, each EF is its own Olympic event.

To fix the issue, one can standardise to use only the combustion EF. This maintains MTCO2e as a derived unit because it maintains a power law. This also fixes the boundary issue because the emission counted only when it is added to the atmosphere. The emissions can then be passed along the supply chain when downstream entities purchase a good and additional emissions can be added due to future work. The eLiability system works in this manner (Kaplan & Ramanna, 2021).

The constraint of only using combustion EF implies that the activity data will be constrained to energy-based activities. A commonality across Scope 1, 2, and 3 is that the fundamental activity being measured and counted is the consumption of energy. LCA or EEIO is applied iteratively until all fossil fuel emissions from a physical activity are uncovered. The preponderance of energy measurements makes sense, especially since energy-related emissions now constitute over 76% of all global emissions (ClimateWatch, 2022). Therefore, energy-based activity data will be able to account for the preponderance of global emissions.

4.4. Noncomparability of GHGI via the similarity facet

Comparability studies in financial accounting notes that similar activities should be reported similarly, and different activities should be reported differently (Yip & Young, 2012). However, our analysis will show how this is not the case when using GHGI.

We begin by explaining data quality issues facing generating GHG inventories and methodological tiers used to model emissions. Although created to simplify the burden of data availability, it creates multitude of options for representing an activity. This creates conditions where the same activity can be reported in many ways.

4.4.1. Methodological tiers, based on data quality and availability

The IPCC methodology acknowledges challenges in data access and quality. It recommends a tiered approach, with higher tiers being more accurate than lower tiers. Table 9 depicts the tiers to estimate emissions from stationary combustion. The default approach (Tier 1) uses national consumption statistics as the AD and a default EF derived from international averages. However, EFs are also technology dependant – new power plants with the latest technologies and operating at highest efficiencies can have lower emissions per unit of fuel. A Tier 2 approach would be to use country-specific EF to better reflect the technology available in the nation. Finally, the most accurate data would be to obtain AD and EF data for individual plants, reflecting actual operations and the installed technology. This is the Tier 3 approach.

The GHGP adopts the tiered approach to modelling for Scope 3. Each Scope 3 category has several recommended approaches in descending order of accuracy. Although the reporting organisation can pick any of the methodologies, they are encouraged to use the one with the most accurate data from available resources.

Table 9 Method tiers to estimating emissions from stationary combustion in the IPCC (Garg & Weitz, 2019)

Method tier	Activity data	Emission factor
Tier 1 (*Default*)	National energy statistics	Default EF
Tier 2	National energy statistics	Country-specific EF
Tier 3 (*Most accurate*)	Data from individual plant	Data from individual plant

For example, Table 10 depicts the options available to model *Category 6: Business Travel*. The most accurate model is to derive emissions from fuel consumed. Known as the fuel-based method, this uses energy as the AD – fossil fuels for combustion engines and electric energy for electric vehicles – and multiplies it by either a combustion EF, fuel life cycle EF and/or electricity EF. The distance-based method is considered to be less accurate than the fuel-based method. In this approach, the distance travelled per mode of transportation is added up. The AD might include miles of first-class flights, taxis, boats, and so on. The EF used is based on passengers per mode of travel. Lastly, one can pick the spend-based method. One would total up the market-value of expenditures on travel costs and multiply it by the national EEIO average to determine the emissions.

EFs found from EEIO are bounded by economy-wide averages of a sector. This is due to the method being based on economic and environmental data gathered from national or supra-national statistics.

Table 10 Method tiers for Category 6 Business travel, in descending order of accuracy. Items in light blue are optional to count (WRI/WBCSD, 2013).

Description	Method	AD	EF
Category 6: Business travel This category includes emissions from the transportation of employees for business-related activities in vehicles owned or operated by third parties, such as aircraft, trains, buses, and passenger cars	Fuel-based method (*most accurate*)	• Energy (Quantities of fuel + electricity) • ***Optional***: number of hotel nights	• Combustion EF *OR* fuel life cycle EF • Electricity EF • ***Optional***: EF per hotel per night
	Distance-based method	• Quantity (Distance travelled per mode of transport) • ***Optional***: number of hotel nights	• EF by vehicle and distance • ***Optional***: EF per hotel per night
	Spend-based method (*least accurate*)	• Monetary (Spending)	• EEIO EF
	Optional	• *Life cycle emissions associated with manufacturing vehicles or infrastructure*	

4.4.2. Similar items may be reported differently

Emission factors, being calculated from LCA, have embedded boundary assumptions, and an entity has the choice of which EF to use. This can create methodological differences for the same activity. Although each of the three methods in Table 10 model the same activity, the choice of EF changes the boundaries. First, the reporting organisation can choose between combustion EF and the fuel life cycle EF. Combustion EF only takes into consideration the emissions of the fuel itself while the life cycle EF also includes the cradle to gate emissions. Further, both the fuel-based and distance-based methods allow for optional counting of emissions for hotel night stays. The spend-based method would then include economy-wide effects rather than merely organisational effects. Finally, it is also optional to include the life cycle emissions associated with the manufacturing of the vehicle or infrastructure in addition to any of these options.

The options of EFs presents a challenge to the similarity facet. When reporting GHG emission due to business travel, it becomes difficult to determine whether the difference in emissions is due to operational decisions or accounting choices. For example, there is first a choice of whether to include the emissions due to hotel stays. There is also a choice to include life cycle emissions of manufacturing vehicles. Additionally, there are choices for which EF to use. This creates boundary challenges, as each EF implies different boundary assumptions. Combustion EF stays within the entity's boundary, a cradle to gate EF represents the value chain, and an EEIO EF represents the broader economic impacts.

