

**Investigating compatibility between physical greenhouse gas emissions accounting  
and general-purpose financial statements**

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To my mom



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## **Abstract**

This thesis identifies greenhouse gas (GHG) accounting as an emerging field that sits at the intersection of financial accounting and life cycle assessment. This research advances knowledge of how to align the two disciplines, creating impact in improving decision making for achieving a net zero economy. The thesis identifies a gap: (1) primary users of financial reports require a temporal presentment of financial data and (2) contemporary greenhouse gas (GHG) accounting lacks temporal characteristics. The current incompatibility calls into question a fundamental assumption of the climate finance field, that GHG accounting values can be used to make financial decisions. First, I performed a rapid systematic review of 102 GHG accounting standards to find that all standards are based on the GHG Protocol system. Second, I analysed the GHG Protocol for the ability to make comparative assertions between entities, a primary use case for financial decision making. In analysing the information architecture of the GHG Protocol and conducting an empirical analysis of corporate GHG data, I conclude that the lack of temporal characteristics prevents the GHG Protocol from being used to make comparisons. Third, the thesis proposes a solution, general-purpose life cycle assessment (GP-LCA), which introduces a temporal information architecture into GHG accounting aligning it with financial accounting. In using empirical data from a real estate project, I show how GP-LCA can mediate information transfer between financial accounting and the GHG Protocol. Finally, I research climate-aligned decision making in a real estate project by forecasting physical GHG emissions using GP-LCA and cost of damage using financial accounting. The results show that decisions diverge depending on the accounting system being used, calling into question the use of financial assumptions to manage physical flows and physical outcomes. In summary, the thesis demonstrates the importance of temporal alignment of business activities with GHG emissions. Today, the two systems can produce opposing results as to what actions are climate aligned. The result of this thesis opens the door for further research to improve alignment of environmental and financial indicators for climate finance decisions.



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## List of Abbreviations

AD	Activity data
AFOLU	Agriculture, forest, and other land use
aLCA	Attributional LCA
BSI	British Standard Institution
BSOL	British Standards Online
BTU	British thermal unit
Carbon	Used interchangeably with GHG
CBAM	Carbon boarder adjustment mechanism
CBS	Carbon balance sheet
CDP	An organization formerly known as the Climate Disclosure Project
CDSB	Climate Disclosure Standards Board
CEE	Collaboration for Environmental Evidence
CEI	Cost effective indicator
CFS	Carbon flow statement
CH <sub>4</sub>	Methane
cLCA	Consequential LCA
CO <sub>2</sub>	Carbon dioxide
COGS	Cost of goods sold
CR&W	Carbon releases and withdrawals statement
CTBO	Carbon take-back obligations
DAC	Direct air capture
DEBK	Double-entry bookkeeping
DEFRA	Department of Environment, Food & Rural Affairs (UK)
DESNZ	Department for Energy Security and Net Zero (UK)
DLCA	Dynamic LCA
EC	Embedded carbon dioxide

ECB	European Central Bank
EEIO	Environmentally extended input-output models
EF	Emission factor
EPA	Environmental Protection Agency (US)
EPC	Energy performance certificate
EPD	Environmental product declarations
ESG	Environmental, social, and governance
ETS	Emissions Trading Scheme
EU	European Union
FASB	Financial Accounting Standards Board
FCA	Financial Conduct Authority
GAAP	Generally accepted accounting principles
GDP	Gross domestic product
GFANZ	Glasgow Financial Alliance for Net Zero
GHG	Greenhouse gas (used interchangeably with 'carbon')
GP-LCA	General-purpose LCA
GPFS	General purpose financial statements
GRESB	Global Real Estate Sustainability Benchmark
GRI	Global Reporting Initiative
GWP	Global warming potential
HFC	hydrofluorocarbons
IAM	Integrated assessment models
IASB	International Accounting Standards Board
IASC	International Accounting Standards Committee
IC	Intrinsic carbon dioxide
IEA	International Energy Agency
IFRS	International Financial Reporting Standard

IO	Input-output models
IOSCO	International Organization of Securities Commissions
IPCC	Intergovernmental Panel on Climate Change
IPPU	Industrial processes and product use
ISO	International Organization for Standardization
ISSB	International Sustainability Standards Board
kg CO <sub>2</sub> e	Kilogram CO <sub>2</sub> equivalents
kWh	Kilowatt-hour
LADWP	Los Angeles Department of Water and Power
LCA	Life cycle assessment
LEED	Leadership in Energy and Environmental Design
LRVC	Long-run variable cost
MBS	Methane balance sheet
MJ	Megajoule
MQ	Measurement quantum
MR&W	Methane release and withdrawal statement
N <sub>2</sub> O	Nitrous oxide
NBS	Nitrous oxide balance sheet
NF <sub>3</sub>	Nitrogen trifluoride
NPV	Net present value
NR&W	Nitrous oxide releases and withdrawals
OC	Operational carbon dioxide
P&L	Profit and Loss Statement
PCAF	Partnership for Carbon Accounting Financials
PFC	Perfluorocarbons
PPA	Power purchase agreement
PPE	Plant, property, and equipment

PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
R&W	Releases & Withdrawals
RGGI	Regional Greenhouse Gas Initiative
RICS	Royal Institution of Chartered Surveyors
SASB	Sustainability Accounting Standards Board
SBTi	Science Based Target Initiative
SCC	Social cost of carbon
Scope 2L	Location-based Scope 2
Scope 2M	Market-based Scope 2
SEBK	Single entry bookkeeping
SEC	Securities and Exchange Commission
SEEA	System of Environmental Economic Accounting
SETAC	Society of Environmental Toxicology and Chemistry
SF <sub>6</sub>	Sulphur hexafluoride
SIC	Standard Industrial Classification
SPC	Shadow price of carbon
SRI	Socially responsible investing
TC	Total carbon
TCD	Total cost of damage
TCFD	Taskforce for Climate-related Financial Disclosures
tCH <sub>4</sub>	Metric tonnes of CH <sub>4</sub>
tCO <sub>2</sub>	Metric tonnes of CO <sub>2</sub>
tCO <sub>2</sub> e	Metric tonnes of CO <sub>2</sub> equivalents
TCR	The Climate Registry
TJ	Terrajoules
tN <sub>2</sub> O	Metric tonnes of N <sub>2</sub> O
UK	United Kingdom

UN	United Nations
UNEP	United Nations Environment Programme
US	United States
WBCSD	World Business Council for Sustainable Development
WLCA	Whole life carbon assessment
WRI	World Resources Institute



## Chapter 1. Introduction: It's about time

*If you can't describe what you are doing as a process, you don't know what you're doing.*

- W. Edwards Deming (Attributed)

It has been well established that the release of anthropogenic greenhouse gases (GHGs) has been the driving force behind climate change (Myhre et al., 2013), making climate finance - a broad term indicating the public and private financial sector's involvement in supporting mitigation and adaptation actions – crucial in addressing climate change (CPI, 2018). Climate finance as a field presupposes that investors can make rational investment choices to counter the negative climate impact of an entity (ISSB, 2023). After all, climate change presents an urgent problem of global concerns for many sectors, presenting broad implications for the financial sector. Rising physical climate risks are projected to increase damage to physical assets, reduce production capabilities, and increase credit risk and insurance losses (Battiston et al., 2021). Overall, global GDP can be depressed by 1 – 3.3% in the short term, and up to 23% by 2100 (OECD, 2015) by these climate impacts.

Personally, I have witnessed the effects of climate change during my lifetime. I have a strong association with the California coast, having grown up in Monterey within walking distance of the tide pools. The starfish that I used to delight in seeing are now scarce due to sea star wasting disease (Miner et al., 2018). The fishermen I grew up with have shifted to catching squid, an animal that can tolerate the lower oxygen that is now found in the region's water (Monterey Bay Aquarium, 2024). The kelp forest off the coast have mostly disappeared, falling victims to a population explosion of purple sea urchins, a species that thrives in

today's marine environment (Mcpherson et al., 2021). In short, climate change is causing shifts in the marine ecosystem (Chavez et al., 2017), drawing a personal urgency to addressing climate change.

Interest in corporate GHG emissions have only increased over this time, with over 90% of the global economy announcing net zero emissions targets (UNFCCC, 2022). Investors are routinely utilising corporate GHG emissions data, one of many climate indicators, 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), creating thematic investment vehicles (PRI, 2016), modifying a firm's valuation (Matsumura et al., 2014), among other activities. In 2024, the market capitalisation of the green economy was estimated to be roughly \$7.1 trillion, expected to grow to \$109 – 275 trillion by 2050 (LSEG, 2024).

Foundational to financial decision making is the ability to compare choices that are spread out over long periods of time (Berk & DeMarzo, 2020). The financial accounting system was designed to support such temporal analysis (Quattrone, 2005), where judgements about present and future decisions are based on knowledge of the past (Chambers, 1989). Tools analyse the trade-off between upfront capital investments against ongoing operational cash flow, such as net present value (NPV), payback analysis, and others (Berk & DeMarzo, 2020). When capital choices are mutually exclusive, the upfront capital investments will lock-in an expected value of returns from ongoing operations for a certain duration. The choices need to be weighed against each other for optimal returns, timing of liquidity events, and other variables.

Yet, as this thesis explores, there lacks tools that weigh the temporality of physical GHG emissions (herein used interchangeably with 'carbon emissions') in climate finance decisions, in a manner that is similar to the principles used in financial accounting. For example, should one invest in building a Passivhaus? The Passivhaus standard is a set of

## **Chapter 1 – Introduction: It's about time**

stringent energy efficiency standards with a lower operational energy threshold, reducing energy consumption, and thereby reducing carbon emissions by roughly 76% (Williams, 2023). However, the additional material needed to insulate the building can increase upfront embedded emissions by roughly 30%. If one is optimising for lower emissions, should one pick the traditional house with lower upfront embedded emissions or the Passivhaus with lower ongoing emission?

Fundamentally, this decision is about time. When is the right time to build? How long to use it? When should it be replaced? The Passivhaus scenario is exemplary of the type of temporal trade-off choices facing climate finance sector. Are the increased upfront emissions of construction worth it for the decrease of ongoing future emissions? In another example, corporate transition plans are a set of short-, medium-, and long-term strategies of how entities will achieve net zero ambitions, including their investment strategies for supporting decarbonising the economy (TPT, 2023). Implicit in these plans are what are companies investing in *today* to prepare for a low carbon *future*. Which increases in emissions today are aligned with achieving net zero in the future? A second type of temporal question examines the duration of use, as whether an item is the lower emissions option is dependent on the time horizon of the analysis (Lueddeckens et al., 2020). When will the increased upfront emissions of a Passivhaus be worth it? The demolition of a Passivhaus before it becomes the lower carbon option could negate the good intentions of prior managers. Thus, some items may become the low carbon option only after a certain time period, locking in a duration of use and limiting the future manager's optionality. Finally, should one emit upfront emissions today or delay their emissions into the future? For example, the UK is legally mandated to achieve net zero emissions by 2050. As part of that strategy, the electric grid is projected to decarbonise by 55% between 2025 and 2030 (UK DESNZ, 2023). Thus, delaying a project that consumes electricity by five years could theoretically result in lowered

emissions. In all these examples, investors are making a time-based comparative decision. Yet, the current GHG measuring system does not capture such time sensitive decisions.

While corporate decision making is traditionally based on financial accounting data, the increased inclusion of GHG emissions raises the question of exploring the intersection of the two systems. The aim of this research is to study the overlap between the two systems, identify gaps, and propose theoretical frameworks to bridge the gap. The overarching question of this thesis is, "*How can the financial accounting discipline take into consideration physical emissions of GHGs for corporate reporting/decision making?*" The thesis presents four empirical papers that address three sub-questions:

1. What are the gaps between the financial and GHG accounting systems?
2. How can the gaps be bridged between financial and GHG accounting systems?
3. What insights are possible once the gaps are bridged between the two accounting systems?

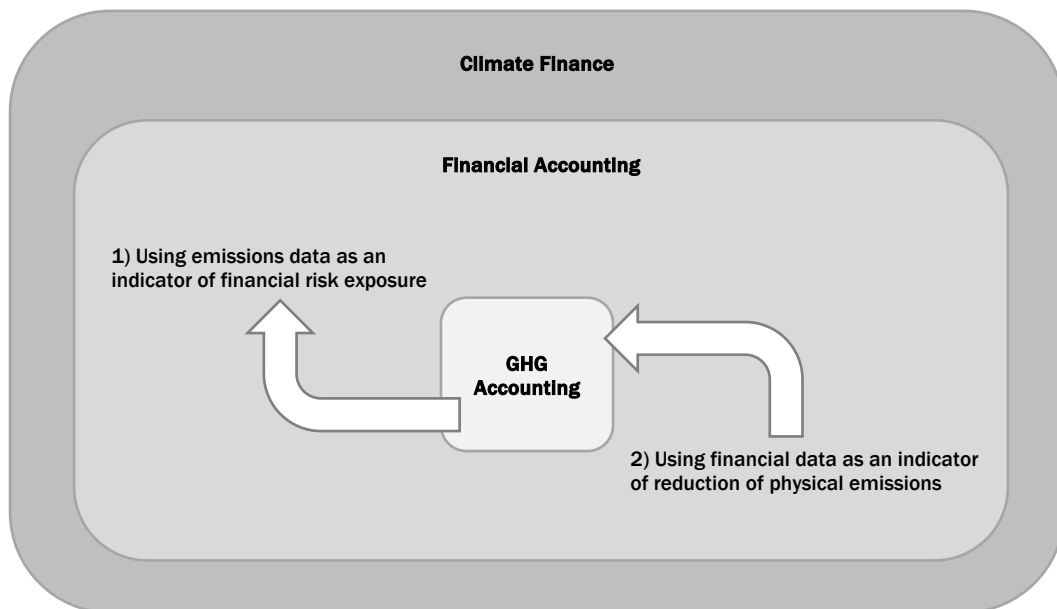
To address the first question, I develop two papers to provide insights into the current system of corporate GHG accounting. The first paper identifies the GHG Protocol as the dominant standard for corporate GHG accounting. The second paper studies the gap between the GHG Protocol and the International Financial Reporting Standard (IFRS), an accounting standard used in 168 countries. My findings indicate that a difference in temporal attributes is a barrier to integrating the two accounting systems. I develop two additional papers, addressing the second question by aligning disclosure data from the past and the third question by aligning models that forecast the future. Thus, I offer fresh insights into GHG accounting by incorporating temporal attributes that are aligned with financial accounting.

## **1.1. Research approach**

Climate finance is a transdisciplinary field, one that crosses academic and non-academic disciplinary boundary, to create new knowledge and practice (Tress et al., 2005). Investment

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decisions rely on data from the financial accounting discipline, which studies monetary flows, and the GHG accounting discipline, which studies physical GHG flows. However, as shown in Figure 1-1, GHG emissions are generally subsumed into financial accounting, and is a subordinate indicator for financial decision making (Dillard et al., 2005). Financial users may incorporate GHG information to enhance financial decision making (Eccles et al., 2011; Matsumura et al., 2014; PRI, 2016), essentially using GHG emission flows to predict future monetary flows. Additionally, investors routinely use GHG emissions as an indicator of future monetary flows (Choi & Luo, 2021), where a higher GHG emissions can reduce future cash flows, thereby lowering a firm’s value. Other financial users make investment decisions that will have an impact on reducing GHG emissions to meet their emission reduction targets (Ko & Prakash, 2024; West & Euler, 2024). GHG emissions are also embedded into efforts to slow or stop the continued release of anthropogenic emissions by being incorporated into climate-related standards (EU Commission, 2023; ISSB, 2023), net zero policies (ISO, 2022; UNFCCC, 2020), and laws (EU, 2022).



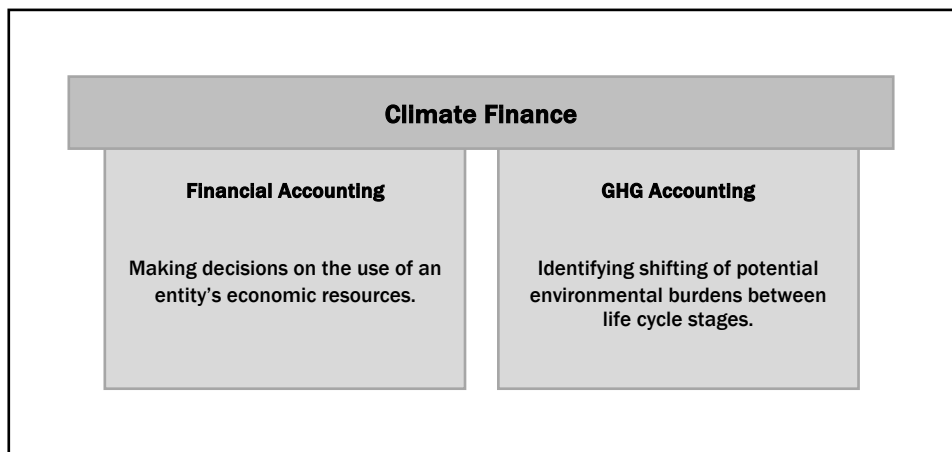
**Figure 1-1** How the climate finance community utilises financial and GHG accounting information today. GHG data is often subordinated into financial accounting, either (1) using GHG data to influence financial decision making or (2) using financial decisions to influence GHG emissions (Source: Author’s creation)

The financial and GHG accounting fields have their own epistemic frame, and several researchers have pointed out discrepancies between the two accounting systems. Within financial accounting the boundary used is the corporate entity, while in GHG Protocol the boundary used is the corporate entity's supply chain (Dong & Srivastava, 2013). Further, within financial accounting, double counting is not permitted but in the GHG Protocol, double counting is commonplace. One manifestation of the difference in boundary is that in GHG accounting, there is systemic under- and overcounting of emissions across the supply chain (Kaplan & Ramanna, 2021). These issues have also underlain studies which conclude that the GHG Protocol does not adhere to the IFRS conceptual frameworks' principles of decision usefulness (Glenk, 2023), calling into question whether the GHG Protocol is fit-for-purpose for corporate decision making. Some has called gone as far as to question what the GHG Protocol is fit-for-purpose for, criticizing it for failing to manage GHG risks, identify reduction opportunities, improve participation in voluntary or mandatory GHG reduction programmes and its relevance (Gillenwater, 2023b) and its relevance to climate mitigation progress. (Marlowe & Clarke, 2022). Researchers have questioned whether GHG metrics can be used by the financial sector to make comparative assertions amongst multiple companies (Andrew & Cortese, 2011). It is obvious that one cannot use chess competition wins to determine a golf handicap. Earning a gold medal in swimming is not a judge of success in the fencing or the ski jump events. A country should not use number of elite athletes as a decision factor into how much to invest in their healthcare system. Each of these metrics are valid in their own context but are invalid when the context changes. If the wrong metrics become institutionalised, then the discrepancies between epistemic frames can prevent actual progress towards achieving sustainability goals (Gray, 2010). Worse, such discrepancies may reinforce business-as-usual and create conditions for un-sustainability (Milne & Gray, 2013).

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There are broad implications for the climate finance community if the GHG accounting system cannot be used to make financial decisions. The ability to make comparative assertions between entities is an enhancing principle of financial decision usefulness (IASB, 2018), and a foundational attribute for making capital allocation decisions (Barlev & Haddad, 2007). If GHG metrics cannot be adopted by financial users, then trillions of dollars of capital that are intended for improving climate outcomes could be potentially misallocated (Chatterji et al., 2016).

Rather than subordinating GHG accounting into financial accounting, I contribute to the discourse by examining the epistemic differences that separate financial and GHG accounting systems, as demonstrated in Figure 1-2. The purpose of general-purpose financial accounting (GPFS) is to support financial decision making. The information is presented using three statements, a statement of position (the balance sheet), a statement of performance (the profit & loss statement), and a statement of cash flow. The content of these statements is governed by the Financial Accounting Standards Board (FASB) in the USA and the International Accounting Standards board (IASB), adopted in 168 national jurisdictions. Meanwhile, the GHG Protocol is a joint project of the World Resources Institute (WRI) and



**Figure 1-2** *Depicting the difference in purpose behind financial and GHG accounting. These differences arise from the different epistemic framing of the two fields (Source: Author's creation).*

the World Business Council for Sustainable Development (WBCSD). The system has roots in the environmental life cycle analysis (LCA) modelling field (Gillenwater, 2023a). The purpose of LCA models are to identify environmental burdens of a product across stages of an entire life cycle, from raw material extraction, energy and material production, manufacturing, use, and end-of-life disposal (BSI, 2020a). The life cycle approach enables identification of shifting of burdens between stages of a product's useful life. LCA is a general approach, able to be applied to any environmental burden, such as energy, water, GHGs, and to any item, including products (BSI, 2020b) and organisations (BSI, 2014). The GHG Protocol adopted the LCA approach for GHG burdens of organisations. It takes an inventory of corporate emissions and presents them in the categories of Scope 1, 2, and 3. Briefly, Scope 1 is an entity's direct emissions from combustion of fossil fuel in operations, Scope 2 is indirect emissions from electric energy consumption, and Scope 3 is all other emissions due from operations.

I use the lens of information architecture to study the epistemology of each system. Information architecture is the study of the structure of how information is formally arranged and organised, whether in a computer database, in a filing cabinet, or in piles of paper on a desk. According to researchers, "Information architecture is a foundation discipline describing the theory, principles, guidelines, standards, conventions and factors for managing information as a resource. It produces drawings, charts, plans, documents, designs, blueprints and templates, helping everyone make efficient, effective, productive and innovative use of all types of information," (Evernden & Evernden, 2003, p1). Importantly, information architecture encodes the epistemological frame, formalising what is to be included and valued while excluding what is deemed unimportant (Bowker & Star, 1999).

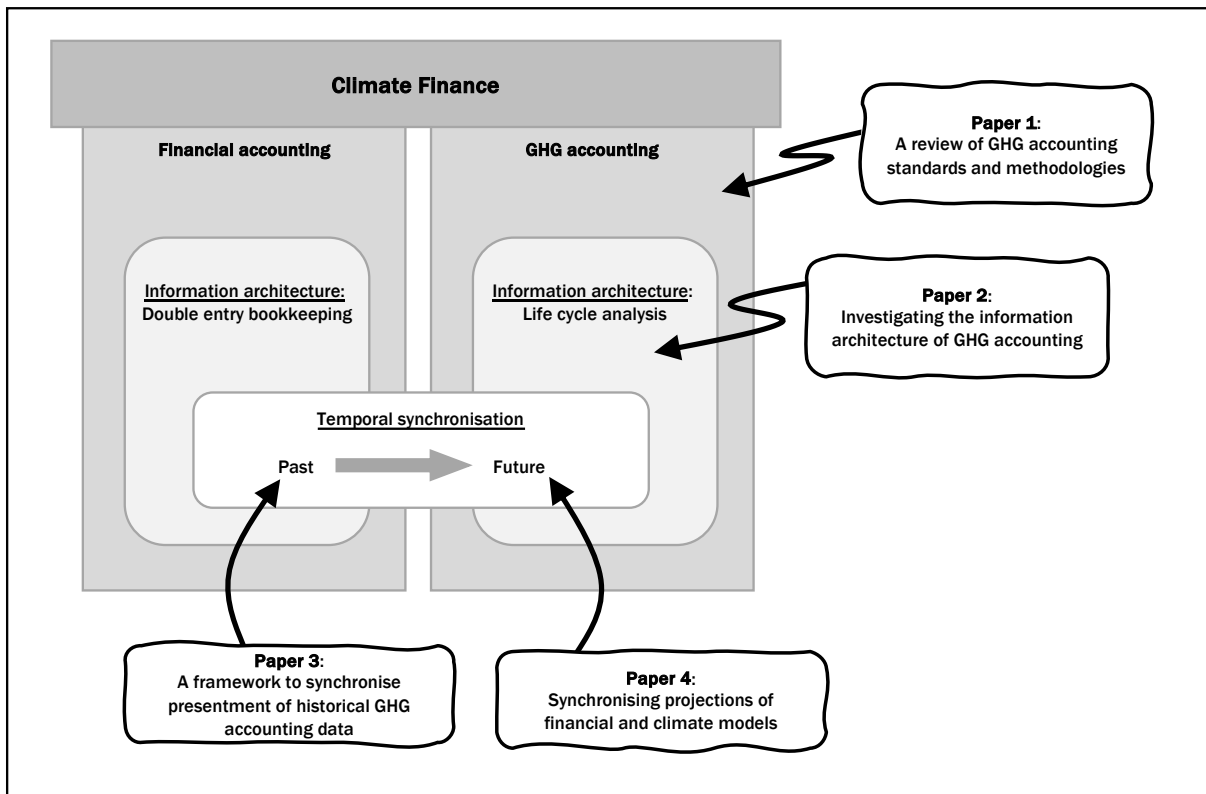
The information architecture of financial accounting is double entry bookkeeping (Chanphakeo, 2016) while that of GHG accounting is LCA. Within the information technologies field, it is well known that using different datasets simultaneously requires

merging the underlying data structures (Dong & Srivastava, 2013). The merging of data, or data integration, is a well-known and well-studied problem in many fields, including systems biology (Krohs & Callebaut, 2007), power systems (Kezunovic & Abur, 2005), data mining (Hernandez & Stolfo, 1998), among others.

## **1.2. Research output**

My thesis presents four empirical papers, with each paper refining the research question and identifying the focal areas for subsequent investigations. The first paper studied the GHG accounting landscape to find that all corporate GHG accounting standards are derivative works of the GHG Protocol. The second paper studied the information architecture of the GHG Protocol to find that it is lacking in temporal attributes. The third paper studied how the financial accounting system accounts for temporal synchronisation and introduces that methodology to GHG accounting. The fourth paper builds on the temporal synchronisation methodology to create models of future scenarios. The links between the four papers are shown in Figure 1-3 and Table 1-1.

Paper one / chapter four asks, “*How many corporate accounting standards for physical GHG emissions are being used by financial users?*” Financial users follow one of two standards, generally accepted accounting principles (GAAP) in the USA or International Financial Reporting Standard (IFRS), in 168 other countries. However, although the GHG Protocol is the dominant GHG accounting standard, there are many standards that are commonly referenced, with The CDP (formerly the Carbon Disclosure Project) accepts values from 69 different standards (CDP, 2023). We conduct a systematic rapid review of GHG accounting standards. Empirically, we gathered 102 standards and performed an archival analysis of the document database of 51 standards. We concluded that all the GHG accounting standards are derivative works of the GHG Protocol. Further analysis showed that the GHG Protocol is



**Figure 1-3** A depiction of the links between papers presented in this thesis. We frame financial and GHG accounting as separate disciplines due to their distinct information architectures, rather than subsume one into the other. Paper 1 and 2 study the GHG accounting field, while Paper 3 and 4 bridge the gap between financial and GHG accounting (Source: Author's creation)

based on the information architecture of LCA. Because of the results of this paper, I was able to focus my subsequent research onto the GHG Protocol.

Paper two / chapter five builds on the finding that the GHG Protocol is the only standard by asking, "Is the GHG Protocol decision useful to primary users of general-purpose financial statements?" As GHG information is increasingly sought after by users of financial statements, our goal is to understand if the GHG Protocol has the information architecture that is compatible with financial decision making. Financial users require the ability to make comparative assertions, an attribute of financial decision usefulness. Comparability is considered by some to be the most important reason for the development of financial statements (Barlev & Haddad, 2007).

Paper 2 took a mixed method approach, performing a comparative analysis of corporate GHG emissions data and an archival analysis of normative conditions for comparability.

## **Chapter 1 – Introduction: It's about time**

Through an empirical analysis of Scope 1, 2, and 3 data for 5,800 companies from the CDP database, we find that 85% of the companies in the dataset make unique assumptions for their GHG inventory. Thus, making comparative assertions of GHG performance between entities is effectively impossible. We then develop normative conditions of comparability from three disciplines, financial accounting, engineering, and social science, to theoretically evaluate the information architecture of the GHG Protocol.

One key finding is the difference in the treatment of time between the two accounting systems. The information architecture of financial accounting is based on double entry bookkeeping (Sangster, 2010), a system where the accounting for time is of central importance (Quattrone, 2005). However, GHG accounting is based on LCA, and it is well known that LCA lacks temporal characterisation, ever since the early days of its development (Lueddeckens et al., 2020). The temporal considerations are lost because the results are a summation of all processes across time to provide a snapshot of potential impacts (Beloin-Saint-Pierre, 2020). The outcome of the research is a set of necessary conditions that information architectures of environmental indicators must satisfy to maintain entity-level comparability. One condition is a synchronisation of temporal activities. The next two papers address the temporal gap.

Paper three / chapter six proposes a methodology to synchronise the temporal activities of GHG and financial accounting. Because financial accounting already uses an information architecture that performs temporal synchronisation, the paper asks, "*Can the information architecture of general-purpose financial statements be adopted to account for physical GHG emissions of a corporation?*" We adopt the normative information architecture of double entry bookkeeping, found in general-purpose financial accounting for financial flows, to create general-purpose life cycle analysis (GP-LCA) for environmental flows. Essentially, GP-LCA is a mechanism to align temporal characteristics of environmental flows with financial flows. We apply the principles of GP-LCA to carbon flows, developing a set of carbon statements with a

carbon balance sheet (CBS) to depict historic emissions, a carbon releases and withdrawal (CR&W) statement to depict current emissions, and a carbon *pro forma* to depict future emissions. We empirically demonstrate its application by presenting the embedded GHG emissions associated with the recently opened Gradel Quadrangle, a mixed-used educational facility located at New College, Oxford. We synchronise the historical GHG and financial information from the construction process, thereby demonstrating how to account for past and current emissions information.

Finally, because the carbon statements are synchronised with the financial statements [paper four / chapter seven](#) asks “*Do forecasts made using GP-LCA and GPFS converge or diverge?*” The paper explores whether additional insights can be gained from aligning the models of physical emissions and financial costs. We use the financial data from the HM Treasury Green Book, that sets the methodology for evaluating the cost effectiveness of UK climate policy interventions, and the physical GHG emissions of the Gradel Quadrangle. Because the Gradel Quadrangle was built to a Passivhaus standard, there was higher upfront embedded emissions and lower ongoing operational emissions, as compared to a counterfactual building (Passivhaus Trust, 2024). In running a payback analysis, we found that the year the Passivhaus became the lower carbon option was not necessarily the year that the Passivhaus became the lower financial option. The payback gap, depending on assumptions, spanned years to decades, where the physical and financial models disagreed. One reason for the divergence is because physical attributes are not discounted while financial costs are. In running a NPV analysis, I found that both models are more sensitive to physical characteristics than financial variables. Both the Passivhaus and the counterfactual conventional building are within one standard deviation of typical embedded and operational emissions value as derived from literature and industrial surveys. The results highlight the importance of relying on measurements to determine whether an emissions intervention is the lower carbon value, rather than rely on modelled assumptions.

Table 1-1 Summary of four papers, and their linkages (Source: Author's creation).

Paper / Chapter	Linkage with other papers	Target journal
<p><b>Paper 1 / Chapter 4 – Greenhouse gas accounting standards: A rapid review</b></p> <p>Broad analysis of the corporate GHG accounting landscape.</p>	<p>In gathering 102 GHG accounting standards and performing an archival analysis 51 standards, I find that all standards are derivative works of the GHG Protocol.</p> <p>The results focused my research efforts onto the GHG Protocol (<a href="#">link to paper 2, 3, 4</a>)</p>	<p>Energy Policy</p>
<p><b>Paper 2 / Chapter 5 – Designing for comparability: A foundational principle of analysis missing in GHG accounting systems</b></p> <p>A study of the information architecture of the GHG Protocol and identifying differences from that of financial accounting.</p>	<p>I use the normative principles of comparability to identify that the GHG Protocol (<a href="#">link to paper 1</a>) and financial accounting differ in their treatment of time.</p> <p>In identifying the key discrepancy within the information architectures, I propose a research agenda to bridge the gap (<a href="#">link to paper 3, 4</a>)</p>	<p>Journal of Cleaner Production</p> <p>Industrial Ecology</p>
<p><b>Paper 3 / Chapter 6 – A reporting framework for general purpose life cycle assessment to align entity-level GHG accounting with general purpose financial statements</b></p> <p>Proposes a method to synchronise temporality of historical activities between GHG and financial accounting systems by introducing periodic emissions reporting.</p>	<p>I incorporate time into GHG accounting (<a href="#">link to paper 2</a>) by applying double entry bookkeeping to GHG accounting. I then develop historical GHG emission statements for a real estate asset.</p> <p>The paper proposes how time can be incorporated into GHG accounting, setting the stage for modelling future projections (<a href="#">link to paper 4</a>)</p>	<p>Journal of Environmental Management</p> <p>Journal of Cleaner Production</p>
<p><b>Paper 4 / Chapter 7 – Divergence of dynamics: Temporal issues between physical carbon emissions and the monetary cost of damage</b></p> <p>Studies divergences of models that predict future physical GHG emission and future cost of damage that arise from emissions.</p>	<p>Building on a periodic GHG accounting system (<a href="#">link to paper 3</a>), I show how models of future physical emissions diverge from models of future emissions-related costs.</p> <p>The results demonstrate the importance of analysing temporality of physical GHG emissions when making decisions on how to achieve a low-carbon future (<a href="#">link to paper 2</a>)</p>	<p>Nature Climate Change</p> <p>Journal of Cleaner Production</p>

## 1.2.1.Paper 1 / Chapter 4 – Greenhouse Gas accounting standards: A rapid review

### Abstract

*Policies, standards, and voluntary initiatives aimed at mobilising businesses to address the challenges of climate change reside on the foundation of greenhouse gas (GHG) accounting. The existence of multiple, yet similar, standards can create market confusion for businesses. We did a rapid systematic review of GHG accounting standards globally to find that all are derivative works of the GHG Protocol. Further, commonly used GHG accounting standards are based on three methodologies. We found that the field converges quickly and there are fewer options than expected. Due to the convergence observed, the global standardisation community has an opportunity to reduce fragmentation and improve interoperability by explicitly referencing, and adopting the terminology, and frameworks of the dominant standard rather than create derivative works. However, having only one global standard also comes with possible risks, including the potential for path dependency on existing frames. There are also possible advantages to one global standard (if updates are coordinated across derivatives of the standard) for keeping up with the latest science and innovation, as it may be easier for experts to input into one standard than to engage with many. This may become increasingly relevant as standards work respond to rapid changes in climate science, new emissions measurement tools, and innovations in business and accounting.*

## 1.2.2. Paper 2 / Chapter 5 – Designing for entity-level comparability: A foundational principle missing in the GHG accounting ecosystem

### Abstract

*We conduct a systematic study of the physical greenhouse gas (GHG) accounting ecosystem for conditions of entity-level comparability. Climate finance is a transdisciplinary field, depending on both physical greenhouse gas (GHG) accounting as well as financial accounting to support decision making. It presupposes that investors can make investment choices to improve the climate impact of an entity. We focus on the investor's ability to make decisions that affect physical GHG emissions. Investors require the ability to make entity-level comparisons, yet a large body of research has focused on the non-comparability of physical GHG accounting between entities. We frame the GHG accounting ecosystem as an information architecture and investigate how the challenges to comparability are organised in relationship to each other. We apply the conditions of comparability from the multiple fields that comprise GHG accounting, studying the epistemological differences of financial accounting, environmental economics, life cycle assessment, and social science. We find that non-comparability is pervasive across GHG accounting, with methodological variations introduced by many different fields. We propose a research agenda to improve entity-level comparability of physical GHG emissions.*

### **1.2.3.Paper 3 / Chapter 6 – A reporting framework for general purpose life cycle assessment to align entity-level GHG accounting with general purpose financial statements**

#### **Abstract**

*One gap between general purpose financial statements and greenhouse gas accounting is how they account for the passage of time. While financial statements were designed to synchronise upfront and ongoing activities through the use of double entry bookkeeping (DEBK), GHG accounting uses life cycle assessment (LCA) methodology, a system that sums all emissions over all time and attributed to the present. This paper proposes general purpose life cycle assessment (GP-LCA) as a mechanism to introduce temporality into environmental accounting. GP-LCA synchronises the usage of long-term environmental assets with short-term operational activities. We apply the system to emissions accounting of a newly constructed building by New College, Oxford and present how it can be used to comply with present-day emissions disclosure requirements.*

### 1.2.4. Paper 4 / Chapter 7 – Divergence of dynamics: Temporal issues between modelling forecasts of physical carbon emissions and the monetary cost of damage

#### Abstract

*While the relationship between physical emissions and economic damage is well studied at the macroeconomic level, this paper studies their relationship at the corporate decision-making level. In using an energy efficient Passivhaus as a case study, we examine the effects to payback and net present value to financial and physical indicators. A Passivhaus generally emits more upfront emissions due to construction to achieve lower emissions over the lifetime of the building's operations. For the payback analysis, modelling physical GHG emissions alongside economic costs identifies false positives (negative) where the financial model suggests a project is (is not) worthwhile while physical emissions models indicate otherwise. These gaps can be as short as a few years to as long as decades. Second, we find that net present value is more sensitive to changes in physical characteristics than financial variables. Both the Passivhaus and the counterfactual benchmark building fall within one standard deviation of typical emissions values for construction. The results highlight the importance of relying on measurements to determine whether an emissions intervention is the lower carbon value, rather than rely on modelled assumptions*

### **1.3. Research contributions and use**

This thesis is the first study that approaches financial and GHG accounting as data integration issue, contributing to the field by examining and aligning the data structures behind the two systems. The primary contribution of this thesis is to further the development of the climate finance as a field by designing an accounting system for its unique use. Climate finance, as a transdisciplinary field, relies on financial and GHG accounting disciplines for data for decision making on funding allocations and disbursements. The synchronisation of financial and GHG accounting can help increase engagement of the climate finance sector in achieving positive climate outcomes. While carbon pricing subjugates environmental attributes into financial concerns, the synchronisation of carbon and financial flows enables the ability to analyse the non-linear complexities at the heart of climate indicators. We therefore open a new stream of research for climate finance and climate economists – the study of the non-linear dynamics between financial and physical GHG emission systems, potentially providing a more sophisticated analysis of interactions at the heart of GHG-finance nexuses.

A second contribution to the climate finance field is that GP-LCA is developed from the perspective of the primary user of financial reports. GHG Protocol was developed from a multi-stakeholder engagement and is intended to meet the needs of multiple users in a supply chain (Ranganathan, 2024). There have been calls to focus GHG accounting onto a single audience, to improve quality of reports and reduce costs of preparing them (Barker, 2025). As financial professionals are the users who are integrating GHG quantities into climate financial decision making, this thesis develops the accounting framework from their epistemic frame. The alignment can increase engagement of the traditional finance communities, professionals, and researchers with the climate finance field.

For accounting organisation scholars, carbon accounting holds different meanings for different frame of references (Ascui & Lovell, 2011). The carbon accounting system can be

seen as a mediating instrument, enabling the interactions between multiple fields (Miller & O'Leary, 2007). As the GP-LCA mediates between financial and carbon fields by synchronising temporal activities, it offers a new way to study the disciplines that are involved in generating a carbon quantity – climate scientists, LCA engineers, environmental economics, and business practitioners. Further, financial accounting is foundational to many business fields beyond finance, such as management studies, decision-making, long-term strategy, among others. In aligning GHG indicators to financial indicators, GP-LCA may open new avenues for business scholars to study climate-related decision making with the firm.

As GHG emissions is one of many non-financial indicators, this thesis makes a broader contribution of how to synchronise the information architecture of other environmental indicators with financial accounting. This thesis demonstrated the creation of carbon dioxide, methane, and nitrous oxide accounting systems that are built on top of the GP-LCA system. Future research can be conducted to develop accounting systems for energy, water, materials, and other environmental flows. Therefore, GP-LCA can contribute to the financial sector's effort to further integrate additional environmental, social, and governance (ESG) indicators into financial decision making, fulfilling a pressing need to formulate sustainability information architecture such that they are decision useful for financial decisions (Cort & Esty, 2020; Feger et al., 2018; Hopwood et al., 2010).

## **1.4. Structure of the thesis**

The thesis is structured as follows. We begin by reviewing carbon accounting methodologies, describing the current practices and techniques used to model corporate emissions (chapter 2). Next, we provide the research literature foundation that culminates into the carbon accounting field (chapter 3). We review the foundations of financial and GHG accounting, their history, purpose, and information architectures. The chapter also discusses current approaches to improve alignment between the two disciplines, setting the stage for the theoretical framing of GP-LCA. The four empirical papers that constitute the main results are

present next (chapters 4, 5, 6, and 7). We then conclude with a discussion of general insights and potential future work (chapter 8).

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## Chapter 2. Introduction to carbon accounting

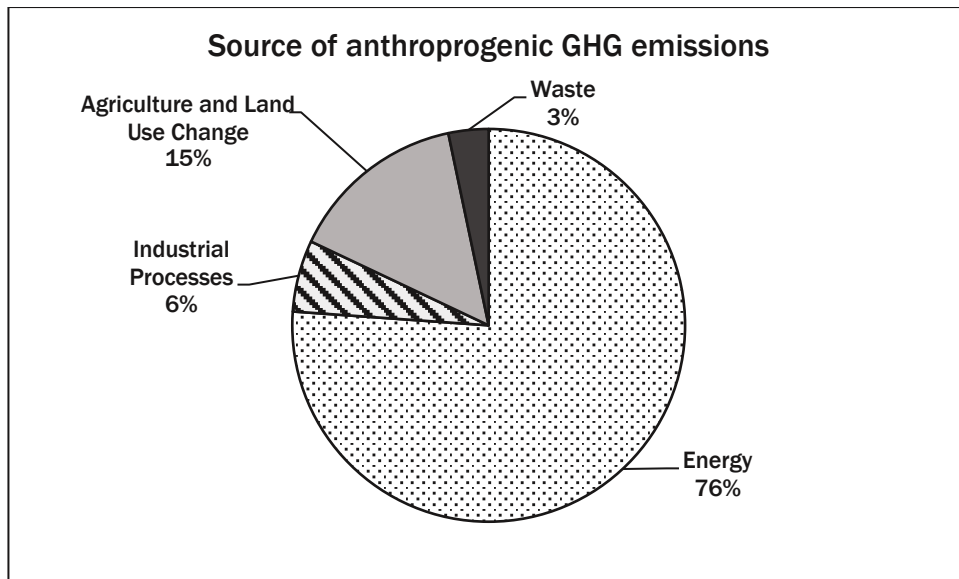
*Where there is no order there is confusion*

- Luca Pacioli, Summa de arithmetica, geometria, proportioni et proportionalita, 1494

This chapter reviews greenhouse gas (GHG) accounting methodologies, discussing what is being identified, measured and communicated. The purpose of this chapter is to build a foundational understanding of GHG accounting methodologies, assumptions, and purposes. It further explores the relationships between the methodologies as they build on top of each other. The chapter consolidates the various methodologies referenced across the thesis, setting the stage for deeper analysis within the individual chapters, namely,

- **Chapter 4 / Paper 1** – Performs a detailed study of the technical methodology of the different accounting standards, expanding on the summary explanations of this chapter.
- **Chapter 5 / Paper 2** – Critiques the GHG Protocol accounting system, which is built on top of many methodologies described herein.
- **Chapter 6 / Paper 3** – Proposes general-purpose life cycle assessment (GP-LCA) as a bridge between GHG accounting systems reviewed here, and financial accounting.
- **Chapter 7 / Paper 4** – Investigates decision making impacts gained by aligning GHG and financial accounting.

For the purpose of this chapter, we use the term “carbon” and “GHGs” interchangeably. Over 76% of all anthropogenic carbon emissions are caused from the burning of fossil fuel



*Figure 2-1 Sources of GHG emissions due to human activities (ClimateWatch, 2022). Energy is the dominant source of GHGs, accounting for 76% of all global emissions.*

(ClimateWatch, 2022). As shown in Figure 2-1, the remaining 24% are caused by industrial processes (6%), agriculture and land use changes (15%) and the waste (3%). There are six (GHGs) as defined by the original Kyoto Protocol – carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O), hydrofluorocarbons (HFCs), perfluorinated compounds (PFCs) and sulphur hexafluoride (SF<sub>6</sub>) – with a seventh, nitrogen trifluoride (NF<sub>3</sub>), being added later (WRI & WBCSD, 2013).

The field of GHG accounting can be understood through definitions of boundaries, both the physical item being evaluated and the temporal time horizon over which its environmental impact is measured. Each boundary condition contains assumptions for the resultant emissions value. This chapter reviews the boundaries and assumptions of emissions accounting for five items, each one building into the method of the prior item. First, fuel-based emissions are those that arise from the combustion of fossil fuels, the foundational methodology used across all items. Second, national emissions accounting is an inventory of fuel-based emissions within a national boundary and within a year. Similarly, facility-level emissions are an inventory of fuel-based emissions limited to a manufacturing facility boundary within a year. Fourth, product-level emissions are an allocation of facility-level

emissions to a product plus the emissions of the product's useful life. Finally corporate emissions are a summation of fuel, product, and other emissions within an entity boundary. This chapter reviews three corporate accounting systems, the GHG Protocol, which takes a life-cycle approach, E-liability, which take a cost-accounting approach, and GP-LCA, the output of this thesis, which takes a financial accounting approach. The chapter ends with a summary.