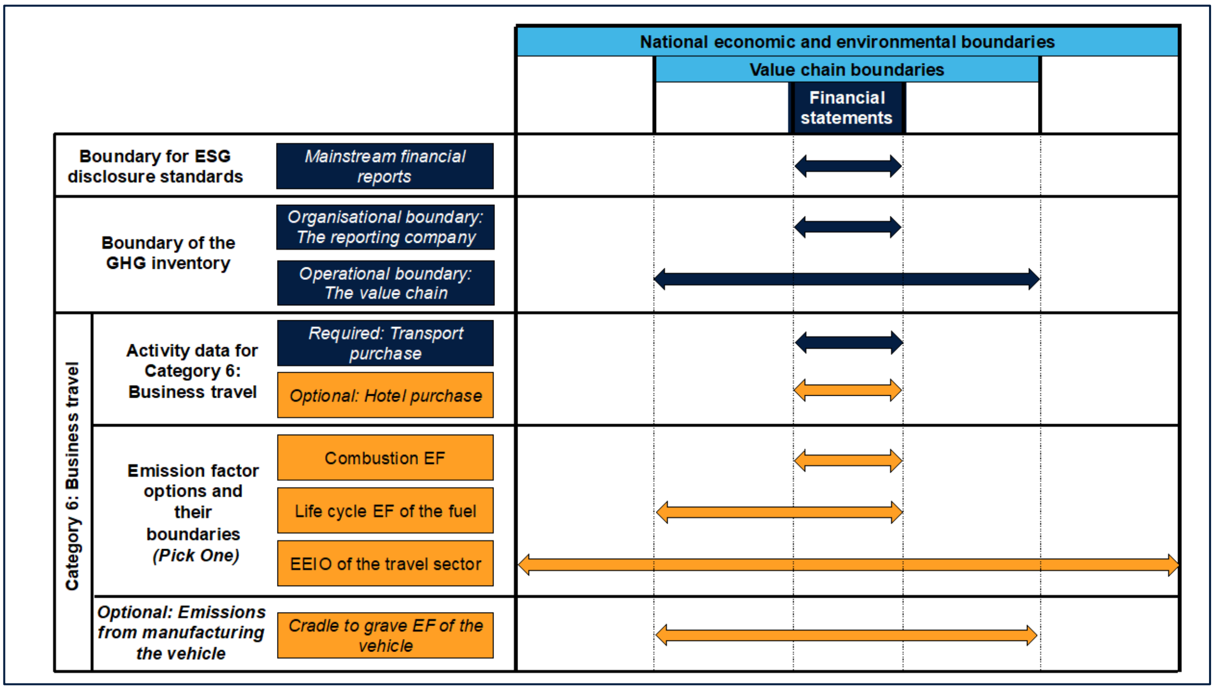

Figure 12 Differences in boundaries among emission factor choices (WRI/WBCSD, 2013)**.**

Figure 12 visualizes boundary assumptions amongst emission factors when calculating business travel. Although the activity data, purchased business travel, is within the corporate boundary, the emission factors used may include assumptions that are beyond that boundary. Furthermore, different databases of EFs will also present different values (PCAF, 2020). Thus, differences in emissions could be due to genuine operational changes differences in business travel activities, or a methodological difference between choice of activities, EFs, or EF databases.

4.4.3. Different items may be reported similarly

In financial reporting, one key difference between consumable products and capital goods is their treatment over time. Consumable products are accounted for as an expense or cost of goods sold on the P&L and inventory or capital goods are recorded as an asset in the balance sheet. Depreciation associated with capital goods are recorded on the P&L to signify its usage over time, helping to track when it needs to be maintained or replaced.

The GHGP, however, does not treat capital goods and consumable products differently. In fact, according to the technical standard, “The calculation methods for category 1 (Purchased goods and services) and category 2 (Capital goods) are the same.” Furthermore, the standard states:

> *“For purposes of accounting for scope 3 emissions, companies should not depreciate, discount, or amortize the emissions from the production of capital goods over time. Instead, companies should account for the total cradle to gate emissions of*

purchased capital goods in the year of acquisition, the same way the company accounts for emissions from other purchased products in category 1." (WRI/WBCSD, 2013)

Thus, consumable products and capital goods, which financial reporting considers to be different, are treated the same within GHG reporting.

4.4.4. ISO standards has similar challenges to the GHGP

As ISO 14064 also uses the LCA system, many of the challenges are the same. It uses a functional unit and system boundary, thereby subject to the same EF issue of value chain counting. The financial transactions represented by the activity data is not a complete count of all transactions on the reporting organisation's P&L. It also takes a tiered approach to data quality, with instructions for a best, intermediate, and minimum scenario. Lastly, it suggests the use of several EFs, each with different boundary assumptions.

We analyse whether like items are reported similarly and unlike items reported differently using the ISO standards. We analyse Category 9 Purchased Products and Category 10 Capital Equipment within the ISO system, as depicted in Table 11.

The AD is a count of the purchases of either products or capital. The best scenario AD is when the exact amount is known. The minimum scenario for products is based on the monetary value of purchases while that for capital equipment is based on the categories of capital goods. The EF procedure used for purchased products and capital equipment are the same. The best scenario asks for a cradle to gate EF that is provided by the supplier using ISO 14067. If that is not possible, one should use an EF from a recognised database. As these databases have different assumptions, one should report what stages the database uses.

The boundary choices available to the reporting organisation means that the same activity does not necessarily have to be reported similarly. The emissions for products can count the upstream (cradle to gate), only between the supplier and the reporting organisation (gate to gate), or the entire value chain (cradle to grave).

Also, different activities do not have to be reported differently. ISO acknowledges that capital good has an extended lifetime and is not sold to other organisations. It suggests three options for how to handle the time value of GHG: (1) apply the organisation's financial accounting rules to ensure consistency with financial reporting, (2) amortise the emissions based on the lifetime of the equipment, or (3) take full account of the emissions in the year of acquisition. Thus, if the reporting organisation choses option (3), purchased products and capital equipment will be reported similarly.

Table 11 Method tiers for purchased products (ISO Category 9) and capital equipment (ISO Category 10) (BSI, 2013)

Recommended approaches to ISO/TR 14069 Category 9 - Purchased Products			
	Method	**AD**	**EF**
Category 9: Purchased products Indirect emissions from ***purchased*** products are emissions from goods and services brought into the organisation.	Best Scenario	Exact physical amount (weight, volume, number of units)	• Cradle to gate EF specific to the supplier, based on ISO 14067 • Use national or international databases for EF. Report the stage of EF: ○ Cradle to gate, ○ Gate to gate, or ○ Cradle to grave
	Intermediate Scenario	Estimate based on a mix of parameters, taken from best and minimum scenarios	
	Minimum Scenario	Monetary value of contracts	
Recommended approaches to ISO/TR 14069 Category 10 - Capital Equipment			
	Method	**AD**	**EF**
Category 10: Capital equipment This category includes all upstream emissions from the production of capital goods ***purchased or acquired*** by the organisation.	Best Scenario	Number of equipment is site specific and known	Use same EF as in Category 9
	Intermediate Scenario	Disaggregate assets by date of acquisition, life time, materials, weight, volume, etc.	
	Minimum Scenario	Only an estimate of capital equipment life is known. Disaggregate by category of capital goods	

In summary, within the ISO system, similar items may be reported differently, and different items can be reported similarly.

4.4.5. Insights from the similarity facet

Both the GHGP and ISO systems of classifying GHG categories can result in similar items being reported differently and different items being reported similarly. The problem is two-fold. First, the available options of methodology results in uncertainty of emission factors were used in the models. Second, each emission factor has its own embedded boundary assumption.

Unless the reporting organisation discloses their methodology, it is unclear what assumptions are being used for the model of emissions. Yet, even if an organisation discloses their assumptions, it does not increase comparability because it only verifies that the firms used different boundary conditions (Stanny, 2018).

5. Discussion: Evaluating some approaches to improve comparability

Some solutions have been proposed to address comparability between entities, however, this section shows that they have been insufficient. Figure 13 depicts the options for comparing an entity's emissions. One can compare entities by the MFF or by their GHGI. We have already shown why we cannot compare based on GHGI.

One approach is to define the organisational boundary as the same as the mainstream financial filings (MFF) as an attempt to remove variations of boundary definition. As shown in Table 12, most ESG disclosures will make this declaration. However, the ESG disclosure standards will still require disclosure of GHGI, which utilises an operational boundary. This operational boundary is still set at the discretion of the reporting entity. A second approach is to limit disclosures to Scope 1 and 2. However, Scope 1 and 2 are only single line-items of the total corporate GHG emissions. Although the metrics might be comparable, they do not tell the full story of total corporate emissions, creating opportunities to shift emissions out of the corporation's control.

This section begins by analysing the relational logic of categories within the MFF. After that, we show that we show that GHGI is not a complete count of all emissions-related activities within the MFF. This means that using the MFF as a boundary condition, or selectively picking a subset of GHGI, will result in an undercount of an entity's GHG inventory.

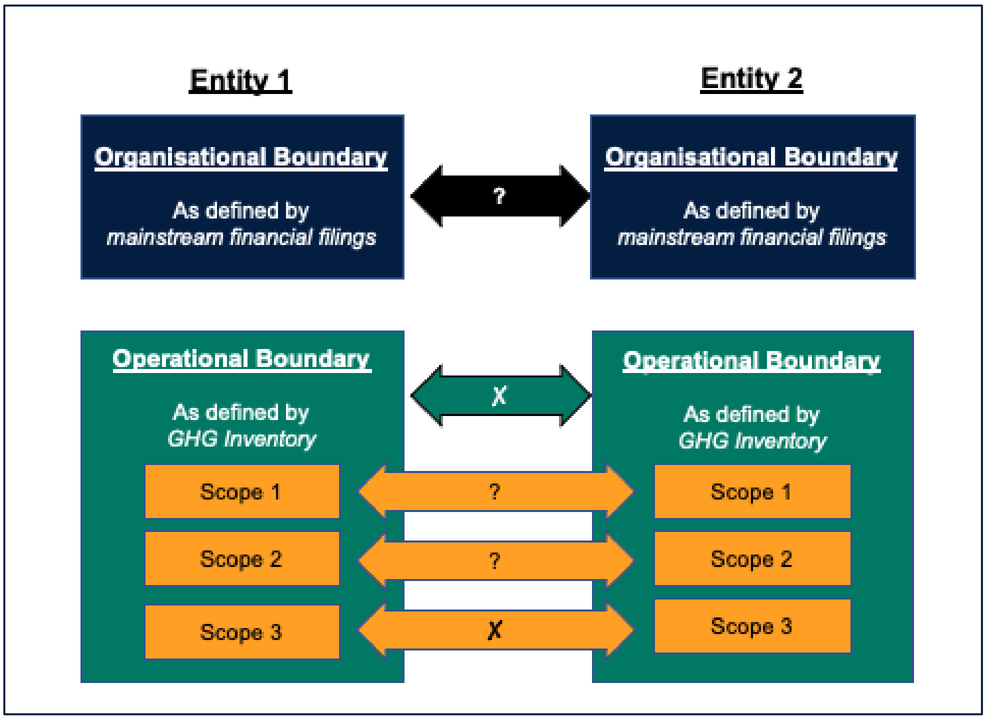

Figure 13 Options for boundaries when comparing emissions across entities.