## **2.1. Fuel-based emissions accounting**

The general method to model GHG emissions is to multiply the extent of human activity, or the activity data, with a coefficient that represents the emissions of the human activity, or the emission factor (Rypdal et al., 2006). Because there are multiple GHGs, a global warming potential (GWP) normalises the damaging effects to that of CO<sub>2</sub> for comparability. This model of emissions is depicted in Equation 2-1.

$$\begin{bmatrix} \text{Activity} \\ \text{Data} \end{bmatrix} \times \begin{bmatrix} \text{Emission} \\ \text{factor} \end{bmatrix} \times \begin{bmatrix} \text{Global} \\ \text{warming} \\ \text{potential} \end{bmatrix} = \begin{bmatrix} \text{Emissions} \\ \text{(in CO}_2 \text{ equivalents)} \end{bmatrix} \quad \text{Equation 2-1}$$

The simplest case is the modelling of emissions from the combustion of fossil fuel. The activity data is the amount of fuel combusted (Garg & Weitz, 2019). Fuels are typically measured in physical quantities, such as tonnes or litres. These quantities are converted into a common energy unit, such as joules. Emission factors are specific to the fuel being combusted and specific to the GHG being modelled. Values are given in Table 2-1 for the release of CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O for a selection of fuels (Gómez et al., 2006). As the table shows, natural gas has a much lower carbon dioxide content than anthracite coal, supporting the argument that natural gas is a transition fuel away from coal power (Gürsan & de Gooyert, 2021). As these global values are derived statistically, we also present the 95% confidence interval of upper and lower values.

**Table 2-1 Default emission factors for stationary combustion, representing global averages, for a selection of fuels. The upper and lower bounds are based on the 95% confidence interval (Gómez et al., 2006). The emission factors are used to calculate the mass of emissions for each GHG.**

Fuel	CO <sub>2</sub> (in kgCO <sub>2</sub> / TJ)			CH <sub>4</sub> (in kgCH <sub>4</sub> / TJ)			N <sub>2</sub> O (in kgN <sub>2</sub> O / TJ)		
	Default	Lower	Upper	Default	Lower	Upper	Default	Lower	Upper
Crude oil	73,300	71,100	75,500	3	1	10	0.6	0.2	2
Jet kerosene	71,500	69,700	74,400	3	1	10	0.6	0.2	2
Natural gas	56,100	54,300	58,300	1	0.30	3	0.10	0.03	0.30
Anthracite coal	98,300	94,600	101,000	1	0.30	3	1.5	0.5	5

The GWP is a model that combines and weights the different GHGs by their lifetime and damage to the environment (Fuglestvedt et al., 2003). As shown in Table 2-2, trace amounts of CO<sub>2</sub> will still exist in the atmosphere after 500,000 years (Lord et al., 2016) while methane's lifetime is significantly shorter at 11.8 years. Radiative efficiency represents the strength of the GHG to trap heat in the atmosphere. Methane is about four times stronger as a GHG than carbon dioxide. GWP is a relative measure and normalised each gas against CO<sub>2</sub>. By default, the GWP of CO<sub>2</sub> is set to one (1) and all other gasses are represented by the equivalent amount of CO<sub>2</sub> that would need to be released to cause the same damage. GWP-20, GWP-100, and GWP-500 represents different time horizons of the metric – damage over 20 years, 100 years, and 500 years respectively. As shown in Table 2-2, the GWP values vary greatly depending on the time horizon (P. Forster et al., 2021). Longer GWPs places more weight on the damaging effects of long-duration gasses while shorter GWPs places more weight on the damaging effects of short-duration gasses. The resultant emission is commonly presented in metric tonnes of carbon dioxide equivalents (tCO<sub>2</sub>e) normalising the damage caused by all GHGs to CO<sub>2</sub>-equivalent.

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**Table 2-2 The 100-year global warming potential of select greenhouse gases. The error represents the 95% confidence interval (P. Forster et al., 2021). CO<sub>2</sub> data from (Lord et al., 2016).**

GHG	Lifetime (Years)	Radiative Efficiency (W / m <sup>2</sup> ppb)	GWP-20	GWP-100	GWP-500
CO <sub>2</sub>	500,000	$1.33 \pm 0.16 \times 10^{-5}$	1.000	1.000	1.000
CH <sub>4</sub> -Fossil	$11.8 \pm 1.8$	$5.7 \pm 1.4 \times 10^{-4}$	$82.5 \pm 25.8$	$29.8 \pm 11$	$10 \pm 3.8$
N <sub>2</sub> O	$109 \pm 10$	$2.8 \pm 1.1 \times 10^{-3}$	$273 \pm 118$	$273 \pm 130$	$130 \pm 64$

**Table 2-3 A stylised example of calculating GHG emissions from crude oil and coal. Lines A-C calculates the emissions of three GHGs, line E normalises all GHGs to CO<sub>2</sub>, and line F is the total of all fuels combusted. (Source: Author's creation)**

Line	Activity Data Description	kg CO <sub>2</sub>	kg CH <sub>4</sub>	kg N <sub>2</sub> O
(A)	1 TJ of crude oil	73,300 kgCO <sub>2</sub>	3.0 kgCH <sub>4</sub>	0.6 kgN <sub>2</sub> O
(B)	2 TJ of anthracite coal	196,600 kgCO <sub>2</sub>	2.0 kgCH <sub>4</sub>	3.0 kgN <sub>2</sub> O
(C)	Subtotal: (A+B)	269,900 kgCO <sub>2</sub>	5.0 kgCH <sub>4</sub>	3.6 kgN <sub>2</sub> O
(D)	GWP-100	1	29.8	273
(E)	Emissions (C x D)	269,900 kgCO <sub>2</sub> e	149 kgCO <sub>2</sub> e	983 kgCO <sub>2</sub> e
(F)	Total emissions (Sum of row E)	271,032 kgCO <sub>2</sub> e		

Table 2-3 is a stylised example of modelling the emissions of 1 terajoule of crude oil and 2 terajoule of coal (the activity data). By applying the default emission factors in Table 2-1, we calculate the mass of emissions of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O (line C). Next, we apply the central value for GWP-100, normalising each GHG to the equivalent damage of CO<sub>2</sub>. Finally, we add the emissions of individual GHGs together, arriving at the value of 271,032 kgCO<sub>2</sub>e for the emissions.

For combustion modelling, the boundaries of the resultant emissions are straight forward. It represents the fuel being consumed, and the GWP attributes all future damage to the year in which emitting occurred. In the next section, we examine emissions from fuel usage within national boundaries.

## 2.2. IPCC: National emissions accounting

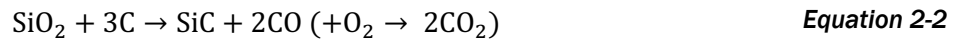
The Intergovernmental Panel on Climate Change (IPCC) developed methodologies to estimate emissions from four sectors: energy, industrial processes and product use (IPPU), agriculture, forest, and other land use (AFOLU), and waste that occurs due to human activities within national borders. We will review the methodologies of energy and IPPU, as the two categories combined constitute 81% of the anthropogenic emissions (Figure 2-1).

For energy emissions, the activity data is the quantity of fossil fuel consumed by the country per year. This data can be gathered from country-level data, such as those collected by the International Energy Agency (IEA). The emission factors can depend on a myriad of factors, such as the moisture content of the fuel, and the temperature of the smokestack, amongst others (Jeon et al., 2010). Therefore, the IPCC uses a tiered approach for data quality (Garg et al., 2006). Tier 1, the least accurate, uses global default emission factors published by the IPCC. Tier 1 emission factors are used when more granular or specific data is unavailable. Tier 2 uses country-average emission factors to account for the nuances of the fuel combustion to that country. For example, one study of the South Korean power sector found that the country had 10.8% higher emissions for anthracite and 5.5% lower emissions for bituminous coal than the IPCC global averages (Jeon et al., 2010). Finally, for Tier 3, the most accurate, one would measure or model the emissions of an individual plant. These measurements can be continuous emissions monitoring, or statistical sampling of fuel from a flow meter, or other well validated methodologies.

For industrial process emissions, one has several choices for activity data. First, GHGs can be emitted due to a chemical reaction. For example, Equation 2-2 is the chemical formula to produce silicon carbide (SiC), showing how CO<sub>2</sub> is a byproduct of the manufacture from silica sand (SiO<sub>2</sub>). The activity data can be either the quantity of carbide production or quantity of petroleum coke consumed during the process. The emission factor would be chosen relevant

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to the activity data, either CO<sub>2</sub> emissions per unit of carbide output or CO<sub>2</sub> emissions per unit of petroleum coke input (Harnisch et al., 2006).



Second, fossil fuels can be consumed as a feedstock for production purposes rather than for energy purposes (Olivier et al., 2006). For example, paraffin wax and asphalt are manufactured from petroleum products. The activity data is typically a physical quantity of material used, and the emission factors represent the fraction of fossil fuel that is oxidised during use. Third, fossil fuels can be used both as a chemical reducing agent as well as a source of heat. For example, in steel making, the coke, which is derived from metallurgical coal, serves two purposes. It is a reducing agent, converting iron oxides to iron, and a provider of heat for the process. Therefore, for steel making, the activity data is tonnes of product, and the emission factors are chosen based on the manufacturing technology used, such as blast furnace, electric arc furnace, and so on.

Table 2-4 is a summary of national carbon accounting of energy and industrial processes. The activity data is a unit of energy or a unit of industrial process that took place within national boundaries within a given year. The emission factor converts that activity data into an emissions value. The resultant emissions value has the spatial boundaries of nations and temporal boundaries of a reporting year.

Because of the national boundary, the IPCC method is effectively an inventory of the fuel consumed by the country per year. However, there are several applications that require sub-national level GHG accounting. The rest of this chapter describes three applications, how GHG accounting is applied to factories, products, and companies. In the next section, we describe how the methodology of national accounting can be applied to facility-level accounting, such as factories, power plants, and others.

*Table 2-4 The choices for activity data and emission factors in national accounting of energy-related emissions (Garg et al., 2006)*

Types of emissions	Activity data (per country, per year)	Emission factor
Energy emissions	Total fuel consumed	<b>Tier 1:</b> Global default emission factors <b>Tier 2:</b> Regional emission factors <b>Tier 3:</b> Plant-specific emission factors
Process emissions	Chemical reactions	Stoichiometric emission factor
	Fossil fuel as feedstock	Fraction of fossil fuel that is oxidised during use
	Dual use in production processes	Allocation of emissions to multiple products.

### **2.3. Emission trading schemes: Facility-level emissions**

Emission trading schemes (ETS) are designed to limit emissions across a region by creating a cap-and-trade system. Generally, ETS targets the facilities of major producers of emissions, such as electricity generation or large manufacturing plants. The entities that own the facilities are allocated an annual emissions allowance by the government. If the entity has excess emissions allocated by the end of the year, they can trade their surplus on the ETS market. Conversely, if an entity has exceeded their allocation, they can purchase additional emissions rights from the ETS market.

Broadly, ETS adopt the IPCC methodology to facility-level emissions by setting the activity data boundary as the fuel consumed or processed at a plant within a given year. The emission factor converts that activity data into an emissions value, representing the annual emissions of the plant. Individual ETS systems have some variations of the approach. For example, in the European Union (EU), the EU ETS uses the quantity of fuel consumed per facility or plant as the activity data. The emission factors can follow IPCC Tier 1, 2, 3, or any combination of the three tiers (EU Commission, 2023). The Regional Greenhouse Gas Initiative (RGGI), a program of 11 northeast US states, only permits carbon emission values

through continuous flow measurement, or Tier 3 of the IPCC methodology, for its monitoring programme. The California regulation on mandatory GHG emissions reporting builds on the IPCC methodology and includes other assumptions, such as transmission losses in the allocation of emissions to a facility (CARB, 2019).

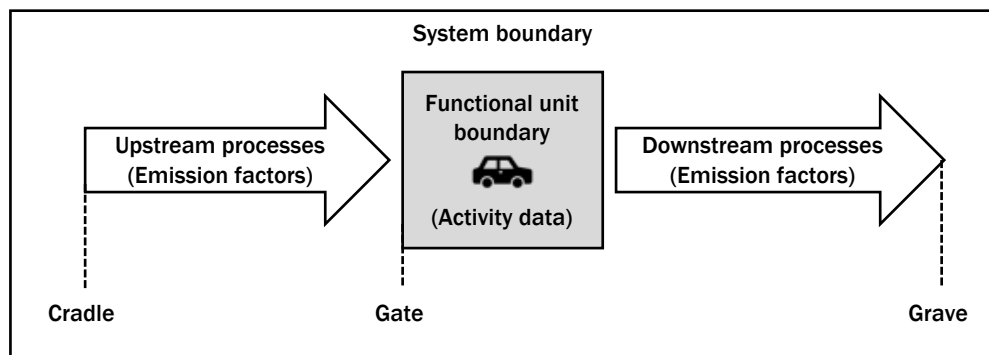
Although facility-level GHG accounting are useful for managing the emissions of an industry sector, consumer users may wish to know the GHG emissions associated with the products being produced. For example, a consumer might want to know the emissions associated with an automobile, not the emissions associated with the entire automobile factory. In the next section, we describe how the emissions of a facility can be allocated to a product for product-level emissions accounting.

## **2.4. Life cycle assessment: Product-level emissions accounting**

Up until now, the chapter has only evaluated operational emissions, or those that arise from operational energy use. However, if the manufacture of 1 tonne of steel emitted 0.5 tCO<sub>2</sub>e, one can consider the steel to have a carbon footprint of 0.5 tCO<sub>2</sub>e. A product's carbon footprint is referred to as its embodied carbon, representing all emissions of a product to its manufacture, assembly, transport, construction, lifetime use, and disposal (Ibn-Mohammed et al., 2013). Life cycle assessment (LCA) was developed to model environmental burdens associated with products over its useful life (Hou et al., 2015), including both upfront embodied and ongoing operational emissions.

Figure 2-2 is a stylised example to model the product emissions of an automobile. In an LCA study, there are two boundaries that need to be determined. First, the user determines the boundary of the functional unit, or the item being studied. In this example, the functional unit is the automobile. Second, the user determines the system in which the functional unit will be studied. Typical systems boundaries for LCAs can be cradle-to-gate or cradle-to-grave

analysis. *Cradle* is defined as the beginning of the value chain, starting with raw material extraction. *Gate* represents when the material becomes part of the functional unit, by entering the manufacturing company's jurisdiction. *Grave* denotes the end of the value chain, or how one disposes of, recycles, or reuses materials. Temporally, cradle represents past processes, as material extraction and manufacturing occur in the past. Grave represents future processes as downstream use of product and demolition has yet to occur (BSI, 2020).



**Figure 2-2** There are two boundaries of product emissions accounting. The functional unit describes the item being evaluated and the system boundary represents the processes included. Note that the activity data depends on the functional unit and the emission factor represents which system processes are included (Source: Author's creation)

The user gathers the relevant activity data that represents the functional unit. For our automobile functional unit, the user can decide how far upstream to go, from the extraction of iron ore or just to the production of steel. The user does this for all materials that go into the automobile, steel, aluminium, plastics, fabric, and so forth for cradle-to-gate analysis till the automobile is manufactured and ready for use. If the user is performing a cradle-to-grave analysis, one would also include estimates of fuel consumed over the vehicle's useful life, disposal activities, and so on. For each activity data, the user applies the appropriate emission factor of emissions per material or fuel. The user then adds together the emissions of each material to generate the emissions of the automobile.

The emissions LCA of a product can be considered a new emission factor. For example, a fleet operator might own several thousand vehicles. Performing an LCA on each automobile would require calculating quantities of steel, aluminium, plastics, and other materials per

vehicle, an onerous activity. Instead, the fleet operator can use the number of vehicles as the activity data and emissions per automobile as the emission actor. Thus, LCA-based product emissions are recursive. Each result can be used in subsequent modelling of emissions.

In essence, product emissions use the item as the physical boundary. The temporal time horizon is a choice of the user. It could represent upstream processes, downstream processes, or a combination of both. Consequently, product-based LCA can have widely varying results (Perkins & Suh, 2019).

The next three sections show how emissions from energy and products form the basis of corporate GHG accounting. We begin by describing the dominant standard, the GHG Protocol, performs an inventory of supply chain impacts of an individual company.

## **2.5. GHG Protocol: Corporate carbon supply chain inventory**

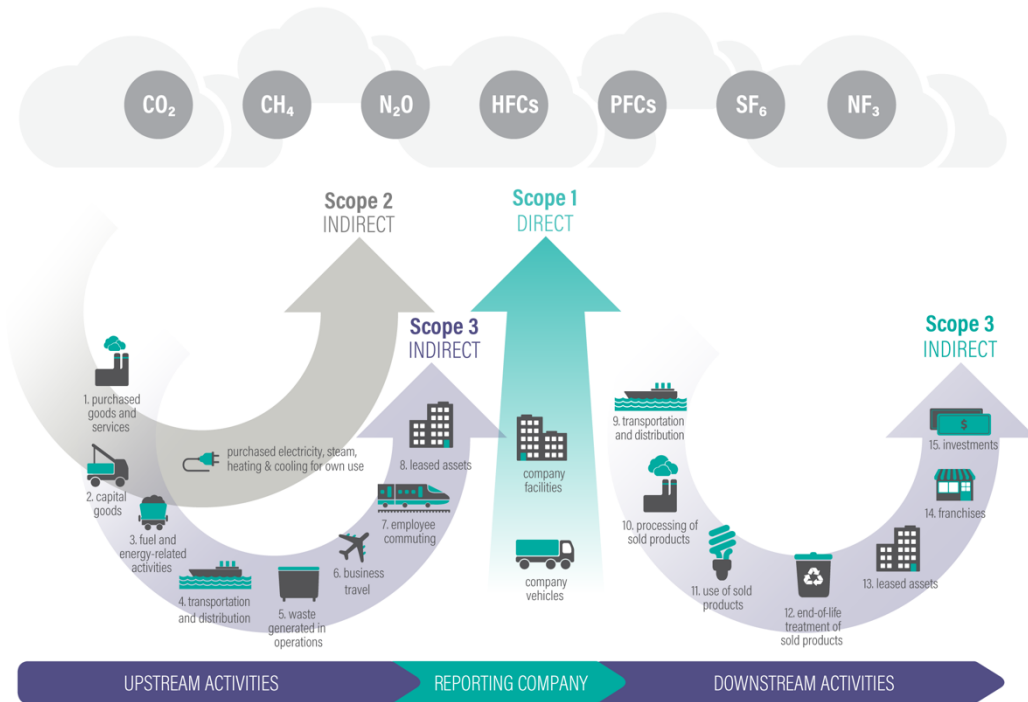
The GHG Protocol was formed as an initiative by the World Resources Institute (WRI) and World Business Council for Sustainable Development (WBCSD) to hold companies accountable for their GHG emissions. The key challenge was how to draw the boundary around emission responsibility of an organisation (Walenta, 2021). Some argued to use private property and facility ownership as a means to determine emissions, focusing on emissions that are owned and controlled by the organisation. Others advocated for a broad sense of emission ownership, not limited by private property ownership. The challenge is that not all companies consume fossil fuels directly but are enabled by a supply chain that consumes fossil fuels. For example, BP produces fossil fuels as a product, but most of the emissions occur by other companies that combust it. Alternatively, Ford Motor Company buys steel and other components from upstream suppliers that emit GHGs in manufacturing those components and sells automobiles to consumers who need to buy fossil fuels to run their vehicles. The key question in emission calculation and reporting is whether a company

should be responsible for the emissions directly under their control or those occurring across its broader value chain?

The resulting system was a compromise that accounted for both situations. Scope 1 are emissions that arise as a direct result of company operations, Scope 2 are indirect emissions that arise indirectly due to a company's consumption of electricity, and Scope 3 are other indirect emissions that arise from upstream and downstream impact (WRI & WBCSD, 2004).

The first step in emission calculations is for the reporting entity to set its organisational boundary. The GHG Protocol states that an organisation boundary is determined by consolidation rules in the financial accounting system, such as operational control, financial control or equity share (WRI & WBCSD, 2004). A point to note is that financial accounting standards, such as those of the International Financial Reporting Standards (IFRS) separately define the boundary of a reporting entity and the consolidation rules for the entity. In the IFRS, a reporting entity is one which is required to prepare financial statements (IASB, 2018), effectively bounding an entity by the content of the financial statements. The consolidation rules, however, are defined based on control of subsidiaries (IFRS, 2011). Therefore, the GHG Protocol's entity definition is technically not aligned with a financial accounting's boundary definition but is a set of consolidation rules. From an LCA perspective, the organisational boundary is analogous to the functional unit in an LCA, as it defines the item from which one determines relevant processes (Figure 2-3).

Next, the reporting entity determines its operational boundaries, or the extent of the value chain that it has indirect influence over. For BP, the value chain may include downstream users of its petroleum product and for Ford Motor company, that includes upstream materials production as well as downstream operations and demolition of their automobiles. From an LCA perspective, the operational boundary is analogous to the system boundary as it represents the value chain (Figure 2-3). Within the organisational boundary, the entity then categorises their emissions as Scope 1, 2, and 3.



**Figure 2-3 Graphical depiction of Scope 1, 2, and 3, from the GHG Protocol. The organisational boundary is analogous to the functional unit and represents the entity being evaluated. The operational boundary is analogous to the systems boundary and represents the value chain in which the reporting entity operates (WRI & WBCSD, 2013, Page 6).**

Scope 1 is a measure of emissions from fuel combustion in assets owned by the entity for the reporting year. It is bounded by the organisational boundary of the reporting entity.

Because Scope 1 is a measure of fuel combusted, it follows the IPCC methodology and its derivatives, such as ETS methodologies for calculating the emissions.

For Scope 2, the activity data is the quantity of electricity consumed within the organisational boundary of the entity. The emission factor is a choice between location- or market-based (WRI & WBCSD, 2015). The location-based emission factor represents a grid-average mix of suppliers, such as fossil fuel generation and solar power plants, in the locality where one is placed. However, some companies enter long-term contracts with renewable energy suppliers for the purpose of reducing their carbon footprint. Although the electricity is still delivered via the local grid, the reporting entity can use the emission factor of their contracted electricity rather than the grid average. This is known as the market-based approach.

The goal of Scope 3 is to capture the indirect emissions of the broader system of the operational boundary that the reporting entity operates within (WRI & WBCSD, 2011a). Scope 3 further comprises fifteen categories representing both upstream and downstream emissions, as shown in Figure 2-3. Within each category, many different types of activity data and emission factors are accepted. Emissions can be directly reported, as Scope 1 and 2 emissions can be reported directly for *Categories 8: Upstream leased assets* and *Category 14: Franchises*. In these situations, no emission factors are required.

The activity data can be energy-based, such as for *Category 3: Energy-related activities not included in Scope 1 or Scope 2* and *Category 8: Upstream leased assets*. In these situations, combustion emission factors are used.

Many activity data are based on physical quantities, such as quantity of goods, distance, volume or weight, square area, and others. In these situations, the emission factors are derived from LCA and product emissions accounting (WRI & WBCSD, 2011b), as described in section 2.4.

The GHG Protocol acknowledges that activity data in energy and product units might be challenging for a company to gather. Therefore, it permits the use of monetary units for activity data to simplify data collection, referred to as spend-based method. For example, rather than recording the quantity of fuel consumed or distance travelled, one could record the amount spent on flights, hotels, and taxis as the activity data. Then, there are two methods for calculating a monetary emission factor, cost-based LCA and environmentally-extended input-output (EEIO) models.

In a cost-based LCA, one uses financial value as the unit of analysis. For example, rather than modelling emissions per widget produced, one models the emissions per cost of widget. Cost-based LCAs are still subject to supply chain assumptions, as the cost can be modelled as cradle-to-gate or cradle-to-grave. EEIO is based on input-output (IO) analysis, a method

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to indicate structures within an economy (Leontief, 1951). An IO table represents the linkage between producing and consuming intermediary products by assuming that the output of one industry is consumed by other industries at fixed ratios (Tukker et al., 2006). EEIO is an extension that shows how the economy interacts with the environment. EEIO tables are developed to link economic inputs or outputs with environmental extraction and emissions.

One challenge of using monetary values is that prices can have large variations for the same distance travelled. For example, as of this writing, the cost of a flight between London and Paris, a distance of roughly 280 miles (450 km), can range between £60 to £530, depending on the airline and time of flight. Further, at the cost of £530, one can find a discount fare between London and San Francisco, a distance of 5,350 miles (8610 km). Therefore, a spend of £530 can represent 0.13 tonnes of CO<sub>2</sub>e (London to Paris) or 3.58 tonnes of CO<sub>2</sub>e (London to San Francisco)<sup>1</sup>, a difference of 186%. The cost will also change over time, due to inflation and other economic variables. Thus, although spend-based method is the simplest to perform, the quality of the results is considered the poorest.

**Table 2-5 Methodologies and underlying data that are accepted to model Category 6: Business travel (WRI & WBCSD, 2013)**

	Acceptable activity data (AD)	Acceptable emission factors (EF)
Fuel-based method	<ul style="list-style-type: none"> <li>Quantities of fuel</li> <li>Quantities of electricity</li> <li>Amount spent on fuel and average cost of fuel</li> </ul>	<ul style="list-style-type: none"> <li>Combustion EF</li> <li>Fuel life cycle EF</li> <li>Electricity EF</li> </ul>
Distance-based method	<ul style="list-style-type: none"> <li>Quantity (Distance travelled per mode of transport)</li> </ul>	<ul style="list-style-type: none"> <li>By passenger-kilometre per mode of transport</li> </ul>
Spend-based method	<ul style="list-style-type: none"> <li>Monetary (Spending)</li> </ul>	<ul style="list-style-type: none"> <li>Cradle-to-gate EF</li> <li>EEIO emission factor</li> </ul>
<i>Optional</i>	<ul style="list-style-type: none"> <li>Number of hotel nights and emission factor per hotel per night</li> <li>Life cycle emissions associated with manufacturing vehicles or infrastructure</li> </ul>	

<sup>1</sup> <https://calculator.carbonfootprint.com>

The different methods are organised into a data quality hierarchy. The assumption is that data more specific to the entity will be of higher data quality than those derived from industry surveys. Table 2-5 shows the hierarchy of methodologies for modelling emissions related to Category 6 Business travel. Fuel-based methods are considered the highest data quality with spend-based method being the lowest. Broadly, this makes sense as fuel-based methods have less uncertainty than spend-based methods. However, the different methods have different time horizon boundaries. A cradle-to-gate emissions factor will be bounded as upstream activities while a cradle-to-grave emissions factor will have a much longer time horizon, including upstream and projected downstream emissions as well. As Table 2-5 shows, combustion, cradle-to-gate, and life cycle emissions associated with manufacturing of vehicles are all accepted emissions factors to represent business travel activity, even though each emission factor represents a different phenomenon of emissions due to traveling.

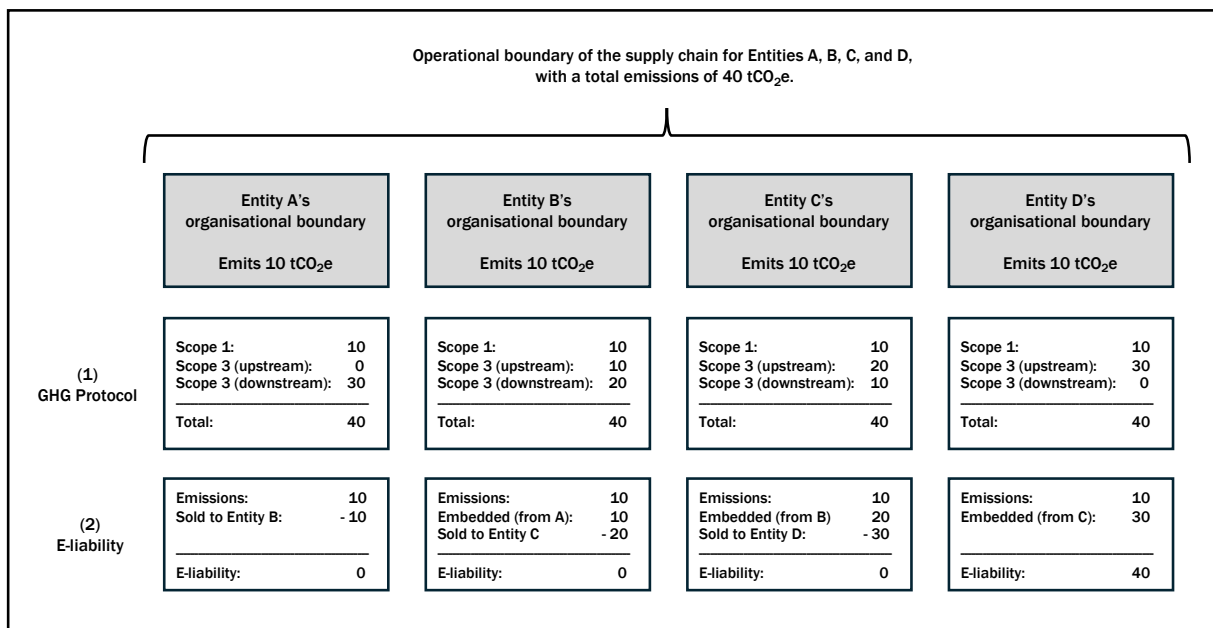
The problem of boundary choices is ingrained in and pervasive across all Scope 3 categories. Each category accepts two-to-four different approaches, with each approach representing a different phenomenon. The acceptance of multiple models explains observed inconsistencies of Scope 3 values from different sources. Empirically, several studies found that Scope 3 values from different providers can differ by over 190% (Harangozo & Sziget, 2017; Simmons et al., 2022). Practitioners have made well-intentioned recommendations to address this gap: reduce the number of methodologies by standardising onto GHG Protocol (ISSB, 2023). However, research found that the alignment to the GHG Protocol has not improved consistency (Busch et al., 2022). This is not surprising, as the GHG Protocol is what permits the variations of models to be accepted (Wegener et al., 2019). For example, in the Scope 3 standard, it recommends setting a minimum boundary of cradle-to-gate, with cradle-to-grave being acceptable as well (WRI & WBCSD, 2011a).

Double counting is also pervasive in the GHG Protocol. For a single entity, the summation of Scope 1, 2, and 3 should not have any double counting concerns. It becomes prevalent

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when summing together entities within the same value chain. Double counting was intentional by design. By encouraging double counting of the supply chain, it had hoped to facilitate “Simultaneous action of multiple entities to reduce emissions throughout society,” (WRI & WBCSD, 2011a, p28). However, double counting is not a desirable consequence when trying to understand the total impact across multiple entities that share a value chain (Caro et al., 2013).

Figure 2-4(1) depicts a stylised example of a supply chain that only has four entities. Assuming each entity emits 10 tCO<sub>2</sub>e, and consumes no electricity, the emissions of the entire supply chain is therefore 40 tCO<sub>2</sub>e. As Scope 1 is bounded by the organisational boundary, each entity reports 10 tCO<sub>2</sub>e. In this example, Scope 2 is zero because of no electricity consumption. Scope 3 is defined by the operational boundary of the supply chain. As Entity A sells its products to Entity B, and so forth until purchased by the final customer Entity D, the four entities share the same operational boundary. Each entity estimates their Scope 3 supply chain emissions independently. Unlike in financial accounting where costs are transferred to the next entity in the supply chain, Scope 3 emissions are not transferred to other entities. In this example, for Entity A, there are no upstream emissions, but the downstream emissions would be the sum of Scope 1 emissions from Entities B, C, and D, for a total downstream emission of 30 tCO<sub>2</sub>e. For Entity B, the upstream emissions would be that incurred by Entity A, or 10 tCO<sub>2</sub>e, and downstream emissions would be that incurred by Entities C and D, or 20 tCO<sub>2</sub>e in total. This exercise is repeated by each entity, culminating in Entity D reporting upstream emissions of 30 tCO<sub>2</sub>e, incurred by Entities A, B, and C, and no downstream emissions. If each entity summed up their Scope 1 and 3, they would arrive at the same value, 40 tCO<sub>2</sub>e, which correctly represents the emissions of their supply chain.



**Figure 2-4 (1) and (2) comparing emissions reporting based on GHG Protocol and E-liability (in tCO<sub>2</sub>e)**  
(Source: Author's creation)

As shown in this example, the GHG Protocol system depicts the emissions footprint that arises due to an entity, when examined independently. However, caution needs to be taken when examining multiple companies within a supply chain. In comparing Entity A and D, one can understand where the entity sits within the supply chain, based on whether the bulk of Scope 3 emissions are upstream or downstream. If one were to perform a summation of Entity A, B, C and D's total emissions, or 160 tCO<sub>2</sub>e, one is merely counting the supply chain emissions four times! A summation of emissions of the entire value chain would therefore include double counted emissions.

In summary of the GHG Protocol, the emissions can represent many assumptions. It can represent the current emissions of the reporting entity (Scope 1, and 2). Scope 3, which represent upstream and downstream value chain, accepts different time horizon assumptions. Thus, it can represent historical impact, future impact, or a combination of both. Further, all life cycle emissions are attributed to the reporting year, thus the historical or future impacts are attributed to the current year.

Although the GHG Protocol is a supply chain inventory, it has been increasingly incorporated into financial data to make investment decisions. This creates a challenge, namely, how to incorporate a supply chain value into decisions about a single entity. The next section describes the E-liability system, which identified the double-counting issue of the supply chain and sought to disentangle it.

## **2.6. E-liability: Activity-based corporate carbon accounting**

E-liability is an emissions accounting system first published in 2021 that addresses several shortcomings in the GHG Protocol (Kaplan & Ramanna, 2021). It recognised the double counting issue of LCA emission factors as a summation of all processes across a value chain, whether they are within the entity's control or not. E-liability disaggregates value chain processes and has the reporting entity report only the processes under their control. E-liability also pointed out problems with using industry averages to make company-specific choices. For example, if an entity is undergoing a cost-reduction initiative, it will create strategies based on actual expenses of the company, not industry average expenses of peer entities.

E-liability adds several additional constraints to corporate emissions accounting. First, E-liability defines the corporate boundary as an entity as that which prepares financial statements (Ramanna, 2024), mirroring the definition of financial accounting (IASB, 2018), rather than the consolidation rules of GHG Protocol. Second, E-liability requires entities to report on emissions due to direct activities and emissions due to economic activities. Direct activities are those that are directly affected by the reporting entity, equivalent to the Scope 1 value calculated either from energy consumption or industrial processes (Kaplan & Ramanna, 2021). Economic activities are transactions of products which have embedded emissions within the materials and products being offered (Ramanna, 2024). Unlike the GHG Protocol, where emissions are not transferred, the E-liability system transfers emissions

through the sales of products and services. The resulting sum, the company's E-liability, represents emissions due to direct activities and indirect purchases of the reporting entity. E-liability does not include downstream emissions, or indirect emissions of customers due to purchasing a product.

E-liability adapts the value-added concept from cost accounting, where one sums the marginal additional costs per process step to arrive at the final cost per product. An entity reports embedded emissions from materials purchased upstream and adds to it their own additional emissions. The E-liability method is equivalent to the cradle-to-gate emissions that is specific to the company. A sequential ordering of transactions in E-liability is analogous to the cradle-to-gate processes found in LCA. However, because E-liability only adds the marginal emissions emitted by each supplier, the value is specific to the entity. The embedded emissions from upstream entities are passed down to customers via a sales transaction. Because each entity only reports emission caused under direct control, there is no double counting of emissions. Further, because only direct emissions are reported, one does not have the challenge of multiple methodologies used to model emissions. Only combustion of fossil fuel is used.

Within the E-liability approach, there is no double counting within the supply chain. New direct emissions and transactive emissions are added to one's ledger. When a product is sold, the E-liability is transferred to the buying entity. Figure 2-4(2) depicts a stylised example of the supply chain using E-liability. The 10 tCO<sub>2</sub>e emitted by Entity A is sold to Entity B, so Entity A's E-liability is zero. Entity B then emits 10 tCO<sub>2</sub>e and adds that to the purchased E-liability from Entity A. The emissions are ultimately passed to Entity D, which records an E-liability of 40 tCO<sub>2</sub>e due to the 10 tCO<sub>2</sub>e it emitted and the 30 tCO<sub>2</sub>e procured from Entity C. The sum of the supply chain's E-liability, 40 tCO<sub>2</sub>e, would be equal to the actual emission of the supply chain.

By eliminating double counting, the E-liability system enables improved accounting of offsets. One concern within the GHG Protocol is the double counting of carbon offsets, where multiple companies claim credit for the same withdrawal of atmospheric carbon within the supply chain. Because E-liability eliminates supply chain double counting, it can be held on a corporate ledger until it is neutralised or extinguished by an offset (Roston et al., 2022). The E-asset is an emissions offset that is held on the entity's environmental balance sheet (Kaplan et al., 2023). Together, E-liabilities and E-assets form the E-ledger, a system of accounts that depicts an entity's progress towards net zero (Penman, 2024).

Although E-liability addressed the challenge of double counting, it introduced several other limitations. As we will develop more fully in Chapter 3, the E-ledger is actually a single-entry bookkeeping approach, rather than a double-entry bookkeeping approach used in financial accounting. In the next section, we introduce GP-LCA, a double-entry bookkeeping approach to corporate GHG accounting. The method is fully developed in Chapter 6 / Paper 3 of this thesis.

## **2.7. GP-LCA: Financial reporting-based corporate carbon accounting**

This thesis presents the foundational basis for general-purpose life cycle assessment (GP-LCA). While E-liability uses cost accounting principles to disaggregate emissions-related LCA processes, GP-LCA uses financial accounting principles to disaggregate time for any environmental indicator that uses LCA. The two systems share many similarities. Because LCA processes are sequential, a consequence of E-liability's process disaggregation is to create a sense of the passage of time. E-liability was designed as emissions accounting system that replaced LCA, however GP-LCA is designed to be a bridge between financial reporting and LCA systems. First, GP-LCA uses the temporal categories of general-purpose financial statements, aligning emissions reporting to that of financial reporting. By disaggregating time, it adds the ability to temporally synchronise between economic,

emissions, and the broader climate science, engineering, and environmental fields, something not possible with E-liability. Second, GP-LCA adheres to LCA principles, enabling it to be used in performing LCA studies. As LCAs are used to quantify any environmental flow, such as emissions, energy, water, materials flow, particulates, and others, GP-LCA is applicable beyond emissions accounting, usable by any environmental indicator that is quantified by LCA methodologies. Because E-Liability is designed only for emissions, it is not extendable to other climate indicators.

GP-LCA began in 2015 as an observation that energy and cash are both in balance (Jia & Crabtree, 2015). Energy is always in balance, that is never created nor destroyed but merely shifts from one to another. Cash is always in balance, as demonstrated with double entry bookkeeping. Further, both energy and cash have stocks and flows. Financial assets have embedded energy and embedded carbon within them, all stocks of their respective resources. Financial operations depend on the consumption of energy, and results in the emissions of GHGs, or resource flows. Financial statements are organised into three statements, the balance sheet, profit & loss statement, and the cash flow statement. Stocks are represented by a balance sheet that give a snapshot in time of the position of the company. Flows are represented between two balance sheets by a profit & loss statement, depicting the performance of trade activities, and a cash flow statement representing cash inflows and outflows during the two balance sheet periods (Sangster et al., 2021).

The first version of extending the framework of financial statements to account for energy was first proposed in 2017 (Jia, 2017). It separated out a statement of energy position to depict the state of energy assets, opportunities and risks, from statements of energy flows, where decarbonisation workflows could be created. It was an early prototype at creating a set of leading and lagging indicators for corporate environmental decision making. In 2020, a second prototype was published, which included trade activities (Jia, 2020). It showed how different temporal decision cycles could be mediated with an Energy Activities Statement.

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This included energy consumed within the period, thermal insulation provided by a building, and synchronise the storage durations of different battery technologies. It was noted that the energy system could be extended to any additional environmental flow, including carbon emissions.

This thesis, the third version, builds on earlier iterations in two ways. First, it generalises energy accounting into LCA accounting, enabling the inclusion of other environmental indicators. This thesis extends the principle of energy and cash balance to the analogous principle of mass balance used in GHG sciences. The research develops statements for carbon dioxide, methane, and nitrous oxide emissions, aligning their accounting with that of financial reporting. As a result, the statements also show how different GHG temporal decision cycles could be mediated, between operational carbon emitted within a period, embedded carbon emitted upfront, and allocation of carbon assets over time in different long-term infrastructures. Second, GP-LCA was formally designed to be a bridge between LCA and financial accounting fields. It builds on the observation that financial and environmental systems have stock and flows (Barker, 2025). By aligning the information architecture behind both systems, GP-LCA enables the two fields to align disclosures of data, but also to share knowledge, insights, and improve collaboration for achieving environmental goals.

### **2.8. Summary**

On the surface, emissions accounting is simple. It is the product of a human activity data with an emission factor that converts the activity into emissions. However, as summarised in Table 2-6, complexities arise in the choice of physical and temporal time horizon boundaries. Further complications are introduced with interdependencies amongst the systems, as LCA emission factors can be used recursively. Corporate GHG inventories, as standardised by the GHG Protocol, are built on top of methods developed by the IPCC for energy combustion and the LCA community to quantify emissions of a product. E-liability improved on the double counting limitations of the GHG Protocol by disaggregating processes within an LCA. GP-

LCA improves on the GHG Protocol by aligning temporal characteristics of emissions with that of financial accounting. As a result, it enables the synchronisation of activities between different disciplines and fields.

*Table 2-6 Summary of emission accounting systems reviewed in this chapter. Only GP-LCA is synchronised with financial accounting. (Source: Author's creation)*

Type	System	Purpose	Activity Data X	Emission Factor =	Emissions
Corporate GHG Accounting (Non-Kyoto entities)	<b>GHG Protocol</b>	Inventory of corporate emissions	Business activity	Choice between <ul style="list-style-type: none"> <li>• LCA-based</li> <li>• Combustion</li> <li>• EEIO</li> </ul>	Category system based on LCA
	<b>E-lability</b>	Disaggregate supply chain processes	Business activity	Combustion only	Category system based on processes
	<b>GP-LCA</b>	Synchronised with financial accounting	Business activity	Combustion only	Category system based on time
National (For Kyoto entities)	<b>IPCC</b>	Inventory of national emissions	Fuel consumed in national boundary	Combustion only	Categorised by nations
Product	<b>LCA</b>	Inventory of product emissions	The Item (functional unit)	Choice between <ul style="list-style-type: none"> <li>• LCA-based</li> <li>• Combustion</li> <li>• EEIO</li> </ul>	Categorised by product

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## Chapter 3. Literature review

*A problem well put is half-solved*

- John Dewey, *Logic: The Theory of Inquiry* (1938)

Accounting, whether financial or non-financial, must be understood in relationship to the social context within which it resides (Davis et al., 1982; Hopwood, 1983). Climate finance, as an interdisciplinary field, is built on top of the financial and GHG accounting disciplines. In this chapter, I follow the convention of using the terms “GHG” and “carbon” interchangeably.

To create context for the overarching research question, “*What are the gaps between financial and GHG accounting?*”, I review the theoretical foundations of the financial accounting system in section 3.1 and then the GHG accounting system in section 3.2. For both systems, I begin by reviewing the stakeholders involved in their respective systems, describing how their historical evolutions shaped their purpose, and end with discussing the design of their information architecture. I use information architecture to investigate the two systems because it carries with it the perspective from which they describe and measure (Evernden & Evernden, 2003). Financial accounting is a normative system that follows the rules of double entry bookkeeping. As [paper 1 / chapter 4](#) shows, corporate GHG accounting is a normative system that follows the rules of life cycle assessment.

The review of the two systems identifies temporal misalignment as a gap that arise when the two systems are used simultaneously. [Paper 2 / chapter 5](#) is a more detailed study of the temporal misalignment. Next, section 3.3 reviews current efforts to bridge the gaps between financial and GHG accounting system. It describes both efforts of the financial sector to improve GHG accounting as well as the GHG accounting sector to improve alignment with

financial accounting. However, I will explain how the current efforts do not address the temporal gap. Section 3.4 then reviews the theoretical foundations for the methodology provided in [paper 3 / chapter 6](#), general-purpose life cycle assessment (GP-LCA), that does address the temporality gap between the two systems. These two sections, in combination provides a foundation for the second sub-question, “*How can the gap be bridged?*”

The third sub-question, “*What insights are possible once the gaps are bridged between the two accounting systems?*”, is also addressed in section 3.4. I also describe how GP-LCA can be applied to create accounting systems for GHGs, energy, water, and other environmental indicators. These indicators are intertwined, but their dynamics may diverge. As [paper 4 / chapter 7](#) explores more fully, modelling the flows distinctly yet simultaneously enables a richer analysis of the scenarios under consideration.