Table 12 Reporting boundaries of disclosure standards

ESG DISCLOSURE STANDARDS			
Standard	**Boundary**	**Reference**	**Document**
CDP	GHG Inventory	C0.5	CDP Climate Change 2021 Questionnaire (CDP, 2021)
CDSB	Same as mainstream financial filings	REQ-07	Framework for reporting environmental & climate change information (CDSB, 2019)
IR	Same as mainstream financial filings	3.31	International <IR> Framework (IIRC, 2021)
ISSB	Same as mainstream financial filings	Paragraph 19	General requirements for disclosure of sustainability-related financial information prototype (ISSB, 2021c)
SASB	Same as mainstream financial filings	3.0	SASB Standards Application Guidance (SASB, 2018e)
TCFD	Same as mainstream financial filings	1. Background	Implementing the recommendations of the task force on climate-related financial disclosures (TCFD, 2021b)
GHG EMISSION METHODOLOGIES			
Protocol	**Boundary**	**Reference**	**Document**
GHGP	GHG inventory boundary	Chapter 3 and chapter 4	A Corporate Accounting and Reporting Standard
ISO 14064-1	GHG Inventory	5.1 and 5.2	ISO 14064-1

5.1. Relational logic of the mainstream financial filings

The mainstream international financial filing is based on financial reporting standards, as managed by the IAS. The IAS defines a reporting entity as “an entity that is required, or chooses, to prepare financial statements. It can be a single entity or a portion of an entity or can comprise more than one entity [3.10]” (IASB, 2018). The reporting system includes the balance sheet and profit and loss statements. These two statements are related via double-entry bookkeeping (DEBK). Although the origin of the system is debated, most generally attribute the first recorded description of the current system to Luca Pacioli who wrote about it as a chapter in a mathematical textbook in 1494 (Sangster, 2016). There is extensive literature regarding the comparability of mainstream financial reports (Barlev & Haddad, 2007; De Franco et al., 2011; Pantić, 2016; Yip & Young, 2012)

DEBK can be thought of as a relational database (Chanphakeo, 2016) between five categories: assets, liabilities, equity, revenue, and expense. With DEBK, each transaction is recorded twice, first as a debit and second as a credit. The relationship of what to debit and credit is depicted in the Master T-Table of Figure 14A. For example, if one makes a sale, the transaction is recorded both as an increase the Credit column of *Revenue* and an increase in the Debit column of cash (an *Asset*). A second example: an accrued expense, such as unpaid invoices, is a debit in the expense category and a credit in the liability category under

(A)
The Master T-Table from
Double-Entry Bookkeeping

	Debit	Credit
Assets	↑	↓
Liabilities	↓	↑
Equity	↓	↑
Revenue	↓	↑
Expense	↑	↓

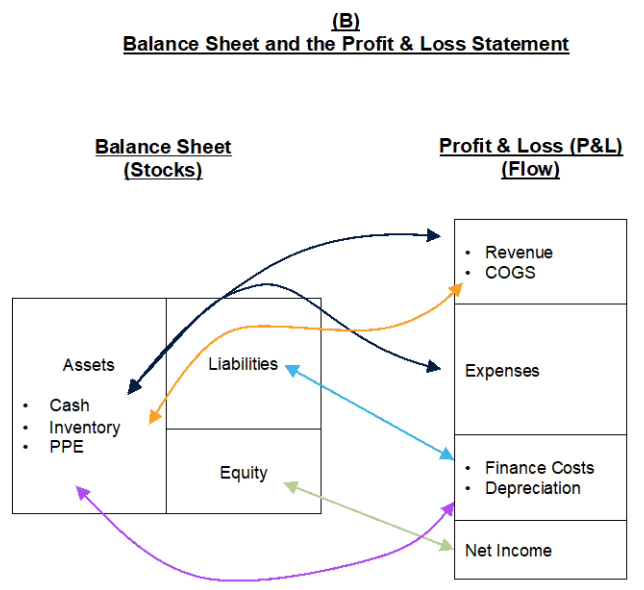

Figure 14 Mainstream Financial Filings include the Balance Sheet and Profit & Loss statement, both created via Double Entry Bookkeeping

accounts payable. This Master T-Table results in several relationships between balance sheet and P&L categories, as shown in Figure 14B. Revenue and expenses affect Cash, costs of goods sold (COGS) affects inventory, finance costs affect liabilities, depreciation affects plant, property, and equipment (PPE), and net income affects equity.

This internal relationship is useful to demonstrate the relationship between what a company owns (stocks) versus what activities a company does (flows). For example, for a manufacturing entity, the P&L statement can record manufacturing for the products that are sold from this period while balance sheets accumulate products that were manufactured but not sold as stocks. As another example, the balance sheet can record a capital outlay made many years ago (PPE), but the P&L can demonstrate the usage of the capital in this period (depreciation). In other words, DEBK can be used to depict the relationship between capital and operational expenditures.

The DEBK relational database also creates a relationship between entities as well. As shown in Figure 15, what is recorded as revenue for the producer entity is recorded as an expense for the buyer entity. As an example, a couch factory will need to purchase steel, wood, and fabric from upstream suppliers to manufacture a couch. These raw materials are recorded by the couch factory as an expense while they are recorded as revenue by the raw material supplier. Similarly, the couch factory would record as revenue the sale of a couch to a hotel. For the purposes of this example, we will assume the hotel records the couch as an expense, and not as a capital purchase.