### **3.1. Theory of the financial accounting system: Decision support**

Accounting scholarship is the link between measurement processes to decision processes through standardised categories (Kinney, 2001). Yet measurement processes, standardised categories, and decision have their own epistemological assumptions. While measurement embeds perspectives in the numbers, categories imply certain items are to be grouped together and others separately. Further, the point-of-view of a decision process will influence the type of data a user seeks and ultimately acts upon (West & Euler, 2023). This section reviews the different perspectives of measurements, categories, and decision applications that are within the emissions accounting fields.

For the measurement process, the numbers being counted are supposed to represent some descriptor of reality (Morgan, 1988). As Quattrone point out, “If one is accounting for bottles of water, only bottles of water will be seen. If one is accounting for profits, only profits will be visible. If one is accounting for CO<sub>2</sub> emissions, one will see only CO<sub>2</sub> emissions. This is

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common sense. Every way of seeing something is a way of not seeing something else,” (Quattrone, 2022, p547).

For example, one can wish to know the speed of the fastest human. Some may point to Usain Bolt, who ran the 100-meter sprint in 9.58 seconds, achieving a land speed of 27.78 miles per hour (44.72 km per hr). However, Bolt ran for less than 10 seconds in duration and is the fastest human at his distance. Kelvin Kiptum, on the other hand, ran for over 2 hours and 35 seconds in the Chicago marathon, for a speed of 14.85 miles per hour (23.90 km per hr). Kiptum is thus the fastest runner over a different distance. However, the two time durations are different by over 50% and who is faster depends exclusively on one’s definition (and perspective) of what it means to be the fastest human. Within accounting, these tacit assumptions thus construct, communicate, and reinforce epistemological assumption behind the numbers (Hines, 1988).

The standardised categories of accounting also pre-determine an epistemological framing of what counts and how to organise them (Hines, 1988). Categories are a component of classification systems, communicating 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,” (Bowker & Star, 1999, p10). An example of a spatial segmentation is zoning laws, which categorises land by usage, thereby affecting residents and neighbourhoods of the locale. National boundaries for GHG emissions are another example of spatial categories. An example of temporal segmentation is to categorise buildings by their age, historical era, or cause-and-effect such as wear and tear through usage. For financial and GHG accounting, the reporting year is a segmentation by time. A spatio-temporal classification systems are both geographically and temporally segmented. Accounting systems are spatio-temporal by nature. Both financial and GHG emissions are

*Table 3-1 The hierarchy of performance measurement systems (Power, 2004), with examples given from the financial and GHG accounting system.*

Hierarchy of performance measurement systems	Financial accounting examples	GHG accounting examples
2 <sup>nd</sup> order meta measurements	Ratings, valuations, ratios, policies, market-level dynamics, etc.	Net zero targets, corporate carbon management, sustainable finance investments, etc.
1 <sup>st</sup> order classification systems	General purpose financial statements  <i>(Information architecture of DEBK)</i>	Scope 1, 2, 3 (GHG Protocol)  <i>(Information architecture of LCA)</i>
Measurement quantum (MQ)	Transactions	Measurement (via sensors)  OR Models (LCA, EEIO, combustion)

reported by spatially (by company, nation, etc.) and temporally (monthly, quarterly, annually, etc.).

Michael Power organised measurement and classification systems into a hierarchy for performance measurement systems (Power, 2004). Power identified three interrelated components to any accounting system, counting, controlling, and calculations. As summarised in Table 3-1, performance measurement systems are based on a measurement quantum (MQ) system, or the items being counted, a 1<sup>st</sup> order classification system, and 2<sup>nd</sup> order meta-measurement systems.

The MQ is independent of where or by whom performs the measurement, implying a sense of stability and repeatability. Once established, measurements can be used in further aggregation and calculations. For example, financial transactions form the basis for the monetary value that is counted (Sangster et al., 2021). These financial transactions are recorded in what is called the general ledger. Next, 1<sup>st</sup> order measurements are classification systems that organise the measurement quantities into categories. For financial accounting, the transactions are organised into categories such as assets, liability, revenue, and

expenses. These categories are presented on balance sheets, and profit and loss statements, otherwise known as general-purpose financial statements (GPFS). The information architecture behind the classification system is double entry bookkeeping (DEBK). Lastly, 2<sup>nd</sup> order meta-measurements are further aggregation of numbers that are used in decision and policy making. Broadly, these are calculations, based on GPFS and other data sources, that are made for specific users. For example, the GPFS is used to perform financial analysis, set government policies, analyse market dynamics, among other decision-making activities. In short, by organising the relationships of components of the financial accounting systems, Power's hierarchy demonstrates relationships between stakeholder and their interactions, an attribute I explore next.

### **3.1.1. The financial accounting system as a mediating instrument**

Organisational scholars consider mediating instruments as those that enable the exchange of metaphors, knowledge, and information between disciplines (Miller & O'Leary, 2007). They can be physical items, such as the steam engine as a mediating instrument between the value of labour and optimising the economy (Power, 1994). They can be theoretical items, such as frameworks and models that bridge between practice and theory (Morrison & Morgan, 1999). Power's hierarchy demonstrates a relationship between the disciplines and processes within the accounting ecosystem.

In the financial accounting system, GPFS mediates interactions between the stakeholder groups that participate in the financial accounting system. Bookkeepers, who maintain the measurement quantum, have methods, procedures, and technologies to record and tally transactions in individual journal entries that make up the general ledger. Financial accountants take the data from bookkeepers and have processes to prepare the financial statements (1<sup>st</sup> order). The statements are then presented to management, investors, and

policy makers who make additional calculations to make judgements on investments and forecasts (2<sup>nd</sup> order).

As I will show in section 3.2.1, the GHG accounting system can also be considered a mediating instrument, bringing together disciplines at the heart of environmental decision making. Power's hierarchy will be used to point out inconsistencies between disciplines and provide a roadmap for how to bridge the gaps. The next section uses the history of the financial accounting system to explain how it frames the modern-day purpose of financial decision making.

### **3.1.2.A history of the financial accounting system: Accounting for time**

The passage of time is inherent in the design of the modern financial statements. For example, an asset is defined as a resource as a result of *past* events from which *future* economic benefits are expected to flow (IASB, 2018). Some scholars have pointed out the role that double entry bookkeeping has played in being able to account for time (Quattrone, 2005). Through most of history, time passed between events, such as the time it takes to cook rice, or the time between harvests. A single-entry bookkeeping (SEBK) system of accounts was sufficient for the needs of the day. Double-entry bookkeeping systems (DEBK) appeared during the Italian Renaissance when there was a need to coordinate activities between multiple offices of Italian banks across Europe (Sangster, 2016). Further, during the industrial revolution, the proliferation of clocks made it possible to coordinate and synchronise human activities (Quattrone, 2005). Accounting became a mechanism to synchronise labour, within a corporate environment as well as between entities. Large scale coordination arose in the railroad industry, where trains had to run on time between cities that were geographically disperse (Chandler & Daems, 1979). Enterprises had to coordinate their business activities through both space and time. This section traces the history of the

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origins of DEBK, the challenges it solved, and the reasons for its widespread adoption. It also discusses the information architecture of DEBK and how it structurally functions.

Single entry tabular accounting system can be traced back to Roman times (Sangster, 2016). Single entry systems were used to help participants in trade to memorialise, or record transactions (Yamey, 1949). For example, if a banker extends a loan to an individual, the bank would record a transaction as a credit on their tablet and the recipient would record it as a debit on another tablet (Goldthwaithe, 1985). In this manner, merchants and bankers could keep track of debt obligations, whether as a borrower or lender (de Roover, 1938). By the medieval era, the tablets were replaced with books, hence the rise of 'bookkeeping' as an accounting function.

One advantage of the single-entry method is that one could conduct trade in the local currency (Sangster, 2016). Separate credit and debit books could be kept for Florentine florins, Venetian liras or Milano soldos. One did not need to consolidate them into a single ledger, as doing so would require accounting for currency exchange rates (Martinelli, 1974). A second advantage is that by not having a book recording cash, it was easier to circumvent the Catholic Church's usury laws, which prevented banks from earning interest on money-lending activities (Goldthwaithe, 1985). Bankers would need to take an inventory of the cash box whenever they needed to draw up a balance. By only maintaining records for debit and credit, bankers could conceal movements of cash (Sangster, 2016).

Historians largely agree that our current system of double entry bookkeeping (DEBK) emerged in the 13<sup>th</sup> century Italy to address the emerging needs of the banking community (Sangster, 2016). From a managerial perspective, single entry record keeping, can perform most business and administrative functions, but likely limited to situations where the proprietor is intimately familiar with the details of the firm (Yamey, 1964). As such, single entry methods were suitable for small entities, such as sole proprietors or small businesses. However, by the 13<sup>th</sup> century, Italian banking houses spread across Europe (Sangster,

2016). Banks required funds that were beyond the capabilities of an individual's wealth (Martinelli, 1974). This was an era where stay-at-home merchants used agents and employees to perform functions at-a-distance from themselves. Double entry bookkeeping emerged as an improvement over traditional record keeping (Sangster, 2016).

Luca Pacioli, a Franciscan friar, is credited with the earliest complete recorded treatise on the subject, found in his mathematics textbook *Summa de arithmetica, geometria, proportioni et proportionalita* (Sangster, 2010). Written in 1494, it was based on the accounting system used in Venice at the time. The book compiles all the rules that a good merchant needs to carry on business carefully and keep all their accounts and books in an orderly way (Geijsbeek, 1914).

Mechanistically, DEBK added three additional books, cash, inventory, and expenses, to the debit and credit books (Sangster, 2016). With these five books, businesses could both report their inflows and outflows, with debit, credit, and expenses books, and their position of stocks, with cash and inventory books. Each transaction is recorded twice, in two different books, and crucially, the locations of each contra record are also recorded. The recording of the locations of the transaction creates a relationship between the various books. Thus, DEBK can be thought of as a relational database, that records transactions and shows a relationship between stocks and flows (Chanphakeo, 2016).

A distinction must be made between DEBK and dual-entry systems, as both systems record every transaction twice, but for different purposes (Sangster, 2016). In dual entry systems, recording every transaction twice is for the purpose of reducing errors and can be used to prove correctness. For example, in the medical field, a study comparing manual entries of health care data found that single-entry processes introduced 8 times the errors as dual-entry processes (Paulsen et al., 2012). The DEBK system, however, makes it easier to calculate wealth and profit. This is because the location of each transaction and its contra account is also recorded, (Sangster, 2016), thereby creating a clear relationship between

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stock and flow categories (Chatfield, 1977). The articulation of category relationships made financial calculations easier as wealth and profit were simply the remainder when integration the various books. As such, one can always know their profit (fortune) and from the balance account, once can always know their wealth (ultimatum of the whole) (Yamey, 1949). These calculations culminate in the construction of the income statement, the distinguishing feature of DEBK systems (Ijiri, 1992).

Although a single-entry and dual-entry system can be used to perform the same functions as a double-entry system, DEBK streamlined the recordkeeping and management controls. Italian banks were also dealing between cities with many currencies, and the DEBK system requires the conversion of all transactions to a single currency. Thus, monetary exchanges between currencies were simplified (Goldthwaithe, 1985). Further, banks could conduct inter-bank settlements. For example, if an individual owed banks X but had a credit with bank Y, the two banks could settle the debt directly. Finally, DEBK made it simpler to record interest, an item that was kept hidden in the past. By the 15<sup>th</sup> century, usury laws had eroded, and bankers became interested in being able to record interest from transactions.

Prominent sociologist and economic historian, Max Weber and Werner Sombart, attribute the rise of capitalism to the success and widespread adoption of DEBK (Vollmer, 2003). By the early 20<sup>th</sup> century, industrialisation benefitted greatly from DEBK systems. Profits needed to be recorded and divided between the partnerships behind large, industrial enterprises (Chatfield, 1977). Reports became standardised into regular intervals so that industrialists could get an estimate of their net worth and how much money was available to pay the bills.

During the industrial revolution, periodic reporting created a new problem – how to distinguish between events of different periods (Chatfield, 1977). Up till now, most merchants had to keep track of inventory as it moved in and out of their company. However, railroads were capital intense, and the fixed assets lasted for a very long time. For a while, the upfront capital costs were not expensed, making railroads seemed more profitable than they really

were. They needed a method of spreading the capital costs over time. Manufacturing businesses had a different but related challenge. The fixed assets were used to manufacture goods, and they needed a mechanism to allocate the upfront capital costs over the production of products. To address these two issues, depreciation, as a mechanism to allocate costs over time and usage, became central to financial accounting.

As successful as DEBK was in being used to record financial transactions, in the early 20<sup>th</sup> century, there was a lack of standardisation in the presentment of financial statements to investors and the general public (Dillon, 1977). Corporate accountants had broad freedom to innovate new approaches to preparing financial statements, reflecting the rapid development of new businesses and securities that accountants had to prepare statements for. Although there was a lack of radical departures from accounting convention, the absence of standardised accounting rules meant that companies could report however they wished, leading to many investors complaining about the paucity of information to make financial decisions. This lack of a standardised accounting practices of 1920's is generally acknowledged to be one of the contributing factors to the 1929 stock market crash (Chatfield, 1977). After the stock market crash, the Securities and Exchange Commission (SEC) was created to regain public trust in financial reporting (Tucker, 2003). One action the SEC took was to establish a committee to identify acceptable accounting practices for the US. By 1973, the Financial Accounting Standards Board (FASB) emerged, having the responsibility of setting the Generally Accepted Accounting Principles (GAAP), used in the USA. Companies had to follow GAAP accounting standards in order to be listed in US-based stock markets (Camfferman & Zeff, 2018).

Meanwhile, In Europe, the International Accounting Standards Committee (IASC) was formed in 1973 to harmonise accounting practices internationally (Camfferman & Zeff, 2018). However, because GAAP was perceived as a more stringent standard, the SEC required non-US entities to reconcile their accounting books to GAAP before being allowed to be

### *Chapter 3 – Literature review*

listed in US-based stock markets. As a result, the IASC dissolved in 2011, being replaced by the International Accounting Standards Board (IASB), addressing many of the concerns of the SEC. Today, the IASB has responsibility for the International Financial Reporting Standards (IFRS), adopted worldwide in 168 jurisdictions (IASB, 2023). Companies listed on US-based stock markets can follow either GAAP or IFRS. Convergence of the two dominant standards is valued by both organisations and in 2002, the FASB and IASB published a joint memorandum of understanding, agreeing to work together to converge their two accounting standards (Tweedie, 2005).

The purpose of the GPFS is to provide information that is useful in making business and economic decisions for a broad audience (IASB, 2018). The primary users of GPFS are defined as, “Present and potential investors, lenders and other creditors, who use that information to make decisions about buying, selling or holding equity or debt instruments, providing or settling loans or other forms of credit, or exercising rights to vote on, or otherwise influence, management’s actions that affect the use of the entity’s economic resources [1.2]” (IASB, 2018). In practice, the users include investors and capital markets to efficiently allocate resources in the economy (Storey & Storey, 1998), managers to make day-to-day decisions, governments for tax inspection, regulators who require disclosures, supplier who are offering credit, among others (Sangster et al., 2021).

Special purpose accounting is to be differentiated from general purpose accounting. Special purpose financial statements are those that are prepared for a limited audience of users who seek to perform specific decisions (IAASB, 2023). For example, special accounting statements are used for tax reporting, cash reporting, loan reporting, or industry specific reporting, among others. There is no established standards or guidance on how to report transactions and what modifications are appropriate (Deloitte, 2024). Special purpose statements rely on expert judgement, who carry a specific perspective for an intended decision (Power, 2004), that may not be suited for a general audience. As such, 2<sup>nd</sup> order

meta-measurements are a form of special purpose accounting, as the financial values are customised for specific outcomes, such as performance ratios, valuation analysis, ratings, and so forth (Kinney, 2001).

In summary, the historical evolution of the financial accounting system was to provide management controls, investor insights for trading, and reduce errors. It accomplished this by adopting DEBK, creating a relationship between stock and flow indicators. For this thesis, I use the IFRS conceptual framework and documentation as the basis for analysis for financial accounting. The next section reviews how the purpose of financial accounting is designed into its information architecture.

### **3.1.3. The information architecture of double entry bookkeeping**

The IFRS defines five elements of GPFS assets, liability, equity, revenue, and expenses.

Three of these categories represent financial position, or stock of the company's assets.

These values are reported on the balance sheet. The following definitions are taken from the IFRS conceptual framework (IASB, 2018).

- An *asset* is defined as a resource controlled by the entity as a result of past events and from which future economic benefits are expected to flow to the entity [F 4.4(a)].
- A *liability* is a present obligation of the entity arising from past events, the settlement of which is expected to result in an outflow from the entity of resources embodying economic benefits [F 4.4(b)].
- *Equity* is the residual interest in the assets of the entity after deducting all its liabilities [F 4.4(c)].

Two categories are related to financial performance or flows that change a company's position. These activities are known as trade accounts and are recorded on a profit and loss

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(P&L) statement (also called an income statement) (Sangster et al., 2021). The flows that are measured are the transactions and trades of an entity.

- *Income* are increases in economic benefits during the accounting period in the form of inflows or enhancements of assets or decreases of liabilities that result in increases in equity, other than those relating to contributions from equity participants [F 4.25(a)].
- *Expenses* are decreases in economic benefits during the accounting period in the form of outflows or depletions of assets or incurrences of liabilities that result in decreases in equity, other than those relating to distributions to equity participants [F 4.25(b)].

Table 3-2, is a map of the evolution of categories from single entry to GPFS. The five categories today are descendants of Pacioli’s five categories, with *cash* and *inventory* both considered assets. Although *liability* and *equity* are not explicit in Pacioli’s system, liabilities represent debts against assets. Equity is the modern-day measure of wealth, as described in Pacioli’s system. The *debits* and *credits* of single-entry systems are still recorded but are considered part of the general ledger from which one generates financial statements.

Table 3-2 The evolution of accounting categories, from single entry to double-entry, to modern-day general-purpose accounting. (Source: Author’s creation)

	Single entry bookkeeping categories (Romans)	Double-entry bookkeeping categories (Pacioli, 1490’s)	General-purpose accounting categories (1930’s)	General-purpose financial statements (1930’s)
Single Entry System	Debit Credit	Debit Credit	(Recorded in the general ledger)	(Recorded in the general ledger)
Double Entry Bookkeeping System		Cash Inventory	Assets	Balance Sheet
		(Wealth, calculated)	Liability Equity	
		Expenses	Revenue Expenses	Profit and Loss Statement

**Table 3-3 The Master T-Table, showing the relationships between the five categories of general-purpose financial statements. (Source: Author's creation)**

	<b>Categories</b>	<b>Debit</b>	<b>Credit</b>
<b>Stocks</b>	<b>Assets</b>	(+) Increase	(-) Decrease
	<b>Liability</b>	(-) Decrease	(+) Increase
	<b>Equity</b>	(-) Decrease	(+) Increase
<b>Flows</b>	<b>Revenue</b>	(-) Decrease	(+) Increase
	<b>Expenses</b>	(+) Increase	(-) Decrease

Double entry bookkeeping has been generalised into a mathematical system (Ellerman, 1985), enabling its analysis as an information system with its own data structure and architecture. The information architecture of DEBK can be thought of as a relational database between stocks and flows (Chanphakeo, 2016). A common visualisation to depict the relationships between categories is with a Master T-Table, as shown in Table 3-3. This table depicts how to record increases and decreases for each of the categories. Each book has two columns, the left one to record debits and the right one to record credits. For historical reasons, increases to assets and expenses are recorded in the debit column while increases for liability, equity, and revenue are recorded in the credit column. Further, each category is further divided into accounts. For example, under asset, one will find accounts for cash, inventory, fixed assets, among others. Under the expenses, one will find cost of goods sold, sales and general administration, and so forth.

Table 3-4 presents three example transactions, demonstrating the relationships between categories. Each transaction has two parts, the *item exchanged* and the *form of settlement* (Sangster et al., 2021). In the first transaction, one is purchasing equipment to be used for a long time with cash for £100. Conceptually, the equipment is the item entering the company. To increase the equipment account, as an asset, one would record a debit of £100 (line 2). Simultaneously, £100 in cash flows out of the company, so it is recorded as a credit to represent a decrease in assets (line 3). In the second transaction, one is buying a £5 coffee on credit. The coffee account, as an expense, is increased by recording £5 in the debit

Table 3-4 Three example transactions, depicting the relationship between DEBK categories. All transactions are in debit/credit pairs between two categories. (Source: Author's creation)

Line	Transaction	Debit	Credit
1	<i>Transaction 1: Purchasing long-term equipment with cash</i>		
2	Equipment (an asset)	£ 100	
3	Cash (an asset)		£ 100
4			
5	<i>Transaction 2: Buying a coffee with credit</i>		
6	Coffee (an expense)	£ 5	
7	Accounts Payable (a liability)		£ 5
8			
9	<i>Transaction 3: Selling a product</i>		
10	Cost of Goods Sold (Expense)	£ 50	
11	Revenue		£ 50
12	Cash (Asset)	£ 50	
13	Inventory (Asset)		£ 50

column. Credit, as a form of settlement, is recorded in accounts payable. To show an increase in accounts payable, as a liability category, £5 is recorded it in the credit column. In the third example, one is selling a product. There are two sets of transactions. First, one records the product leaving the company as a cost of goods sold, an expense, in exchange for revenue entering the company. The second is to adjust the inventory of stock, an asset. The inventory is decreased in exchanged for cash, which is increased. After recording all the transactions, the sum of the debit column should equal the sum of the credit column, thus being in balance for all the transactions.

The five categories within modern day accounting are also related by time. A balance sheet is a snapshot in time of the entity on the day in which the statement was prepared (Sangster et al., 2021). Because balance sheets are presented in regular intervals, it is common to denote the time as Period A, Period B, etc. A *cash flow statement* is a presentation of historical changes in cash of an entity between two time periods (IAS, 1992). As the cash account is a balance sheet item, a cash flow statement shows the change to the cash account between two balance sheets, or between two points in time (Equation 3-1).

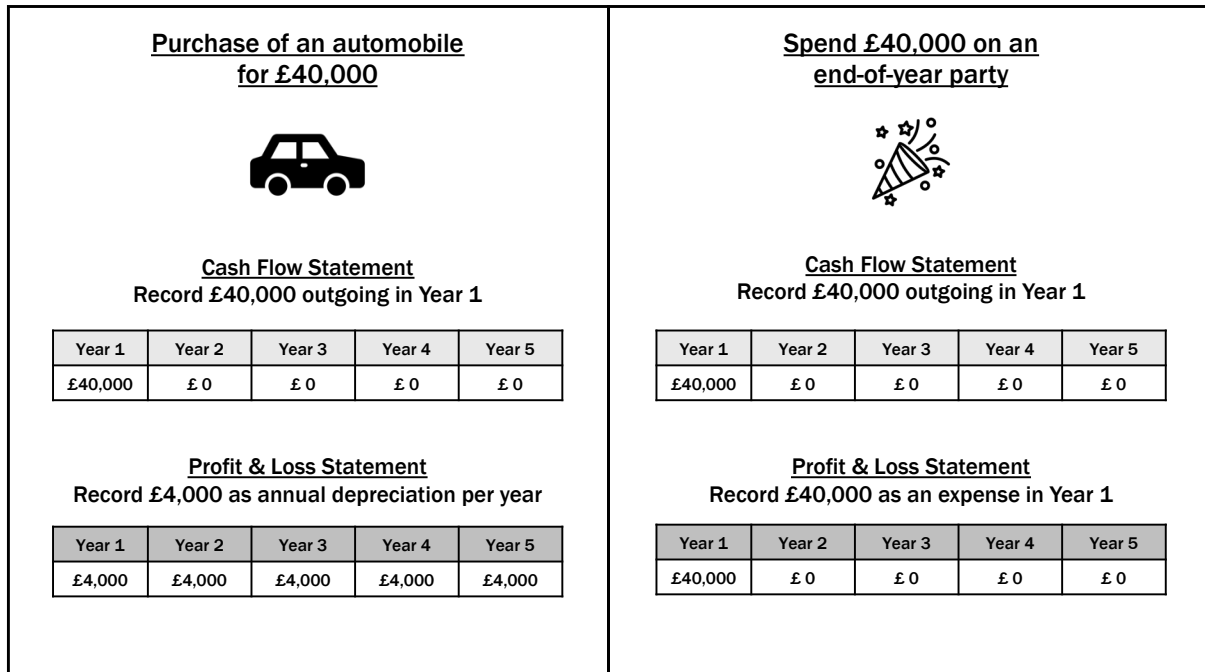
$$\left[ \begin{array}{l} \text{Cash flow} \\ \text{statement} \end{array} \right] = \left[ \begin{array}{l} \text{Cash on} \\ \text{Balance Sheet} \\ \text{in Period A} \end{array} \right] - \left[ \begin{array}{l} \text{Cash on} \\ \text{Balance Sheet} \\ \text{in Period B} \end{array} \right] \quad \text{Equation 3-1}$$

The P&L statement is a record of inflows and outflows due to trade activities that occur between two periods (Sangster et al., 2021). Net profit is calculated by subtracting expenses from revenue. The net profit on the P&L is recorded as retained earnings under equity category on the balance sheet (Equation 3-2).

$$\left[ \begin{array}{l} \text{Retained earnings} \\ \text{on balance sheet} \end{array} \right] = \left[ \begin{array}{l} \text{Net profit} \\ \text{on Profit and Loss} \end{array} \right] = [\text{Revenues} - \text{Expenses}] \quad \text{Equation 3-2}$$

Although both the P&L and the cash flow statements depict inflows and outflows between two balance sheets, the information they provide is different, as shown in Figure 3-1. A cash flow statement measures the inflows and outflows of cash when they occur. For example, assume a company paid £40,000 for an automobile and the same amount for an end-of-year party. On a cash flow statement, both transactions would be recorded as an outflow of £40,000 in Year 1. However, the automobile can be used for a long period of time, say 10 years, while the end-of-year party is a one-time expense. The P&L can demonstrate usage of the automobile by recording £4,000 per year for 10 years as depreciation. If one depended exclusively on a cash flow statement to make decisions, the purchase of an automobile and a party would be treated as equal. However, the P&L can show the longevity of usage for an investment. As a result, relying only on a cash flow statement can create temporal distortions of profitability.

A P&L is prepared using accrual basis, or to record items when they are used, not when cash is exchanged (Sangster et al., 2021). Accrual basis applies the matching concept, where the usage of resources is matched to the income or expenses of the same period (Storey & Storey, 1998). When an asset's lifetime is longer than the reporting period, the depreciation account is used to spread out the asset's upfront investment over its operational



*Figure 3-1 Comparing the cash flow statement and profit & loss statements for the first five years of the purchase of an automobile and a party. For both purchases, the cash flow statement can look the same. However, the P&L, can represent how long a purchase is used for. (Source: Author's creation)*

lifespan. For the automobile, the annual depreciation expense is £4,000 over a 10-year life. In other words, £4,000 is 'used' each year over the lifespan of the vehicle. Meanwhile, the party occurs within a single reporting period, so the P&L records an expense of £40,000. Thus, a P&L provides temporal information on how an asset is used while a cash flow statement provides information of how the cash changes hands.

As this section shows, the information architecture of financial accounting was designed for the temporal needs of management control and investment decision making. The financial account system separately presents the performance, or flow of exchanges, with the position, or stock of wealth and assets. It further separately depicts changes to both stock and flows over time. In the next section, I review corporate GHG accounting, to enable a comparison between the two systems.

## 3.2. Theory of corporate GHG accounting: Accounting for impact

GHG Accounting can also be theorized using Power's performance measurement hierarchy, as shown in Table 3-1. As this section explains, the MQ are emissions either measured with sensors or modelled using life cycle assessment (LCA), environmentally extended input-output (EEIO), or combustion emission factor models. First order emission values are categorised into Scope 1, 2, and 3 as determined by the GHG Protocol. These values are then used for 2<sup>nd</sup> order systems, such as setting net zero targets (SBTi, 2023), internal carbon prices (Bento 2020), sustainable investment strategies (PRI, 2016), set carbon taxes, (European Commission, 2024), among other activities.

### 3.2.1. The GHG accounting system as a mediating instrument.

Similar to financial accounting system, the corporate GHG accounting acts as the mediating instrument between environmental disciplines that quantify emissions and financial disciplines that are applying corporate GHG values in capital allocation decisions. Equation 3-3, the general method to model GHG emissions, reproduced from Chapter 2, demonstrates the fields that are involved in the quantification of emissions.

$$\begin{bmatrix} \text{Activity} \\ \text{Data} \end{bmatrix} \times \begin{bmatrix} \text{Emission} \\ \text{factor} \end{bmatrix} \times \begin{bmatrix} \text{Global} \\ \text{warming} \\ \text{potential} \end{bmatrix} = \begin{bmatrix} \text{Emissions} \\ \text{(in tCO}_2 \text{ equivalents)} \end{bmatrix} \quad \text{Equation 3-3}$$

The *activity data* is gathered from a business function, such as invoices of purchases, bill of materials of deliveries, or other record of a financial transaction. It is derived from the domain of management. Typical activity data include fuel consumed (in litres), a physical measurement (floor area, distance, volume, etc.), a count of an item (number of products, franchises, employees, etc.), or total spent on the activity (business travel, products purchased, products sold, etc.). This is analogous to the recording of transactions within financial accounting.

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There are three families of *emission factors*, derived from multiple disciplines. Combustion emission factors are measured by industrial engineers or quality engineers in laboratory settings. They represent the emissions of a combustion activity. Because they are merely a coefficient, temporally, the resultant emissions represent activities within the reporting period. LCA emission factors are derived from environmental engineering discipline. They are used to represent the environmental burden of a product's supply chain. They are typically performed from the *cradle*, or resources consumed for raw material manufacturing (upstream), to the *gate*, or when a product enters the reporting entity, or to the *grave*, or disposal of the product at end of life (downstream). Input-output (IO) tables are created by economists that study linkages of economic consumption and production between industrial sectors and subsectors. Environmental economists have extended IO tables into EEIO emission factors, representing resource consumption and emission linkages. EEIO tables are static representations of the structure of the economy in the year when the table was created (Kitzes, 2013). Resultant emissions from using EEIO emission factors represent the structure of the economy in the year of the EEIO's creation.

*Global warming potentials* (GWP) were developed by climate scientists as a way to compare the contributions of different GHGs to global warming (Smith & Wigley, 2000). It was introduced in the First Assessment Report by the IPCC (IPCC, 1990). The Kyoto Protocol introduced six (now seven) GHGs to be reduced, there was an effort to create a single metric that could combine and weigh the different gasses into a single target (Fuglestvedt et al., 2003). Because GHGs have different atmospheric lifetimes, GWPs come in several different time horizons – 20, 100, and 500 years – that represent the amount of damage caused within that time horizon. The GHG Protocol advises the use of GWP-100 for all emissions modelling (WRI & WBCSD, 2011a). Thus, 100-years of damage is attributed to the reporting period.

Table 3-5 GHG protocol categories, as organised into a value chain (WRI & WBCSD, 2011a)

Upstream categories	Reporting company	Downstream categories
<ul style="list-style-type: none"> <li>• <b>Scope 2:</b> Energy indirect emissions</li> <li>• <b>Scope 3 Category 1:</b> Purchased goods and services</li> <li>• <b>Scope 3 Category 2:</b> Capital goods</li> <li>• <b>Scope 3 Category 3:</b> Energy-related activities not included in scope 1 or scope 2</li> <li>• <b>Scope 3 Category 4:</b> Upstream transportation and distribution</li> <li>• <b>Scope 3 Category 5:</b> Waste generated in operations</li> <li>• <b>Scope 3 Category 6:</b> Business travel</li> <li>• <b>Scope 3 Category 7:</b> Employee commuting</li> <li>• <b>Scope 3 Category 8:</b> Upstream leased assets</li> </ul>	<ul style="list-style-type: none"> <li>• <b>Scope 1:</b> Direct emissions</li> </ul>	<ul style="list-style-type: none"> <li>• <b>Scope 3 Category 9:</b> Downstream transportation and distribution</li> <li>• <b>Scope 3 Category 10:</b> Processing of sold products</li> <li>• <b>Scope 3 Category 11:</b> Use of sold products</li> <li>• <b>Scope 3 Category 12:</b> End-of-life treatment of sold products</li> <li>• <b>Scope 3 Category 13:</b> Downstream leased assets</li> <li>• <b>Scope 3 Category 14:</b> Franchises</li> <li>• <b>Scope 3 Category 15:</b> Investments</li> </ul>

The quantified *emissions* are then categorised into 1<sup>st</sup> order classification system by the GHG Protocol's system of Scope 1, 2, and 3. These categories are organised by the value chain, as shown in Table 3-5. While Scope 1 and 2 are directly attributable to the reporting company, Scope 3 represents upstream and downstream activities (WRI & WBCSD, 2011a).

The information architecture of the GHG Protocol is analogous to that used in LCA, with defined upstream and downstream activities. Thus, LCA serves a dual function, as an MQ methodology as well as an information architecture for the 1<sup>st</sup> order classification system, possibly creating methodological confusion. Temporally, the system only accounts for current year emissions. Although it may seem that upstream (past) and downstream (future) emissions are included, they are summed together and attributed to the year of the activity data. Thus, past and estimated future emissions are accounted for in the present year.

The GHG Protocol is increasingly being used by users of financial reports in making 2<sup>nd</sup> order investment choices. Major financial companies, such as the S&P Trucost (Trucost, 2019), MSCI (MSCI, 2023), and FTSE Russell (FTSE, 2018), are among those that incorporate

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Scope 1, 2, and 3 into their environmental, social and governance (ESG) scores (PRI, 2016). The goal is to compare entities to make climate-informed capital allocation decision and investment choices. These scores are updated on an annual basis. Corporate transition planning (TPT, 2022) and net zero targets (SBTi, 2023) typically set 2030 interim targets and 2050 net zero targets, or, as of this writing, 5 years and 25 years into the future. The goal of this application is to track trends of corporate emissions, comparing a company against itself over time.

In essence, as a mediating instrument, the GHG Protocol facilitates between business operators, climate scientists, LCA engineers, to generate emission values. However, these emission values are a summation of different time horizons and attributed to the present. The emissions values are then used by economists, policy makers, corporate strategists, among others, who require the ability to make judgements about the future based on information about the past (Chambers, 1989). The next section reviews the organisation of these stakeholders throughout the historical evolution of corporate GHG accounting.

#### **3.2.2.A history of corporate GHG accounting**

The timeline in Figure 3-2 depicts how different sectors, environmental assessment, GHG inventory, socially responsible investing, environmental, social, and governance (ESG) disclosures, and financial accounting, influenced each other in the development of contemporary corporate GHG emissions.

The contemporary corporate GHG accounting system grew out of research in the 1960's on environmental assessment, which sought to understand environmental impacts of products (Guinée, 2011). By the 1990's, LCA became the dominant method of modelling the environmental burdens associated with a product (Hou et al., 2015). The International Organization for Standardization (ISO) and the Society of Environmental Toxicology and

Chemistry (SETAC) began standardising LCA methodologies (Guinée, 2011). The current version of the ISO LCA standard was adopted in 2006 (BSI, 2020).

LCA takes a life cycle perspective, which is to consider the entire life cycle of a product, from raw material extraction through production and manufacturing to end of life treatment. The goal is to identify potential shifts in environmental burdens between life cycle stages (BSI, 2020). LCA is a process-based approach as emission inventories are conducted based on the processes identified relevant to the item being studied. Although LCA can be used to quantify any environmental burden, GHG emissions as a specific metric has become the most frequent application of the LCA method (Hou et al., 2015).

In 1998, the Kyoto Protocol required nations to estimate anthropogenic emissions of all greenhouse gases (UNFCCC, 1998). It adopted the methodologies developed by the Intergovernmental Panel on Climate Change (IPCC) to take inventories and report national GHG emissions (IPCC, 1995). The IPCC gave guidance for how to determine national boundaries, what activities needed to be counted, and which emission factors to use (Eggleston et al., 2006). The most recent version of the IPCC guidelines was written in 2019 (Calvo Buendia et al., 2019).

In the late 1990's, there was an interest to develop a carbon assessment and accounting tool for non-Kyoto organisations (Walenta, 2021). The Greenhouse Gas Protocol (GHG Protocol) first proposed a system for corporate emission accounting in 2001, later revised in 2004 (WRI & WBCSD, 2004). In it, they introduced the categories of Scope 1, 2, and 3 to represent a company's GHG inventory. The system attempted to distinguish responsibility of emissions a company had direct control (Scope 1) and indirect control via a company's value chain (Scope 2, 3) (Walenta, 2021). While LCA uses a life cycle perspective to describe upstream and downstream process, GHG Protocol uses a value chain perspective to describe the same. The system is designed such that for the reporting entity, there is no

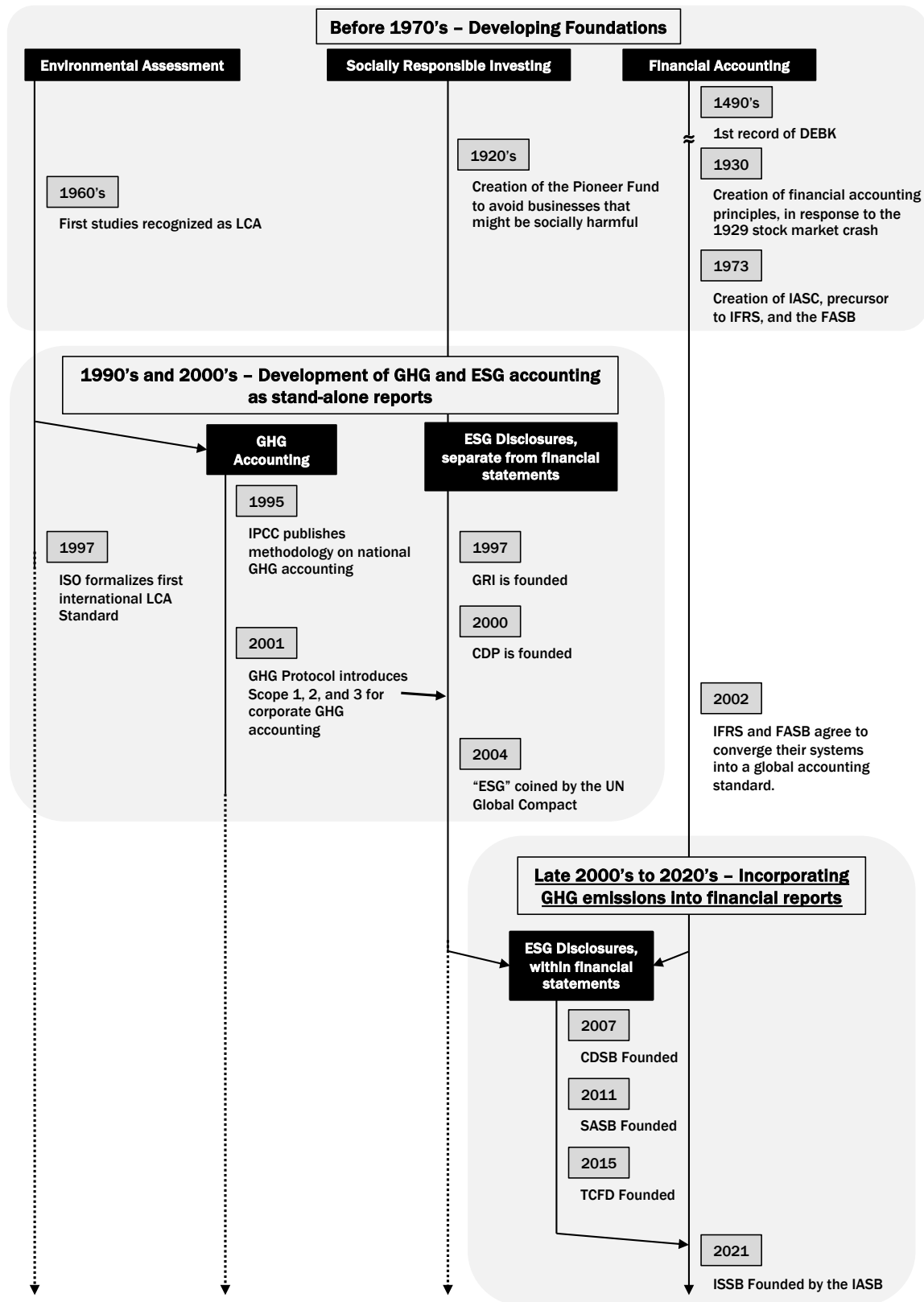


Figure 3-2 How different accounting narratives for GHG indicators were incorporated into the financial accounting field. Environmental assessment and LCA formed the basis for GHG accounting, which was used by socially responsible investors. Recently, the financial accounting field developed their own standards for the inclusion of climate indicators inside existing GPFs. (Source: Author's creation)

double counting of Scope 1, 2, and 3. Between companies, double counting can be avoided in Scope 1 and 2. However, Scope 3, by design, includes double counting between entities. This is because Scope 3 shows shared responsibility and encourages collaboration to reduce supply chain emissions (WRI & WBCSD, 2011a).

Also, in the late 1990's, socially responsible investors began to gain an interest in an entity's sustainability, including its GHG footprint. Socially responsible investing (SRI) is the practice of avoiding business practices that were deemed socially harmful. Its modern-day origins can be traced back to the 1920's with the creation of the Pioneer Fund that screened for companies that might be socially harmful (Trelstad, 2016). SRI strategies have been used to divest from defence contractors during the Vietnam war, to pressure South Africa to dismantle apartheid, and protest Bhopal, Chernobyl, and Exxon Valdez human and environmental disasters (Schueth, 2003). As such, SRIs began using GHG emissions as an exclusionary criterion.

Corporations began disclosing environmental attributes as part of their social accounting disclosures (Owen et al., 1997) in a separate document from the annual mainstream financial reports. Known as non-financial disclosures, early reporting initiatives that aggregated these metrics included Global Reporting Initiative (GRI), founded in 1997 (GRI, 2024) and the CDP, formerly Climate Disclosure Project, found in 2000 (CDP, n.d.). Both standards adopted Scope 1, 2, and 3 as metrics for corporate GHG emissions. In 2004, the UN Global Compact coined the term ESG, which stands for environmental, social, and governance issues, in its recommendations to the financial sector on how to integrate non-financial metrics into its decision making (UN Global Compact, 2004). Scope 1, 2, and 3 were included as a component of environmental issues.

In the late 2000's, there began a movement to integrate financial and non-financial reports, stemming from the financial sector's effort to understand their own effects on climate-related risks and opportunities. Some of these standards included the Climate Disclosure Standards

Board (CDSB), founded in 2007 (CDSB, 2019), the Sustainability Accounting Standards Board (SASB), founded in 2011 (IFRS, 2024), and the Taskforce for Climate-related Financial Disclosures (TCFD) founded in 2015 (TCFD, 2021). All three of these standards advocated for including the disclosure of Scope 1, 2, and 3 within existing financial reporting.

In 2021, the IASB founded the International Sustainability Standards Board (ISSB). Its creation was supported by the TCFD and consolidated the CDSB, SASB, and other standards (IASB, 2021). The goal of the ISSB is to make sustainability information useful to the primary users of financial statements, as the financial sector recognised that GHG emissions, among other environmental indicators, could influence resource allocation decisions (ISSB, 2023). One manifestation is that the ISSB adopted the IFRS' principles in their entirety. The ISSB requires entities to report their Scope 1, 2, and 3 emissions.

In summary, the LCA system of inventorying environmental burdens underlies contemporary corporate GHG accounting system. The LCA life cycle perspective directly influenced the value chain perspective used in GHG Protocol. The metric was originally used as an exclusionary criterion for socially responsible investors. Today, Scope 1, 2, and 3 are included in sustainability disclosures by financial standard setters. Financial users are incorporating them alongside financial statements to support making capital allocation decisions. In the next section, I review how the purpose of corporate GHG accounting is designed into its information architecture.

### **3.2.3. The information architecture of GHG accounting**

LCA serves a dual purpose, producing emission factors as part of measurement quantification systems, as well as influencing the structure of the Scope 1, 2, and 3 information architecture. This section firsts reviews LCA as a measurement quantification (MQ) methodology and then the GHG Protocol as 1<sup>st</sup> order classification system. It concludes

by discussing some of the limitations of the GHG Protocol when being used in conjunction with the financial accounting system.