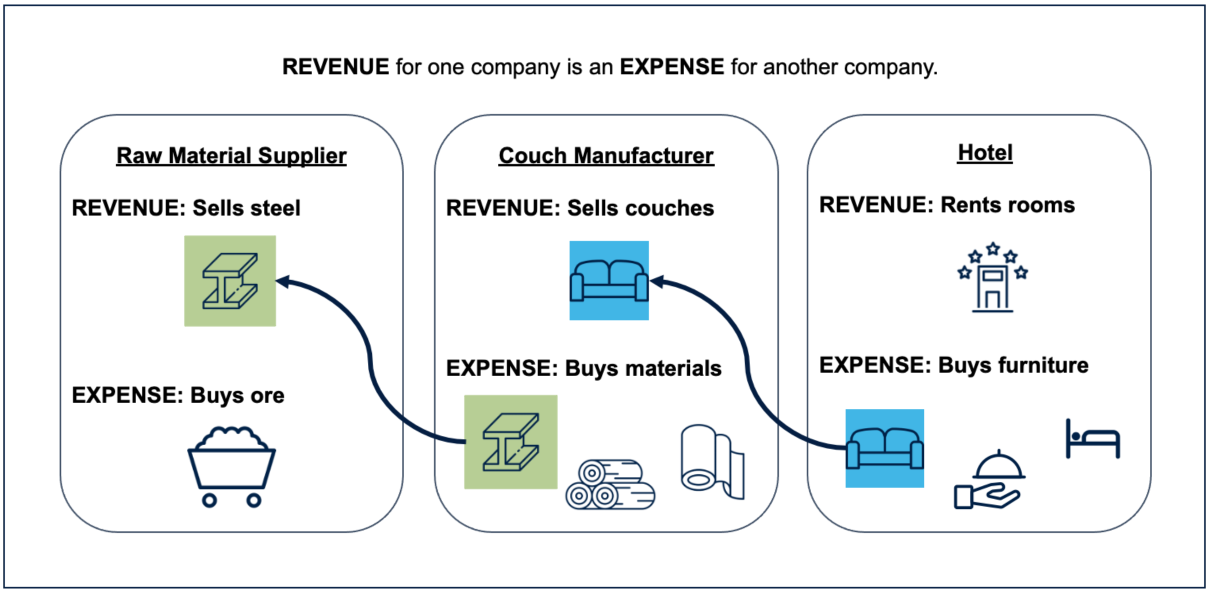

Figure 15 Double-Entry Bookkeeping governs relationships between entities

5.2. Overlaying MFF and GHGI

The GHGP commonly defines a reporting organisation's activity data as a purchase. Purchases are financial transactions recorded on the mainstream financial filings. For example, Scope 1, is described as the quantity of purchased fuel. This could be recorded as a cost of goods or a general administration expense on the Profit & Loss (P&L). Scope 3 Category 4 models the purchased transportation and storage for shipping of products. This is related to the cost of shipping and handling, frequently recorded in the invoice of the purchased product.

Some GHGI categories define the activity data from a source of revenue. For example, Scope 3 Category 11 are emissions that arise from downstream use of a sold product. Auto manufactures, such as GM, will report on the expected tailpipe emissions over expected lifetime of cars sold(GM, 2020). These tailpipe emissions occur only after a customer has purchased a vehicle. Because these are after-sales emissions, the emissions are related to the revenue transactions of the reporting entity. Purchases and sales represent opposite flows of money, yet Scope 3 implies that GHG flows into the reporting organisation under both scenarios. We standardise by converting all transactions into an expense, such that the GHG flows in the opposite direction of money. In this manner, we can assign each GHG emission category to the value chain entity which records the transaction as an expense.

Table 13 Harmonising categories between mainstream financial filings and GHG inventory

	(A) GHGP Category		(B) Mainstream Financials Filings
	(A.1) Scope categories related to the Reporting Organisation's Expense	**(A.2) The transaction that the AD represents**	**The P&L line item for the AD transaction**
Box 1	Scope 1	Purchased fuel	General administration/COGS
Box 1	Scope 2	Purchased electricity	General administration/COGS
Box 1	Scope 3 Category 1: Purchased goods and services	Purchased goods and services	Purchase price of consumables
Box 1	Scope 3 Category 3: Fuel- and energy-related activities not included in scope 1 or scope 2	Purchased fuel	General administration/COGS
Box 1	Scope 3 Category 4: Upstream transport and distribution	Purchased transportation and storage for shipping of products	Purchase price of consumables
Box 1	Scope 3 Category 5: Waste generated in operations	Purchased waste management services	General administration
Box 1	Scope 3 Category 6: Business travel	Purchased travel for employees	General administration
Box 1	Scope 3 Category 8: Upstream leased assets	Leased an asset	Rent
	Scope categories related to a customer's or franchisee's expense (Reporting organisation's revenue)	**The transaction that the AD represents**	**The P&L line item for the AD transaction**
Box 2	Scope 3 Category 9: Downstream transportation and distribution	Customer purchased transportation and storage for shipping of products	Purchase price of consumables
Box 2	Scope 3 Category 10: Processing of sold products	Customer purchased products for further processing	General administration/COGS
Box 2	Scope 3 Category 11: Use of sold products	Customer purchased products for use	General administration
Box 2	Scope 3 Category 13: Downstream leased assets	Customer leased an asset	Rent
Box 2	Scope 3 Category 14: Franchises	Franchise fees	General administration
	Scope categories related to the Reporting organisation's Balance Sheet	**The transaction that the AD represents**	**The balance sheet line item for the AD transaction**
Box 3	Scope 3 Category 2: Capital goods	Purchased capital goods	Plant, property, and equipment
Box 3	Scope 3 Category 15: Investments	Has financial holdings in company or project	Equity or asset
	Scope categories that are not represented on the Reporting organisation's financial statements	**The transaction that the AD represents**	**The P&L line item for the AD transaction**
Box 4	Scope 3 Category 7: Employee commuting	Purchased travel for commuting	N/A
Box 4	Scope 3 Category 12: End-of-life treatment of sold products	Purchased waste management services	General administration

Table 13 Column A depicts the GHGP categories and the transaction that the activity data represents. Column B depicts the financial transaction related to that activity. Further, we group the activities into four boxes. Box 1 are transactions that are recorded on the P&L by the reporting organisation. Box 2 are transactions that are recorded on the P&L by the reporting organisation's customer. Box 3 are emissions found on the balance sheet of the reporting organisation and Box 4 are transactions found on companies that are neither the reporting organisation nor its customers.