As stated earlier, the MQ should be stable and repeatable regardless of who conducts the measurement (Power, 2004). However, the user conducting the LCA study decides the value chain boundary, choosing between a cradle-to-gate, cradle-to-grave, or any other subset of the supply (Moncaster et al., 2018). Temporally, *cradle* represents the past, as material extraction presumably occurred in the past, and *grave* represents the future, as disposal has yet to occur. Temporal considerations are lost because the results are an aggregation of all processes to provide a snapshot-in-time of potential impacts (Beloin-Saint-Pierre, 2020). This is because the user gets the freedom to determine the time horizon of analysis. The problem with LCA time horizons is well known, ever since the early days of its development (Lueddeckens et al., 2020). When using LCA emission factors, the resultant emissions that are attributed to the current reporting period may represent different time horizons.

Summing up different supply chain processes can create widely differing results (Yuan et al., 2015). For example, one study found that, because LCA-based environmental accounting depends on an assumed value chain, results can differ by as much as 50% due to truncation error of where the value chain ends (Suh et al., 2004). A critical gap in carbon accounting is that the GHG Protocol does not give financial users the ability to connect past, present, and future activities.

In addition, LCA is further separated into attributional and consequential LCA (aLCA and cLCA, respectively). The UN Environmental Programme (UNEP) defines attributional accounting as a “Modelling approach in which inputs and outputs are attributed to the functional unit of a product system by linking and/or partitioning the unit processes of the system according to a normative rule,” (UNEP / SETAC, 2011, p132) and a consequential LCA as a “Modelling approach in which activities in a product system are linked so that activities are included in the product system to the extent that they are expected to change

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as a consequence of a change in demand for the functional unit,” (UNEP / SETAC, 2011, p133). Weidema explains the difference as aLCA models how environmental items flow within a temporal window and cLCA models how flows change in response to a decision (Weidema et al., 2018). ALCA methodologies require setting a boundary while cLCA necessitates a decision question to assess the consequences of the action (Brander et al., 2019). Studies have shown how the two systems can be coupled, where the first step is to report aLCA values to identify hotspots, and a second step is to ask question from which cLCA can evaluate possible changes (Yang, 2016).

As an MQ system for carbon accounting, both aLCA and cLCA emission factors are accepted and used. Generally, the GHG Protocol uses aLCA emission factors for Scope 3 (WRI & WBCSD, 2011b), while Scope 2 uses both. This is because market-based emission factors are considered a cLCA method while location-based emissions are an aLCA method (Brander et al., 2018).

As a 1<sup>st</sup> order classification system, the GHG Protocol is an aLCA method, prescribing normative rules on boundaries, categories, and allocates responsibility between reporting entities. The information architecture of the GHG Protocol has the characteristics of single-entry bookkeeping. First, the GHG Protocol is a flow-based metric, accounting for the emissions of activities for the present period (Ratnatunga et al., 2011). Inventories of stocks and flows are conducted separately and attributed to the current year. For example, emissions that arise due to annual operations of the entity are reported as Scope 1 and 2, representing flow-based emissions. Emissions that arise due to the procurement of capital assets are reported under *Scope 3 Category 2 Capital goods*. However, these emissions from capital assets must be fully accounted for in the year that they are emitted as firms are not allowed to spread the emissions over the useful life of the capital asset (WRI & WBCSD, 2013). Further, some categories are a combination of emissions from both capital stock and operational flows. For example, *Scope 3 Category 14 Franchises* is an inventory of Scope 1

and 2 flows as well as optionally the life cycle emissions of constructing the franchise, a capital stock. In short, the GHG protocol is a measure of annual emission flows of an entity, whether it is related to operational or capital activities. The GHG protocol is functionally equivalent to cash basis accounting, where all exchanges must be accounted for in the period which they occur.

Second, there lacks a relational logic between emission stocks and emission flows. Unlike the financial system where the Master T-Table serves as the relational database between stocks and flows (Table 3-3), emissions from stock and flows are inventoried every year independently of each other. Third, there lacks a relationship over time. Rather than having flows accumulate into stock, each year's emission inventory is conducted independent from prior year's inventory. Thus, the categories are neither related to each other in the same year nor related to itself between years. Without a spatio-temporal relational logic, accrual accounting is not possible.

Because emission flows do not accumulate into emission stocks, the GHG Protocol does not account for cumulative emissions of the entity, the mathematical equivalent to financial wealth. Wealth, or equity, is a sum of net profits over time, and cumulative emissions is a sum of net emissions over time. Today, if an entity wants to know their historical emissions, it will need to conduct an inventory of all emissions and offsets. This is much like the Italian banker of the renaissance using a single-entry bookkeeping system, taking an inventory of the bank's vault to calculate their wealth.

Because the GHG Protocol is a single-entry system, it does not convey temporal characteristics, such as how long an asset can be used for. Much like the financial accounting of the industrial revolution era, GHG accounting treats the emissions of different fixed assets as the same even though the fixed assets are utilised differently. The lack of temporal attributes creates difficulty when trying to account for emissions offsetting.

Temporal differences between releases, such as GHG lifetime in atmosphere, and withdrawals, such as permanence and duration of GHG storage, is not matched.

In summary, the GHG Protocol can be considered a special purpose reporting framework, taking inventories of specific items and discloses the information to the public. Other applications may use their own accounting system. For example, emissions trading schemes have their own accounting system, dictating their own boundaries, activity data, allowable emission factors, and other variables (CARB, 2019; EU Commission, 2023; RGGI, 2017; WAC, 2022). Further, the EU's carbon border adjustment mechanism (CBAM) also uses their own emissions accounting system of direct emissions from fossil fuels, indirect emissions from electricity, and embedded emissions of precursor materials (European Commission, 2024). The next section reviews current efforts to bridge the gaps between financial and GHG accounting.

### **3.3. Prior research to bridge the financial and GHG accounting gap**

Bringing closer alignment of financial and environmental accounting has been advocated for many years. In 2010, Anthony Hopwood wrote, "Integration of sustainability-related information within financial data collection processes results in data that is reliable, verifiable and auditable and helps to give the credibility needed to be taken seriously, both internally and externally," (Hopwood et al., 2010, p.240). The UN System of Environmental-Economic Accounting (SEEA) states that "Ideally, the time of the recording of physical flows should align with the time of recording of the flows in monetary terms using an accrual approach [2.139]," (UN, 2014, p32). This section reviews two approaches – first the financial accounting discipline's approach to address double counting issues in corporate GHG accounting and second the LCA discipline's to introduce temporality into GHG accounting.

### **3.3.1. Approaches by the financial accounting discipline**

Financial accounting researchers have attempted to apply double entry bookkeeping to the accounting of environmental systems as a means to remove double counting concerns. The mathematics of double entry bookkeeping has been generalised to account for any flow, including for environmental information (Renes & Garst, 2024). One study advocated for aligning granularity of data between financial and GHG emissions (Distler et al., 2024). Because the unit of account in financial accounting are transactions, GHG emissions should also be assigned to every transaction, aligning financial and emissions activities.

DEBK systems have been applied for national emissions accounting. The UN SEEA uses a 'quadruple entry system' for national environmental accounts. In the system, two of the ledgers are to record financial flows and two for environmental flows, thus each transaction is recorded four times (UN, 2014). UN SEEA accounts for national environmental footprints, of which carbon emissions is one indicator. Jang proposed a DEBK system to account for the net accumulation per year into global atmospheric system. It describes how to net atmospheric emissions and atmospheric absorptions for an annual net emissions. The net emissions are then accumulated into an atmospheric stock account, representing the cumulative emissions over time (Jang, 2023).

DEBK methods have also been applied to account for emissions of a corporation. The E-liability system points how that LCA is an entanglement of upstream and downstream processes that needs to be separated out (Kaplan & Ramanna, 2021). Instead, the E-liability system reports upstream activities as embedded emissions that enter the reporting entity and direct combustion emissions as additive to production. Embedded emissions of products can leave a company upon a sale (Ramanna, 2024). The system defines an E-asset as a right to remove carbon from the atmosphere (Kaplan et al., 2023), otherwise known as an offset. E-assets can be used to neutralise E-liabilities, with the remainder representing additional

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emission liabilities that the entity needs to reduce. Penman demonstrated how transactions could be designed for an E-asset and E-liability system (Penman, 2024), creating E-ledgers.

The E-ledger system has observed properties of single-entry bookkeeping systems. The E-liability is a count of emissions-related activities and E-assets is a count of withdrawal-related activities. In other words, E-liabilities count inflows to the atmosphere caused by corporate activities and E-assets count outflows from the atmosphere due to corporate activities.

Mathematically, E-assets and E-liabilities are analogous to the reconciliation of debit and credit books. The two are inventoried separately before being reconciled to produce a net-emissions figure, much like a bank would reconcile their debit and credit books to calculate their net profit.

Further properties of single entry can be observed in the extension of E-ledger to account for carbon allowances in emissions trading systems (Cheung, 2023). Cheung shows that the carbon of equity can be negative. However, the financial analogy, owner's equity, can never be negative. Instead, balance sheet items are always recorded with a positive value, and moving between assets and liabilities should the sign change. The negative owner's equity implies that the E-ledger system is single entry. It has been shown that double entry systems can be mathematically converted into single entry systems (Ijiri, 1992). In doing so, balance sheet-equivalent items can be recorded as both positive and negative values (Hayden, 2014).

While E-ledgers account for emissions, Stefan Reichelstein considered the underlying fixed assets that cause the emissions. He proposed carbon assets as the embedded emissions of a firm's operating assets and carbon liabilities as the direct emissions of operations and indirect emissions from product procurement (Reichelstein, 2024). However, Reichelstein's balance sheet system mathematically represents the embodiment of direct and indirect emissions into a carbon asset. In essence, this system performs a product LCA, calculating the embedded emissions of fixed assets.

### 3.3.2. Approaches by environmental LCA disciplines

Advances in the LCA field has focused on improving the modelling of emissions values. Temporal inclusion within LCA have focused on standardising on temporal boundary or improving temporal resolution of modelling assumptions. For example, if a building is constructed with a 75-year lifespan, but the carbon accountant uses a GWP-100, then there is an assumption of a 100-year time horizon for the asset (Levasseur et al., 2010). Dynamic LCA (DLCA) has emerged as a methodology which takes into consideration items such as time horizon boundary, the temporal resolution of the model, and temporal weighting (discounting) (Lueddeckens et al., 2020). Beloin-Saint-Pierre generalised DLCA methodologies into three processes: determine temporal scope, such as the time horizon of the study, the dynamics of the system, such as ability to model annual changes, and incorporating the temporal attributes into the model (Beloin-Saint-Pierre, 2020). Sohn found three areas of dynamic studies – dynamic process inventories, that account for future technology development, dynamic systems inventory, that use temporally discrete values for inventory accounting, and dynamic characterisations, where adjustments are made for different temporal scales, such as discount factors (Sohn et al., 2020).

However, the purpose of introducing temporality is to improve modelling granularity. It enables the more detailed adjustment of future values and assumptions when making modelling assumptions. The results of the DLCA are still attributed to a single point in time. This is unlike general purpose financial statements, which is a framework for the presentment of temporal data, such that users can construct their own models. The author was not able to find research that presented the underlying LCA data in a periodic manner. In essence, LCA is an emissions *modelling* technique, not an emissions *accounting* technique.

In summary, to address the double counting challenges within LCA, financial accountants have proposed to disaggregate supply chain processes. To address the lack of temporality, the LCA discipline have introduced periodic modelling techniques. A gap still remains: a

method for periodic presentment of LCA data that is aligned with financial accounting. This method needs to achieve the aims eliminating the double counting challenge, needed by the financial sector, as well as able to support the modelling techniques used by the LCA discipline. The next section describes the theoretical foundations of a system that can address this gap.

### **3.4. Theoretical underpinning of general-purpose LCA**

As our literature review has shown, there still is a lack of environmental accounting framework for corporate entities that fits the general-purpose needs of primary users of financial reports. There are broad audience of stakeholders, including corporate management, regulators, investors, analysts, economists, and policy makers that are relying on corporate emissions values. These stakeholders perform a broad set of decisions, such as investing, transition scenario planning, policy setting, and so forth. Emissions values are being used to design a broad set of financial instruments, such as equity and debt products, set carbon tax rates, trading tariffs, carbon pricing, and more.

This thesis follows Hopwood's call to integrate financial and environmental attributes (Hopwood et al., 2010). It aligns with UNEP's definition of attributional LCA and proposes a set of normative rules with spatial and temporal boundaries for corporate emissions accounting (UNEP / SETAC, 2011). It responds to the call for a single-user perspective (Barker, 2025), by considering the perspective of the primary user of financial reports. The paper builds on Distler (2024) by using transactions as our unit of accounts to align the temporal resolution with that of financial accounting. It follows E-liability's principle of only accounting for direct emissions (Ramanna, 2024). It also adopts the mathematics and relational database of double entry bookkeeping (Renes & Garst, 2024) so as to synchronise periodic activities across multiple domains (Quattrone, 2005). The thesis introduces general purpose environmental statements to present the environmental attributes, following the information architecture of general-purpose financial statements (IASB, 2018).

I propose a general-purpose life cycle assessment (GP-LCA) framework, where *general purpose* denotes alignment with the information architecture of financial reports and *LCA* denotes alignment with an aLCA approach to environmental flows. The research presents the data by using financial statement analogies. It uses statement of positions to represent stocks (Balance Sheets) and statement of performance to represent flows due to trade activities (Gains & Uses Statements). In short, GP-LCA follows both the normative rules of financial and environmental accounting. The result is a framework that can function as a mediating instrument, synchronising events between climate science and engineering with financial and policy decision makers.

### **3.4.1. Differences between of input and output accounting**

The GP-LCA framework can be applied to any environmental flow, such as energy, carbon, methane, water, and others. These environmental flows can be highly intertwined. For example, 76% of all emissions coming from combustion for energy (ClimateWatch, 2022). Recall that in Equation 3-3, the activity data represents a unit of human activity, and the emission factor converts the human activity into emissions. In essence, the human activity is a measure of energy *inputs* while the emission is a measure the pollution *output*.

Input and output accounting should theoretically be the same, but their temporal characteristics can differ. Financial accounting has developed rules regarding input and output accounting (FASB ASC 606-10-25-21, 2024; IFRS, 2014). For example, for revenue recognition, the output method recognises revenue based on the value of the item delivered (BDO, 2018; PWC, 2024). This is common in sectors where physical products have a sale price, such as manufacturing, consumer goods, and construction. In the input method, revenue is based on the costs incurred by the entity to satisfy a customer. An example is in the services sector, where labour hours are used as a metric to determine revenue.

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There are distinct behavioural dynamics of energy inputs and carbon outputs, where it can be advantageous to understand the two environmental indicators separately. I present three examples, understanding a single asset, comparing multiple assets, and spreading the environmental attribute over time.

The same physical asset may have distinct energy and carbon benefits. For example, the Avedøre Power Station in Denmark consumes agriculture waste for the generation of thermal energy for district heating, electricity, and operate a carbon capture facility (Ørsted, 2024). As shown in Table 3-6, the power plant has three revenue streams, selling heat, electricity, and carbon capture. Each of the three products consume energy. However, two of the products are a net emitter of carbon (heat and electricity) while the carbon capture is a net withdrawer of carbon. Scrutinising the power station for energy inputs and carbon outputs separately enables better representation of the underlying human activity.

In a second example, different assets can have different upfront and ongoing characteristics for each environmental attribute. Table 3-7 is a stylised depiction of four types of fixed assets, renewable energy, additional insulation, carbon capture equipment, and a traditional thermal power plant. Based on upfront characteristics, the four look similar. Each asset has embedded energy and embedded carbon that arise from the manufacturing and construction process. However, their ongoing characteristics are very different. A solar panel (1) generates electric energy (gains) but does not release any additional GHGs over its useful

*Table 3-6 Non-linear financial, energy, and carbon flows at the Avedøre power plant in Denmark. Depending on the product, financial, energy, and carbon flows may be positive or negative. (Source: Author's creation)*

Product	Financial flows	Energy flows	Carbon flows
Electricity generation	(+) Generates revenue	(-) Consumes energy	(+) net releases
District heating	(+) Generates revenue	(-) Consumes energy	(+) net releases
Carbon capture	(+) Generates revenue	(-) Consumes energy	(-) net withdrawal

*Table 3-7 The GP-LCA framework makes distinct the differences between upfront and ongoing resources. Although all four examples require energy and carbon to construct, their ongoing energy and carbon footprint depends on the operational parameters. (Source: Author's creation)*

Fixed Asset	Upfront "Statement of Position"		Ongoing "Statement of Performance"	
	Embedded Energy	Embedded GHG	Energy Gains & Uses	GHG Releases & Withdrawals
1. Solar panel (Renewable energy)	(+) Embedded Energy	(+) Embedded Carbon	(+) Gains electricity	(0)
2. Additional insulation (Energy efficiency)	(+) Embedded Energy	(+) Embedded Carbon	(0)	(0)
3. Direct air capture (Carbon capture)	(+) Embedded Energy	(+) Embedded Carbon	(-) Uses electricity	(+/-) Net Releases & Withdrawals
4. Thermal power plant	(+) Embedded Energy	(+) Embedded Carbon	(+) Gains electricity	(+) Releases

life. Additional insulation (2), on its own, does not consume additional energy nor GHGs. As part of a larger building system, it may reduce energy consumption. Direct air capture (DAC) technologies (3) consume energy to operate. The releases of emissions due to energy consumption needs to be balanced by the withdrawals achieved from the atmosphere. Thus, DACs need to be measured based on their net releases and withdrawals from operations. A thermal power plant (4) that is combusting fossil fuels will generate electricity (gains) and release carbon. Thus, accounting for energy inputs can have very different characteristics than accounting for carbon outputs.

Third, energy and carbon have different temporal lifetimes, thus spreading out their environmental impact over time will be different. From our examples in Table 3-7(1), solar panels have roughly 25-30 years operational life. The embedded energy and embedded carbon of manufacturing can be recorded as an asset on a statement of position. This embedded attribute will be utilised over the lifetime of the asset. When the panels are decommissioned and disposed of, the embedded energy will no longer 'perform useful work.' However, the embedded carbon will continue to exist in the atmosphere for another 500,000 years (Lord et al., 2016), contributing to environmental damage far beyond the useful life of

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the solar panel. By accounting for the temporal dynamics of environmental attributes separately, decision makers can gain a clearer picture of the impacts due to energy inputs and emissions outputs. Thus, the GP-LCA information architecture can be used to develop both input and output environmental accounting. Energy accounting can be considered a 1<sup>st</sup> order classification system for the activity data input. By corollary, carbon accounting can be considered a 1<sup>st</sup> order classification system for the emissions output.

Finally, the framework also can represent withdrawal accounting, an area of intense research interest within the E-liability scholars (Cheung, 2023; Comello et al., 2023; Kaplan et al., 2023; Penman, 2024; Roston et al., 2022). As shown in Table 3-7(3), GP-LCA system records the manufacture of an offsetting equipment as an embedded carbon asset. The DAC's ongoing operations is recorded in the Carbon Releases and Withdrawals (CR&W) Statement. Net CR&W can be recorded, analogous to net profit and loss on a financial statement.

GP-LCA also enables other characteristics of financial accounting. GP-LCA statements can be periodically refreshed and presented to users, who can gain a better managerial understanding of multiple environmental flows for corporate outcomes. One can use the data to perform further operations, such as calculating Scope 1, 2, and 3, deriving cumulative emissions, forecasting future emissions, and value the impact of resource usage. Importantly, it enables the ability to differentiate between capital assets that have different operational parameters over time.

In summary, it is possible to bridge the temporal gap between GHG and financial accounting by adopting double entry bookkeeping for environmental flows. As different environmental flows have unique dynamics, accounting for the flows independently enables the study of temporal divergences within environmental indicators as well as between them and financial indicators.

### 3.5. Summary

This chapter reviewed key perspectives that are involved in GHG accounting. GHG accounting frameworks, as a mediating instrument, brings together climate scientists, engineers, and business operators, who contribute data to quantify corporate emissions, with investors, policy makers and regulators, who utilise the emissions data. DEBK synchronised activities across multiple stakeholders within financial accounting, enabling the tracking of trade accounts and a firm's performance. Meanwhile, GHG Protocol, as an inventory system, does not have temporal attributes. GP-LCA is grounded in the normative frames of both general-purpose financial statements and attributional LCA. It uses DEBK to synchronise temporal attributes across environmental and financial disciplines, enabling their interoperability.

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# Chapter 4. Greenhouse gas accounting standards: A rapid review

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## Abstract

Policies, standards, and voluntary initiatives aimed at mobilizing businesses to address the challenges of climate change reside on the foundation of greenhouse gas (GHG) accounting. However, the proliferation of multiple, yet similar, standards can create market confusion for businesses, policy makers, and requires scientists to engage with a multitude of derivative works. To this end, we conducted a rapid systematic review of corporate GHG accounting standards, screening 102 standards and analysing 51. Our results found that all are derivative works of the GHG Protocol, making it the *de facto* global standard for GHG accounting. However, within the GHG Protocol, there is a lack of convergence in emission quantification methodologies, as direct measurement, emissions modelling, life cycle assessment (LCA) modelling, and environmentally extended input output (EEIO) modelling are all accepted. We identify the foundational emissions quantification standards and show discrepancies amongst the principles behind quantification and disclosure standards, calling into question whether emission values are fit-for-purpose for financial decision makers. For applications where the GHG Protocol is fit-for-purpose, the global standardization community has an opportunity to reduce fragmentation and improve interoperability by directly referencing the dominant standard rather than creating derivative works. However, for situations where new standards are needed, future research is warranted to design accounting systems that can ensure alignment between policy and practice.

## Keywords

GHG accounting, carbon accounting, GHG Protocol, ISO, standard setting, net zero

### 4.1. Introduction

Policies, standards, and voluntary initiatives aimed at mobilizing businesses to address the challenges of climate change reside on the foundation of greenhouse gas (GHG) accounting. Guidelines for organizational alignment to net zero targets (ISO, 2022; UN HLEG, 2022), frameworks for developing net zero transition plans (TPT, 2022), standards for setting science-based targets (SBTi, 2023), among others, are some efforts that require entities to reduce their GHG footprint from a baseline defined by a GHG accounting system. By 2030, GHG accounting disclosures will be mandatory for activities/areas covering almost 50% of the global GDP (UNFCCC, 2022).

However, the GHG accounting field has a multiplicity of standards and methods. For example, the Taskforce for Climate-related Financial Disclosures (TCFD) cites eight GHG accounting methodologies permissible under their system, whilst the CDP (previously the Carbon Disclosure Project) cites 69, including an option for 'other standards' (CDP, 2023; TCFD, 2021). Further, in 2023, several global GHG accounting and disclosure standards began a consultation process for updating their climate standards (GRI, 2023; WRI & WBCSD, 2023). This created a knock-on effect on other disclosure standards, as the TCFD accepts values from either the Global Reporting Initiative (GRI) or the GHG Protocol (TCFD, 2021), two standards currently being updated. Other standards are being consolidated, such as the International Sustainability Standards Board (ISSB) consolidating the Climate Disclosure Standards Board (CDSB) with the Value Reporting Foundation, itself a consolidation of the Integrated Reporting Foundation and the Sustainable Accounting Standards Board (SASB) (IASB, 2023).

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There is a need to understand how emissions are quantified and whether GHG accounting support the intended impact behind corporate reporting. The overarching research question of this paper is, *“How many corporate GHG accounting systems are there?”* We also ask, *“How many methodologies are used to quantify corporate GHG emission?”*

The existence of multiple, yet similar, standards has created market confusion in deciding which standard to follow (Reinecke et al., 2012). One implication is the reliability of results, with a study of online GHG emissions calculators finding that different assumptions can result in emissions that range between 2.1 tonnes to 92.2 tonnes for the same inputs of activity, a difference of over 4000% (Harangozo & Szigeti, 2017). Such lack of reliability creates challenges in quantitative evaluations of progress towards GHG emission reductions (Ruiz Manuel & Blok, 2023).

Despite growing interest in systematic reviews of GHG accounting, to our knowledge, no large-scale review has been conducted of what standards and methodologies are being used in practice that set policy direction and hold corporations accountable to their climate ambitions. Existing systematic reviews have found gaps between corporate disclosures and economic activities of the corporation (Bazhair et al., 2022), between operational, accounting, and control actions that can be taken by management (Gulluscio et al., 2020), and between GHG accounting and conventional management information systems (Csutora & Harangozo, 2017). Our work contributes to closing this gap within organizational reporting by reviewing the corporate activities that are being quantified. Other studies have pointed out means-ends decoupling in the GHG accounting system, or where operational practices (means) do not enable achievement of the impact (ends) (Bromley & Powell, 2012). One review found that the term carbon accounting has different definitions and applications in different fields, such as for organizations, products, projects, and nations (Stechemesser & Guenther, 2012), raising the question whether the GHG accounting system is fit for purpose for different end users (Gillenwater, 2023). Because our work identifies the foundational

standards used in GHG accounting, researchers can further study gaps between means and ends.

We contribute to the field by conducting a rapid review, a well-known methodology to synthesize, assess, and appraise information to meet policy objectives (CEE, 2022). A document database of standards currently in use was created to identify the foundational standards by tracing references to origin. Further analysis was conducted of the linkages between GHG accounting and corporate activities, and whether GHG accounting system is fit-for-purpose for decision makers.

This research will be of interest to standard setters, who are in the process of updating the standards, as to how to improve data quality, and to academics and practitioners who need to understand applications of GHG accounting standards. This work will help policy makers understand the relationship between the various GHG accounting standards, and their role as one key metric within the broader corporate ESG disclosure environment.

Michael Powers (2004) developed a heuristic for distinguishing the purpose of performance measurement systems, of which accounting systems are a part of. The heuristic organizes accounting standards into a hierarchy of a 0<sup>th</sup> order measurement quantum, 1<sup>st</sup> order categorization systems, and 2<sup>nd</sup> order meta-measurement systems, as shown in Table 4-1. All accounting systems reside on the ability to standardize on a 0<sup>th</sup> order measurement quantum. For example, financial accountants and economists count money as the quantum of measure of economic value. First-order classification systems are used to categorize the measurement quantum, translating relevance into the measurement quantum. Financial accountants organize transactions into categories, such as assets, liabilities, revenues, and expenses (Sangster et al., 2021). These categories are then further organized into balance sheets and profit and loss statements as per the International Financial Reporting Standard (IFRS) (IFRS, 2024) or the U.S. generally accepted accounting principles (US GAAP) (FASB, 2024). Second order meta-measurements are other aggregations of numbers used in

Table 4-1: Hierarchy of performance measurement systems with examples from financial and GHG accounting.

Hierarchy for performance management systems	Financial accounting examples	GHG accounting examples
2 <sup>nd</sup> order meta-measurement systems	Indices, ratios, and other calculations that are used by policy makers, investors, and other decision makers.	Disclosure frameworks, pledges and targets that are used by policy makers, investors, and other decision makers.
1 <sup>st</sup> order classification systems	Financial statements categories, such as assets, revenue, etc. that are organized into balance sheet, profit and loss statement, etc.	GHG accounting categories, such as Scope 1, 2, and 3 or direct and indirect emissions.
0 <sup>th</sup> Measurement quantum	Financial transactions, following the rules of recognition.	Direct measurement of emissions due to combustion of fuel, or indirect modeling of emissions via cradle-to-gate emissions, or other methodologies.

decision and policy making. For example, from the financial statements, one might calculate financial ratios, valuations, and performance characteristics, upon which business, macroeconomic, and policy decisions are based.

GHG accounting was developed to measure GHG performance of organizations (WRI & WBCSD, 2004) and the ecosystem can also be understood through Power’s hierarchy. For example, corporate disclosure frameworks, net zero pledges, and decarbonization targets are forms of 2<sup>nd</sup> order meta measurements that policy makers and investors use for decision making. These aims are built upon the 1<sup>st</sup> order categorization system of GHG accounting frameworks. Two popular 1<sup>st</sup> order systems are GHG Protocol’s Scope 1, 2 and 3 (WRI & WBCSD, 2004) and ISO’s direct, energy indirect, and indirect emissions (BSI, 2019). We make the distinction that 1<sup>st</sup> order standards are ‘emission standard setters’ that define the categories and metrics being reported while 2<sup>nd</sup> order systems are ‘emission standard takers’ that utilize pre-defined GHG metrics for further decision making. Finally, 0<sup>th</sup> order measurement quantum systems are methodologies that quantify GHG emissions. Example

standards include direct measurement with sensors (Eggleston et al., 2006) or indirect estimation techniques, such as using life cycle assessment (WRI & WBCSD, 2011).

To address the aims of this research, we asked the following questions:

- (1) How many foundational GHG accounting systems (1<sup>st</sup> order) are accepted by corporate disclosure standards (2<sup>nd</sup> order)?
- (2) How many foundational GHG emissions quantification methodologies (0<sup>th</sup> order) are accepted by GHG accounting systems (1<sup>st</sup> order)?

Then, we examine whether the measurement quantum standards are fit for purpose, asking:

- (3) Are the principles of the foundational measurement quantification (0<sup>th</sup> order) standards aligned with those of 1<sup>st</sup> and 2<sup>nd</sup> order standards?

The structure of the paper is as follows: We begin by describing the method of our rapid review for sourcing a document database of standards. We then present results and discuss policy implications for each research question. We end with conclusions and a summary of policy recommendations.

## **4.2. Methods**

This research follows the rapid systematic review methodology of the Collaboration for Environmental Evidence (CEE) (CEE, 2022). The review was conducted between March 2023 and March 2024.

### **4.2.1. Search strategy**

The document database acquisition was conducted manually using snowball sampling (CEE, 2022). This is due to GHG accounting and disclosure standards being a form of grey literature, published by government and non-government organizations. They are not stored within academic databases, nor do they reliably have reference sections or abstracts.

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This research focuses on corporate disclosures and what measurement methodologies they rely on and utilized corporate disclosure frameworks as the seed documents (Sayers, 2007). The seed documents represent the latest documentation from six organizations that have broad adoption within the global economy. The research team were able to quickly identify the seed disclosure frameworks due to involvement with the Global Reporting Initiative (GRI), the International Organization for Standardization (ISO), and the Science-based Target initiative (SBTi). Citation analysis (Belter, 2016) was used to search for other referenced GHG standards and methodologies. The seed documents are:

- **CDP Climate Change 2023 Questionnaire** (CDP, 2023). Over 13,000 companies worth over 64% of the global market capitalization discloses data through CDP (CDP, 2021). The CDP was founded in 2000.
- **ESRS E1 Climate Change** (EU Commission, 2023a). The European Sustainability Reporting Standards (ESRS), adopted in 2023, is a disclosure requirement developed for all companies that are subject to the corporate sustainability reporting directive (CSRD). Around 50,000 companies will be subject to the requirement (EU Parliament, 2022).
- **GRI 305: Emissions** (GRI, 2016). The GRI, founded in 1997, is one of the oldest sustainability disclosure standards, and is used by 78% of the world's largest 250 companies (KPMG, 2022).
- **IFRS S2: Climate-Related Disclosures** (ISSB, 2023b). The ISSB, founded in 2021, is backed by the G7, the G20, the International Organization of Securities Commissions (IOSCO), Financial Stability Board, African Finance Ministers and Finance Ministers and Central Bank Governors from more than 40 jurisdictions (IASB, 2023).
- **SBTi Corporate Manual 2023** (SBTi, 2023). Over 2200 companies across 70 countries and 15 industries, representing more than one third (\$38 trillion USD) of

global market capitalization, have approved emissions reductions targets or commitments with SBTi (SBTi, 2022). SBTi was founded in 2015.

- **TCFD Guidance on Metrics, Targets, and Transition Plans** (TCFD, 2021). The TCFD, founded in 2015, has support of over 120 regulators and governments, including the G7 and G20, representing over 80% of the global economy (TCFD, 2022). As of October 2023, the TCFD has been disbanded, with the responsibility for climate disclosure monitoring and progress now transferred to the IFRS Foundation (TCFD, 2024). Despite this transition, the TCFD guidance remains in use and continues to be referenced.

#### **4.2.2. Screening for eligibility**

The documents were screened as to whether they met the inclusion criteria. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method was adapted for screening our document database, as shown in Figure 4-1. The screening and coding were independently completed by two authors who have technical expertise as practitioners in modelling corporate GHG emissions for publicly listed entities.

First, standards were included if available via online search tools. Copies of British Standard Institution (BSI) documents, including ISO standards, were obtained via the University of Oxford's subscription to the electronic Legal Deposit of the British Standards Online (BSOL) database. Second, due to linguistic capacity of the review team, only documents available in English were included. Third, only documents which represented the most recent version were included, eliminating documents that were no longer current or documents of organizations that no longer existed. For example, both the 2011 and 2017 versions of the *European Public Real Estate Association Guidelines* are listed as acceptable methodologies, but only the 2017 guidelines were included in our analysis (EPRA, 2017). We included a replacement document if one could be found. For example, the *New Zealand - Guidance for Voluntary, Corporate Greenhouse Gas Reporting* was last published in 2015 (NZ MfE, 2015).

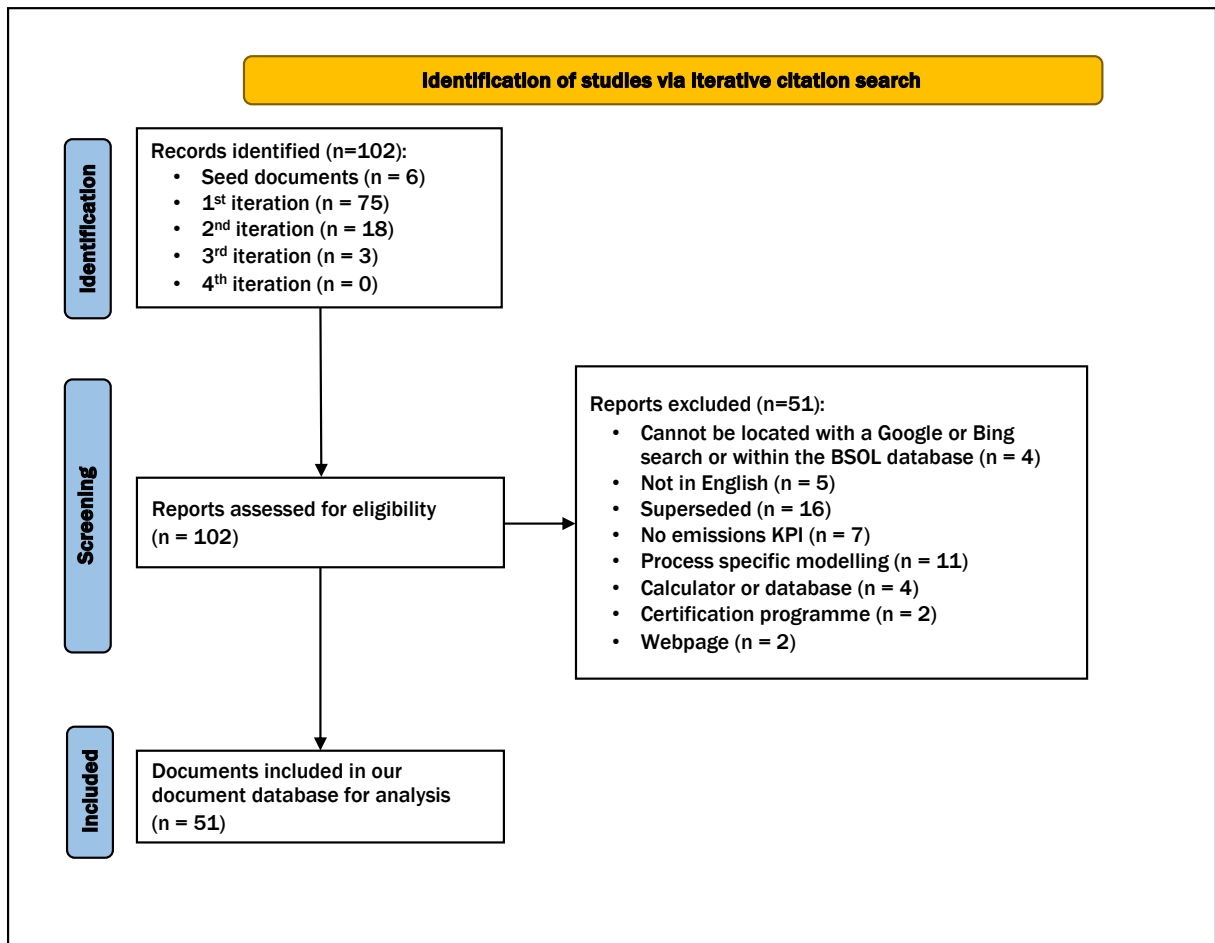


Figure 4-1 Overview of article identification, screening, and inclusion in the systematic review (Adapted from PRISMA)

Instead, we included its replacement, *Measuring emissions: A guide for organisations 2022 detailed guide* (NZ MfE, 2022), although this document was not directly cited. In a third circumstance, some organizations which published a standard no longer existed or was consolidated into other organizations. For example, the Sustainable Accounting Standards Board (SASB) has been folded into the ISSB and thus the *SASB Standards Application Guidance* (SASB, 2018) was excluded. Fourth, standards were included if they used emission KPIs for their reporting metric. For example, the *Act on the Rational Use of Energy* by Japan in 2005 uses energy metrics rather than emission metrics (Government of Japan, 2005), and was thus excluded. Fifth, because we are interested in corporate reporting, we excluded documents that describe process specific modelling of emissions. For example, *Environment Canada, Lime Production, Guidance Manual for Estimating Greenhouse Gas*

*Emissions* (Environment Canada, 2004) presents methodologies that are only applicable to emissions from the lime production process, rather than general corporate emission disclosures. Sixth, online calculators and databases were excluded, such as *The Cool Farm Tool* (Haverkort & Hillier, 2011) and the *World Steel Association CO2 Emissions Data Collection Guidelines* (WSA, 2023). Seventh, we excluded certification programs, such as the *Toitū carbonzero programme* (Toitū, n.d.). Finally, we excluded websites which, as of this research, linked directly to the GHG Protocol's documentation, such as the *India GHG Inventory Programme* (India GHG Program, 2012).

### **4.3. Results and Policy Implications**

From the six seed documents, we found a total of 102 documents. Of these,  $n=51$  were added to our document database, having met our eligibility criteria for further analysis. The document database was coded based on Power's performance measurement hierarchy, as shown in Table 4-2. Documents were categorized as 2<sup>nd</sup> order meta measurement if they were an 'emissions standard taker', relying on other standards to define a GHG metric. Documents were categorized as 1<sup>st</sup> order classification system if they were an 'emissions standard setter,' or defined the metric and characteristics of emissions to be disclosed. Documents were deemed a 0<sup>th</sup> order measurement quantum if it provided methodologies or guidance to measure or model emissions.

Thirty-eight disclosure standards were found (2<sup>nd</sup> order meta-measurements) and grouped based on which metrics they accept. Twenty-seven disclosures, rely on the GHG Protocol's system of Scope 1, 2, and 3. One standard, Bilane Carbone® was built on ISO 14064 system of direct emissions, energy indirect, and other indirect emissions. Five standards accepts either the GHG Protocol or ISO systems. Five standards referenced emission quantification methodologies directly, bypassing GHG accounting systems. These include four that permitted either modelling of emissions from the combustion of fuel or direct

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Table 4-2: List of our document database sorted by accounting hierarchy and use case. We list each document as [Organisation: Full Document Title (Citation)]. Seed documents denoted in bold

† The 2006 IPCC guidelines is categorized twice times because it describes methods for both national inventories (2<sup>nd</sup> order system) and emissions modelling (measurement quantum system).

Organisation / Document Title	Number
(A) 2 <sup>nd</sup> order meta-measurements: Use cases (n=39)	
<p><i>Corporate disclosures</i></p> <ul style="list-style-type: none"> <li>• <b>ABC</b>: Bilan Carbone® V8: Methodological guidelines (ABC, 2017)</li> <li>• <b>CDP</b>: <b>CDP Climate Change 2023 Questionnaire [SEED DOCUMENT] (CDP, 2023)</b></li> <li>• <b>ECB</b>: Guide on climate-related and environmental risks: Supervisory expectations relating to risk management and disclosure (Section 13.5) (ECB, 2020)</li> <li>• <b>EFRA</b>: <b>ESRS E1 Climate change: Exposure draft [SEED DOCUMENT] (EFRA, 2022)</b></li> <li>• <b>EU Commission</b>: Guidelines on non-financial reporting: Supplement on the reporting climate-related information (2019/C 209/01) (Section 3.5) (EU Commission, 2019)</li> <li>• <b>GRI</b>: <b>GRI 305 Emissions: 2016 [SEED DOCUMENT] (GRI, 2016b)</b></li> <li>• <b>IFRS</b>: <b>IFRS S2: Climate-related disclosures [SEED DOCUMENT] (ISSB, 2023b)</b></li> <li>• <b>NZ MfE</b>: Measuring emissions: A guide for organisations – 2022 detailed guide (NZ MfE, 2022)</li> <li>• <b>SBTI</b>: <b>SBTI Corporate manual version 2.1 [SEED DOCUMENT] (SBTI, 2023)</b></li> <li>• <b>TCFD</b>: <b>Guidance on metrics, targets and transition plans [SEED DOCUMENT] (TCFD, 2021)</b></li> <li>• <b>TCR</b>: General reporting protocol (TCR, 2019)</li> <li>• <b>UK DEFRA</b>: Environmental reporting guidelines: Including streamlined energy and carbon reporting guidance (UK DEFRA, 2019)</li> <li>• <b>US EPA</b>: Mandatory reporting of greenhouse gases: Final rule (US EPA, 2009)</li> </ul>	13
<p><i>Emissions trading schemes (ETS)</i></p> <ul style="list-style-type: none"> <li>• <b>EU ETS</b>: The monitoring and reporting regulation – General guidance for installations (EU Commission, 2023b)</li> <li>• <b>EU ETS</b>: The monitoring and reporting regulation – General guidance for aircraft operators (EU Commission, 2022)</li> <li>• <b>RGGI</b>: Model rule part XX CO<sub>2</sub> Budget trading program (RGGI, 2017)</li> </ul>	3
<p><i>Government</i></p> <ul style="list-style-type: none"> <li>• <b>Australia</b>: National greenhouse and energy reporting act 2007 (Australia, 2022)</li> <li>• <b>California</b>: AB-32 California global warming solutions Act of 2006 (California Global Warming Solutions Act of 2006, 2006)</li> <li>• <b>EU</b>: Commission regulation 2018/2026 amending Annex IV to Regulation (EC) No 1221/2009 of the European Parliament and of the Council on the voluntary participation by organisations in a community eco management and audit scheme (EU Commission, 2018)</li> </ul>	3
<p><i>National Inventory</i></p> <ul style="list-style-type: none"> <li>• <b>IPCC</b>: 2006 IPCC guidelines for national greenhouse gas inventories (Eggleston et al., 2006)</li> <li>• <b>UNFCCC</b>: Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC, 1998)</li> </ul>	2*
<p><i>Sector specific GHG accounting guidance</i></p> <ul style="list-style-type: none"> <li>• <b>ENCORD</b>: Construction CO<sub>2</sub>e measurement protocol: A guide to reporting against the Greenhouse Gas Protocol for construction companies (ENCORD, 2012)</li> <li>• <b>EPRA</b>: Sustainability best practice recommendations guidelines, third version (EPRA, 2017)</li> <li>• <b>GHG Protocol</b>: GHG Protocol agricultural guidance: Interpreting the corporate accounting and reporting standard for the agricultural sector (WRI &amp; WBCSD, n.d.)</li> <li>• <b>GHG Protocol</b>: The Greenhouse Gas Protocol for the U.S. public sector: Interpreting the corporate standard for U.S. public sector organizations (WRI &amp; LMI, 2010)</li> <li>• <b>GLEC</b>: Global logistics emissions council framework for logistics emissions accounting and reporting, version 2.0 (GLEC, 2019)</li> <li>• <b>Hong Kong</b>: Guidelines to account for and report on greenhouse gas emissions and removals for buildings (commercial, residential or institutional purposes) in Hong Kong, 2010 Edition (HK EPD, 2010)</li> <li>• <b>ICLEI</b>: Local government GHG Protocol (TCR et al., 2010)</li> <li>• <b>IPIECA</b>: Petroleum industry guidelines for reporting greenhouse gas emissions, 2<sup>nd</sup> edition (IPIECA, 2011)</li> <li>• <b>PCAF</b>: The global GHG accounting &amp; reporting standard for the financial industry (PCAF, 2020)</li> <li>• <b>TCR</b>: Electric power sector protocol for the voluntary reporting program (TCR, 2009)</li> <li>• <b>TCR</b>: Local government operations protocol (TCR et al., 2010)</li> <li>• <b>TCR</b>: Oil &amp; gas protocol (TCR, 2010)</li> <li>• <b>US EPA</b>: Direct emissions from mobile combustion sources (US EPA, 2016)</li> <li>• <b>US EPA</b>: Direct emissions from stationary combustion sources (US EPA, 2020a)</li> <li>• <b>US EPA</b>: Direct fugitive emissions from refrigeration, air conditioning, fire suppression, and industrial gases (US EPA, 2020b)</li> <li>• <b>US EPA</b>: Indirect emissions from events and conferences (US EPA, 2018)</li> <li>• <b>US EPA</b>: Indirect emissions from purchased electricity (US EPA, 2020c)</li> <li>• <b>WSA</b>: The CO<sub>2</sub> data collection user guide version 11 (WSA, 2023)</li> </ul>	18

Table 4-2 (Continued)

Organisation / Document Title	Number
<b>(B) 1<sup>st</sup> order classification systems: GHG accounting systems (n=4)</b>	
<b>GHG Protocol</b> <ul style="list-style-type: none"> <li>• <b>GHG Protocol:</b> The Greenhouse Gas Protocol: A corporate accounting and reporting standard, revised edition (WRI &amp; WBCSD, 2004)</li> <li>• <b>GHG Protocol:</b> Corporate value chain (Scope 3) accounting and reporting standard (WRI &amp; WBCSD, 2011a)</li> </ul>	2
<b>ISO GHG accounting standard</b> <ul style="list-style-type: none"> <li>• <b>ISO:</b> ISO 14064-1:2019 Greenhouse gases (BSI, 2019)</li> <li>• <b>ISO:</b> ISO 14069 Greenhouse gases – Quantification and reporting of greenhouse gas emissions for organizations – Guidance for the application of ISO 14064-1 (BSI, 2013)</li> </ul>	2
<b>(C) Measurement quantum: GHG quantification methodologies (n=10)</b>	
<b>Guidance on the GHG Protocol</b> <ul style="list-style-type: none"> <li>• <b>GHG Protocol</b> Scope 2 guidance: An amendment to the GHG Protocol corporate standard (WRI &amp; WBCSD, 2015)</li> <li>• <b>GHG Protocol:</b> Technical guidance for calculating Scope 3 emissions (version 1.0) (WRI &amp; WBCSD, 2013)</li> </ul>	2
<b>LCA</b> <ul style="list-style-type: none"> <li>• <b>BSI:</b> PAS 2050:2011 Specification for the assessment of the life cycle greenhouse gas emissions of goods and services (BSI, 2011)</li> <li>• <b>EU:</b> Commission recommendation: On the use of common methods to measure and communicate the life cycle environmental performance of products and organisations (2013/179/EU) (EU Commission, 2013)</li> <li>• <b>GHG Protocol:</b> Product life cycle accounting and reporting standard (WRI &amp; WBCSD, 2011b)</li> <li>• <b>ILCD Handbook</b> - General guide for life cycle assessment - Detailed guidance (EC JRC, 2010)</li> <li>• <b>ISO:</b> ISO 14040:2006+A1:2020 Environmental management - Life cycle assessment - Principles and framework (BSI, 2020a)</li> <li>• <b>ISO:</b> ISO 14044 Environmental management - Life cycle assessment - Requirements and guidelines (BSI, 2020b)</li> <li>• <b>ISO:</b> ISO 14067 Greenhouse gases - Carbon footprint of products (BSI, 2018)</li> </ul>	7
<b>Emissions modelling</b> <ul style="list-style-type: none"> <li>• <b>IPCC:</b> 2006 IPCC guidelines for national greenhouse gas inventories (Eggleston et al., 2006)</li> </ul>	1*

measurement of emissions with sensors. One standard, the Regional Greenhouse Gas Initiative (RGGI), only permitted direct measurement of emissions.

Within 1<sup>st</sup> order categorization systems, four documents that belonged to two accounting systems, the GHG Protocol or ISO were identified. Finally, within 0<sup>th</sup> order measurement quantum documents, seven documents were for life cycle assessment (LCA) methodology and two documents were technical guidance on the GHG Protocol. Notably, the *2006 IPCC guidelines for National Greenhouse Gas Inventories* were classified twice, due to its dual function: offering guidance on disclosing national inventories (2<sup>nd</sup> order) and providing a methodology for quantifying those inventories (0<sup>th</sup> order).

### **4.3.1. The number of GHG accounting standards (1<sup>st</sup> order classification systems)**

In this section, we demonstrate that there is one categorization system for GHG accounting: the GHG Protocol, convened and maintained by the World Resource Institute (WRI) and World Business Council for Sustainable Development (WBCSD). The two GHG accounting systems in use, the GHG Protocol and ISO 14064, are intentionally aligned and harmonized (ISO, 2007). As early as 2007, the WRI, WBCSD, and the ISO agreed to jointly promote and standardize the tools from both organizations. Further, ISO/TR 14069, the technical report on quantifying GHG emissions for organizations, states that it incorporates many key concepts used in the GHG Protocol (BSI, 2013).

The alignment also can be observed in the structure of the categories, as depicted in Table 4-3. The GHG Protocol categorizes Scope 1 direct emission as those from assets that are owned or controlled by the reporting entity (WRI & WBCSD, 2004), including direct combustion from generators, vehicles, manufacturing facilities, and others, that are owned by the entity. The ISO makes distinct each of the emission sources into separate categories. Indirect emissions are those caused by activities of, but not from assets owned or controlled by, the reporting entity. Scope 2 is a subcategory of indirect emissions resulting from the purchase of electricity, steam, heating, and cooling (WRI & WBCSD, 2015). The ISO separates out the reporting of electricity into Category 6 and steam, heating, and cooling into Category 7. Scope 3 comprises other indirect emissions resulting from upstream and downstream activities within the value chain. The GHG Protocol further subdivides Scope 3 into 15 categories (WRI & WBCSD, 2013). ISO consolidates some Scope 3 categories, such as ISO Category 18 on the Use stage of the product as a combination of both Scope 3 Categories 10 and 11. Lastly, ISO introduces three new categories not found in the GHG Protocol. This includes Category 5 direct emission from land use change, Category 16 client and visitor transport and Category 23 other indirect emissions or removals not included in the other categories.

*Table 4-3: A comparison of GHG accounting categorization systems. The GHG Protocol and ISO systems are harmonized, with only small differences between the categories.*

<b>GHG Protocol</b>	<b>ISO/TR 14069</b>
<b>Scope 1</b> - GHG emissions from sources they own or control. This includes stationary sources, mobile sources, physical or chemical processing and fugitive emissions.	<b>Category 1</b> - Direct emissions from stationary combustion
	<b>Category 2</b> - Direct emissions from mobile combustion
	<b>Category 3</b> - Direct process related emissions
	<b>Category 4</b> - Direct fugitive emissions
N/A	<b>Category 5</b> - Direct emissions and removals from land use, land use change and forestry (LULUCF)
<b>Scope 2</b> - Emissions from generation of acquired and consumed electricity, steam, heat, or cooling (collectively referred to as "electricity").	<b>Category 6</b> - Indirect emissions from imported electricity consumed
	<b>Category 7</b> - Indirect emissions from steam, heating, cooling, and compressed air, excluding electricity
<b>Scope 3 - Category 1</b> Purchased goods and services	<b>Category 9</b> - Purchased products
<b>Scope 3 - Category 2</b> Capital goods	<b>Category 10</b> - Capital equipment
<b>Scope 3 - Category 3</b> Energy-related activities not included in scope 1 or scope 2	<b>Category 8</b> - Energy-related activities not included in direct and energy indirect
<b>Scope 3 - Category 4</b> Upstream transportation and distribution	<b>Category 12</b> - Upstream transport and distribution
<b>Scope 3 - Category 5</b> Waste generated in operations	<b>Category 11</b> - Waste generated from organizational activities
<b>Scope 3 - Category 6</b> Business travel	<b>Category 13</b> - Business travel
<b>Scope 3 - Category 7</b> Employee commuting	<b>Category 22</b> - Employee commuting
<b>Scope 3 - Category 8</b> Upstream leased assets	<b>Category 14</b> - Upstream leased assets
<b>Scope 3 - Category 9</b> Downstream transportation and distribution	<b>Category 17</b> - Downstream transport and distribution
<b>Scope 3 - Category 10</b> Processing of sold products	<b>Category 18</b> - Use stage of the product
<b>Scope 3 - Category 11</b> Use of sold products	
<b>Scope 3 - Category 12</b> End-of-life treatment of sold products	<b>Category 19</b> - End of life of the product
<b>Scope 3 - Category 13</b> Downstream leased assets	<b>Category 21</b> - Downstream leased assets
<b>Scope 3 - Category 14</b> Franchises	<b>Category 20</b> - Downstream franchises
<b>Scope 3 - Category 15</b> Investments	<b>Category 15</b> - Investments
N/A	<b>Category 16</b> - Client and visitor transport
	<b>Category 23</b> - Other indirect emissions or removals not included in the other 22 categories

Thus, we can answer research question (1): The GHG Protocol is the foundational standard for corporate GHG accounting (1<sup>st</sup> order system), with the ISO system structurally similar, with some differences in how the activities are categorized.

The convergence indicates that the multiple GHG accounting standards do not yield the innovation benefits expected from a truly competitive standards marketplace. Despite the variously named and sourced offerings, GHG accounting standards are largely diverse in name only, suggesting a lack of pathways for new ideas and innovations to be introduced, as

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anticipated from a Schumpeterian view of a competitive market (Schumpeter, 2010). Further, our snowball analysis revealed a number of sector specific GHG Protocol standards (WRI & LMI, 2010; WRI & WBCSD, n.d.) and those that received the mark “Built on GHG Protocol” (ENCORD, 2012; GLEC, 2019; PCAF, 2020), demonstrating the dependence our seed documents have on the GHG Protocol. In short, the GHG accounting standards landscape has inadvertently converged on the GHG Protocol, making it the *de facto* standard for GHG accounting.

For systems that are foundationally based on the GHG Protocol, we recommend policy makers explicitly call for alignment with the dominant standard and/or establish an independent meta-coordination body positioned between governmental and voluntary GHG accounting standard bodies to enhance alignment and interoperability. At a minimum, derivative standards should explicitly reference the GHG Protocol texts to prevent market confusion and foster greater international cooperation.

Having only one standard can aid governments and standard-setting bodies in reducing the need for cross-boundary negotiation or interpretation and improve policy interoperability between countries. Further, it can also alleviate reporting burdens for stakeholders, who, in a globalized world, essentially report the same data for different jurisdictions but the format may differ. This recommendation aligns with a trend in environmental standardization known as ‘Meta-Standardization’ which aims for convergence at the ‘rules of the game’ level (Reinecke et al., 2012).

One potential drawback to such a system is that a formally recognized foundational or ‘base’ standard would likely receive a sharp increase in demand for engagement with users. For instance, the GHG Protocol recently received over 400 responses to the Scope 2 Guidance survey (WRI, 2023). Second, formal consolidation towards a single standard could also carry a possible risk of co-optation by an interest group, which could compromise the integrity of the entire GHG accounting ecosystem. This is a risk currently faced, as some are concerned

that the GHG Protocol is jointly governed by the WBCSD, a CEO-led organization, while others are concerned by the influence of Big Tech and corporate group over the SBTi and the GHG Protocol in setting and changing net zero and GHG accounting standards (Financial Times, 2024). A substantial body of literature underscores concerns about interest group involvement in centralized environmental and wider accounting standards, including examples from market-based Scope 2 emission factors (Brander et al., 2018), Fair Trade Certification (Fridell et al., 2008; Jaffee & Howard, 2010), and the Financial Accounting Standard Board (Ramanna, 2016).

Given the findings of this study on the centrality of the GHG Protocol as the cornerstone of emissions accounting, it is crucial that the organization maintains measures to prevent interest group capture, especially in the case of more formal convergence or consolidation (Ramana, 2024). Any meta-standardization process, or standard body with centralized authority for GHG Accounting will need sufficient staffing, governance, and support to meet this demand. This is a common challenge across climate standards as they mature from niche voluntary initiatives to widely used governance tools.

#### **4.3.2. The number of emissions quantification methodologies (0<sup>th</sup> order)**

We show there are four emissions quantification methodologies, direct measurement, emissions modelling, life cycle assessment (LCA), and environmentally extended input-output (EEIO) modelling. We begin answering question (2) by noting that several disclosure standards, at the measurement quantum level, rely on emissions modelling or direct measurement of emissions, as shown in Table 4-2(C). Both methods are described in IPCC documentation (Eggleston et al., 2006). We now examine the quantification methodologies within the GHG Protocol and ISO systems.

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Both GHG Protocol and ISO acknowledge that although quantification of emissions by direct monitoring is preferred, modelled methodologies are also acceptable if direct measurement is not possible. Equation 4-1 is the general formula used to model emissions (BSI, 2013; WRI & WBCSD, 2011).

$$Emissions = \left( \begin{matrix} activity \\ data \end{matrix} \right) \times \left( \begin{matrix} emission \\ factor \end{matrix} \right) \times \left( \begin{matrix} global \\ warming \\ potential \end{matrix} \right) \quad \text{Equation 4-1}$$

The activity data represents a unit of corporate activity, such as purchase of fuel, sale of product, or distance travelled for business. The emission factor is a conversion from the activity data to the quantity of emissions it releases. Because there is more than one GHG, and each has a different duration in the atmosphere, one uses a global warming potential (GWP) to normalize their long-term effects to that of CO<sub>2</sub>. Thus, emissions are typically reported in metric tonnes of carbon dioxide equivalents (tCO<sub>2</sub>e). For this study, we focus our analysis on the activity data and emission factors of the models.

Table 4-4 depicts the activity data and emission factor choices for Scope 1 (direct emissions) and Scope 2 (energy indirect) in both the GHG Protocol and ISO systems. For Scope 1, the two systems are broadly similar, with the combustion method referring to emissions modelling within IPCC documentation. For Scope 2, the GHG Protocol allows two methods for emission factor, a location-based system that uses the emission factor of the local grid, and a market-based system, where the emission factor is based on energy procurement contracts of the organization, with the differences discussed elsewhere (Brander et al., 2018). The ISO only permits location-based or combustion emission factors.

**Table 4-4 Activity data and emission factors for emission modelling of Scope 1 (Direct) and Scope 2 (Energy Indirect).**

Activity Data	Emission factors within the GHG Protocol	Emission factors within ISO/TR 14069
	<b>Scope 1</b>	<b>Direct emissions</b>
Quantities of fuel purchased  (litres, gallons, etc.)	<u>Combustion method:</u> <ul style="list-style-type: none"> <li>• Published emission factors</li> </ul>	<u>Combustion method:</u> <ul style="list-style-type: none"> <li>• Emission factor by fuel</li> <li>• Emission factor by kWh</li> <li>• Relevant emission factors</li> <li>• Emission factor from approved database</li> <li>• Site-specific emission factor</li> </ul>
	<b>Scope 2</b>	<b>Energy Indirect emissions</b>
Quantities of electricity purchased  (kWh, MWh, etc.)	<u>Location based:</u> <ul style="list-style-type: none"> <li>• By region (regional, national, international, I.E., IEA, US eGRID, UK DEFRA)</li> </ul> <u>Market based:</u> <ul style="list-style-type: none"> <li>• By supplier, contract, or energy attribute certificates</li> <li>• By residual mix</li> <li>• Other</li> </ul>	<u>Combustion method:</u> <ul style="list-style-type: none"> <li>• By fuel</li> </ul> <u>Location based:</u> <ul style="list-style-type: none"> <li>• By specific supplier</li> <li>• By specific company</li> <li>• By grid</li> <li>• By country</li> </ul>

Table 4-5 is a comprehensive list of activity data and emission factors used within Scope 3/other indirect emissions. The table is grouped by activity data (Column A), such as quantities of emissions, fuel, electricity, physical goods, monetary value. Both GHG Protocol and ISO hierarchies are organized based on how specific the emission factor is to a unique supplier. The preferred emission factor is a product-specific LCA by supplier, with corporate, industry, and national average data as acceptable (WRI & WBCSD, 2013). GHG Protocol emission factors that are considered best data quality for each category is listed in Table 4-5 Column B, and all other emission factors in Column C. The ISO system instructs that higher data quality is when the activity data is known exactly (best scenario), and the lower data quality is when the activity data is estimated (minimum scenario). The choices of emission factor can be applied to activity data of either data quality. In general, ISO prioritizes supplier specific life cycle approaches as preferred, literature database as second, and LCA as third. If the activity data is a monetary value, one uses either a monetary LCA or EEIO. ISO emission factors are aggregated in Column [D].

Table 4-5 Activity data and emission factor options for Scope 3 (Other indirect) emission modelling

[A] Activity data type	[B] Scope 3 emission factors for best data quality methods	[C] Scope 3 emission factors for other data quality methods	[D] Other indirect emission factors for ISO 14069 for all data quality methods
Quantities of emissions (tCO <sub>2</sub> e)	<ul style="list-style-type: none"> <li>None needed</li> </ul>	<ul style="list-style-type: none"> <li>None needed</li> </ul>	
Quantities of fuel purchased (litres, gallons, etc.)	<p><u>Combustion method:</u></p> <ul style="list-style-type: none"> <li>By fuel</li> </ul> <p><u>LCA method:</u></p> <ul style="list-style-type: none"> <li>Cradle-to-gate of fuel</li> <li>Life cycle emission factor for fuel</li> </ul>	<p><u>Combustion method:</u></p> <ul style="list-style-type: none"> <li>By fuel</li> </ul> <p><u>LCA method:</u></p> <ul style="list-style-type: none"> <li>Emission factor (upstream)</li> <li>Average upstream emission factor</li> <li>Life cycle emission factor for fuel</li> </ul>	<p><u>Combustion method:</u></p> <ul style="list-style-type: none"> <li>By fuel</li> </ul> <p><u>LCA method:</u></p> <ul style="list-style-type: none"> <li>Cradle-to-gate of fuel</li> <li>By fuel, transport mode, and distance</li> </ul>
Quantities of electricity purchased (kWh, MWh, etc.)	<p><u>From supplier:</u></p> <ul style="list-style-type: none"> <li>By supplier</li> </ul> <p><u>From databases:</u></p> <ul style="list-style-type: none"> <li>Electricity emission factors</li> <li>By regional or site</li> <li>Upstream, for extraction, production, transportation of fuels</li> </ul>	<p><u>From databases:</u></p> <ul style="list-style-type: none"> <li>Electricity emission factors</li> <li>By region</li> <li>Upstream, by grid, country, or region for extraction, production, transportation of fuels</li> </ul>	
Quantities of physical units purchased, sold, or otherwise incurred (kg, km, m <sup>2</sup> , # of unit, etc.)	<p><u>LCA method:</u></p> <ul style="list-style-type: none"> <li>Cradle-to-gate, by unit product, using GHG Protocol's Product life cycle accounting and reporting standard)</li> </ul> <p><u>Method not specified:</u></p> <ul style="list-style-type: none"> <li>Fugitive emission factors</li> <li>Refrigerant emission factors</li> <li>By waste output</li> <li>Average, waste treatment specific</li> </ul>	<p><u>LCA method:</u></p> <ul style="list-style-type: none"> <li>Cradle-to-gate, by unit product, using GHG Protocol's Product life cycle accounting and reporting standard)</li> <li>Cradle-to-gate, by economic value</li> <li>Life cycle emission factor per unit</li> </ul> <p><u>Method not specified:</u></p> <ul style="list-style-type: none"> <li>By unit (product sold, purchased, asset, etc.)</li> <li>Fugitive emission factors</li> <li>By mode of transport</li> <li>By waste output</li> <li>Average, waste treatment specific</li> <li>Other</li> </ul>	<p><u>LCA method:</u></p> <ul style="list-style-type: none"> <li>Cradle-to-gate (or cradle-to-grave) by unit of product, using ISO 14067</li> <li>Cradle-to-gate (or cradle-to-grave) of transportation mode</li> <li>Cradle-to-grave, of waste disposal infrastructure</li> </ul> <p><u>Method not specified:</u></p> <ul style="list-style-type: none"> <li>By unit</li> <li>By region and type of waste treatment</li> <li>By distance and transport mode</li> <li>By waste treatment method</li> </ul>
Quantities of monetary value exchanged (\$, £, €, etc.)		<p><u>LCA method:</u></p> <ul style="list-style-type: none"> <li>Cradle-to-gate, by economic value</li> </ul> <p><u>EEIO method:</u></p> <ul style="list-style-type: none"> <li>EEIO</li> </ul>	<p><u>Method not specified:</u></p> <ul style="list-style-type: none"> <li>Emission factor by investment</li> </ul>
Other activity data		<ul style="list-style-type: none"> <li>Other emission factors</li> </ul>	<ul style="list-style-type: none"> <li>Other emission factors</li> </ul>

There are two new quantification methodologies, LCA, which is widely used within all data qualities of Scope 3, and EEIO, which is used in minimum data quality methodologies. LCA is a grounds-up approach which attempts to take inventory of all individual components of a process, from raw sourcing of the material (denoted by cradle) to the end of life of the resource (denoted by grave). Gate denotes the step where product enters the reporting company's boundary. Both the GHG Protocol's Life cycle product standard (WRI & WBCSD, 2011b) and the ISO 14067 standard on carbon footprint of products (BSI, 2018) are built on top of the foundational life cycle assessment standards, ISO 14044/14040 (BSI, 2020a, 2020b).

EEIO is a top-down, economy-wide estimate of environmental impact that uses nation- or region-wide statistics and estimates industry-wide impact. It extends traditional input-output (IO) analysis to also include environmental effects and can be used to estimate GHG footprints of sectors, processes, industries, and trade between nations (Tukker et al., 2006). EEIO takes into consideration capital goods and overhead as inputs to a product system (Suh et al., 2004). The data for EEIO tables are usually developed from literature or national IO tables and extended with national GHG inventories. For example, in the US EEIO, the IO tables are developed by the Bureau of Economic Analysis within the U.S. Department of Commerce (Yang et al., 2017). The GHG emissions are taken from the US GHG Inventory published by the U.S. EPA, which are calculated using the IPCC guidelines (US EPA, 2015).

Some emission factors do not specify a method, such as emission factor by waste output. In these situations, one follows the data quality hierarchy, as described previously.

Therefore, in answer to research question (2), there are four emission quantification methodologies used across the disclosure standards and within GHG accounting: 1) direct measurement of emissions, 2) emissions modelling, 3) LCA, and 4) EEIO. Direct measurement and emissions modelling are based on IPCC methodologies, LCA is based on ISO 14040, and EEIO methods are based on scientific literature and national statistics.

Except for direct measurement, all methods use an activity data, which is linked to items under corporate managerial control, and an emission factor, which represents the extent of the supply chain to model per activity. All four methods are accepted by GHG Protocol and ISO when quantifying corporate emissions.

### **4.3.3. Are the measurement quanta standards (0<sup>th</sup> order) fit-for-purpose for corporate disclosures (2<sup>nd</sup> order)?**

We observed a lack of alignment between 0<sup>th</sup>, 1<sup>st</sup>, and 2<sup>nd</sup> order standards, calling into question whether emission values are fit-for-purpose for corporate disclosures. Table 4-6 is a comparison of principles between our seed documents (2<sup>nd</sup> order), the GHG Protocol (1<sup>st</sup> order), and the foundational LCA standard, ISO 14040 (0<sup>th</sup> order). The CDP and SBTi were excluded in the analysis as they do not have reporting principles nor data quality guidelines.

First, no two disclosure standards are completely aligned on principles. The IFRS S2 and ESRS E1 are most similar, differing only in materiality and timeliness. Only three principles - relevance, complete, and consistent - are shared between GHG Protocol and the disclosure standards. No disclosure standards share principles with those of the LCA standard.

Further, not all principles are similarly defined, such as the definition of comparability (Gillenwater, 2023). The ISSB considers comparability as the principle that enables users to make choices between alternatives, defining it as the “Characteristics that enable users to identify and understand similarities in, and differences among, items,” (ISSB, 2023a, p40). The GHG Protocol does not define comparability, instead stating that the principle of consistency is “Essential to producing comparable GHG emissions data over time,” (WRI & WBCSD, 2004, p8). The ISSB disagrees, stating that consistency is related to, but not the same as, comparability. Further, misalignment of principles can be found between 2<sup>nd</sup> order and 0<sup>th</sup> order systems. For example, the Scope 3 technical guidance advises suppliers to use the *GHG Protocol’s Product life cycle accounting and reporting standard* when generating

Table 4-6 Comparison of principles across 0<sup>th</sup>, 1<sup>st</sup>, and 2<sup>nd</sup> order systems.

- [1] Fundamental qualitative characteristics of useful sustainability related financial information
- [2] Enhancing qualitative characteristics of useful sustainability-related financial information
- [3] Reporting principles for defining report content
- [4] Reporting principles for defining report quality
- [5] Qualitative characteristics of information
- [6] Characteristics of effective climate-related metrics
- [7] GHG accounting and reporting shall be based on the following principles
- [8] These principles are fundamental and should be used as guidance for decisions relating to both the planning and the conducting of an LCA

	DISCLOSURE STANDARDS (2nd order)				GHG ACCOUNTING (1st order)	LCA (Measurement Quantum)
	IFRS S2 (ISSB, 2023a)	GRI 101 (GRI, 2016a)	[5] ESRS E1 (EU Commission, 2023a)	[6] TCFD (TCFD, 2021)	[7] GHG Protocol (WRI & WBCSD, 2004)	[8] ISO 14040 (BSI, 2020a)
	Shared between disclosures standards					
Clarity		YES [4]		YES		
Comparability	YES [2]	YES [4]	YES			
Faithful representation	YES [1]		YES			
Materiality	YES [1]	YES [3]				
Reliability		YES [4]		YES		
Timeliness	YES [2]	YES [4]				
Understandability	YES [2]		YES	YES		
Verifiability	YES [2]		YES	YES		
	Shared between some disclosure standards and GHG accounting					
Relevance	YES [1]		YES		YES	
Complete		YES [3]			YES	
Consistent				YES	YES	
					Shared between GHG Protocol and LCA	
Transparency					YES	YES
	Used by only one standard					
Accuracy					YES	
Balanced		YES [4]				
Comprehensiveness						YES
Decision Useful				YES		
Environmental focus						YES
Forward looking				YES		
Iterative approach						YES
Life cycle perspective						YES
Objective				YES		
Priority of scientific approach						YES
Relative approach and functional unit						YES
Stakeholder inclusiveness		YES [3]				
Sustainability context		YES [3]				

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emission factors (WRI & WBCSD, 2013). However, the product life cycle standard specifically prohibits making comparisons, stating,

*Claims regarding the overall environmental superiority or equivalence of one product versus a competing product, referred to in ISO 14044 as comparative assertions, are not supported by the Product Standard (WRI & WBCSD, 2011b, p6).*

In short, the principle of comparability required by the ISSB for emissions disclosures is not permitted by the method for quantifying GHG emissions. Therefore, in answer to research question (4), we find that the current measurement standards for quantifying emissions may not be fit-for-purpose for corporate disclosure standards. This is a problem. Documents such as IFRS S2 and ESRS E1 are designed for a broad section of the global economy. However, they are utilizing metrics from accounting system which may not adhere to the principles of the disclosure standards.

We recommend that policy makers and academics perform a deeper context analysis to identify gaps between measurement, classification, and disclosure standards. Our analysis calls into question whether the GHG Protocol, as the *de facto* standard, can fulfil the different needs of disclosure standards, such as transition planning (TPT, 2022), target setting (SBTi, 2023), or providing information to investors (ISSB, 2023b). Policy makers and standard setters should ensure means-ends coupling (Bromley & Powell, 2012) between the measurement standard and intentions behind disclosure standards. One approach is to evaluate GHG accounting systems for their intended user. For example, several new classification systems for GHG accounting have been proposed recently, each designed for different purposes. The e-Liability system (Kaplan & Ramanna, 2021) has been identified as a consumer-centric approach (Brander & Gatzweiler, 2024), carbon takeback obligation (CTBO) is a producer-centric accounting frame (Lackner et al., 2023), and general-purpose life cycle assessment (GP-LCA) is designed for primary users of financial reports (Chapter 6 / Paper 3).

## 4.4. Conclusions

In this study, we demonstrated that GHG accounting standards predominantly stem from the categorization system of the GHG Protocol. We illustrated how the ISO family of standards serves as derivative work of the GHG Protocol's Scope 1, 2, and 3 system. Competing standards are essentially derived from the same foundational system. The GHG accounting field narrows rapidly, with fewer options than anticipated. Further, we identified four methodologies to quantify emissions: direct measurement, emissions modelling, LCA, and EEIO.

This work has consolidated a document database of existing standards and foundational documents that are used within GHG accounting. Future research can be conducted on the differences amongst standards, such as to what extent different GHG gasses are included in each standard, a deeper analysis of (mis)alignment of principles, how data quality is affected when both mandatory and voluntary systems are accepted, and other variations between the standards.

For policy makers, we encourage determining whether a measurement standard and GHG accounting standard is fit-for-purpose of the disclosure standard. For situations where GHG Protocol is suited, we advocate for formalized reference to the GHG Protocol to reduce market confusion. For other situations, policy makers should choose a different standard if one exists or determine the design criteria for the creation of a new standard.

For standard setters, our work can avoid duplicate efforts and establish guidance to improve consistency and data quality of reporting. We also encourage strengthening the governance system around GHG Protocol to reduce the risk of interest group co-optation, and improve interoperability between mandatory and voluntary standards.

For practitioners, our work will help them keep apprised of evolving standards that may affect their stakeholders. Further, practitioners can study the connection of activity data, used in emission accounting, to activities monitored under managerial control systems.

## Declaration of interest

No potential conflict of interest was reported by the author(s).

## Data availability statement

ISO and BSI standards were obtained via a university license to the British Standards Online (BSOL) database. All other documents were derived from public domain resources and found via a Google or Bing search.

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# Chapter 5. Designing for comparability: A foundational principle missing in entity-level GHG accounting

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## Abstract

We conduct a systematic study of the greenhouse gas (GHG) accounting of entities to identify the conditions under which their reporting is comparable. Climate finance is an interdisciplinary field, depending on both physical GHG accounting as well as financial accounting to support decision making. It presupposes that investors can make investment choices to improve the climate impact of an entity. We focus on the investor's ability to make decisions that affect physical GHG emissions. Investors require the ability to make entity-level comparisons, yet a large body of research has focused on the non-comparability of physical GHG accounting between entities. We frame the GHG accounting ecosystem as an information architecture and investigate how the challenges to comparability are organised in relationship to each other. We apply the conditions of comparability from the multiple fields that comprise GHG accounting, studying the epistemological differences of financial accounting, environmental economics, life cycle assessment, and social science. We find that non-comparability is pervasive across GHG accounting, with methodological variations introduced by many different fields. We propose a research agenda to improve entity-level comparability of physical GHG emissions.

## Keywords

GHG Protocol, life cycle assessment, financial statements, comparability,

## 5.1. Introduction

It has been well established that the release of anthropogenic greenhouse gases (GHGs) has been the driving force behind climate change (Myhre et al., 2013). Climate finance is a broad term indicating the public and private financial sector's involvement in supporting mitigation and adaptation actions to address climate change (CPI, 2018). It presupposes that investors can make investment choices to improve the climate impact of an entity. Over \$130 trillion in assets, have been committed by the financial sector to support the GHG emissions goals of the Paris Agreement (GFANZ, 2022).

Because making comparisons between entities is a primary function of investing (Barlev & Haddad, 2007), the research question of this paper is, "*Can investors compare GHG disclosures of different entities to identify which company has better climate performance?*" We address the research question by first studying the information architecture of GHG accounting, and second by conducting a comparative analysis of the information architectures of GHG and financial accounting. Specifically, we ask, "*Does the information architecture of GHG accounting allow comparative assertions to be made?*" We develop four hypotheses to investigate the research question and conduct an empirical analysis of corporate emissions data from the CDP (formerly Carbon Disclosure Project), an archival study of GHG accounting standards to understand its information architecture, and a comparative analysis of GHG and financial accounting standards.

As an interdisciplinary field, climate finance depends on both financial accounting and GHG accounting to support decision making. Physical GHG accounting involves quantification of the mass of atmospheric GHG fluxes, including their changes (Gillenwater, 2023b). Financial users require the ability to compare entities to make a decision choice. We study the different disciplines, the methodologies that comprise GHG accounting, and the epistemic differences of the fields. The topic is timely. If GHG metrics cannot be adopted by financial users, then

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trillions of dollars of capital that are intended for improving physical climate outcomes could be potentially misallocated (Chatterji et al., 2016).

The GHG Protocol is the dominant GHG accounting system in use today, with coverage as high as 80% of the global economy (Andrew & Cortese, 2011). Created in 2001 as a joint effort between the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD), it established the classification system of scopes for corporate emissions. Briefly, Scope 1 are direct emissions from an entity's owned assets, Scope 2 are indirect emissions from electricity consumption, and Scope 3 are other indirect emissions from an entity's upstream and downstream supply chain.

However, researchers have pointed out that the GHG Protocol may not be fit for purpose for the financial sector (Gillenwater, 2023c). Some will use the GHG Protocol to account for physical GHG emissions in the atmosphere, for the purpose of allocating responsibility or monitor reductions (Gillenwater, 2023b). These activities include setting and verifying net-zero targets (SBTi, 2022; UNFCCC, 2020) and disclosing transition plans to low-carbon economy (TPT, 2022). Others use GHG Protocol to make a monetary valuation of the underlying assets that emit GHGs (Gillenwater, 2023b). For example, investors are routinely utilising GHG emissions data, one of many climate indicators, 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). In short, the financial sector uses GHG accounting both to price emissions and quantify emissions.

Comparability is regarded by some as the primary reason for the development of financial accounting standards (Barlev & Haddad, 2007). According to the International Accounting Standards Board (IASB), that governs financial accounting, "Comparability enables users to identify and understand similarities in, and differences among, items [2.24-2.25]," (IASB, 2018). An improvement to comparability is achieved when similar items becoming more

similar while different items do not become any less different (Yip & Young, 2012). Unlike the IASB, the GHG Protocol considers comparability as an outcome of consistency, stating, “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, p8). Although the two concepts are similar and consistency is a necessary ingredient for comparability, it is not a sufficient condition for comparing entities (Barlev & Haddad, 2007).

The lack of comparability of GHG emissions have been identified as early as the 1990's (Ranganathan, 1998) and recent research on the conceptual framework of GHG accounting has found non-comparability throughout the GHG Protocol (Gillenwater, 2023a). Lack of comparability have primarily focused on differences in boundaries and methodologies. For example, empirical researchers of product GHG accounting found boundary thresholds for products are subjectively determined by each analyst (Alvarez et al., 2016). Corporate GHG emissions then rely on product GHG accounting, where non-comparability is first introduced. Other empirical studies researched comparability on data from the CDP (formerly the Carbon Disclosure Product), a database of voluntary corporate disclosures. These studies focused on specific sectors, finding high flexibility of system boundaries in the electric sector (Stanny, 2018) and availability of multiple methodologies in mining industries (Andrew & Cortese, 2011). Other empirical studies use facility-level data, finding limited evidence for comparability between oil & gas facilities within a company (Wegener et al., 2019). One suggested solution is to encourage global adoption the GHG Protocol to reduce methodological variation (Andrew & Cortese, 2011). However, others have pointed out that the GHG Protocol itself is a source of multiple reporting methodologies (Gillenwater, 2022), as its guidance accepts values from multiple sources that have varying results (Aikman et al., 2023). Despite these known challenges, regulators and standard setters continue to promote the simultaneous usage of metrics from the two accounting systems. For example, in 2021,

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the IASB founded the International Sustainability Standards Board (ISSB), to serve financial users in making decisions relating to providing resources to the entity. The ISSB adopts the IASB's definition of comparability (ISSB, 2023), yet simultaneously requires entities to report their Scope 1, 2, and 3 i.e. direct and indirect emissions from their upstream and downstream activities.

We contribute to the literature in several ways. We update a prior empirical study of comparability within CDP data, done on 2011 data (Andrew & Cortese, 2011), to 2021, showing that the challenges identified then have yet to be resolved. We answer the call to take an interdisciplinary approach (Siedlok & Hibbert, 2014). As climate finance is an interdisciplinary field, relying on methods from financial accountants, LCA engineers, environmental economists, and social scientists, we analyse comparability based on normative conditions from each of those fields. Our research identifies that some challenges are systemic across the GHG accounting ecosystem, such as large discretion to determine reporting boundaries, while others are unique to a specific aspect, such as non-standard dates for a reporting year. We contribute to the development of the climate finance field by proposing a set of necessary conditions to enable bridging the gap between the multiple disciplines. We propose future research of what interventions may be necessary by whom and where in the system to improve the ability to make comparative assertions between entities.

The paper is structured as follows. We first provide context of the information architecture of the GHG accounting ecosystem, including a description of the GHG Protocol. Next, we develop our hypotheses used in this paper, analysing different aspects of the GHG accounting ecosystem. We also describe the methodologies used to test our hypotheses. We then present our analytical results, discuss our findings. We conclude with recommendations of a research agenda to improve entity-level comparability.

## 5.2. Context: Information architecture of the GHG accounting ecosystem

Climate finance depends on the disciplines of financial accounting, social science, LCA, and environmental economics. We use the structure of information to understand epistemic assumptions across these different disciplines. The structure of information is how the information is formally arranged and organised, whether in a computer database, in a filing cabinet, or in piles of paper on a desk. These structures become control systems, describing links, dependencies, trade-offs, and synergies between components (Evernden & Evernden, 2003), thus formalising the epistemological frame of the discipline. Evernden further defines:

*“Information architecture is a foundation discipline describing the theory, principles, guidelines, standards, conventions and factors for managing information as a resource. It produces drawings, charts, plans, documents, designs, blueprints and templates, helping everyone make efficient, effective, productive and innovative use of all types of information.” (Evernden & Evernden, 2003 p1).*

Information architectures from different systems may not be compatible. It is obvious that one cannot use chess competition wins to determine a golf handicap. A gold medal in swimming is not a judge of success in the fencing or the ski jump events.

Accounting systems are a form of information architecture, which is the discipline that studies the structure and organisation of information. We organise the GHG accounting ecosystem using the framework developed by Michael Power (2004) to generalise financial accounting systems as part of a broader field of performance measurement systems. All accounting ecosystems are built on top of counting systems, or rules for quantification of measurements. Within financial accounting, transactions are the items being counted. These measurement quanta (MQ) are aggregated into 1<sup>st</sup> order classification systems which translates the measurements into categories, such as assets, expenses, and others which are presented in the financial statements. Finally, 2<sup>nd</sup> order meta-measurements are further aggregations of

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Table 5-1 Using Power’s hierarchy to organise accounting ecosystem, with examples from financial and GHG accounting ecosystems. The table also depicts the tests of comparability used in this paper.

Hierarchy of performance management systems	Financial accounting example	GHG accounting example	Methods used to analyse comparability
<b>2nd order meta-measurements</b>	Indices, ratios, and other calculations that are used by policy makers, investors, and others.	ESG Disclosures, such as the CDP data	<ul style="list-style-type: none"> <li>• <u>Output comparability</u>: Empirical analysis</li> <li>• <u>Input comparability</u>: Similarity and difference facet</li> </ul>
<b>1st order classification systems</b>	Financial statements (Balance sheet, profit and loss statement, etc.)	The GHG Protocol (Scope 1, 2, and 3)	<ul style="list-style-type: none"> <li>• <u>Classification system comparability</u>: Category Theory</li> </ul>
<b>Measurement quantum (MQ)</b>	Financial transactions	<ul style="list-style-type: none"> <li>• Combustion</li> <li>• LCA</li> <li>• EEIO</li> </ul>	<ul style="list-style-type: none"> <li>• <u>Unit comparability</u>: Dimensional analysis</li> </ul>

numbers via statistical techniques into ratios, trends, and other values, that are used by financial institutions for decision making. The relationship between MQ, 1<sup>st</sup>, and 2<sup>nd</sup> order hierarchies are summarised in Table 5-1.

GHG accounting can also be organised similarly. Prior research found three measurement methodologies, emissions from combustion, from life cycle assessment (LCA) studies, and environmentally extended input-output (EEIO) models (Chapter 4 / Paper 1). These comprise the MQ level.

GHG Protocol is a 1<sup>st</sup> order classification system that defines Scope 1, 2, and 3 for corporate emissions. Its purpose is to give visibility on GHG emissions due to corporate activities (WRI & WBCSD, 2004). Table 5-2 depicts a detailed breakdown of categories within the GHG Protocol. Scope 1 is defined to be emissions from sources owned or controlled by the reporting organisation. These emissions can come from stationary, mobile, physical or chemical processes, and fugitive emissions. However, as most entities do not own their own power plants or generate their own power, Scope 2 represents GHG emissions due to the

*Table 5-2 Categories of the GHG Protocol. Scope 1 are direct emissions, Scope 2 are energy indirect emissions. Scope 3 are indirect emissions both upstream and downstream from the reporting entity. Scope 2 and 3 has further subcategories.*

<b>Scope 1</b> - GHG emissions from sources they own or control. This includes stationary sources, mobile sources, physical or chemical processing and fugitive emissions
<b>Scope 2</b> - Emissions from generation of acquired and consumed electricity, steam, heat, or cooling (collectively referred to as "electricity") a) Location-based b) Market-based
<b>Scope 3 - Category 1</b> Purchased goods and services
<b>Scope 3 - Category 2</b> Capital goods
<b>Scope 3 - Category 3</b> Energy-related activities not included in scope 1 or scope 2 a) Fuel b) Electricity c) T&D Losses d) Electricity pass-through
<b>Scope 3 - Category 4</b> Upstream transportation and distribution a) Transportation b) Distribution
<b>Scope 3 - Category 5</b> Waste generated in operations
<b>Scope 3 - Category 6</b> Business travel
<b>Scope 3 - Category 7</b> Employee commuting
<b>Scope 3 - Category 8</b> Upstream leased assets
<b>Scope 3 - Category 9</b> Downstream transportation and distribution a) Transportation b) Distribution
<b>Scope 3 - Category 10</b> Processing of sold products
<b>Scope 3 - Category 11</b> 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
<b>Scope 3 - Category 12</b> End-of-life treatment of sold products
<b>Scope 3 - Category 13</b> Downstream leased assets
<b>Scope 3 - Category 14</b> Franchises
<b>Scope 3 - Category 15</b> Investments a) Equity investments b) Project finance and debt c) Total projected lifetime emissions

consumption of electricity, steam, heating, or cooling purchased from a utility. A location-based Scope 2 represents the grid average emissions based on where a facility is located while a market-based Scope 2 represents the contracts to procure energy directly from a supplier source, such as renewable energy.

Scope 3 represents all other indirect emissions that arise as a “Consequence of the activities of the reporting company, but occur at sources owned or controlled by another company,”

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(WRI & WBCSD, 2011a, p27) This captures both upstream and downstream value chain effects. 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).

Returning to Table 5-1, an example of a 2<sup>nd</sup> order meta measurement organisation within GHG accounting is the CDP (formerly the Carbon Disclosure Project). Founded in 2000, it collects self-reported environmental, social, and governance (ESG) data via an annual questionnaire for the use of investors. Scope 1, 2, and 3 are metrics within its disclosure requirements. Over 13,000 companies worth over 64% of the global market capitalisation discloses data through CDP (CDP, 2021). The dataset has been used in the past to study entity-level comparability (Andrew & Cortese, 2011; Stanny, 2018).

### **5.3. Hypothesis development and methodology**

Also shown in Table 5-1 are the methods used to evaluate the GHG ecosystem for comparability. We provide a detailed description of the hypothesis and research methodology.

#### **5.3.1. Conditions for output comparability**

Second order meta measurements rely on the outputs from 1<sup>st</sup> order classification systems. Output comparability is achieved if, the same input and the same accounting framework produces the same output (De Franco et al., 2011). We hypothesise that GHG Protocol outputs can be used to compare entities, namely:

- **Hypothesis 1 (H1):** Outputs of corporate GHG emissions can be compared.

We test H1 by using an empirical methodology developed by De Franco (2011) for financial accounting output comparability. The method builds on top of the idea that the accounting system is a mapping of broad economic events to a firm's financial statements (De Franco et al., 2011). When similar firms are facing the same economic conditions, the financial reports should also be affected similarly. The method was developed to understand if the information architecture within the financial statements enables comparability of business operational choices. If it does not, then there may be differences in the accounting methodologies or choices used to create the financial statements. The method has since been adopted to evaluate environmental comparability at the corporate level (Fang et al., 2022; Thuy et al., 2021; Wang et al., 2020) and at the facility level (Wegener et al., 2019).

We apply the De Franco method to analyse the GHG disclosures from the CDP. For 2021, 8,300 entities disclosed to the CDP. Our analysis builds upon prior research that has used the method to analyse subsets of CDP data, such as on 20 US electric utilities (Stanny, 2018). Our analysis also updates prior research that has found CDP data lacking in comparability between the years of 2007 and 2009 (Andrew & Cortese, 2011).