Recall the first principle of category theory is that all categories need to have a relational principle to all other categories within the system. If one is defining an entity by their MFF, then one should only count activities that are within the financial statements. However, Table 13 shows that only categories within Box 1 and 3 represent activities made within the reporting organisation. Categories within Box 2 and 4 model emissions from decisions made by other entities.

The second principle is that everything within the boundary needs to be counted. If defining an entity by their MFF, one should count all emissions contained within the entity. However, not every P&L line item is counted – only the line items represented within Box 1 and 3. This indicates that GHGI is an undercount of corporate GHG emissions due to activities within a corporation's operational control.

The second principle also demonstrates why limiting reporting to Scope 1 and/or Scope 2 does not improve comparability between entities. Scope 1 and 2 are specific line-items with an entity's emissions footprint – they are not a complete representation of the company's emissions. Missing is embodied carbon from products that are supplied by upstream suppliers and vendors. Thus, only considering Scope 1 and 2 does not improve comparisons of entire entities, they only inform us of how a company managed those two activities.

5.3. Summary of current approaches to improve comparability

This section overlayed the categories of GHGI and MFF, demonstrating the two systems are incompatible. GHGI is a relative system based on the value chain while MFF is an absolute system based on temporal relationships.

Limiting the disclosure boundary to the MFF does not increase comparability of emissions. GHGI itself spans beyond the MFF, defying the boundary limit. Selectively picking GHG categories that fall within MFF also does not help. This would only represent a subset of emissions due to corporate activities, resulting in an undercount of the entity's emissions.

6. Recommendation: The design principles of a comparable GHG emissions accounting system

We propose design principles of a comparable GHG accounting system. The dimensional analysis preformed showed that the basic activity being measured is energy consumption. Using a combustion emission factor maintains comparability of GHG emissions as it adheres to the entity's MFF boundary. Based on category theory, the new system needs to count the emissions of all transactions within the entity's MFF boundary. Finally, the new system can be evaluated based on the similarity and difference facet.

Table 14 summarizes the necessary conditions for a metric system to enable comparative assertions.

Table 14 Necessary conditions for comparability within a metric system

Condition 1: Similar items need to be reported similarly and different items need to be reported differently. **Analysis technique:** Apply the similarity and difference facet	**Issue for GHGI:** Within the GHGI, it is not possible to tell whether a difference is due to an operational change or an accounting choice.	**Solution:** Separate out the accounting of activity data, which represent operational decisions, with emission factors, which are accounting choices.
Condition 2: Only derived units that represent the same phenomenon have additive and comparative properties. **Analysis technique:** Apply dimensional analysis	**Issue for GHGI:** The unit MTCO2e is not a derived unit and each category of Scope 1, 2, and 3 represent different phenomena.	**Solution:** Combustion emission factors maintain the requirement for being a derived unit. The use of LCA- and EEIO-based emission factors do not.
Condition 3: Only categories that belong to a classification system can be used to make comparative assertions. **Analysis technique:** Category theory	**Issue for GHGI:** By definition, nomenclatures do not give the ability to compare. The GHGI system is a nomenclature because it does not follow the rules for a classification system.	**Solution**: Use an accrual-based system that has a spatio-temporal relationship between the categories.

6.1. Limit emission factors to combustion emission factors as much as possible.

Our analysis showed that energy is the basic activity being modelled in Scope 1, 2, and 3. The importance of energy measurements is validated by the GHGP system. Table 15 depicts whether the energy metric is found in the activity data or the emissions factor in the various methodological tiers of modelling emissions. The most accurate models of emissions are based on direct measurement of energy as the activity data (Table 15 column B). This could be as litres of fuel, electric energy consumption, or modelled Scope 1 and 2 emissions. Conversely, the least accurate emission models utilize the emission factor as a proxy for energy consumed (Table 15 column C).

Energy as a basic measurement to model GHG makes sense. First, 76% of all global emission in 2019 was a consequence of energy-related activities (ClimateWatch, 2022). Second, energy is a universal 'common denominator' that can normalize different physical forms of energy – chemical fuel energy, photovoltaic energy, geothermal energy, hydro electric energy, and so on. This can be extended to renewable energy sources, such as solar, wind and geothermal. The efficiency of conversion from one form of energy to another can be scientifically determined and the GHG emissions of each conversion can be modelled. These conversion models maintain dimensional comparability and additive properties.

Therefore, to minimize uncertainty of emissions in what to count, we recommend the following:

- Standardize on energy as the basic unit being counted.
- Model GHG emissions by using combustion EFs or location-based electricity EFs in order to adhere to the entity's boundary, as defined by the mainstream financial filings.
- Record and report the EFs used, along with any other assumptions, to aid in understanding how the energy was consumed.

Table 15 High and Low tier models of the Scope 3 Categories. The location of energy is highlighted in blue (WRI/WBCSD, 2013).