De Franco found that comparability improved when similar firms were first partitioned by industry, and economic attributes. De Franco used the two-digit Standard Industrial Classification (SIC) codes to determine industry classification and created quintiles for market capitalisation, and book-market values. The result was 25 mutually exclusive partitions within which comparability analysis could be run.

We attempted to see if economic events were a map onto GHG accounting disclosures. We analysed the comparability of Scope 1 and 2 data for 2021 that were disclosed within 2022 Climate Change Questionnaire, gathered by the CDP (CDP, 2022). The CDP data of 8393

reporting entities was made available by an academic license granted to the Smith School of Enterprise and the Environment at the University of Oxford.

If H1 is true, entities can be compared using physical GHG emissions. If H1 is false, then entities may have methodological differences in their inputs when applying GHG Protocol.

### **5.3.2. Conditions for input comparability**

Next, we examined the GHG Protocol for input comparability. Measurements, in principle, should not depend on the methodology used to measure it (Power, 2004). Otherwise, the accounting systems are reflecting accounting choices rather than business activities. In other words, accounting is supposed to reflect activities that an entity undertakes and not be subject to methodological choices to account for them. We apply this condition to GHG accounting outcome, hypothesising:

- **Hypothesis 2 (H2):** Inputs of corporate GHG emissions can be compared.

We test H2 with the Similarity and Difference Facet, as used to evaluate comparability within the financial accounting field. The two facets that determine information comparability are, “The similarity facet, which indicates whether firms engaged in similar economic activities report similar accounting amount, and the difference facet, which indicates whether firms engaged in different economic activities report dissimilar accounting amounts,” (Yip & Young, 2012, p1768). This paper conducts the first study that applies the similarity and difference facet to an archival analysis of GHG Protocol accounting standards and technical guidance documentation. Although prior research has found that flexibility of choice hampers comparability (Alvarez et al., 2016; Gillenwater, 2023a; Stanny, 2018), our study applies a condition of comparability used by the financial accounting discipline.

We perform an archival study of the Scope 3 technical guidance documentation (WRI & WBCSD, 2013). We analysed the options within *Scope 3 – Category 6 Business Travel* to

see if entities can report the same activity differently. We also analyse *Scope 3 – Category 1 Purchased goods and services* and *Scope 3 – Category 2 Capital goods* to test if different categories can be reported similarly.

If H2 is true, then two firms engaging in similar operational activities will report similar results. Financial users can use emission values from the GHG Protocol to compare physical GHG emissions from entities. If H2 is false, then there is an underlying divergence of methodologies. There are two possible sources of methodological variation. The classification system that is an aggregation of measurements, and the underlying measurement systems themselves.

### **5.3.3. Conditions for classification system comparability**

We next examine whether the GHG Protocol is a classification system. Classification systems are a form of information infrastructure that communicate relationships among categories, informing data acquisition standards, support decision-making, among other activities. Otherwise, the systems are known as nomenclatures, or an agreed-upon naming scheme without the ability to compare (Bowker & Star, 1999). Therefore, we hypothesise:

- **Hypothesis 3 (H3):** The GHG Protocol framework is a classification system that enables financial entities to be compared.

According to category theory, there are three observed properties of an ideal classification system (Bowker & Star, 1999):

- (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, either spatially or temporally, or both. Property 2 states that the ideal classification system provides total

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coverage of the world it describes. If gaps exist, then items may be undercounted. Property 1 and 2 create the boundary condition of the world being described. Lastly, property 3 states that the categories within the system should be unique and fit into clearly demarcated bins. Everything is counted only once, with no overcounting.

A classification system is therefore a “Spatial, temporal or spatio-temporal segmentation of the world,” (Bowker & Star, 1999, p10.). An example of spatial segmentation in GHG accounting is dividing emissions by national or region, thereby affecting citizens of the location. An example of temporal segmentation is to classify emissions by the year it was released into the atmosphere. A spatio-temporal classification system can be exemplified by a series of events that occur in a specific order, such as a company’s annual emissions.

We perform an archival study of GHG Protocol documentation to examine the spatio-temporal boundaries. To study spatial boundaries, we first use the financial user’s definition of an entity, following their normative practice. We apply that definition to the GHG Protocol to examine if the emissions are spatially aligned. To examine temporal boundaries, we examine the relational logic between past, present, and future statements. Financial reports are known to be temporal in nature (Quattrone, 2005) while systems based on life cycle assessment are known to lack temporal attributes (Gillenwater, 2023a; Lueddeckens et al., 2020).

If H3 is true, then GHG accounting uses the same spatio-temporal boundary conditions as financial accounting, and entity-level GHGs can be compared. If H2 is false, then alignment is needed between the two systems, if one is to compare entities.

### **5.3.4. Conditions for unit comparability**

Lastly, we examine if the measurements are comparable. GHG emissions are quantified in units of *metric tonnes of carbon dioxide equivalents* (tCO<sub>2</sub>e). We hypothesise:

- **Hypothesis 4 (H4):** Items measured in  $tCO_2e$  can be compared.

To test H4, we perform dimensional analysis (Sonin, 2001), and engineering technique that depicts the similarity between two physical terms. We use it to determine whether the unit  $tCO_2e$  is being used to describe the same physical phenomenon or different phenomena.

Within dimensional analysis, a *base unit* is the description of a physical property, such as the meter, kilogram, second, mole, ampere, kelvin, and candela, from which all other units and measures are derived from. *Base quantities* are physical measurements that describes how much one has of the base unit (i.e., 5 mile, 12 kilograms, 25 seconds, etc.). 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 ( $C = A + B$ ). There are usually several options for a base unit, such as inches or centimetres to measure length. To perform a comparison or addition, the base units must be the same, as one cannot add inches to centimetres.

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

$$Q = \alpha A^a B^b C^c \dots \quad \text{Equation 5-1}$$

Derived units may or may not retain the properties of comparison and addition, depending on their derivation and the physical representation of the measurement. For example, energy, measured in Joules, is a derived unit because it can be expressed with base units in a power law form ( $J = kg \cdot m^2 \cdot s^{-2}$ ). However, torque, measured in the Newton-meter (N-m) also has the same base units ( $N-m = kg \cdot m^2 \cdot s^{-2}$ ). The difference is that Joules are a scalar quantity while the Newton-meter is a vector quantity and defined only for rotational systems. Even though they both share the same base units, torque and energy cannot be added nor compared to each other because they describe different phenomena. To prevent confusion,

torque is commonly represented in Newton-meter (N-m) while energy is represented in Joules (J).

We conduct a dimensional analysis of the unit tCO<sub>2</sub>e that are derived from three methods to measure and quantify emissions. These are combustion, LCA, and EEIO methods. If H4 is true, then each of these methods describe the same phenomenon and the values can be added and compared. Improvements to comparability can be achieved by improving measurement accuracy. If H4 is false, then the methods are describing different phenomena and comparative assertions cannot be made. There lacks a standardised method for quantifying emissions.

## **5.4. Analysis and results**

### **5.4.1. Results of output comparability analysis**

The CDP dataset from 2021 includes 8,393 reporting entities. We partitioned the CDP data based on six characteristics that companies make when disclosing their emissions. Only companies that use the same characteristics can be compared. Table 5-3 lists the datapoints from the CDP used in our analysis.

We first cleaned the dataset for missing or incomplete data for the first five characteristics from the CDP. The criteria used to eliminate entities are shown in Table 5-4, resulting in 5,853 that was used for further analysis. We found 20 companies had incomplete survey answers. As we are attempting to compare Scope 1 and 2, we eliminated the 1,817 entities that disclosed neither. Third, we eliminated entities that did not disclose their reporting boundary (32) nor their standard or methodology used (157).

*Table 5-3 The characteristics and their corresponding datapoint in the CDP database.*

<b>Characteristics</b>	<b>Corresponding datapoint in the CDP questionnaire</b>
The primary industry	<ul style="list-style-type: none"> <li>• Primary Industry</li> </ul>
The reporting year	<ul style="list-style-type: none"> <li>• C0.2_C2_State the start and end date of the year for which you are reporting data. - End date</li> </ul>
The reporting boundary	<ul style="list-style-type: none"> <li>• C0.5_Select the option that describes the reporting boundary for which climate-related impacts on your business are being reported</li> </ul>
Standard or combination of standards used to calculate emissions	<ul style="list-style-type: none"> <li>• C5.3_Select the name of the standard, protocol, or methodology you have used to collect activity data and calculate emissions.</li> </ul>
The scopes that were disclosed	<ul style="list-style-type: none"> <li>• C6.1_C1_What were your organization's gross global Scope 1 emissions in metric tons CO2e? - Gross global Scope 1 emissions (metric tons CO2e)</li> <li>• C6.3_C1_What were your organization's gross global Scope 2 emissions in metric tons CO2e? - Scope 2, location-based</li> <li>• C6.3_C2_What were your organization's gross global Scope 2 emissions in metric tons CO2e? - Scope 2, market-based (if applicable)</li> </ul>
The quintile of emissions	<ul style="list-style-type: none"> <li>• Based on the sum of Scope 1 and 2</li> </ul>

*Table 5-4 Criteria used to clean the dataset.*

<b>Exclusion Reason</b>	<b>Number of companies excluded</b>	<b>Total</b>
Number of companies in CDP Dataset		8,393
Incomplete answers when aggregating across survey results	20	
Does not disclose Scope 1 nor Scope 2 (leaves blank, not a number, "not applicable", etc.)	1,817	
Does not disclose boundary choice	32	
Does not disclose standard or methodology used	157	
Reporting year ends prior to 30 June 2020	311	
Reporting year ends after 1 July 2022	203	
<b>TOTAL companies analysed</b>		<b>5,853</b>

Table 5-5 Distribution of entities by primary sector

Primary sector	Number of entities	Primary sector	Number of entities
Air transport	31	Metal products manufacturing	476
Bars, hotels & restaurants	38	Metal smelting, refining & forming	101
Biotech & pharma	107	Metallic mineral mining	33
Cement & concrete	30	Non-energy utilities	27
Chemicals	330	Nuclear power generation	1
Coal mining	6	Oil & gas extraction & production	46
Commercial & consumer services	68	Oil & gas processing	26
Construction	164	Oil & gas retailing	12
Convenience retail	48	Oil & gas storage & transportation	18
Crop farming	13	Other materials	53
Discretionary retail	105	Other mineral mining	9
Electrical & electronic equipment	765	Other services	45
Energy utility networks	80	Paper products & packaging	129
Entertainment facilities	17	Plastic product manufacturing	239
Financial services	409	Powered machinery	237
Fish & animal farming	11	Print & publishing services	37
Food & beverage processing	264	Questionnaire sector	3
Government agencies	1	Rail transport	20
Health care provision	14	Renewable energy equipment	19
Industrial support services	76	Renewable power generation	35
Intermodal transport & logistics	91	Road transport	76
International bodies	1	Specialized professional services	242
IT & software development	193	Textiles & fabric goods	169
Land & property ownership & development	55	Thermal power generation	55
Leisure & home manufacturing	82	Tobacco	13
Light manufacturing	108	Trading, wholesale, distribution, rental & leasing	156
Logging & rubber tapping	2	Transportation equipment	119
Marine transport	29	Web & marketing services	70
Media, telecommunications & data center services	129	Wood & paper materials	22
Medical equipment & supplies	61	Wood & rubber products	37
		<b>TOTAL</b>	<b>5,853</b>

Next, we present descriptive statistics for each characteristic.

**The primary industry:** The CDP asks entities to report the sector they are in from one of 60 primary sectors. Table 5-5 depicts the distribution of CDP data by the entity’s primary sector.

**The reporting year:** In the 2021 dataset, we found 142 report end dates disclosed, with the earliest being 31 December 2017 and the latest 28 September 2022. As our goal is to compare entity’s emissions from 2021, we only analysed entities whose report end dates fell between 1 July 2021 and 30 June 2022, or where over 50% of the year fell within calendar year 2021. As shown in Table 5-6, we eliminated 311 entities whose end date was too early

and 203 entities whose end date was too late. Of the entities that remained, most entities reported an end date of 31 December 2021 and 31 March 2021. However, there were 79 distinct report end dates that were also used.

*Table 5-6 Range of report end dates that were excluded and included in our analysis. The end dates that were included had a majority of dates within the 2021 reporting year.*

<b>EXCLUDE:</b> Report end date prior to 1 July 2021		<b>EXCLUDE:</b> Report end date after 30 July 2022	
Number of end dates:	17	Number of end dates:	46
Number of entities:	311	Number of entities:	203

<b>INCLUDE:</b> Report end dates between 1 July 2021 to 30 June 2022 (79 dates)					
Report End Date	Number of entities	Report End Date	Number of entities	Report End Date	Number of entities
2021-07-01	2	2022-01-03	4	2022-05-04	1
2021-07-28	1	2022-01-04	1	2022-05-05	2
2021-07-31	25	2022-01-05	2	2022-05-09	1
2021-08-01	1	2022-01-12	1	2022-05-10	1
2021-08-02	1	2022-01-29	4	2022-05-16	1
2021-08-20	1	2022-01-30	3	2022-05-18	1
2021-08-30	1	2022-01-31	42	2022-05-20	1
2021-08-31	27	2022-02-01	1	2022-05-28	1
2021-09-25	3	2022-02-02	1	2022-05-29	1
2021-09-27	3	2022-02-20	1	2022-05-31	34
2021-09-30	126	2022-02-28	31	2022-06-01	23
2021-10-01	3	2022-03-01	2	2022-06-02	1
2021-10-02	1	2022-03-06	1	2022-06-03	1
2021-10-03	2	2022-03-20	1	2022-06-08	2
2021-10-20	1	2022-03-26	3	2022-06-09	3
2021-10-31	28	2022-03-28	1	2022-06-11	1
2021-11-01	1	2022-03-30	1	2022-06-15	2
2021-11-28	1	2022-03-31	816	2022-06-16	1
2021-11-29	1	2022-04-01	12	2022-06-18	1
2021-11-30	15	2022-04-04	1	2022-06-20	1
2021-12-01	1	2022-04-05	1	2022-06-23	1
2021-12-20	1	2022-04-12	1	2022-06-27	1
2021-12-25	1	2022-04-20	1	2022-06-28	2
2021-12-30	1	2022-04-27	1	2022-06-29	1
2021-12-31	4,372	2022-04-30	39	2022-06-30	117
2022-01-01	44	2022-05-01	12		
2022-01-02	1	2022-05-02	2		
				<b>TOTAL</b>	<b>5,853</b>

Table 5-7 Distribution of entities by their choice of boundary

Boundary option	Number of entities	% Dataset
Equity share	124	2.1%
Financial control	1,035	17.7%
Operational control	3,153	53.9%
Other, please specify	138	2.4%
Question not applicable	1,403	24.0%
<b>TOTAL</b>	<b>5,853</b>	<b>100%</b>

**The reporting boundary:** The GHG Protocol allows three methodologies for determining entity boundaries: equity share, financial control or operational control (WRI & WBCSD, 2004). For the equity share approach, entities account for emissions based on ownership percentage of an asset. For the financial control approach, entities account for all emissions of assets where it can direct financial policies and gains the majority of the financial benefits. For the operational control approach, entities account for emissions for assets where it has full authority over operational decisions. Prior research found that emissions can differ by up to 73% based on which boundary option a reporting entity chooses (Smith, 2016) and that there is no consistency of reporting boundary choice (Stanny, 2018). Table 5-7 depicts the distribution of entities by their boundary choice from our dataset. The most common boundary choice is Operational control with over 53% of entities using it. For the option “Other (please specify)”, entities were permitted to describe the boundary conditions they used. For the option “Question no applicable”, it is uncertain what boundary conditions were used. Therefore, for these two options, we categorised each entity into their own partition.

**The standard or combination of standards used to calculate emissions:** The CDP permits 72 different options for methodologies to calculate emissions. Although our prior work found that all GHG accounting standards are built on top of the GHG Protocol’s system (Chapter 4 / Paper 1) each system may recommend different applications, boundaries, or

require specific assumptions. Therefore, each methodology needs to be partitioned separately.

In addition, the CDP permits also reporting entities to pick more than one option. Because it is unclear how the multiple methodologies were combined, each multiple option choice were also partitioned separately. Further, the CDP permits reporting entities to specify “other” and list other methodologies used.

*Table 5-8 The CDP accepts 72 methodologies and their combinations for corporate GHG disclosures. This table lists the top 10 combination of methodologies used for GHG emissions accounting as well as summarises the other 2070 unique combination of methodologies.*

<b>Standard, protocol, or methodology used</b>	<b>Number of entities</b>	<b>% of dataset</b>
The Greenhouse Gas Protocol: A Corporate Accounting and Reporting Standard (Revised Edition)	873	14.9%
China Corporate Energy Conservation and GHG Management Programme	304	5.2%
The Greenhouse Gas Protocol: A Corporate Accounting and Reporting Standard (Revised Edition) AND The Greenhouse Gas Protocol: Scope 2 Guidance	242	4.1%
Japan Ministry of the Environment, Law Concerning the Promotion of the Measures to Cope with Global Warming, Superseded by Revision of the Act on Promotion of Global Warming Countermeasures (2005 Amendment)	198	3.4%
ISO 14064-1	178	3.0%
Brazil GHG Protocol Programme	146	2.5%
Korea GHG and Energy Target Management System Operating Guidelines	103	1.8%
Japan Ministry of the Environment, Law Concerning the Promotion of the Measures to Cope with Global Warming, Superseded by Revision of the Act on Promotion of Global Warming Countermeasures (2005 Amendment) AND The Greenhouse Gas Protocol: A Corporate Accounting and Reporting Standard (Revised Edition)	77	1.3%
Taiwan - GHG Reduction Act	72	1.2%
ISO 14064-1 AND The Greenhouse Gas Protocol: A Corporate Accounting and Reporting Standard (Revised Edition)	70	1.2%
⋮		
<i>2070 additional partitions, each a unique combination of the 72 methodologies</i>		
273 partitions with 2-70 entities within each	1793	30.6%
1797 partitions with only 1 entity	1797	30.7%
<b>TOTAL</b>	<b>5,853</b>	<b>100%</b>

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Table 5-8 shows the distribution of methodologies used by entities to disclose their emissions. First, the table lists the top 10 combination of standards that are most common. Some entities only follow one standard, such as the GHG Protocol being used by 873 entities, representing 14.9% of the dataset, and the Japan Ministry of the Environment methodology being used by 198 entities, or 3.4% of the dataset. Further, 77 entities (1.3%) report to have followed both the GHG Protocol and Japan Ministry of the Environment methodology. The top ten combination of methodologies used only represents 39.7% of the dataset.

Beyond the top 10 most popular combinations, there are 2,070 additional combinations of standards used. Of these, 273 combinations of standards are used by multiple entities while 1797 combination of standards are used by only a single entity, representing 30.6% and 30.7% of the dataset, respectively.

**The scopes that were disclosed:** Location-based Scope 2 is a measure of the local grid where the reporting organisation is physically located, while market-based Scope 2 are measures of purchasing and investing activities the reporting organisation pursues in procuring renewable energy (WRI & WBCSD, 2015). The CDP permits reporting entities the option of reporting either location-, market-based Scope 2, or both.

Table 5-9 shows a distribution of the disclosed Scopes. Entities that only disclosed Scope 1 constituted 9.3% of the dataset. If an entity disclosed both location- and market-based information, we used the location-based information for our partition, representing 83% of the dataset. Otherwise, we used Scope 2 Market.

Table 5-9 Distribution of entities by location-based and market-based Scope 2 choice.

Scopes Disclosed	Number of entities	% of dataset
Scope 1 only	546	9.3%
Scope 1 + Scope 2 Location	4,860	83.0%
Scope 1 + Scope 2 Market	447	7.6%
<b>TOTAL</b>	<b>5,853</b>	<b>100%</b>

Table 5-10 Descriptive statistics of partitioning of emissions into quintiles

Quintile	Minimum (tCO <sub>2</sub> e)	Average (tCO <sub>2</sub> e)	Maximum (tCO <sub>2</sub> e)	Number of entities
Quintile 1	0	339	1,158	1,171
Quintile 2	1,159	4,205	9,599	1,170
Quintile 3	9,600	24,504	47,905	1,171
Quintile 4	47,993	138,962	328,268	1,170
Quintile 5	328,402	51,775,668	37,590,938,119	1,171
			<b>TOTAL</b>	<b>5,853</b>

**Quintiles of emissions:** The final step is to partition the sum of Scope 1 and Scope 2 into quintiles of emissions. This is a step within the De Franco methodology where it was found to be advantageous to compare entities that were roughly the same size. Table 5-10 depicts the statistics of the quintiles.

**Results of partitioning:** We now combine the six characteristics (primary industry, reporting year, reporting boundary, standard used, scopes disclosed, and quintile) to create partitions within which one can compare companies. For the 5,853 entities in the CDP database, we found 4,944 unique partitions, as shown in Table 5-11. Of these, 4,583 partitions had only one entity each. The largest partition had merely 29 entities. These 29 entities shared the following characteristics:

- **Primary Sector:** Metal products manufacturing
- **Reporting Boundary:** Operational control

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Table 5-11 Descriptive statistics of the partitions based on assumptions for GHG emissions. As shown, 95.7% of entities are in partitions that have less than 10 entities.

	Number of partitions	Number of entities	Average number of entities per partition	% of dataset
Largest partition <ul style="list-style-type: none"> <li>• <b>Sector:</b> Metal products manufacturing</li> <li>• <b>Boundary:</b> Operational control</li> <li>• <b>Methodology:</b> China Corporate Energy Conservation and GHG Management Programme</li> <li>• <b>Scopes:</b> Scope 1, Scope 2 Locational</li> <li>• <b>Quintile:</b> Q2</li> </ul>	1	29	29	0.5%
Number of partitions with 20 or more entities	2	50	25.0	0.9%
Number of partitions with 10-19 entities	15	201	13.4	3.4%
Number of partitions with 2-9 entities each	344	1,019	3.0	17.4%
Number of partitions with 1 entity only	4,583	4,583	1.0	78.3%
<b>TOTAL</b>	<b>4,944</b>	<b>5,853</b>	<b>1.2</b>	<b>100.0%</b>

- **Methodology:** China Corporate Energy Conservation and GHG Management Programme
- **Scopes disclosed:** Scope 1 and Scope 2 Locational
- **Quintile:** Q2

Only 17 partitions had more than 10 entities and two partitions had 20 or more members.

Roughly 95.7% of the dataset are in partitions that have less than 10 entities. Because of the small number of entities within each partition, it is not possible to conduct a correlation analysis for the vast majority of the entities within the CDP. In essence, the result of the partitioning exercise demonstrates the challenge to empirically compare entities based on GHG emission disclosures.

Hypothesis 1 state that “*Outputs of corporate GHG emissions can be compared.*” We have shown that the vast array of options available creates a situation where most entities are using a unique set of assumptions. Therefore, H1 is proved to be false.

## 5.4.2. Results of input comparability analysis

It is well known that GHG Protocol permits a variety of methodologies for the modelling of emissions (Alvarez et al., 2016, Chapter 4 / Paper 1). The different methods are organised into a data quality hierarchy, with the assumption is that data more specific to the entity will be of higher data quality than those derived from industry surveys. In this section, we analyse Scope 3 for whether the methodologies represent similar or different phenomena.

To model emissions, one uses the general formula multiplying an activity data by the emission factor, as shown in Equation 5-2.

$$\left[ \begin{array}{c} \textit{emissions of} \\ \textit{a gas (by mass)} \end{array} \right] = \left[ \begin{array}{c} \textit{activity} \\ \textit{data} \end{array} \right] \times \left[ \begin{array}{c} \textit{emission} \\ \textit{factor} \end{array} \right] \quad \textit{Equation 5-2}$$

The activity data represents a unit of human activity and the emission factor is a conversion ratio that relates the activity data to an expected quantity of GHG emitted. The model of emissions thus depends on the choice of activity data and emission factor.

### 5.4.2.1. Similar items may be reported differently

Scope 3 Category 6 is the category for emissions due to business travel. Table 5-12, adopted from the technical guidance, shows the activity data and emission factors that are acceptable for the modelling of travel-related emissions (WRI & WBCSD, 2013). The three methods, fuel-based, distance-based, and spend-based, are listed in descending order of data quality.

A fuel-based method is a measure of the emissions that arise from the combustion of fossil fuel. It follows the methodology presented by the Intergovernmental Panel on Climate Change (IPCC).

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**Table 5-12 Method tiers for Category 6 Business travel, in descending order of accuracy. 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. Items in italics are optional to count (WRI/WBCSD, 2013).**

Method	Activity data	Emission factor (EF)
Fuel-based method <i>(most accurate)</i>	<ul style="list-style-type: none"> <li>Energy (Quantities of fuel + electricity)</li> <li><i>Optional: number of hotel nights</i></li> </ul>	<ul style="list-style-type: none"> <li>Combustion EF <i>OR</i> fuel life cycle EF</li> <li>Electricity EF</li> <li><i>Optional: EF per hotel per night</i></li> </ul>
Distance-based method	<ul style="list-style-type: none"> <li>Quantity (Distance travelled per mode of transport)</li> <li><i>Optional: number of hotel nights</i></li> </ul>	<ul style="list-style-type: none"> <li>EF by vehicle and distance.</li> <li><i>Optional: EF per hotel per night</i></li> </ul>
Spend-based method <i>(least accurate)</i>	<ul style="list-style-type: none"> <li>Monetary (Spending)</li> </ul>	<ul style="list-style-type: none"> <li>EEIO EF</li> </ul>
<i>Optional:</i>	<ul style="list-style-type: none"> <li><i>Life cycle emissions associated with manufacturing vehicles or infrastructure</i></li> </ul>	

Life cycle emission factors are derived from LCA studies. LCA emission factors are modelled based on the value chain. A whole life LCA is a cradle to grave inventory of emissions.

*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. A partial LCA represents a subset of the value chain, such as cradle to gate, where *gate* refers to the point when materials transfer into a company (BSI, 2020). A cradle to gate LCA is also referred to as an upstream LCA.

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 the structure of the economy. While LCA is suited to primary sectors, such as manufacturing, EEIO can help understand secondary sectors, such as the service sectors (Yang et al., 2017). The data

*Table 5-13 Choice of emission factors, and the processes they include.*

<b>Method used</b>	<b>What the emissions represents</b>
Combustion emission factor	Combustion efficiency of the equipment
Fuel life cycle emission factor	Production efficiency of the fuel
EEIO emission factor	Impact of business travel within the structure of the economy
<i>Optional:</i>	<i>Nights of hotel stays</i>
<i>Optional:</i>	<i>Life cycle emissions of the vehicle and infrastructure</i>

for EEIO is based on economic and environmental data gathered from national or supra-national statistics.

Thus, similar items can be reported differently. The choice of activity data and emission factors changes what is being represented. As shown in Table 5-13, business travel can be a measure of combustion efficiency, production efficiency, the structure of the economy, hotel stays, or vehicle and infrastructure life cycle. In short, reporting entities have many ways to report the same activity. This is due to the information architecture of the standard itself, accepting a wide range of methodologies that represent epistemologically different definitions of business travel.

#### *5.4.2.2. 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 Statement of Profit and Loss (P&L). 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 GHG Protocol, however, does not treat capital goods and consumable products differently. In fact, according to the technical standard, “The calculation methods for Category

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1 (Purchased goods and services) and Category 2 (Capital goods) are the same,” (WRI & WBCSD, 2013, p37). 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, p37).

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

Hypothesis 2 states that *“Inputs of corporate GHG emissions can be compared.”* As we showed using the similarity and difference facet, within the GHG Protocol similar items can be reported differently and different items can be reported similarly. As a result, hypothesis 2 is shown to be false.

### **5.4.3. Results of classification system analysis**

Hypothesis 3 states that *“The GHG Protocol framework is a classification system that enables financial entities to be compared.”* As stated earlier, condition (2) of category theory is that for a system to be a classification system, it must completely represent the item. Financial entities are defined by its financial boundaries and their constituent categories. We can consider the financial categories as the ‘complete system’ which represents an entity. Therefore, we analyse Hypothesis 3 by asking, *“Do the GHG Protocol categories overlap with the financial entity categories?”* To begin, we first analyse the financial definition of an entity. We then examine the financial definition for its spatial and temporal boundaries. We then analyse the GHG emissions of the financial entity categories, focusing on spatial and

temporal boundaries. Finally, we examine relationships between spatial and temporal categories, both within the entity and between entities.

#### 5.4.3.1. *Analysis of spatial and temporal boundary*

According to the IFRS, an entity's boundary is defined as "An entity that is required, or chooses, to prepare financial statements [3.10]," (IASB, 2018). Financial statements comprise of the balance sheet, profit & loss, and cash flow statements.

The balance sheet is a statement of position, that represents a snapshot-in-time of the state of the company's assets (Sangster et al., 2021). The balance sheet has three items, assets, liabilities, and equity. Assets are defined as a resource controlled by the entity as a result of past events and from which future economic benefits are expected to flow to the entity (F 4.4(a), IASB, 2018). The P&L represents trade activities between two balance sheets (Sangster et al., 2021). Some trade activities, such as revenue and expenses, occur within the reporting period. These are reported directly on the P&L. Other trade activities are for capital assets that are used for multiple reporting periods, such as real estate and automobiles. These costs are permitted to be spread out, or depreciated, over the useful life of the asset. In this manner, the profit and loss statement represent the real-time trade activities and the cost of usage of capital assets. A *cash flow statement* is a presentation of historical changes in cash of an entity between two time periods (IAS, 1992). Cash flows can be projected into the future, (IASB, 2018), commonly called a financial *pro forma*.

In summary, the definition of an entity is bounded by what is reported on the financial statements and temporally bounded by which statement the data resides on, based on whether the data represents the past, present or future.

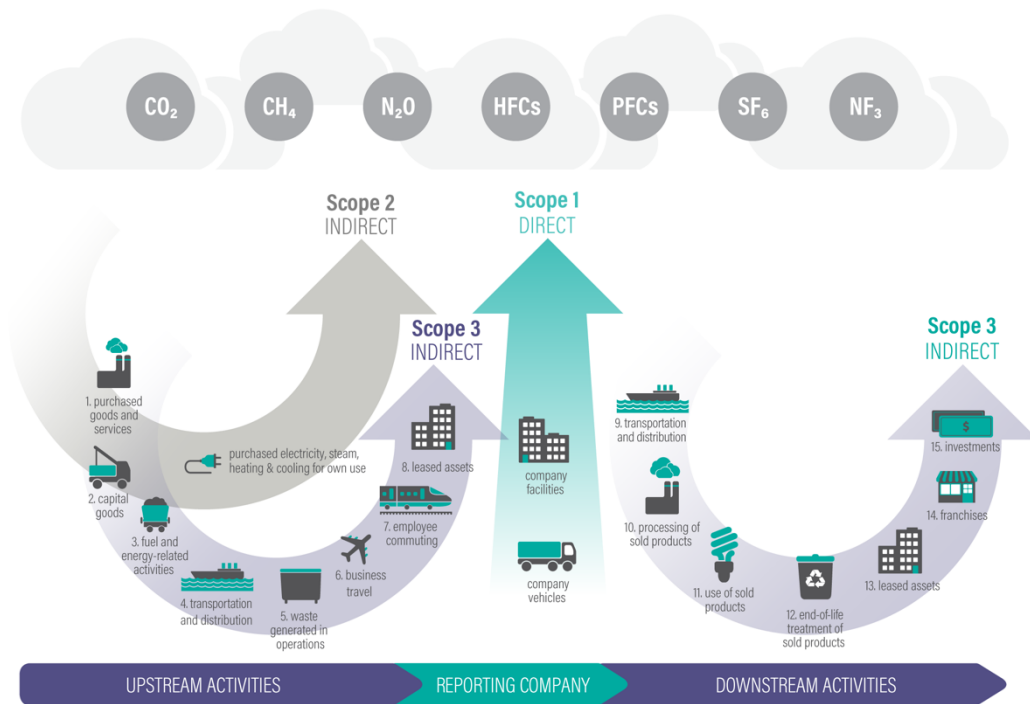
The GHG Protocol defines both an organisational boundary and an operational boundary. The organisational boundary defines the reporting company and are a set of rules on how an

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entity and their subsidiaries consolidate their organisational structures, using one of three options. 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 (WRI & WBCSD, 2004). However, the organisational boundaries follow the consolidation rules within *IFRS 12 - Disclosure of Interests in Other Entities* (IFRS, 2011). In essence, the GHG Protocol adopted the consolidation rules for financial statement as an entity's boundary, rather than explicitly defining the boundary of an entity.

Next, the GHG Protocol defines an operational boundary as the value chain within which the organisation operates. 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.

As shown in Figure 5-1, Scope 1, 2, and 3 are defined based on organisational and operational boundaries (WRI & WBCSD, 2011). As explained earlier, Scope 1 are direct emissions of the reporting company, that arise from its organisational boundary. Scope 2 and 3 are indirect emissions of the reporting company that arise from its operational boundary. Scope 2 and certain categories of Scope 3 represent upstream activities of suppliers while the remaining Scope 3 categories represent downstream activities of customers and waste disposal services. In essence, direct emissions are those that are directly caused by the reporting company while indirect emissions are those that are caused by the supply chain and attributable to the reporting company.



**Figure 5-1 The relationship between categories of the GHG Protocol (WRI & WBCSD, 2013, page 6)**

Upstream activities represent emissions from events that have occurred in the past while downstream activities represent events that are expected to occur in the future. To model Scope 3 emissions, the GHG Protocol uses purchase and sale activities (WRI & WBCSD, 2013). Table 5-14 depicts the purchase and sale activity that are used to model the various GHG Protocol categories. Although upstream and downstream represents different times, they are only attributed to the reporting company at point of purchase or sale.

According to Table 5-14 there seems to be missing a mechanism to accumulate emissions into a stock. Instead, *Category 15 Financed Emissions*, is calculated based on the monetary holdings of debt and equity instruments. This is the only category that uses a balance sheet item as the activity data rather than a purchase or a sale.

In summary, a spatial boundary of the reporting company is defined by the consolidation approach. Further, there is a separate spatial boundary of the reporting company's value chain. Temporally, emissions due to new activities are reported based on what has been

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purchased or sold. The historical and/or future emissions associated with the new activity may also be included in the report.

*Table 5-14 Depicting the overlap between categories of GHG Protocol and the financial statements.*

**Panel A: GHG Protocol categories that measure a purchasing activity**

<b>GHG Protocol category</b>	<b>A purchase activity data</b>
Scope 1	Purchased fuel
Scope 2	Purchased electricity
Scope 3 Category 1: Purchased goods and services	Purchased goods and services
Scope 3 Category 2: Capital goods	Purchased capital goods
Scope 3 Category 3: Fuel- and energy-related activities not included in scope 1 or scope 2	Purchased fuel
Scope 3 Category 4: Upstream transport and distribution	Purchased transportation and storage for shipping of products
Scope 3 Category 5: Waste generated in operations	Purchased waste management services
Scope 3 Category 6: Business travel	Purchased travel for employees
Scope 3 Category 7: Employee commuting	Purchased travel for commuting
Scope 3 Category 8: Upstream leased assets	Leased an asset

**Panel B: GHG Protocol categories that measure a sales activity**

<b>GHG Protocol category</b>	<b>A sale activity data</b>
Scope 3 Category 9: Downstream transportation and distribution	Transportation and storage for shipping of sold products
Scope 3 Category 10: Processing of sold products	Sold products for further processing
Scope 3 Category 11: Use of sold products	Sold products for use
Scope 3 Category 12: End-of-life treatment of sold products	Waste management services of sold products
Scope 3 Category 13: Downstream leased assets	Leased asset to customers
Scope 3 Category 14: Franchises	Franchise fees collected from franchisees

**Panel C: GHG Protocol categories aligned with an entity's Balance Sheet - Assets**

<b>GHG Protocol category</b>	<b>A balance sheet allocation</b>
Scope 3 Category 15: Investments	Monetary quantity of debt or equity holdings in company or project

We now compare the boundary definitions between financial and GHG accounting. A financial entity reports its stock on a balance sheet. GHG accounting does not have an analogue to a Statement of Position. Instead, every year, the reporting entity is to conduct an inventory of activities, and attributes historical emission to it. Within financial accounting cumulative profit is presented as equity in the balance sheet. However, to calculate cumulative emissions, one would need to retrieve all historical GHG reports and sum it up.

A financial entity reports trade activities on the P&L, which includes items used within the reporting period and spreading costs of items used for more than one period. As shown in the Similarity and Difference facet analysis, capital goods and purchased goods are treated the same. Both emissions are accounted for in the year of the purchase, and emissions are prohibited to be spread across the useful life of an asset. As a result, there lacks a representation of how long an asset is used for. If someone is comparing two physical assets, one is not able to consider the useful life of the asset in the GHG accounting system. This means that Scope 1, 2, and 3 is functionally equivalent to a cash flow statement, representing the GHG emissions that arise due to current activities.

#### *5.4.3.2. Analysis of spatial and temporal relationships*

The relationships between financial statement categories are well understood and can be defined with mathematical rules of double entry bookkeeping (DEBK) (Ellerman, 1985). DEBK can be thought of as a relational database (Chanphakeo, 2016) between the five financial categories: assets, liabilities, equity, revenue, and expense. When one item is increased or decreased, DEBK contains the rules as to how to change a different category.

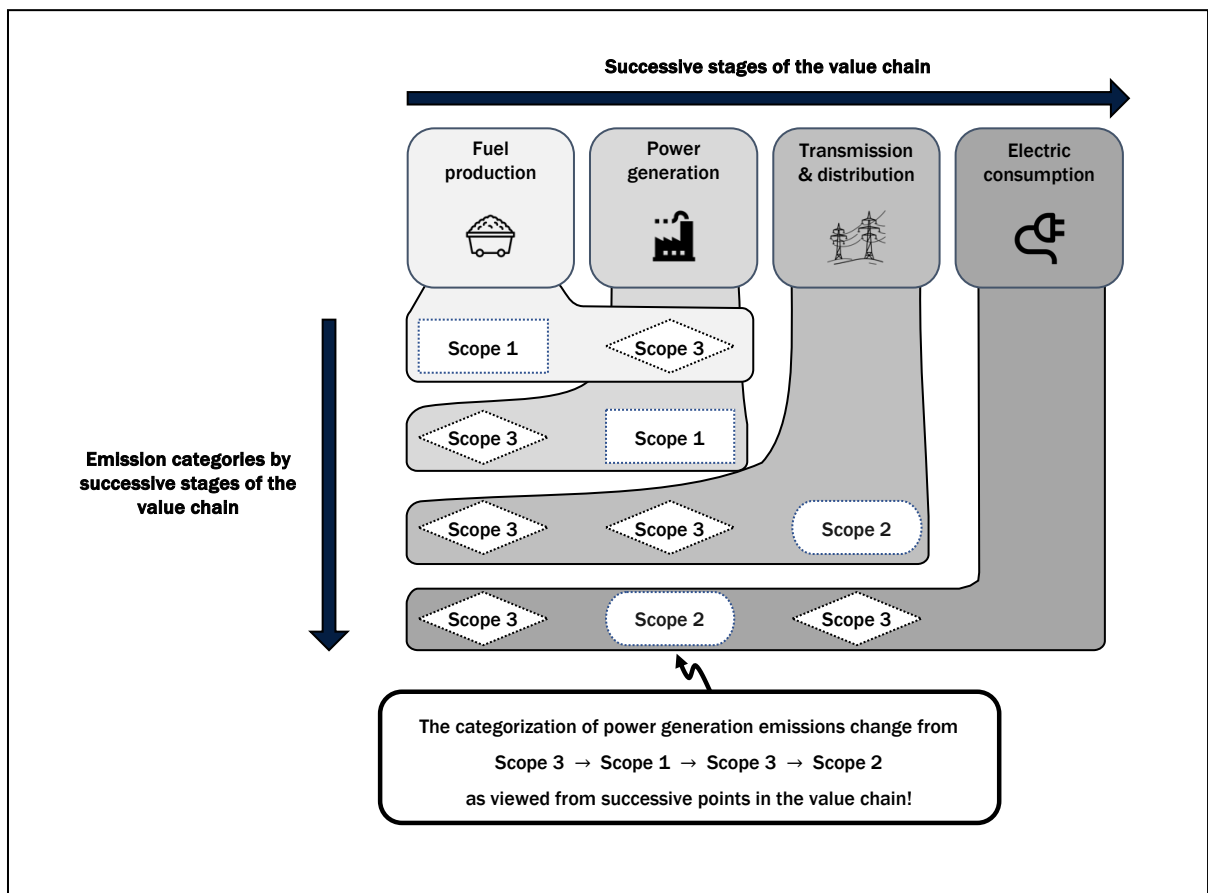
The GHG Protocol is based on the information architecture of LCA (Gillenwater, 2023a). As shown in Figure 5-1, the categories are a description of a value chain that the reporting company operates within (WRI & WBCSD, 2011). There lacks a relationship between the categories. Inflows emissions due to purchased goods and services (Scope 3 Category 1) do not accumulate into emissions of capital goods (Scope 3 Category 2). Rather, the two categories are modelled separately.

Further, the two systems use different mathematics. In financial accounting, expenses are subtracted from revenue to derive net profit, or net inflow of resources. However, in GHG Protocol, emissions due to sales are added to emissions due to purchases, meaning a

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company reports the total emissions of sales and purchases. There is a lack of ability to depict the net of resources that flow in and out of the entity.

Relationships between entities are also described with the DEBK system. What a producer entity records as revenue due to a sale is recorded as an expense by a buyer entity due to a purchase. However, the GHG Protocol does not describe relationships between entities in the value chain. Naively, one could assume that Scope 1 for a producer entity becomes Scope 2 and then Scope 3 for downstream entities. That is not the case. Figure 5-2 depicts four entities involved in the value chain of generating electric energy, modified from an example from the Scope 2 Guidance (WRI & WBCSD, 2015). The fuel producer's GHG



**Figure 5-2** Scope 1, 2, and 3 emissions are categorised based on where an entity is in the value chain. Thus, the emissions from power generation can be considered as Scope 1, 2, or 3 depending on the entity performing the emissions inventory. (Source: Author's modification of (WRI & WBCSD, 2015))

footprint would look like this: Scope 1 would represent emissions from fuel production and Scope 3 would represent downstream power generation. The power generator's GHG footprint would look like this: Scope 1 would be emissions from power generation and Scope 3 would represent upstream fuel production. The switch occurs because the Scopes are determined based on where an entity sits relative to others within the value chain, not based on how emissions are passed from one entity to another. We can see this effect by examining only the power generator's emissions. To the fuel producer, power generation emissions is Scope 3. To the power generator, its own emissions is Scope 1. To the transmission and distribution entity, the power generation emissions is Scope 3, and to the electric consumer, it's Scope 3. The reason for the lack of a relationship is because each entity takes their own inventory, separate from other entities in the value chain.

A critical difference between DEBK and LCA information architecture is their difference in the accounting for time. Within financial statements, time is linked between two tasks, synchronised by periodic reporting of the past, present, and future (Quattrone, 2005; Sangster et al., 2021). Historical activities are represented in the balance sheet (IASB, 2018). Current costs are recorded twice, once in the Cash Flow Statement to record of monetary flows when it occurs and once in the P&L to record of a resource when it is utilised. Future costs can be estimated with present value projections of future cash flows (IASB, 2018), commonly called a financial *pro forma*. These reports are generated at a regular frequency (monthly, quarterly, annually, etc.). In essence, the net flows of current activities are accumulated into the balance sheet.

However, it has been well known that LCA lacks temporal characterisation, ever since the early days of its development (Lueddeckens et al., 2020). The temporal considerations are lost because the results are an aggregation of all processes, and the potential impacts are attributed to a single moment in time (Beloin-Saint-Pierre, 2020). Upstream (historical) and downstream (future) emissions due to present-day activities are inventoried and reported in

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the current year. The emissions are not accumulated and carried over to the next period. As a result, there lacks an ability to update projected emissions for activities that actually occurred.

In essence, the GHG Protocol is an inventory system, meaning that the values of Scope 1, 2, and 3 are calculated each year, separate from each other. On the other hand, financial accounting is an accrual-based system, meaning that new figures are added to historical figures to arrive at a new set of financial statements. Functionally, Scope 1, 2, and 3 is analogous to the financial cash flow statement. It is an incomplete set of categories that define an entity.

**Table 5-15** The definition of an 'entity' is determined by the spatio-temporal categories within financial accounting. Panel A shows that the GHG Protocol is an incomplete inventory of an entity. Panel B compares the relationships found within the categories for the two systems.

Panel A: A summary of spatio-temporal category boundaries

<b>Spatio-temporal categories</b>	<b>Financial accounting</b>	<b>The GHG Protocol</b>
<b>Stock</b>	YES: Balance sheet	NO: Lack of ability to accumulate current activities into stock.
<b>Trade activities:</b> Items utilised in the reporting period	YES: P&L (Revenue and Expenses)	YES: Scope 1, 2, 3
<b>Trade activities:</b> Items utilised for more than one reporting period	YES: P&L (Depreciation and Amortisation)	NO: Specifically prohibited.
Flow of resource	YES: Cashflow statement	YES: Carbon flow as represented by Scope 1, 2, 3

Panel B: A summary of spatial and temporal relationships between categories.

<b>Type of relationship between categories</b>	<b>Financial accounting Information architecture: Double entry bookkeeping</b>	<b>The GHG Protocol Information architecture: Life cycle assessment</b>
<b>Spatial Relationships:</b> (intra-company)	YES: The five categories are related based on DEBK.	NO: Each category of Scope 1, 2, and 3 is inventoried independently
<b>Spatial Relationship</b> (inter-company)	YES: The five categories are related based on DEBK	NO: Each entity inventories their own emissions independently.
<b>Temporal Relationships</b>	YES: The financial statements have temporal attributes of past, present, and future.	NO: Each year's emissions are inventoried independently from prior and future years.

Hypothesis 3 states “*The GHG Protocol framework is a classification system that enables financial entities to be compared.*” As summarised in Table 5-15, we find that the GHG Protocol does not enable comparisons of an entity’s physical GHG emissions. As shown in Panel A, the boundary of an entity is defined within financial accounting as users of financial reports. However, GHG Protocol is not a complete representation of an entity’s emissions, thus violating property (2) of a classification system. As shown in Panel B, GHG Protocol lacks a consistent, unique classificatory principles that dictates the relationship between categories, thus violating property (1) of a classification system. As a result, hypothesis 3 is shown to be false.

#### **5.4.4. Results of dimensional analysis**

To perform a dimensional analysis, we examine the units used in the models to calculate Scope 1, 2, and 3. The general model for calculating emissions is given in Equation 5-3 (Rypdal et al., 2006). It combines information on the extent of human activity, or the activity data, with coefficients that quantity the emissions per unit of human activity, or the emission factor. There are six GHGs as defined by the original Kyoto Protocol – CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, HFCs, PFCs and SF<sub>6</sub> – with a seventh, NF<sub>3</sub>, being added later (WRI & WBCSD, 2013). A global warming potential (GWP) is used to normalise the damaging effects of different GHGs to that of CO<sub>2</sub>. Table 5-16(A) depicts common combustion emission factors emitted when burning various fuels and Table 5-16(B) the GWP-100, or the damaging effects of GHGs for 100 years (Rypdal et al., 2006).

$$\left[ \begin{array}{c} \text{emissions of} \\ \text{a gas (by mass)} \end{array} \right] = \left[ \begin{array}{c} \text{activity} \\ \text{data} \end{array} \right] \times \left[ \begin{array}{c} \text{emission} \\ \text{factor} \end{array} \right] \times \left[ \begin{array}{c} \text{global} \\ \text{warming} \\ \text{potential} \end{array} \right] \quad \text{Equation 5-3}$$

Table 5-16 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 <sub>2</sub>	CH <sub>4</sub>	N <sub>2</sub> O
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 GHGs (P. Forster et al., 2021)

GHG	GWP-100 (kg CO <sub>2</sub> e/ kg GHG)
CO <sub>2</sub>	1.000
CH <sub>4</sub> -Fossil	29.8
N <sub>2</sub> O	273

#### 5.4.4.1. Dimensional analysis of Scope 1

Scope 1 includes GHG emissions from stationary, mobile, physical, or chemical processes, and fugitive emissions from sources the reporting organisation owns or controls (WRI & WBCSD, 2004). The GHG Protocol recommends the usage of the methodology developed by the IPCC, which developed GHG emissions reporting for nations. The activity data has units of quantity of fuel, such as litres or gallons. The units of the emission factor is kg GHG per quantity of fuel. As shown in Equation 5-4, the resulting unit, *metric tons of CO<sub>2</sub> equivalent* (tCO<sub>2</sub>e), is in multiplicative form. It is a derived unit.

$$\left[ \begin{array}{c} \text{Scope 1} \\ \text{(tCO}_2\text{e)} \end{array} \right] = \left[ \begin{array}{c} \text{litres} \\ \text{of fuel} \end{array} \right] \times \left[ \begin{array}{c} \text{kg GHG} \\ \text{litres} \\ \text{of fuel} \end{array} \right] \times \left[ \begin{array}{c} \text{kg CO}_2\text{e} \\ \text{kg GHG} \end{array} \right] \times \left[ \begin{array}{c} \text{tCO}_2\text{e} \\ 1000 \text{ kg CO}_2\text{e} \end{array} \right] \quad \text{Equation 5-4}$$

#### 5.4.4.2. Dimensional analysis of Scope 2

Scope 2 is a category for emissions from generation of acquired and consumed electricity, steam, heat, or cooling (collectively referred to as "electricity") (WRI & WBCSD, 2015). The activity data is the quantity of electricity consumed by the reporting organisation, measured in energy units, such as kilowatt-hours (kWh) or British thermal units (BTU). There are two options for Scope 2 emission factors, location-based (Scope 2L) and market-based (Scope 2M). Both emission factors have units of tCO<sub>2</sub>e / kWh.

Location-based emissions (Equation 5-5) represent the GHG emissions of the local electric grid.

$$\left[ \begin{array}{c} \text{Scope 2L} \\ (tCO_2e) \end{array} \right] = \left[ \begin{array}{c} \text{Electricity consumed} \\ \text{by reporting org. (kWh)} \end{array} \right] \times \left[ \begin{array}{c} \text{Location based} \\ \text{emission factor} \\ (tCO_2e/kWh) \end{array} \right] \quad \text{Equation 5-5}$$

Both the UK Department for Energy Security and Net Zero (DESNZ) and the US Environmental Protection Agency (EPA) take the same approach to model location-based emission factors (Hill et al., 2020; US EPA, 2021). As shown in Equation 5-6, the numerator is the utility's annual Scope 1 and the denominator is how the total amount of electricity generated in the same year.

$$\left[ \begin{array}{c} \text{location based} \\ \text{emission factor} \\ (tCO_2e/kWh) \end{array} \right] = \frac{\text{Utility's Scope 1 emissions (tCO}_2\text{e)}}{\text{annual electric energy produced (kWh)}} \quad \text{Equation 5-6}$$

Combining and rearranging, we can see that Scope 2L can be interpreted as an allocation of a utility's emissions based on the energy consumption of the reporting organisation (Equation 5-7).

$$\left[ \begin{array}{c} \text{Scope 2L} \\ (tCO_2e) \end{array} \right] = \left[ \begin{array}{c} \left( \frac{\text{electricity consumed}}{\text{by reporting org. (kWh)}} \right) \\ \left( \frac{\text{annual electric}}{\text{energy produced (kWh)}} \right) \end{array} \right] \times \left[ \begin{array}{c} \text{Utility's Scope 1 Emissions} \\ (tCO_2e) \end{array} \right] \quad \text{Equation 5-7}$$

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Scope 2M models long-term contracts with electricity suppliers, such as through power purchasing agreements (PPA). Although the electricity is still delivered via the local grid, the reporting organisation is permitted to use the emission factor of their contracted supply. As shown in Equation 5-8, the activity data used is the electricity purchased from the supplier, measured in kWh.

$$\left[ \begin{array}{c} \text{Scope 2M} \\ (tCO_2e) \end{array} \right] = \left[ \begin{array}{c} \text{electricity purchased} \\ \text{from a PPA (kWh)} \end{array} \right] \times \left[ \begin{array}{c} \text{PPA's} \\ \text{emission factor} \\ (kWh/tCO_2e) \end{array} \right] \quad \text{Equation 5-8}$$

The PPA's emission factor is calculated from the PPA's Scope 1 emissions divided by their annual electric energy produced:

$$\left[ \begin{array}{c} \text{PPA's} \\ \text{emission factor} \\ (kWh/tCO_2e) \end{array} \right] = \frac{\text{PPA's Scope 1 emissions (tCO}_2\text{e)}}{\text{annual electric energy produced (kWh)}} \quad \text{Equation 5-9}$$

The resulting tCO<sub>2</sub>e for both Scope 2L and 2M is in multiplicative form, thus both can be considered derived units. However, Scope 2L and Scope 2M represent different phenomena, and cannot be added together, nor compared to each other. Comparisons of Scope 2 must be made like-for-like between entities.

### 5.4.4.3. Dimensional analysis of Scope 3

Scope 3 extends the activity data to any physical measurement to which human activity takes place (BSI, 2019; Rypdal et al., 2006). Example physical measurements include number of units, by weight, volume, distance, area, monetary expenditures, and others. Similarly, a large variety of emission factors are also permitted. Table 5-17 is a summary table of activity data and emission factor options available to model Scope 3 across all 15 categories. The emission factors are calculated using three methods, combustion, LCA, or EEIO (Chapter 4 / Paper 1). Utility provided emission factors are derived from either IPCC combustion or LCA methodologies. Combustion emission factors have been analysed in the

**Table 5-17 Choices for activity data and emission factors available in Scope 3. Utility provided emission factors are typically derived either from IPCC combustion methodologies or LCA.**

Activity data (AD) options		Emission factor (EF) options	Method to model EF
If AD metric is emissions (tCO <sub>2</sub> e)		None needed	N/A
If AD metric is energy	Fuel (Litres)	Combustion EF	IPCC
		Fuel EF	IPCC
		Cradle to gate of fuel	LCA
		Upstream EF	LCA
	Electric energy (kWh)	Lifecycle EF	LCA
		Supplier specific EF	Utility provided
		Grid average EF	Utility provided
		Electricity EF (Location- or market-based)	Utility provided
If AD metric is a physical measurement (#, kg, m <sup>2</sup> , m <sup>3</sup> , km, etc.)	Upstream EF	Utility provided	
	Per unit or use	LCA	
	By weight	LCA	
	Area	LCA	
	Volume	LCA	
	Vehicle-Distance	LCA	
if AD metric is a monetary value (\$ revenue, \$ cost, etc.)	Other	LCA	
	Monetary LCA	LCA	
	Environmentally extended input-output (EEIO)	EEIO	

dimensional analysis of Scope 1. This section performs a dimensional analysis of LCA and EEIO emission factors.

The advantage of the LCA method is the flexibility of modelling emissions per any unit. LCAs can be conducted per product, volume of material, monetary spend of product, and so forth. Thus, LCA emission factors can be created to match an activity data. As shown in Equation 5-10, LCA-based emissions factors are found by conducting an LCA study of the emissions for a product.

$$LCA \text{ emission factor} = \frac{LCA \text{ of a product's emissions (tCO}_2\text{e)}}{Unit \text{ of product (Unit)}} \quad \text{Equation 5-10}$$

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LCA is a process-based approach which takes an inventory of the individual processes of a value chain (BSI, 2020). As shown in Equation 5-11, it is a summation of the extent of the value chain being modelled, whether cradle-to-gate, cradle-to-grave, or other.

$$LCA \text{ of a product's emissions (tCO}_2\text{e)} = \sum \text{process emissions (tCO}_2\text{e)} \quad \text{Equation 5-11}$$

The tCO<sub>2</sub>e from LCA studies is not in multiplicative form, as required for a derived unit. This is because LCA studies are a representation of the extent of value chain processes that was inventoried. Therefore, emission factors derived from LCA do not have derived units and cannot be used to make comparisons.

Finally, emission factors can be calculated from EEIO, which uses matrix arithmetic.

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

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} \quad \text{Equation 5-12}$$

Equation 5-13 extends monetary IO for environmental purposes. One defines a new  $q \times n$  matrix  $\mathbf{B}$  with  $q$  being the number of pollutants and environmental factors being tracked. The resulting matrix  $\mathbf{M}$  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).

$$\mathbf{M} = \mathbf{B}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} \quad \text{Equation 5-13}$$

Both the technology matrix  $\mathbf{A}$  and the environmental matrix  $\mathbf{B}$  are developed from national statistics. For example, in USEEIO, the IO tables  $\mathbf{A}$  are developed by the Bureau of

Economic Analysis within the U.S. Department of Commerce. It has units of monetary value, such as dollar, euro, pound, and so forth. 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). It has units of tCO<sub>2</sub>e.

To calculate the EEIO, one needs to multiply matrix **B** with matrix  $(I-A)^{-1}$ . The product of two matrixes is to sum the product of the rows of the first matrix with the columns of the second matrix. As shown in Equation 5-14, the product of a 2x2 matrix includes sums of different elements.

$$\begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \times \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix} = \begin{bmatrix} a_{11}b_{11} + a_{12}b_{21} & a_{11}b_{12} + a_{12}b_{22} \\ a_{21}b_{11} + a_{22}b_{21} & a_{21}b_{12} + a_{22}b_{22} \end{bmatrix} \quad \text{Equation 5-14}$$

Because of the summations, EEIO emission factors do not follow the multiplicative rule as required to be a derived unit. Instead, the resultant matrix is a summation of economic activities associated with the production of an item.

Hypothesis 4 states, “*Items measured in tCO<sub>2</sub>e can be compared.*” However, as summarised in Table 5-18, the unit tCO<sub>2</sub>e represents different phenomena, rendering it comparable only in certain situations. For Scope 1 and 2, the unit is a derived unit, but each method represents different phenomena. In this situation, comparisons can be made only with other values generated from the same method. For Scope 3, the unit tCO<sub>2</sub>e calculated using LCA or EEIO is not a derived unit and cannot be used to make comparative or additive assertions. When presented with a number measured in tCO<sub>2</sub>e, it is not always known which method was used. Therefore, comparative assertions between entities cannot be made, and H4 is shown to be false.

Table 5-18 Results of dimensional analysis of tCO<sub>2</sub>e across Scope 1, 2, and 3. Derived units can only be compared with the same phenomenon.

	Method	Type of Unit	Limitations to comparisons
Scope 1	Combustion	Derived unit	Limited to between combustion method.
Scope 2	Location-based	Derived unit	Limited to between location-based method.
	Market-based	Derived unit	Limited to between market-based method.
Scope 3	Combustion	Derived unit	Limited to between combustion method.
	LCA	Not a derived unit	Cannot be used for comparisons. Each LCA is a modelled summation of a value chain.
	EEIO	Not a derived unit	Cannot be used for comparisons. Each EEIO is a modelled summation of the structure of the economy

## 5.5. Discussion

As this paper has shown, comparing entity-level GHG values is challenging. Although comparability researchers have identified methodological choice as a challenge to GHG accounting (Andrew & Cortese, 2011; Stanny, 2018), this study has found that the availability of methodological choices is pervasive across the GHG accounting ecosystem. As shown in Table 5-19, each level introduces a different set of methodologies that one can choose from. At the MQ level, the unit tCO<sub>2</sub>e can represent several different phenomena, such as a measure of fuel combustion or a measure of the environmental impact of the structure of the economy. Further, LCA and EEIO are modelling techniques, not measurements. They embed additional methodological choices within them, and different individuals can arrive at different results based on their modelling assumptions. This is problematic as measurements should be stable, repeatable, and implies administrative replicability (Power, 2004).

At the 1<sup>st</sup> order level, there is a difference of the definition of a financial entity and a GHG entity. The divergence can lead to three different items, a financial entity, a consolidated entity for GHG reporting, or a value chain of the reporting entity, being conflated when comparisons are being made. The GHG Protocol accepts multiple methodologies to quantify emissions.

*Table 5-19 Summary of methodological choices and variations that are introduced by each accounting level. These variations need to be controlled for to enable comparability between entities.*

Level of GHG accounting ecosystem	Methodological choices available
<b>2<sup>nd</sup> order meta-measurements</b>	<ul style="list-style-type: none"> <li>• Choice of end dates</li> <li>• Choice of GHG accounting standard (GHG Protocol, etc.)</li> </ul>
<b>1<sup>st</sup> order classification systems</b>	<ul style="list-style-type: none"> <li>• Definition of an entity               <ul style="list-style-type: none"> <li>○ financial reporting entity</li> <li>○ GHG reporting organisation</li> </ul> </li> <li>• Modelling methodology               <ul style="list-style-type: none"> <li>○ Fuel-based</li> <li>○ Activity-based</li> <li>○ Spend-based</li> <li>○ Hybrid</li> </ul> </li> <li>• Lack representation of embodied emissions</li> </ul>
<b>Measurement quantum (MQ)</b>	<ul style="list-style-type: none"> <li>• Measure of fuel combustion</li> <li>• Measure of upstream LCA</li> <li>• Measure of whole life LCA</li> <li>• Measure of economic structure via EEIO</li> </ul>

A second divergence is in the accounting of historical activities. Because the GHG only permits emissions associated with current year activities, some emissions of past activities are not represented. Within LCA studies, the concept of embodied emissions, or the emissions associated with manufacturing or constructing a product or an asset, is well developed (Cabeza et al., 2021; García-Sanz-Calcedo et al., 2021; Grazieschi et al., 2021; Minunno et al., 2021; Röck et al., 2020; Simonen et al., 2017; Victoria & Perera, 2018; Williams, 2023). Embodied carbon is analogous to a capital asset's value. In GHG accounting, the embodied emissions that arise due to the manufacture of an automobile is fully accounted for in the year of the purchase. By the 2<sup>nd</sup> year, the embodied emissions of the automobile must be recorded as zero because it was fully accounted for in the year of purchase. A financial capital asset's value can be spread over the asset's useful life. Thus, there lacks an ability to account for the usage of an embodied carbon asset over its useful life.

At the 2<sup>nd</sup> order level, the CDP, as a disclosure framework, introduces additional choices to GHG accounting that increase methodological variations. Not only is there is a lack of a

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standard start and end date for the reporting year, but some entities also set report start and end dates that are outside of the year of the disclosure. Second, although entities are asked for their choice for organisational boundary, the CDP permits the choice of “other” and “not applicable”, and over 26% of the dataset chose those two options. Finally, although the GHG Protocol is the foundational standard used by all GHG accounting standards, the CDP permits 72 standards and their combinations. These choices add further variations to GHG accounting ecosystem.

Methodological choices that affect one level will affect the other levels in the system as well. Propagation of uncertainty is the principle that uncertainty in one area can create uncertainty in other dependent areas. Modelling errors propagate either linearly or geometrically depending on the relationship the assumptions have with each other (Taylor, 2022). This creates a compounding effect – the more assumptions that are made, the larger the error becomes.

At the measurement quantum, the LCA and EEIO emission factors are prone to modelling uncertainty, which are introduced based on the choice of system boundary, time horizon, input data, among others (Heijungs & Lenzen, 2014). For example, differences in time horizon assumptions can result in truncation errors upwards of 50% (Suh et al., 2004). A study of in emission factor methodologies have shown that outcomes can differ by 38% (Perkins & Suh, 2019), and emission factors in the UK-Defra database are roughly 10% lower than the US-EPA database (Aikman et al., 2023).

At the 1<sup>st</sup> order level, differences in boundaries and category choices add further variations and uncertainty. One study, which inputted the same activity data values into seven different online corporate carbon calculators, produced Scope 3 values ranging from 2.22 tonnes to 92.2 tonnes, representing a percentage error of 95% (Harangozo & Szigeti, 2017). At the 2<sup>nd</sup> order level, further emissions modelling by financial institutions further compound estimates.

One report found that carbon emission estimation models can differ by greater than 200% (Simmons et al., 2022).

In short, the variation introduced at each level due to the breadth of methodological options can significantly hamper abilities to make judgements about the emissions of a financial entity. Instead, the GHG Protocol is a measure of the reporting entity's value chain and may be applicable to be used to make value-chain related decisions.

## **5.6. Recommendations to improve entity-level comparability of GHG emissions**

Climate finance, as an interdisciplinary field, relies on the expertise from engineering (LCA), environmental economists (EEIO), accounting scholars (similarity / difference facet), among others. In this paper, we developed a set of necessary conditions that GHG accounting must follow, that are based on the constraints and conditions of each of these disciplines. As we showed in this paper, non-comparability of entity-level GHG data is systemic. To enable the financial sector to make comparative assertions between entities will require a multidisciplinary and crosscutting research agenda to harmonise different aspects of their information architecture. Broadly, the number of methodological options available at each level needs to be reduced and the option picked should be the one with the lowest uncertainty and administratively replicable between different actors. These recommendations are summarised in Table 5-20.

At the measurement quantum level, there needs to be a distinction between measured and modelled emissions. The unit  $tCO_2e$  from measured emissions will be a derived unit that has additive and comparative properties. Emissions that arise from fuel combustion and chemical processes can be scientifically measured and quantified (Eggleston et al., 2006). Several

Table 5-20 Recommendations to improve entity-level comparability in GHG accounting

Level	Recommendation	Example research initiatives
<b>2<sup>nd</sup> order systems:</b> <i>Input and output comparability</i>	Test for output comparability	Run empirical analyses of output comparability for any GHG accounting system.
	Test for input comparability	Run analyses of similarity and difference facet on any GHG accounting system
<b>1<sup>st</sup> order:</b> <i>Classification system comparability</i>	Harmonise the entity boundaries of GHG accounting and financial accounting.	Research the standardisation of GHG categories with financial accounting categories
	Harmonise the temporal boundaries, with similar treatment of past, present, and future data.	Research how DEBK can create temporal relationships between embodied and operational emissions.
<b>MQ: Unit comparability</b>	Use only measured emissions	Research adoption of methods that follow principles of an energy balance (combustion emissions) or mass balance (stoichiometric emissions)

GHG accounting framework advocate for the exclusive use of combustion emissions, such as the E-liability system (Ramanna, 2024), emissions trading schemes (ETS) across different jurisdictions (CARB, 2019; EU Commission, 2023; RGGI, 2017). Business operators will need to ensure that quantities of fuel consumed are correct and engineers and scientists will need to ensure that combustion emission factors are accurate.

At the 1<sup>st</sup> order classification system, there needs to be a harmonisation of the definition of an entity. The categories that comprise of a financial entity are not entirely the same to those that comprise a GHG reporting organisation. As a result, there are some attributes of a financial entity that are not represented in a GHG reporting organisation.

Further, there needs to be a harmonisation of the treatment of temporal activities. This can be accomplished by adopting the temporal attributes of double entry bookkeeping. In financial accounting, historical costs are allocated to the entity based on usage, thereby

spreading the cost over time. However, in GHG Protocol, all historical emissions are allocated to the current year in which an event occurs. The GHG Protocol approach is analogous to a cash flow statement, which only accounts for current year activity. Missing is a trade account that records economic usage of embodied carbon assets that span beyond a single reporting period and a stock account that is an accumulation of all historical net emissions. GHG accountants should research a set of categories that is aligned with that of a financial entity and temporally synchronised with activities of financial accounts.

At the 2<sup>nd</sup> order level, disclosures that wish to present entity-level data should use GHG accounting standards that are harmonised with entity-level categories of financial accounting standards. These disclosure standards should evaluate GHG accounting standards with two common tests developed to evaluate comparability, the similarity and difference facet for input comparability and the De Franco analysis for output comparability.

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# Chapter 6. General-purpose life cycle assessment: A reporting framework to align entity-level GHG accounting with general purpose financial statements

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## Abstract

One gap between general purpose financial statements and greenhouse gas (GHG) accounting is how they account for the passage of time. While financial statements were designed to synchronise upfront and ongoing activities through the use of double entry bookkeeping (DEBK), GHG accounting uses life cycle assessment (LCA) methodology, a system that sums all emissions over all time and attributed to the present. This paper proposes general purpose life cycle assessment (GP-LCA) as a mechanism to introduce temporality into GHG accounting. GP-LCA synchronises the usage of long-term assets that have embedded GHG of manufacturing with short-term operational activities that emit operational GHG. We apply the system to GHG emissions accounting of a newly constructed building by New College, Oxford and present how it can be used to comply with present-day emissions disclosure requirements.

## Keywords

Carbon accounting, general purpose financial statements, GHG accounting, life cycle assessment, double entry bookkeeping, temporality

## 6.1. Introduction

This paper studies accounting for temporality in greenhouse gas (GHG) emissions of long-duration assets. Capital-intensive sectors, such as real estate, manufacturing, and infrastructure, have long needed and developed financial tools suited to account for the usage of long-duration physical assets over their useful lives (Chatfield, 1977). However, in GHG accounting, emissions are recorded in the year when they occur, thus aligned with the point-in-time they contribute to atmospheric stock (WRI & WBCSD, 2013). The emissions are unmatched with the use of the asset, as it does not take into consideration the duration of the asset that caused the emissions, or how historical GHG emissions are used beyond a single reporting period. Without information on the time horizon of an asset, it is challenging to understand the total GHGs emitted (Lueddeckens et al., 2020). In essence, it is challenging to attribute emissions to the asset based on use.

Real estate investors have an important role to play in tackling climate action. The physical assets, buildings and their operations, contribute 40% of CO<sub>2</sub> emissions (Grazieschi et al., 2021). However, these emissions are split between upfront and embedded emissions, that occur once and utilised for years if not decades, with ongoing operational emissions that occur annually. Ongoing and operational emissions are interrelated. For example, installing more insulation during construction can reduce ongoing operational energy consumption. In essence, one is increasing upfront embedded emissions of insulation with decreasing ongoing operational emissions of future operations. As ongoing emissions are lowered due to operational efficiencies, the share of upfront emissions in a real estate asset is increasing as a proportion of total emissions (Ibn-Mohammed et al., 2013). Further, improvements to construction materials that achieve lower operational emissions usually have higher emissions of manufacturing (García-Sanz-Calcedo et al., 2021).

There is an underlying temporal issue – the trade-off of increasing (decreasing) upfront embedded emissions to result in decreased (increased) ongoing operational emissions. The

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temporality issues make it a challenge to compare choices in today's carbon accounting system. Emissions are only accounted for, or 'expenses' in the year in which they occur. Although real estate assets are long-term items, the upfront embedded emissions are only accounted for in the year of construction. This can hamper the ability to compare carbon efficient buildings with traditional ones.

Analysis of temporal issues is critical to financial decision making. Real estate investors analyse the upfront construction costs and the ongoing operational costs to decide if the project was a good investment (Baum, 2022). One reason why the analysis is possible is because the financial accounting standards define a relationship between upfront and ongoing activities. An asset is a resource as a result of past activities (upfront costs) from which future economic benefits (ongoing costs) are expected to flow (IASB, 2018). The definition also differentiates between the item, or the asset, and the entity that benefits from the asset. The accounting for the asset may include items such as depreciation that spreads cost of the asset over time to match with its use. The accounting for the entity includes items such as income and expense generated by the asset. Finally, when items are used (accrual accounting) is separately accounted for from when cash is exchanged (cash accounting). For example, in accrual accounting, an automobile might be used for 10 years. Therefore, the cost of purchasing the car is spread out over 10 years, to represent its 10-year lifespan. In cash accounting, the cost of purchase is attributed to the year in which the car was procured, regardless of how long it is used for. These dynamics of stocks and flows follows are represented by sequential presentations on the balance sheet, the profit & loss statement, and the cash flow statement.

However, the climate-conscious investor would find it challenging to analyse the temporality of GHG indicators. For example, would increasing upfront emissions of constructing a more efficient building to decrease ongoing operational emissions be a good GHG choice? Today, this analysis is difficult to make because GHG accounting lacks temporal attributes and a

relationship between upfront and ongoing indicators (Chapter 5 / Paper 2). The GHG Protocol, the dominant standard for emissions accounting (Chapter 4 / Paper 1), requires entities to account for all capital goods emissions in the year of their occurrence, specifically prohibiting depreciating the emissions, or spreading the emissions over time (WRI & WBCSD, 2013). Although the intention is to represent all emissions as they occur to prevent companies from hiding emissions, this rationale makes comparability of long-duration assets difficult. In essence, GHG Protocol is a cash-basis system. There is a lack of an accrual-basis system, showing a relationship between stocks, flows, and changes between them over the years, as items are used.

While the GHG Protocol is a corporate emissions standard, the investor could follow a real estate specific standard, such as the whole life carbon assessment (WLCA) by the Royal Institution of Chartered Surveyors (RICS), which came into full effect in 2024 (RICS, 2024). However, the WLCA system is a modelling technique used to inform the emissions footprint of an asset as early as the design and concept phase. RICS recommends using a 60-year operational life for a building to model a WLCA. Ideally, it is updated frequently during the concept, technical design, and construction phases. After a building becomes operational, a WLCA is updated only when there is a major refurbishment or when an update to the predictions is required. Thus, as a modelling technique, WLCA is not designed to be an annual accounting system for emission.

This paper addresses the lack of temporality by asking, *“How can real estate investors account for the relationship between upfront and ongoing emissions of their physical asset’s useful lifetime?”* This responds to a call to introduce temporality into GHG accounting (Chapter 5 / Paper 2). Further, the prior research identified the lack of temporality as a gap in bringing GHG accounting into alignment with financial accounting. Bringing the two systems into alignment has been a goal of researchers in business (Hopwood et al., 2010),

environmental (Feger et al., 2018) and regulators (Penman, 2024). Therefore, the paper asks, “*How can GHG accounting be more aligned with financial accounting?*”

The two research questions are related because financial accounting was developed to account for the passage of time (Quattrone, 2005). Because of that, we develop an information architecture for GHG accounting that is based on that of financial accounting. Both GHG and financial indicators are based on stocks and flows (Barker, 2025), and both indicators are based on the same business activity (Distler et al., 2024), purchases and sales of products and services. We use an empirical data from a real estate case study to develop a carbon dioxide balance sheet, depicting the interaction between embedded and operational emissions. In essence, by introducing time to GHG accounting, we propose an accrual accounting system for emissions asset.

The paper is structured as follows. In section 6.2, we review the existing information architecture of both financial and GHG accounting standards in use today. We then develop the information architecture of GP-LCA that is aligned with that of financial accounting (section 6.3). Next, section 6.4 applies the information architecture GP-LCA to the development of carbon dioxide statements and show how it can be extended to other GHGs. We provide examples for methane and nitrous oxide statements. Then, section 6.5 builds a case study, applying the carbon dioxide statements to the emissions of a newly operational building that was constructed to the Passivhaus standard. Section 6.6 discusses the implications of aligning temporality of financial and GHG accounting. We end with a summary and conclusions (section 6.7).

## **6.2. Method: Information architecture of financial and GHG accounting systems**

Real estate entities are financial organisations while buildings are the physical asset owned by real estate companies. A financial entity is defined within financial accounting as, “An

*Table 6-1 Information architecture of financial statements (IASB, 2018)*

<b>Type</b>	<b>Statement</b>	<b>Categories</b>
Statement of Position	Balance Sheet	<ul style="list-style-type: none"> <li>• Assets</li> <li>• Liability</li> <li>• Equity</li> </ul>
Statement of Performance	Profit & Loss Statement	<ul style="list-style-type: none"> <li>• Revenue</li> <li>• Expenses</li> </ul>

entity that is required, or chooses, to prepare financial statements [3.10],” (IASB, 2018). GPFS consist of two statements, a statement of position and a statement of performance. Within these statements are five elements, assets, liability, equity, revenue, and expenses (IASB, 2018). Assets, liability, and equity represent an entity’s financial position, or the state of the company’s assets and claims against them. These values are reported on the balance sheet. Revenue and expenses are recorded in the statement of performance, depicting the changes to a company’s position based on economic activities and trades. These activities are recorded on a trade account, more commonly referred to as a profit and loss (P&L) statement, or an income statement (Sangster et al., 2021). The items are shown in Table 6-1.

The five categories have a temporal relationship between each other (Quattrone, 2005). A balance sheet is a snapshot in time of the entity on the day in which the statement was prepared (Sangster et al., 2021). Because balance sheets are presented in regular intervals, it is common to denote the time as Period A, Period B, etc. The P&L statement is a record of inflows and outflows due to trade activities that occur between two periods, Period A and Period B (Sangster et al., 2021). Net profit is calculated by subtracting expenses from revenue. The net profit on the P&L is recorded as retained earnings under equity category on the balance sheet, connecting the two statements.

The categories are interrelated via double entry bookkeeping (DEBK). DEBK can be thought of as a relational database between stocks and flows (Chanphakeo, 2016). A common

Table 6-2 Relationship between financial categories

	Financial category	Debit	Credit
Stock variables	Asset	(+) Increase	(-) Decreases
	Liability	(-) Decreases	(+) Increase
	Equity	(-) Decreases	(+) Increase
Flow variables	Revenue	(-) Decreases	(+) Increase
	Expenses	(+) Increase	(-) Decreases

visualisation to depict the relationships between categories is with a Master T-Table, as shown in Table 6-2. This table depicts how to record increases and decreases for each of the categories. Each accounting book has two columns, the left one to record debits and the right one to record credits. For historical reasons, increases to assets and expenses are recorded in the debit column while increases for liability, equity, and revenue are recorded in the credit column. Further, each category is further divided into accounts. For example, under asset, one will find accounts for cash, inventory, fixed assets, among others. Under the expenses, one will find cost of goods sold, sales and general administration, and so forth.

Financial accounting distinguishes between events of different periods (Chatfield, 1977). For example, railroads are capital intense fixed assets and lasts for a very long time. If the upfront capital was never expensed, the railroad company can seem more profitable than they actually were. Manufacturing business had a different but related challenge. The fixed assets were used to manufacture goods, and they needed a mechanism to allocate the upfront capital costs over the production of products. Thus depreciation, as a mechanism to allocate costs of the asset over time and usage, became central to financial accounting.

Further, the matching concept within financial accounting distinguishes between events that are associated with an item and events that are associated with the entity. In the P&L, the income earned (accomplishment) needs to be matched with the expenses incurred in the period (effort) to earn that income in the same period (Storey & Storey, 1998). Table 6-3 depicts a financial example of the matching concept for a mug manufacturing business. The

*Table 6-3 The Matching concept in a financial P&L. Expenses listed at the top are those that are directly attributable to the revenue.*

<b>Matching Concept</b>	<b>Financial Profit and Loss</b>	<b>Example (a mug)</b>
<b>THE ACCOMPLISHMENT:</b>	(+) Revenue	Sale of a mug
<b>DIRECT MATCHING:</b> Effort (costs) that are directly attributable to the achievement of revenue	(-) Costs of Goods Sold (=) Gross Profit	<ul style="list-style-type: none"> <li>• Cost of the clay, glaze, labour, etc.</li> </ul>
<b>INDIRECT MATCHING:</b> Effort (costs) incurred by the company that are indirectly attributable to revenue	<b>Operating expenses:</b> (-) General Administration (-) Marketing (-) Depreciation / Amortisation (-) etc. (=) Operating Profit	<ul style="list-style-type: none"> <li>• Rent for a store and factory.</li> <li>• Expenses for an accountant.</li> <li>• Software to run the business.</li> <li>• Energy costs for the office.</li> <li>• Depreciation / amortisation</li> <li>• Etc.</li> </ul>
<b>INDIRECT MATCHING:</b> Effort (costs) of the infrastructure to maintain the entity	<b>Non-operating expenses:</b> (-) Interest / Taxes (=) Net Profit (Loss)	<ul style="list-style-type: none"> <li>• Interest / taxes</li> </ul>

revenue from sale of mugs is recorded and matched with the total costs to calculate the profits. Costs that can be directly attributed to the mug, such as the clay, glaze, labour, are represented first, as the cost of goods sold (COGS). Next, there are business functions, such as marketing, legal, accounting, and rent, that general costs for the company that cannot be directly allocated to the unit cost of a specific mug but are necessary for operating the business. Lastly, the factory accounts for financing costs and taxes, which are costs attributed to the entire company rather than a single product. Thus, the accounting for items, such as the mug, is separated from accounting from the entity.

GHG disclosures for the entity-level follow the GHG Protocol's Scope 1, 2, and 3 accounting system with real estate sector-specific resources following the GHG Protocol's disclosure requirements. For example, the Global Real Estate Sustainability Benchmark (GRESB), a tool designed for institutional investors to report and track environmental performance of property investments (Bauer et al., 2011), records disclosures of Scope 1, 2, and 3 (GRESB, 2023). The Partnership for Carbon Accounting Financials (PCAF) have developed technical guidance documents for the real estate investors (PCAF, 2023).

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Table 6-4 Information architecture of GHG Protocol value chain is organised based on the LCA supply chain

Upstream categories	Reporting company	Downstream categories
<ul style="list-style-type: none"> <li>• <b>Scope 2:</b> Energy indirect emissions</li> <li>• <b>Scope 3 Category 1:</b> Purchased goods and services</li> <li>• <b>Scope 3 Category 2:</b> Capital goods</li> <li>• <b>Scope 3 Category 3:</b> Energy-related activities not included in scope 1 or scope 2</li> <li>• <b>Scope 3 Category 4:</b> Upstream transportation and distribution</li> <li>• <b>Scope 3 Category 5:</b> Waste generated in operations</li> <li>• <b>Scope 3 Category 6:</b> Business travel</li> <li>• <b>Scope 3 Category 7:</b> Employee commuting</li> <li>• <b>Scope 3 Category 8:</b> Upstream leased assets</li> </ul>	<ul style="list-style-type: none"> <li>• <b>Scope 1:</b> Direct emissions</li> </ul>	<ul style="list-style-type: none"> <li>• <b>Scope 3 Category 9:</b> Downstream transportation and distribution</li> <li>• <b>Scope 3 Category 10:</b> Processing of sold products</li> <li>• <b>Scope 3 Category 11:</b> Use of sold products</li> <li>• <b>Scope 3 Category 12:</b> End-of-life treatment of sold products</li> <li>• <b>Scope 3 Category 13:</b> Downstream leased assets</li> <li>• <b>Scope 3 Category 14:</b> Franchises</li> <li>• <b>Scope 3 Category 15:</b> Investments</li> </ul>

The GHG Protocol accounts for emissions that arise both as a direct result of company operations as well as indirect activities that arise from the broader value chain (Walenta, 2021). As shown in Table 6-4, *Scope 1* represent direct emissions from assets owned by the reporting company. *Scope 2* represents upstream indirect emissions from purchased electricity and other energy. *Scope 1* and *2* are considered operational emissions. *Scope 3* is further divided into 15 categories that represent both upstream and downstream emissions (WRI & WBCSD, 2011). Some categories of *Scope 3* represent ongoing operations, such as *Category 1 Purchased goods* or *Category 6 Business travel*. Other categories represent upfront activities, such as *Category 2 Capital goods*.

*Scope 3 Category 2 Capital Goods* is where one discloses upfront emissions that arise due to construction of a building. However, the standard prohibits emissions from being depreciated and must be accounted for in the year in which they occur. If capital purchases only occur every few years, emissions to capital goods may fluctuate significantly from year to year, much like the fluctuations on a cash flow statement. In essence, GHG accounting follows cash-basis accounting rules rather than accrual accounting rules.

The emissions of the physical asset, buildings, is commonly found using life cycle assessment (LCA) (Grazieschi et al., 2021; Minunno et al., 2021; Williams, 2023). LCA is a modelling technique that takes into consideration the entire life cycle of a product, from raw material extraction through production and manufacturing to end of life treatment. It is a process-based approach as emission inventories are conducted based on the processes identified relevant to the item being studied. The goal is to identify potential shifts in environmental burdens between life cycle stages (BSI, 2020). The emission of the whole life is then attributed to the present moment (Beloin-Saint-Pierre, 2020). Although LCA can be used to quantify any environmental burden, GHG emissions as a specific metric has become the most frequent application of the LCA method (Hou et al., 2015).

One standard to perform a building level LCA is RICS' WLCA (RICS, 2024), as shown in Figure 6-1. Embodied emissions include upfront emissions that arise from materials manufacturing and construction (module [A]), in use emissions of capital asset replacement and refurbishment (modules [B1-B5]), and end of life emissions related to disposal (module [C]). A whole life carbon assessment representing the system boundary of the building adds the emissions that arise from operating the building (module [B6-B8]). Module [D] represent optional emissions that are beyond the construction of the building used to calculate the whole life carbon assessment. RICS recommends using a 60-year operational life for a building to model a WLCA. Ideally, it is updated frequently during the concept, technical design, and construction phases. After a building becomes operational, a WLCA is updated only when there is a major refurbishment or when an update to the predictions is required.

As shown, neither of these methodologies were designed to account for an entity's usage of an asset over time. The WLCA is a modelling technique of emissions for a building, projecting 60-years of emissions based on assumptions. The GHG value is incorporated into

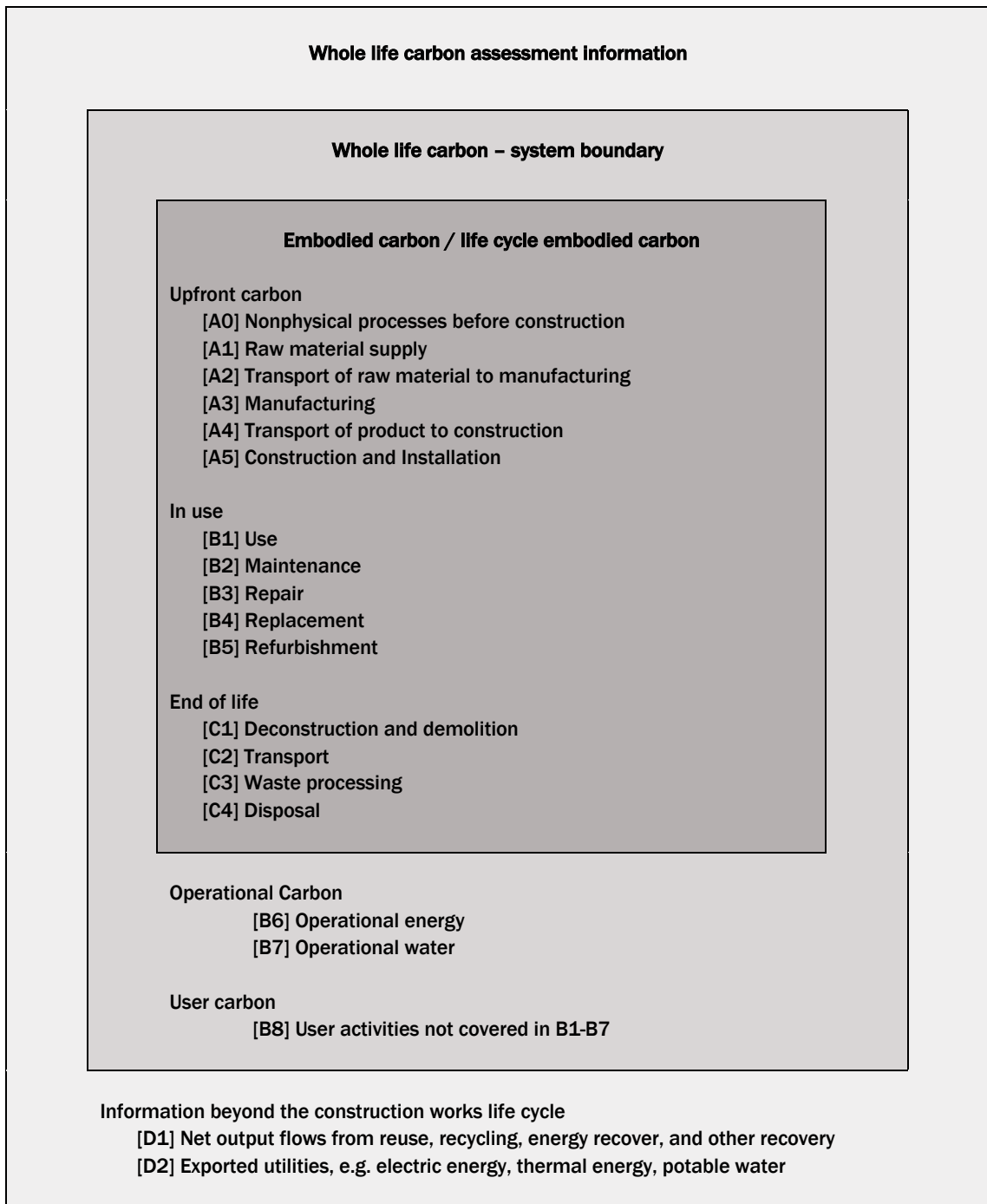


Figure 6-1 Information architecture of whole life carbon assessment is based on the LCA supply chain.  
Figure adopted from RICS (RICS, 2024)

Scope 3 Category 2 Capital goods, but the GHG emissions from the item needs to be fully accounted for in the year of emissions. In WLCA, upfront carbon [A0 – A5] represent modelled historical emissions. However, these historical emissions are not attributed to any particular year, just “the past”. When incorporated into GHG Protocol Scope 3, these

historical emissions are attributed to the year they are recorded, regardless of when in “the past” they occurred. In essence, the temporal nature of historical emissions is not considered in either the WLCA or GHG Protocol systems. Further, neither the WLCA nor GHG Protocol standard differentiate between emissions of the entity and the asset. The distinction is important. For example, if the emissions are allocated to the asset, then the emissions should be transferable to another entity when ownership of the asset is transferred, such as in a sale. But if the emissions are allocated to the entity, then the emissions should not be transferrable.