(A) Scope 3 Category	(B) High tier (most accurate)			(C) Low tier (least accurate)	
	(B.1) Unit of AD	(B.2) EF boundary		(C.1) Unit of AD	(C.2) EF boundary
Category 1 (Purchased goods and services)	kg	cradle to gate of product		$ value	cradle to gate of product
Category 2 (Capital goods)	kg	cradle to gate of product		$ value	cradle to gate of product
Category 3 (Fuel- and energy-related activities not included in scope 1 or scope 2)	kWh (as a quantity)	upstream EF = life cycle EF - combustion EF		kWh (as a quantity)	upstream EF = life cycle EF - combustion EF [Using grid averages]
Category 4 (Upstream transport and distribution)	litres fuel + kWh	fuel EF, electricity EF with optional cradle to gate of fuel		$ spent market value	cradle to gate EF per economic value (inflation adjusted)
Category 5 (Waste generated in operations)	Scope 1 and 2	N/A		tonnes	Average EF per waste disposal
Category 6 (Business travel)	litres fuel + kWh + nights	life cycle EF, electricity EF with optional EF per night		$ spent market value	cradle to gate EF per economic value (inflation adjusted)
Category 7 (Employee commuting)	litres fuel + kWh	life cycle EF, electricity EF		vehicle-km	EF by vehicle, mass, and distance
Category 8 (Upstream leased assets)	Scope 1 and 2	N/A		m^2	average EF by m2
Category 9 (Downstream transportation and distribution)	litres fuel + kWh	fuel EF, electricity EF with optional cradle to gate of fuel		$ spent market value	cradle to gate EF per economic value (inflation adjusted)
Category 10 (Processing of sold products)	litres fuel + kWh	emission factors for fuel		kg	average EF for downstream process OR life cycle EF of final product
Category 11 (Use of sold products)	kWh	fuel EF, electricity EF		N/A	N/A
Category 12 (End-of-life treatment of sold products)	kg	average EF per waste treatment (at grave)		N/A	N/A
Category 13 (Downstream leased assets)	Scope 1 and 2	N/A		m^2	average EF by m^2
Category 14 (Franchises)	Scope 1 and 2	N/A		m^2	average EF by m^2 (or EF by asset type)
Category 15 (Investments)	Scope 1 and 2	N/A		$ Revenue or $ Costs	EEIO by $ Revenue or $ Costs

6.2. Create a classification system for energy

The classification system used to categorize energy also needs to be designed for comparability. We apply the three properties identified by Bowker and Star to categorize energy and emissions accounting.

6.2.1. The system needs to have a spatio-temporal classificatory principle.

The GHG inventory is based on an LCA classification system. The relational logic between categories is spatially designed, with upstream and downstream relative to the position of the reporting company. Within accounting literature, time can be passed, where it is linked between two tasks, or spent, where tasks are synchronised by periodic reporting (Quattrone, 2005). Within LCA, time is passed as a consequence of a sequence of events, regardless of how long has passed in between. On the other hand, mainstream financial filings, through accounting systems, synchronise events into set frequency of reports, recording events that did occur, or are anticipated to occur. MFF categories are related by past-present-future of the balance sheet, the profit and loss statement, and the financial *pro forma*, or models of future scenarios.

The difficulty of representing a periodic temporal relationship for GHGI results in difficulty in modelling time-based scenarios. For instance, some researchers have found that there was no consensus for the time horizon, an assumption which can dramatically change LCA outcomes (Lueddeckens et al., 2020). Yuan pointed out that the data used for LCA frequently have temporal differences and merely summing them up can create inaccurate results (Yuan et al., 2015). A further challenge is to model the time differences of feedback loops. Some resources, such as wind and solar, regenerate instantly. Biotic resources can take several hundred years, and fossil fuels take geological timeframes to replenish and regenerate (Klinglmair et al., 2014).

The difficulty of representing periodic temporal relationships in GHGI can be demonstrated with this thought experiment. Naively, one could assume that Scope 1 evolves into Scope 2 and then into Scope 3. That is not the case. We can visualize the temporal challenge by examining an example depicted by the Scope 2 Guidance (Sotos, 2015), modified for demonstration purposes in Figure 16. The fuel producer, at the beginning of the value chain, needs to account for Scope 1 and Scope 3 while the energy consumer, at the end, should be reporting Scope 2 and Scope 3.

Moving through the value chain also represents a passage of time, as no two steps occur simultaneously. The emissions of the power generator beings as Scope 3 before being considered Scope 1. Then it becomes Scope 3 and ends as Scope 2. This demonstrates that the Scope 1, 2, and 3 system does not describe a temporal relationship.

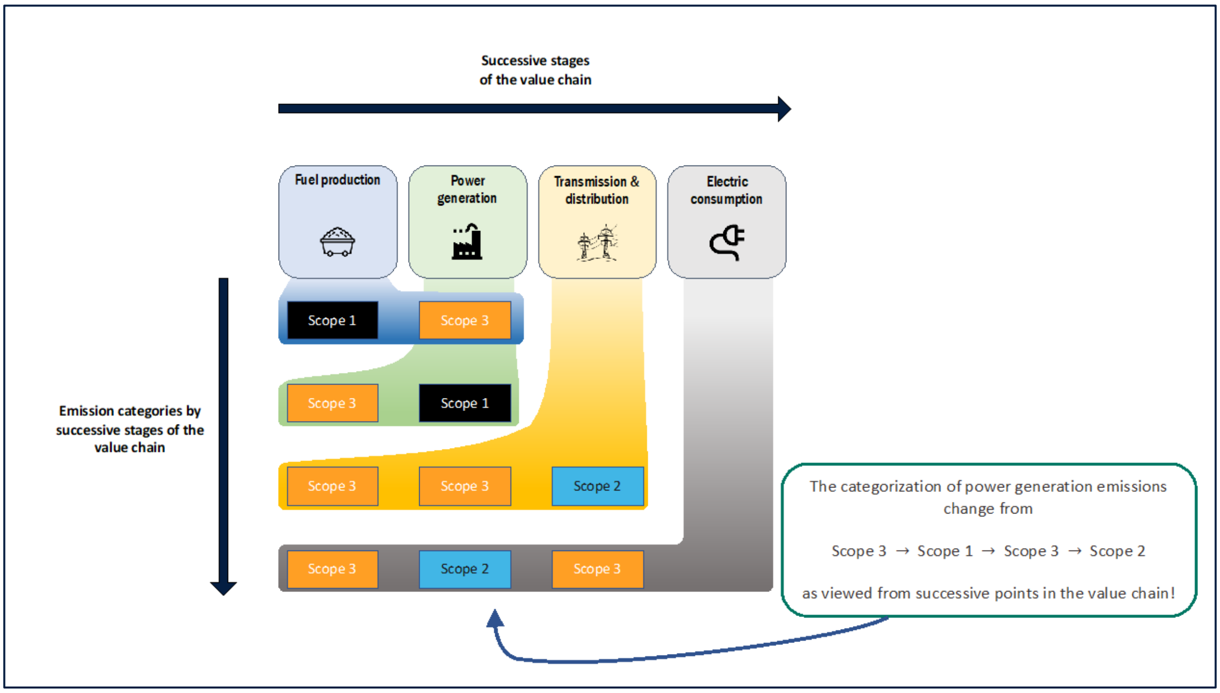

Figure 16 How Scope 1, 2, and 3 evolve through time in the value chain

This event-based temporal relationship means it is difficult to understand how embodied energy and embodied GHG accrues into products and services over periodic time of financial accounting. A periodic time-based framework that is based on double entry accounting would be able to easily support efforts to account for both stocks and flows of GHG through an entity. Therefore, to account for operational and embodied energy, we recommend:

- Adhere to the principles of classification systems.
- The new classification system used for GHG emission must use a spatio-temporal relational logic between its categories.
- The categories should enable the periodic reporting of emissions by using an accrual-based system.
- Enable the modelling of the time-value of GHG and time-value of energy.
- Use a double-entry bookkeeping accounting system to enable the periodic reporting of GHG inventory.

6.2.2. The system is complete: Count emissions of all transactions

Undercounting of emissions occurs within GHGP because not all of the emissions of every financial transaction is considered. Furthermore, the GHGP methodology permits the setting of materiality threshold to determine if an item is counted and what's not. Although GHGP does not set a threshold, it encourages reporting organisations to set a significance threshold for themselves (WRI/WBCSD, 2004). These thresholds, when rolled up across a supply chain, can introduce large errors into estimations. Recall that truncation error in LCA studies can be as high as 50% (Suh et al., 2004).

A complete system would need to account for the GHG found within every transaction, not just the high intensity ones. Some sectors, such as the real estate sector, aspires to account for all emissions associated with their activities (BPP, 2020). Further research is required for the completeness of energy and emissions counting within all corporate activities to support these goals. Therefore, to eliminate undercounting, we recommend:

- Count the emissions of every financial transaction, not just the ones deemed above a certain threshold.
- Notate the categories that use estimates or models as opposed to measured data.
- Research how to improve accuracy, transparency, and data quality of categories derived through estimates or models.

6.2.3. Everything is counted only once (the categories are mutually exclusive)

Scope 3 was designed intentionally with double counting across the value chain. It attempts to capture the embodied GHG that is passed down the value chain, hence one company's Scope 3 is another company's Scope 1 or 2. However, the current system leaves ambiguous what was embodied, by whom, and how was the embodied GHG passed downstream. Thus, there can be systemic over-counting based on how emissions are modelled.

The over-counting is not an issue for consistency purposes, or for the tracking of a company's performance over time. However, it does create a challenge when comparing entities or mobilizing multiple stakeholders to take action, such as target setting (WRI/WBCSD, 2004). Therefore, to ensure all emissions are only counted once, we recommend

- Separately consider embodied energy and embodied GHG from operational energy and operational GHG.
- Depict how embodied attributes are passed from one entity to the next. For example, this could enable the labelling of 'energy facts' onto products that are being purchased.

6.3. The new system should adhere to the similarity and difference facet

Accounting researchers define comparability as the ability to tell similarities and differences between two objects. Any new GHG accounting system should be evaluated via the similarity and difference facet. Namely, the new accounting system needs to make similar items more similar without making different items any less different. Therefore, we recommend

- Evaluate any new GHG emission accounting system with the Similarity and Difference Facet.

7. Summary and future work

We performed a critical analysis of GHG emission metrics to demonstrate their noncomparability between multiple companies. We first mapped ESG standards to their sources for GHG metrics. This showed that all emission standards are based on the GHG Protocol either directly or indirectly. The GHG Protocol is based on LCA methodology, which is known to be noncomparable and does not enable cause-and-effect decision-making.

We conducted a dimensional analysis of MTCO2e, the unit used to report Scope 1, 2 and 3. This analysis separated out what is being measured from what is being modelled. We find that the three models measure energy, yet model different phenomena. Scope 1 is a unit conversion of energy consumption to GHG emissions. Scope 2 is an allocation of the utility's Scope 1. Scope 3 consists of fifteen categories, with each category being its own accounting system. We conclude that MTCO2e is not a derived unit, therefore does not maintain comparative or additive properties.

Scope 1, 2, and 3 are part of the GHG inventory, and we analysed the GHGI using the similarity and difference facet. We found that similar items can be reported differently, and different items can be reported similarly. Thus, the GHGI accounting system is not able to be used for comparisons between entities.

ESG standards have tried improving comparability by asking entities to follow the boundaries of their mainstream financial filings while reporting their GHG inventory. This is insufficient because GHGI are not comparable themselves. Another approach is to limit disclosures to only Scope 1 and 2. This is also insufficient because picking a subset of emissions does not improve the comparability of the entity as a whole.

Finally, we recommend design principles for a comparable emissions classification system. We recommend counting the unit that is being measured – energy consumption. We recommend converting energy into GHG emissions by using the combustion emission factor. This ensures that the measurement stays within the boundary of the reporting entity. We also recommend using a double-entry bookkeeping system to synchronise GHG-related activity into reporting periods.

We leave for future research what categories are needed but suggest that the relational logic of the categories needs to be spatio-temporal so that the time-value of GHG emissions can be modelled. We recommend that there needs to be a mechanism to pass embodied carbon attributes downstream. Further research is needed to determine how to categorize financed emissions. Although energy-related emissions cover 75% of all GHG, emissions from agricultural sources, land use changes, and industrial activity will also need to be categorised in the future.

Procedures will need to be developed for managing supply chain uncertainty. We recommend improving accuracy and completeness only after a classification system is created. In this way, one can improve comparability as well as data quality at the same time. Therefore, we recommend future research on issues with supply chain certainty, energy emissions per product unit, data transparency and accuracy.

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