Despite these challenges, investors are taking into consideration Scope 1, 2, and 3 when adjusting valuations in the real estate sector (PRI, 2016). However, researchers have been pointing out that the GHG Protocol may not be fit for purpose for the financial sector in representing entity-level GHG emissions (Gillenwater, 2023b). The GHG Protocol has been found lacking in decision usefulness for the financial sector, specifically lacking in relevance and faithfully representing actual changes in atmospheric GHGs associated with an entity’s activities (Glenk, 2023). Recent research on the conceptual framework of GHG accounting has found non-comparability throughout the GHG Protocol (Gillenwater, 2023a). The GHG Protocol has pervasive double counting (Kaplan & Ramanna, 2021). Because the GHG Protocol accounts for emissions within a value chain (Chapter 5 / Paper 2), it produces inventories for both purchase activities (Scope 3 Category 1) and sales activities (Scope 3 Category 10 and 11). This is unlike financial accounting, which uses the entity as a boundary. Purchases are items that enter into the entity and sales record items that exit an entity.

One key difference between GHG Protocol and financial accounting is their information architectures. The information architecture of the GHG Protocol follows the information architecture of LCA (Gillenwater, 2023a) while financial statements use DEBK (Chanphakeo, 2016). LCA is a modelling technique used to estimate emissions of an activity while DEBK is

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a technique to record and present information as activities occur. LCA models are updated on an as-needed basis, such as when a refurbishment occurs. These activities can be separated by many years. DEBK information is updated in real time and presented in a periodic manner, such as monthly, quarterly, or annually. LCA methods takes an inventory of stock and flows whenever an LCA study is done. Therefore, stocks and flows are modelled separately from each other, and from prior year's LCA inventories. DEBK systems accumulate flows into stock on an ongoing basis. Therefore, stocks and flows are recorded simultaneously (Chapter 5 / Paper 3).

Finally, financial accounting is a general-purpose system. The purpose of the GPFS is to provide information that is useful in making business and economic decisions for a broad audience (IASB, 2018). Users can make their own calculations to support specific decisions. Investors and capital market users can efficiently allocate resources in the economy (Storey & Storey, 1998), managers to make day-to-day decisions, governments for tax inspection, regulators who require disclosures, supplier who are offering credit, among others (Sangster et al., 2021).

On the other hand, special purpose financial statements are those that are prepared for a limited audience of users who seek to perform specific decisions (IAASB, 2023). For example, special accounting statements are used for tax reporting, cash reporting, loan reporting, or industry specific reporting, among others. There is no established standards or guidance on how to report transactions and what modifications are appropriate (Deloitte, 2024). Special purpose statements rely on expert judgement, who carry a specific perspective for an intended decision (Power, 2004), that may not be suited for a general audience. The GHG Protocol can be considered a special purpose accounting system, for how it takes inventories of specific items and discloses the information to the public. Prior research has shown how GHG Protocol relies on expert judgement and perspective (Chapter

4 / Paper 1), rather than reside on repeatable processes and definitions. The differences between financial and GHG accounting are summarised in Table 6-5.

One key difference is the treatment of stocks and flows. In financial accounting, stocks are financial values at a point in time while flows are accumulation or changes of values over time. The structure of financial accounting depicts how flows on the P&L accumulate into stocks on the balance sheet. GHG accounting has analogous concepts of stocks and flows (Barker, 2025). GHG stocks can be considered the amount of GHGs in the atmosphere at a point in time and GHG flows to be atmospheric GHG accumulated or changed over time. However, in the GHG Protocol, stocks and flows are inventoried separately. For example, Category 15 Financed Emissions is a stock metric because it is based on the amount of equity or debt held in a company, while Category 1 Purchased Goods, Category 2 Capital Goods, Category 4 Upstream Transportation, among others, are flow metrics because they are accounted for in the year of the transaction (see Table 6-27 for a full alignment of GHG Protocol categories with financial accounting categories).

Several efforts have been made to improve GHG accounting by applying DEBK to environmental systems taking advantage of the analogous concepts of stocks and flows between financial and environmental accounting. DEBK can be generalised into a

*Table 6-5 Differences between financial, GHG, and WLCA*

<b>Financial Accounting: IFRS</b>	<b>GHG Accounting: GHG Protocol</b>
<b>Information architecture: DEBK</b>	<b>Information architecture: LCA</b>
<b>Boundary: Financial entity</b>	<b>Boundary: Value chain of financial entity</b>
<b>Usage: Recording and presenting of ongoing activities and changes of stock</b>	<b>Usage: Conducting and presenting annual inventories</b>
Flows accumulate into stocks.	Flows and stocks are inventoried separately.
A general-purpose accounting system	A special purpose accounting system.

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mathematical system (Ellerman, 1985), and the system has been generalised into the accounting for any flow, including for environmental information (Renes & Garst, 2024). One study advocated for aligning granularity of data between financial and GHG emissions (Distler et al., 2024). Because the unit of account in financial accounting are transactions, GHG emissions should also be assigned to every transaction, aligning financial and emissions activities.

Existing application of DEBK to entity-level GHG accounting have focused on separating out upstream and downstream processes (Kaplan & Ramanna, 2021). The E-liability system reports upstream activities as embedded emissions that enter the reporting entity and direct combustion emissions as additive to production. Embedded emissions of products can leave a company upon a sale (Ramanna, 2024). The system defines an E-asset as a right to remove carbon from the atmosphere (Kaplan et al., 2023), otherwise known as an offset. E-assets can be used to neutralise E-liabilities, with the remainder representing additional emission liabilities that the entity needs to reduce. Penman demonstrated how transactions could be designed for an E-asset and E-liability system (Penman, 2024), creating E-ledgers. The E-ledger system has been applied to account for carbon allowances in emissions trading systems (Cheung, 2023) and offsets (Comello et al., 2023).

Although these systems addressed the mismatch of inflows and outflows of entities, they do not address the temporal mismatch of the usage of capital stock assets beyond single reporting periods. Within the GHG Protocol, the emissions of purchased capital goods (Scope 3 Category 2) must be accounted for in the year of purchase and are forbidden to be spread out beyond the reporting period. This is not aligned with accrual accounting systems which permit capital assets to be depreciated, a mechanism to spread the upfront costs over the useful life of the asset. Without it, for a manager or investor, there is no ability to account for the duration of how long an asset is used for. Within the E-liability system, depreciation of emissions from assets is permitted. However, a decrease in emissions due to depreciation

does not represent a withdrawal of emissions from the atmosphere. Literature suggests that discounting should only be applied to economic value and not physical quantities nor the physical phenomena that generate them (Lueddeckens et al., 2020; O'Hare et al., 2009). The E-liability system has yet to address how to account for the continued existence of atmospheric emissions from an emissions-depreciated asset.

We propose a framework to account for temporality of environmental stocks and flows. By introducing temporality, we are able to differentiate between emissions allocated to a physical asset and emissions allocated to the financial entity from the usage of the physical asset. We propose general-purpose life cycle assessment (GP-LCA) framework as a method to record and present emissions-related LCA data. We use *general purpose* to denote alignment with the information architecture of GPFS, and the ability to record and present environmental information as events occur. We use *LCA* to denote support the ability to sum activities for specific purposes, such as supply chain or value chain modelling. In essence, GP-LCA is a set of normative rules for the temporal disentanglement of LCA processes.

We follow prior research's recommendation to temporally harmonise environmental accounting and GPFS (Chapter 5 / Paper 2). These criteria are:

1. Use only attributes from energy or mass balance.
2. Use the same entity boundary as GPFS.
3. Use DEBK to temporally align GPFS and environmental accounting.

To meet the first condition, we limit GP-LCA to environmental systems that can be described by stocks and flows (Barker, 2025). These include energy, GHGs, water, and so forth. To meet the second condition, we follow the IASB's definition of an entity (IASB, 2018) thus aligning the boundaries of financial and environmental accounting. To meet the third condition, we adopt the mathematics and relational database of double entry bookkeeping (Renes & Garst, 2024) to synchronise periodic activities (Quattrone, 2005), aligning the

temporal resolution of environmental accounting with that of financial accounting. We use statement of positions to represent stocks (Balance Sheets) and statement of performance to represent flows due to trade activities (Releases & Withdrawals Statements). In short, GP-LCA follows both the normative rules of financial and environmental accounting.

We then apply the GP-LCA system to GHG emissions specifically, following Kaplan and Ramanna's method of using only energy-related emissions (Kaplan & Ramanna, 2021). We build on Distler (2024) by using transactions as our unit of accounts, giving us detailed granularity of data. We also adhere to literature to not discount physical quantities (Lueddeckens et al., 2020) by transferring the emissions allocation between the item (building) and the entity (financial entity).

## **6.3. A framework for General Purpose**

### **6.3.1. Defining an entity's boundary**

We align the boundary of an environmental entity to that of a financial entity. Environmental entities are those that are required or chooses to prepare financial statements. Thus, GP-LCA describes the environmental attributes of the entire financial entity. We propose a statement of environmental position to represent an entity's environmental attributes and allocation of those attributes. This will include accumulated attributes over time. We propose a statement of environmental performance as changes to an entity's environmental position. We will follow the rules of accrual accounting to spread environmental attributes by use. A statement of environmental flow will depict the actual changes to emissions. Thus, an entity can track environmental attributes aligned to activities of position, performance, and flows.

### **6.3.2. Proposing new environmental categories and statements**

The IFRS defines three elements of financial statements that represent financial position, assets, liability, and equity, and two categories to represent financial performance, revenue

and expenses (IASB, 2018). We propose analogous elements to represent environmental position and performance.

We define *releases* as increases in an entity's environmental attributes. Releases are analogous to revenue, as increases to an entity's resources. The releases can be of atmospheric GHGs, pollutants, or other attributes.

We define *withdrawals* as decreases in an entity's environmental attribute. Withdrawals are analogous to expenses, as decreases to an entity's resources. Withdrawals can be of atmospheric GHGs, pollutants, or other attributes.

We define *embedded* attributes as releases as a result of past events from which one expects future releases or withdrawals to occur. This definition is aligned with the definition of a financial asset being an asset controlled by the entity as a result of past events from which future economic benefits are expected to flow ([F 4.4(a)], IASB, 2018). Embedded attributes are a measure of stock, or cumulative emissions associated with the entity.

We define *responsibilities* as proposed to be a way to assign or allocate responsibility of emissions to financial stakeholders who own the physical assets. Liability and equity can be interpreted as the allocation of ownership of financial assets. A liability is a present obligation of the entity arising from past events ([F 4.4(b)], IASB, 2018). It represents what is owed to debt holders and creditors. *Equity* is the residual interest in the assets of the entity after deducting all its liabilities ([F 4.4(c)], IASB, 2018). It represents the share left for owners. We propose responsibility of debt holders and responsibility of owners to be analogous to liability and equity.

We propose an environmental balance sheet as a statement of performance. Within financial accounting, the balance sheet is governed by assets equalling the sum of liability plus equity:

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$$\text{Assets} = \text{Liability} + \text{Equity} \quad \text{Equation 6-1}$$

We propose that embedded environmental attributes be fully allocated to financial stakeholders. Based on our new category definitions, the sum of responsibility to debt holders and owners must equal the embedded environmental attributes of the company.

$$\left[ \begin{array}{l} \text{Embedded} \\ \text{environmental} \\ \text{attributes} \end{array} \right] = \left[ \begin{array}{l} \text{Responsibility} \\ \text{of debt holders} \end{array} \right] + \left[ \begin{array}{l} \text{Responsibility} \\ \text{of owners} \end{array} \right] \quad \text{Equation 6-2}$$

Therefore, the environmental statement of position describes the accumulation of environmental attributes over time and the allocation of those attributes to financial stakeholders.

A statement of environmental performance shows increases and decreases to environmental position. It represents additional environmental attributes incurred by the entity. The net of release and withdrawals represents the additional (or reduction) of environmental attributes incurred by the entity:

$$\left[ \begin{array}{l} \text{Net releases} \\ \text{and withdrawals} \end{array} \right] = \text{Releases} - \text{Withdrawals} \quad \text{Equation 6-3}$$

Much like how net profit and loss is transferred to equity holders as retained earnings, we propose that net releases and withdrawals is transferred to owners as retained environmental attributes.

In financial accounting, the categories are related to each other via double entry bookkeeping. We intentionally proposed new environmental categories to be analogous to those of financial accounting, thereby adopting similar relationships for environmental accounting. These are shown in Table 6-6.

Table 6-6 Proposed master T-table for GP-LCA, based on financial analogies

<b>Financial analogy</b>	<b>Environmental category</b>	<b>Debit</b>	<b>Credit</b>
<b>Asset</b>	<b>Embedded</b>	<b>(+) Increase</b>	<b>(-) Decreases</b>
<b>Liability</b>	<b>Responsible</b>	<b>(-) Decreases</b>	<b>(+) Increase</b>
<b>Equity</b>	<b>Owned</b>	<b>(-) Decreases</b>	<b>(+) Increase</b>
<b>Revenue</b>	<b>Releases</b>	<b>(-) Decreases</b>	<b>(+) Increase</b>
<b>Expenses</b>	<b>Withdrawals</b>	<b>(+) Increase</b>	<b>(-) Decreases</b>

### 6.3.3. Defining what to count

Financial transactions are the ‘measurement quanta’ within DEBK (Power, 2004). They are a series of events that depict the exchange of items (Sangster et al., 2021). Transactions are recognised, or counted, when they meet the following definitions [F4.37 and F4.38] (IASB, 2018):

- It is probable that any future economic benefit associated with the item will flow to or from the entity; and
- The item's cost or value can be measured with reliability.

These transactions carry not only financial value, but also environmental attributes, as shown in Figure 6-2. For example, the purchase of a mug will carry with it a financial exchange, say £10. The seller will record that a mug exited their entity while the buyer will record that the mug entered their entity. Concurrently, the transaction also represents the exchange of embodied energy and embodied GHG attributes between the seller and the purchaser. For our model, we will only recognise the emissions attribute at the same point-in-time as the financial transaction.

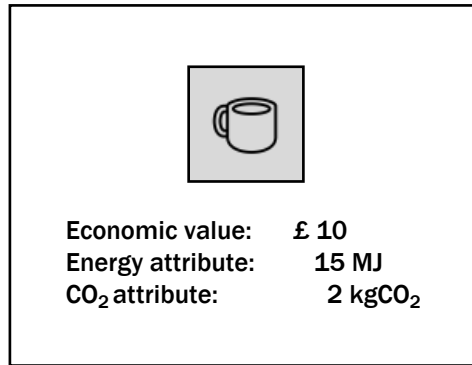


Figure 6-2 The nexus of economic, energy, and emissions attributes, as represented by the transaction of a mug. The mug has financial, embedded energy, and embedded carbon values. (Source: Author's creation)

## 6.4. Developing CO<sub>2</sub> statements from GP-LCA

Emissions are modelled using the equation (Rypdal et al., 2006):

$$Emissions = \left[ \begin{array}{c} Activity \\ data \end{array} \right] \times \left[ \begin{array}{c} Emission \\ factor \end{array} \right] \times \left[ \begin{array}{c} Global \\ warming \\ potential \end{array} \right] \quad \text{Equation 6-4}$$

Activity data represents the extent of human activity while the emission factor is a coefficient that converts the activity to emissions. The Kyoto Protocol introduced six (now seven) GHGs to be reduced, CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, HFCs, PFCs, SF<sub>6</sub>, and NF<sub>3</sub> (WRI & WBCSD, 2013). Each GHG has a different atmospheric lifetime and radiative forcing contribution to global warming. A global warming potential (GWP) is used to normalise the damaging effects of different GHGs to that of CO<sub>2</sub> (Fuglestvedt et al., 2003).

We limit the activity data to those that arise from energy combustion or chemical reactions that have stoichiometric relationships. As we limit activity data to those that arise from energy combustion, we define *intrinsic energy* (IE) as: *The amount of energy stored that is capable of being used for future work*. A lump of coal sitting in a box has stored energy content that could be released in the future if it is placed inside a steam locomotive, an electric power plant, or a fireplace. Similarly, energy can be stored in thermal batteries, chemical batteries, or gravitational batteries. The definition is analogous to cash and cash equivalents, such as

bonds, commercial paper, and other highly liquid notes, can be considered a method of storing cash in various forms.

#### 6.4.1. Statement of CO<sub>2</sub> Position

We propose a CO<sub>2</sub> balance sheet (CBS) to represent the statement of position of carbon dioxide attributes allocated to the reporting entity. Broadly, in financial accounting, assets are comprised of current assets, or items that are expected to be exchanged in the next period, and non-current assets, or are items expected to be used for many reporting periods.

Analogously, we construct the CBS to contain embedded CO<sub>2</sub> of exchange (EC of Exchange) to represent current CO<sub>2</sub> attributes, and embedded CO<sub>2</sub> of use (EC of Use) to represent non-current CO<sub>2</sub> attributes.

We define *Intrinsic CO<sub>2</sub>* (IC) as *the amount of CO<sub>2</sub> that is stored within intrinsic energy that has the potential to be converted into atmospheric emissions*. It is a form of embedded emissions because it models the potential emissions when a fuel is combusted in the future. IC thus represents the CO<sub>2</sub> associated with stored energy. IC is modelled by using IE as the activity data and using an emission factor of intended use.

$$\text{Intrinsic CO}_2 \text{ (IC)} = \text{Intrinsic Energy} \times \text{Emission Factor}_{\text{of intended use}} \quad \text{Equation 6-5}$$

We define *Embedded CO<sub>2</sub>* (EC), as *Intrinsic CO<sub>2</sub> that was emitted as a result of past event from which one expects future CO<sub>2</sub> releases or withdraws to flow*. For example, a building can be considered both a financial asset, with future income and expense, and an EC asset, with future CO<sub>2</sub> emissions and/or offsets. The rules of financial capitalisation can therefore be aligned to the rules of embedment.

$$\text{Embedded CO}_2 \text{ (EC)} = \text{Intrinsic Energy} \times \text{Emission Factor}_{\text{of actual use}} \quad \text{Equation 6-6}$$

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EC is an attribute that describes the amount of CO<sub>2</sub> emitted to produce an item. As an attribute, it stays with the product as it is traded, exchanged, or sold down the supply chain. Thus, EC is not a direct emission itself but represents allocation of CO<sub>2</sub> emitted due to manufacture and production.

The key difference is that intrinsic CO<sub>2</sub> is calculated from an emission factor of *intended* use, modelling the potential emissions from a fossil fuel. Embedded CO<sub>2</sub> is calculated from an emission factor of *actual* use, measuring the actual emissions from combusting a fossil fuel.

We propose five sub-categories of EC:

- *EC of Fuel* – The upstream production, processing, and delivery of fuel. This is distinct from IC, which represents the potential atmospheric emissions of a fuel due to combustion. A consequence of this definition is that indirect emissions due to electricity can be considered embedded CO<sub>2</sub> of electricity.
- *EC of Exchange* – Analogous to the financial category of inventory, this category represents the EC of inventory. EC of Exchange is reduced when items exit the entity.
- *EC of Use* – Analogous to the financial category of plant, property, and equipment (PPE), this category represents the EC of fixed assets. The operations of some assets, such as a building, may release emissions, while other assets, such as a direct air capture facility, may withdraw emissions.
- *EC of Chemistry* – A category for the special case where emissions arise due to chemical reactions rather than combustion. This is common in the usage of concrete, where roughly 10% of the emissions are due to the calcination reaction (Barcelo et al., 2014).

**Table 6-7 A proposed CO<sub>2</sub> balance sheet (CBS): A statement of CO<sub>2</sub> position**

CO <sub>2</sub> Assets	Emissions Responsibilities
Intrinsic CO <sub>2</sub> (IC)	Responsibility of debt holders
EC of Exchange	
EC of Use	
EC of Chemistry	Responsibility of owners <i>Retained Releases &amp; Withdrawals</i>
EC of Entity	

- *EC of Entity* – A financial intangible, this category represents the EC allocated to the corporate entity through use. As we will show in this paper, this category can be used to represent the cumulative emissions over time of the entity.

Table 6-7 composes a CO<sub>2</sub> balance sheet (CBS), describing the statement of position an entity. It allocates responsibility of embedded assets to debt holders and owners. A CBS may be a transparent way to assign financed emissions to equity and debt holders. One allocation methodology of responsibility amongst debt holders and equity holders is to use the same percentage as that of financial holdings. Further, the repayment of debt or disbursement of dividends may be used to represent allocation of emissions of ongoing operations. This is especially relevant today as the financial economy is trying to quantify their financed emissions (PCAF, 2020).

### **6.4.2. Statement of CO<sub>2</sub> performance**

We define *Operational CO<sub>2</sub> (OC)* as *CO<sub>2</sub> resources that were exchanged within the reporting period*. One key difference between operational and embedded attributes is their duration of usage. OC represents emissions that occur within a reporting period while EC represents emission activities that occur beyond a single reporting period. There are two types of operational flows associate with an entity: exchanges between entities and exchanges with

Table 6-8 A proposed Statement of Carbon Dioxide Releases and Withdrawals (CR&W)

<b>R&amp;W FROM OPERATING ACTIVITIES</b>
Releases due to direct activities (+) From fuel combustion
Releases due to indirect activities (+) From procurement IC/EC of Fuel EC of Electricity EC of Products
<hr/> <b>Total Releases</b> <hr/>
Withdrawals due to direct activities (-) Direct removals
Withdrawals due to indirect activities (-) From sales EC of Fuel EC of Electricity EC of Products
<hr/> <b>Total Withdrawals</b> <hr/>
<b>R&amp;W FROM NON-OPERATING ACTIVITIES</b>
(-) Retired purchased offsets (-) Natural processes
<hr/> <b>Total non-operating R&amp;W</b> <hr/>
<hr/> <b>Net Releases (Withdrawals)</b> <hr/>

the atmosphere. Table 6-8 depicts a sample statement of CO<sub>2</sub> Releases and Withdrawals (CR&W). R&W activities can be from operating activities and non-operating activities.

Operating activities include purchases and sales of fuel, energy, products, and services. We refine expand the definition of releases of CO<sub>2</sub> as direct increases in allocated atmospheric emissions due to combustion activity or indirect increases due to purchases. Direct emissions are caused by assets owned by the entity, such as power generation from a generating asset, fuel emissions from owned vehicles, or emissions from a backup generator.

Emissions exchanged between entities due to trade activities are accounted for as indirect releases. This is because the EC represents emissions already released into the atmosphere. Purchases represent an increase of allocated emission due to the inflow of

purchased items. An entity may purchase a variety of items, such as fuel, electricity, office supplies, business travel, and so forth. More specific purchase categories can be created to account for the variety of items procured by the entity.

Similarly, we refine and expand the definition of *withdrawals* as decreases in allocated atmospheric emissions during the accounting period. Direct removals are CO<sub>2</sub> capture activities of assets owned by the reporting entity. For example, if an entity owns a direct air capture facility, they will be able to account for direct withdrawals. Indirect withdrawals are those achieved through an exchange or purchases or sales. The sale of a product represents a decrease of emissions allocated to the entity. Energy companies may sell fuel, electric utilities will sell electricity, and manufacturing businesses will sell products.

Releases and withdrawals can also occur due to non-operating activities. These include the purchase of an offset or a credit from the market that have been retired in the current year.

We propose *withdrawals due to natural processes* as fluxes of GHGs out of the atmosphere into the biosphere or geosphere (Allen et al., 2022). These processes include the natural absorption of CO<sub>2</sub> into ocean cycles, trees and other biomass, and other naturally occurring interactions between the atmosphere and biosphere. These processes take a long time.

According to climate scientists, CO<sub>2</sub> will last in the atmosphere for thousands of years, with traces of emissions remaining after 500,000 years (Lord et al., 2016). Therefore, natural withdrawal of atmospheric CO<sub>2</sub> can be considered 1/500,000 of CO<sub>2</sub> assets per year.

Because methane and nitrous oxide have shorter lifespans, annual withdrawals of them can be considered at 1/11.8 and 1/109, respectively. By separating the accounting of different GHGs, we can account for different absorption characteristics. Because the CR&W already accounts for withdrawals due to natural processes, implicit in the model is that for anthropogenic withdrawals to count, they should be in addition to planetary processes. Much like how depreciation affects fixed assets, this category is only applied to emissions of EC of Use. As shown in Table 6-9, different GHGs have different atmospheric lifetimes.

Table 6-9 Atmospheric lifetimes for CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O (Lord et al., 2016; Smith et al., 2021)

	Atmospheric lifetime (yr)
Carbon dioxide (CO <sub>2</sub> )	+500,000
Methane – Fossil (CH <sub>4</sub> )	11.8
Nitrous oxide (N <sub>2</sub> O)	109

Table 6-10 Transaction of emissions due to the purchase of electricity. Carbon of electricity enters the entity and is recorded on the CR&W as a credit to Releases. Simultaneously, the carbon of electricity is embedded into the entity, and is recorded as a debit to EC of Entity.

Transaction	Journal Entry	Debit	Credit
(T-1) Purchase of Electricity	EC of Electricity (Release)		(+) Increase
	EC of Entity (Embedded)	(+) Increase	

### 6.4.3. Example transactions

We provide examples of how transactions can be recorded using journal entries and DEBK.

#### 6.4.3.1. Recording operational emissions: Purchasing electricity for consumption

Table 6-10 depicts the journal entries of the purchase of electricity for general operations of a business. The emissions of electricity are entering the entity, so it is recorded as a Release on the CR&W. This is noted as a credit to the EC of Electricity because the entity's allocated emissions are increasing. Because the company is consuming the electricity for general operations, the EC of Entity, an asset, is also increases. This is recorded in the Debit column. In this manner, emissions entering an entity can be 'embedded'.

### 6.4.3.2. Recording embedded emissions: Shifting up and down the asset stack

The action of embedment can be depicted using a series of transactions, as shown in Table 6-11. First, Transaction T-2 depicts the purchase of fuel. The IC of fuel is recorded in the CR&W as having entered the company and stored in the balance sheet. Transaction T-3 depicts the consumption of the fuel to produce lumber, thus embedding the CO<sub>2</sub> attribution into the lumber. Transaction T-4 further embeds the EC of lumber into the EC of Building. The construction of the building also consumes energy; thus T-5 represents the IC of fuel that is embedded.

As shown in and Figure 6-3, the sequence of events to accumulate embodied attributes can be depicted as a downward shift within the CBS. Thus, a building is the accumulation of EC activities conducted by the entity. This mechanism is analogous to the financial capitalisation process, where a downward shift of resources represents an increase capital investment. This example also shows how multiple transactions can be linked together over time.

*Table 6-11 A sequence of transactions that show the embedment of CO<sub>2</sub> during the construction of a building*

<b>Transaction</b>	<b>Journal Entry</b>	<b>Debit</b>	<b>Credit</b>
(T-2) Purchase of Fuel	IC of Fuel (Releases)		(+) Increase
	IC of Fuel (Embedded)	(+) Increase	
(T-3) Fuel to manufacture lumber	IC of Fuel (Embedded)		(-) Decreases
	EC of Lumber (Embedded)	(+) Increase	
(T-4) Construct a building with lumber	EC of Lumber (Embedded)		(-) Decreases
	EC of Building (Embedded)	(+) Increase	
(T-5) Fuel to construct a building	IC of Fuel (Embedded)		(-) Decreases
	EC of Building (Embedded)	(+) Increase	

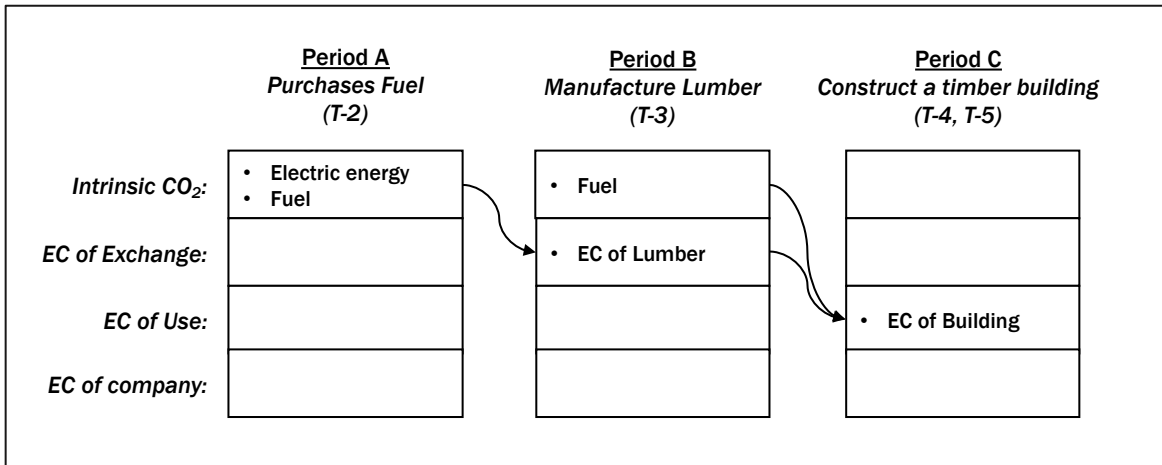


Figure 6-3 Stylised example of embedment of energy into lumber and into a building. (Source: Author creation)

### 6.4.3.3. Embedding emissions: Recording asset usage

Within financial accounting, depreciation is a mechanism by which the upfront capital costs can be spread out over the useful life of a capital asset. A feature of accrual accounting, it is a way to allocate costs over the lifetime usage of an asset. There are several methods to calculate depreciation, with a simple model being the straight-line method,

$$\text{Depreciation amount} = \frac{\text{Value at purchase} - \text{Salvage value}}{\text{Useful lifetime}} \quad \text{Equation 6-7}$$

The value at purchase is the amount paid for the asset, recorded on the balance sheet. The salvage value is the value of the asset at the end of its useful life if the item is sold for scrap. In many cases, the salvage value can be considered to be zero (0). The useful life is the estimated number of years the asset can be used.

Figure 6-4 is a graphical example of the depreciation of an automobile with a £40,000 purchase price and 10 years expected lifetime. The cost of the automobile is capitalised and represented as a balance sheet asset because its economic benefit is derived from use. Assuming a £2,000 salvage value, the annual depreciation amount of the automobile would be £3,800. Thus, a year's usage of the automobile costs £3,800, spreading out the capital

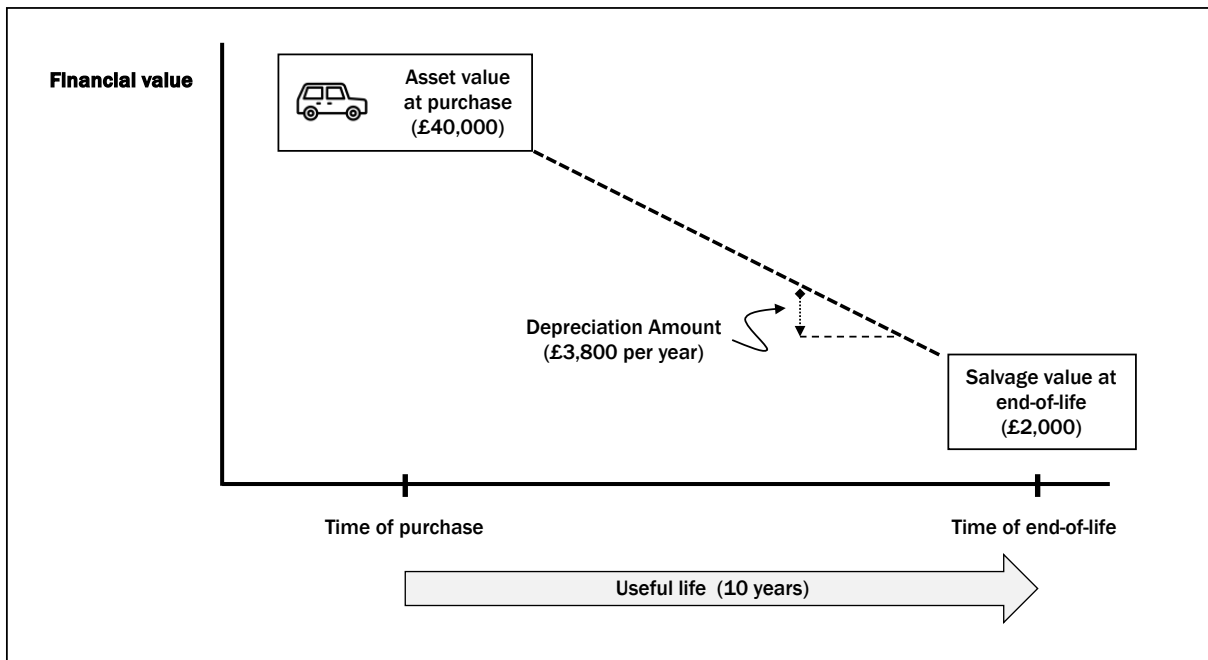


Figure 6-4 A stylised example of straight-line depreciation of an automobile. (Source: Author's creation)

cost over time. The depreciation amount is expensed each year, and the asset value decreases over time.

There is a lack of consensus on the application of depreciation to GHG accounting within the standards community. Standards such as the GHG Protocol does not permit depreciation in any form, advising entities to account for all capital purchases in the year of acquisition (WRI & WBCSD, 2013). Other standards permit entities to use the same depreciation rate as in financial allocation (BSI, 2019).

The application of depreciation to GHGs creates a discrepancy because the useful life of an asset is different than the atmospheric lifetime of emissions. For example, an entity may have a 75-year depreciation policy to represent the useful life of a building. Therefore, at end-of-life, the financial value of the building may be zero. However, emissions associated with constructing the building will last in the atmosphere for 500,000 years. At end-of-life, the building may no longer be usable, but the emissions of construction will still exist for a very long time.

## Chapter 6: General purpose LCA

There are two distinct temporal issues: (1) the actual lifetime of CO<sub>2</sub> in the atmosphere and (2) the EC over the useful life of building. Both needs to be represented. The actual lifetime of CO<sub>2</sub> in the atmosphere is accounted for in *withdrawal due to natural processes*, addressing the first issue. For the second issue, the EC of the building used or 'consumed' by the entity. Therefore, we proposed EC of Use as a line-item to represent its consumption. Simultaneously, we will add the same amount to the EC of Entity, representing an accumulation of EC attributes consumed by the entity. In other words, the depreciation of EC is further embedded into the EC of Entity (Table 6-12). As a result, this transaction is represented as a balance sheet adjustment and EC depreciation is not shown on a CR&W statement (Figure 6-5).

An upward shift in energy represents a release of energy. This is analogous to a write-down during the liquidation of an asset. For example, at end-of-life of a building, Closing CBS, one could salvage the wood and convert the wood into electric energy at a waste-to-energy plant. However, only the intrinsic energy content of the wood can be converted into electric energy. The embodied energy of construction is written off as a loss. Within thermodynamics, a process is irreversible if one cannot return to the original state. Since upward shifts represent a loss of value, by using write-offs, the CBS can depict the irreversibility of energy transformations as well as losses within financial transactions.

### 6.4.3.4. *Embedding emissions: Treatment at end-of-life*

Figure 6-6 presents three stylised examples of EC accounting at a building's end-of-life. In Scenario 1, the entirety EC of Building is embedded into EC of Entity, representing a full usage of the building. In Scenario 2, the building is sold, and any remaining EC of Building is transferred to the new owners. In Scenario 3, the building is demolished, and components are sold. In this case, materials that are recycled can be extracted and sold, such as wood

Table 6-12 Transaction depicting embedment of depreciation into the EC of Entity

Transaction	Journal Entry	Debit	Credit
(T-6) Usage of building over time	EC of Building (Embedded)		(-) Decreases
	EC of Entity (Embedded)	(+) Increase	

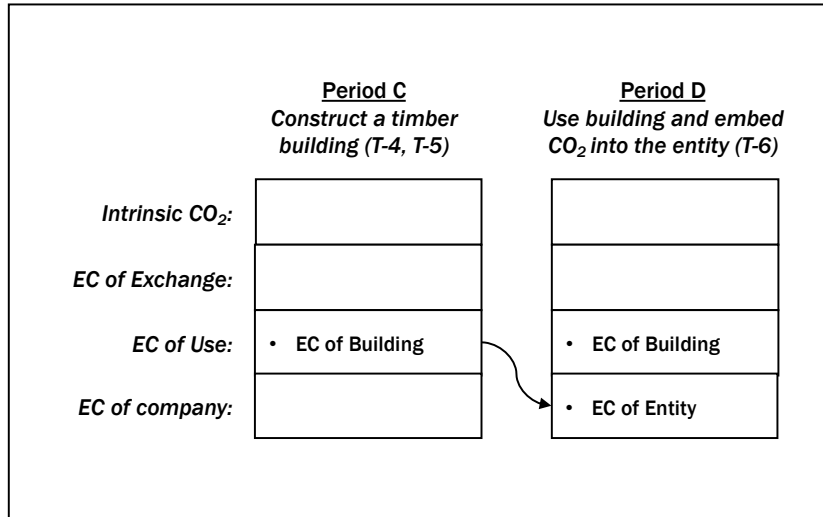


Figure 6-5 Stylised example of embedment of depreciation of EC of Building into EC of Entity. (Source: Author's creation)

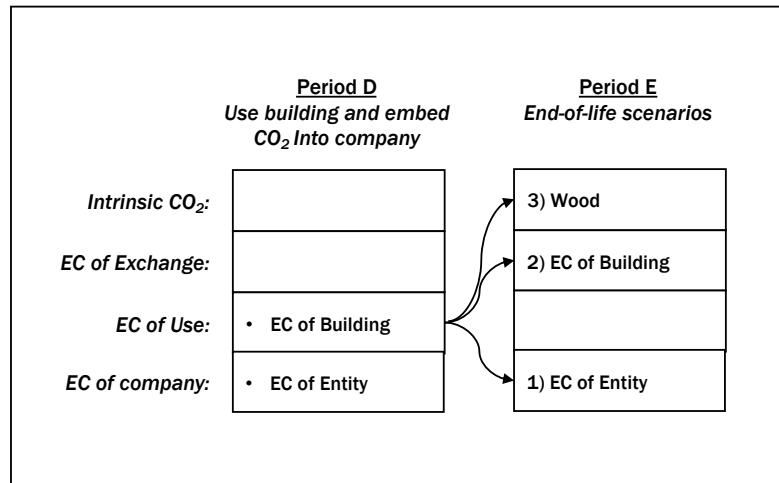


Figure 6-6 Stylised examples of end-of-life EC accounting. (Source: Author's creation)

for being converted in a waste-to-energy facility. Accounting of additional end-of-life activities can be further developed.

#### 6.4.4. Extending to other GHGs Statement System

To extend GP-LCA to other GHGs require applying the appropriate emission factors.

Because our CO<sub>2</sub> values were derived from the combustion of energy, Equation 6-8 and Equation 6-9 shows embedded methane and nitrous oxide values by applying the appropriate emission factors.

$$\left[ \begin{array}{c} \textit{Embedded} \\ \textit{Methane (EM)} \end{array} \right] = \textit{Intrinsic Energy} \times \textit{Emission Factor}_{\textit{Methane}} \quad \textit{Equation 6-8}$$

$$\left[ \begin{array}{c} \textit{Embedded} \\ \textit{Nitrous Oxide (EN)} \end{array} \right] = \textit{Intrinsic Energy} \times \textit{Emission Factor}_{\textit{Nitrous Oxide}} \quad \textit{Equation 6-9}$$

The definitions of embedded and operational emissions, and the constructions of statement of position and performance can be extended to additional GHGs, as shown in Table 6-13.

We leave for future research to develop additional environmental statements.

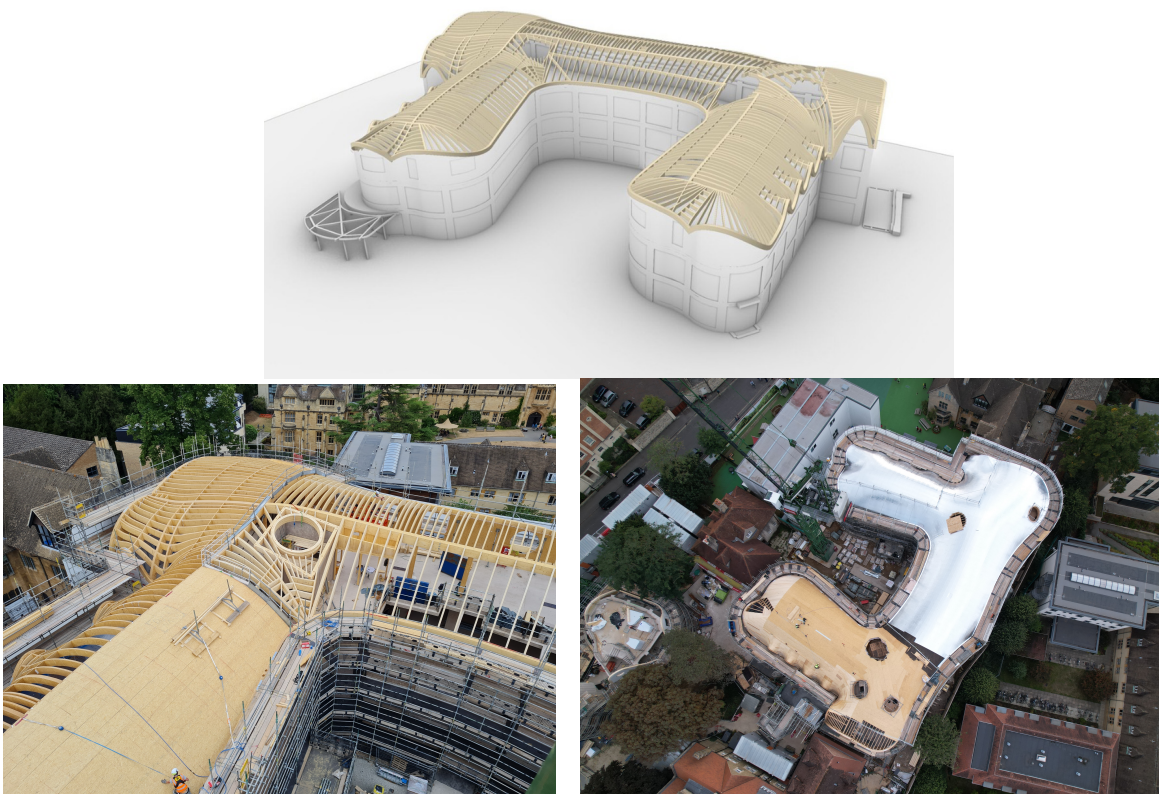
Table 6-13 Extending GP-LCA to other GHGs

Resource	Statement of Position	Statement of Performance
Financial Accounting	Balance Sheet	Profit & Loss
Carbon Dioxide Accounting	Carbon Dioxide Balance Sheet (CBS)	Carbon Dioxide Releases & Withdrawals (CR&W)
Methane Accounting	Methane Balance sheet (MBS)	Methane Releases & Withdrawals (MR&W)
Nitrous Oxide Accounting	Nitrous Oxide Balance Sheet (NBS)	Nitrous Oxide Releases & Withdrawals (NR&W)

## 6.5. Case study: Applying empirical data to CO<sub>2</sub> statements

We apply our accounting framework to the newly constructed Gradel Quadrangle of New College, Oxford, founded in 1379. We calculate (1) embedded emissions prior to commercial start, (2) present operational emissions of first six months, and (3) projections of future usage

The Gradel Quadrangle is the newest addition to the college, with construction beginning in 2019 and finishing in early 2024. The complex has a four-story above-ground building with two basement levels and a four-story student accommodation building with a seven-story tower. The building was constructed to a Passivhaus standard, including natural ventilation, passive heating, ground source heat pump, among other design considerations. Figure 6-7 shows a model of the structure and the building under various stages of construction. It is a reinforced concrete structure with a timber-and-aluminium roof.



*Figure 6-7 The building, while under construction.*

### 6.5.1. Methodology

The data used for our analysis was gathered from New College through their site planning reports, energy models, and analysis. During the planning and construction phase, New College’s contractors acquired data from software that tracked exact quantities and nature of materials delivered to site, the date of delivery, their provenance, mean of transportation, as well as type and amount of energy consumed during the construction process. We treated the data gathered as the transactions for our analysis. In total, there were 1,110 transactions of energy, materials delivery, and transportation in our dataset. We converted all data to units of million joules (MJ) and metric tonnes of carbon dioxide (tCO<sub>2</sub>).

Our analytical process diagram is shown in Figure 6-8. The materials used in construction were recorded in tonnes. A list of materials in the building is shown in Table 6-14(A). The structure used two types of material for concrete. Normal concrete is made from Portland cement, while alternatives, such as ground-granulated blast-furnace (GGBS) slag can have over 40% lower carbon dioxide footprint. The Gradel Quadrangle used a mixture of and of Portland cement, lowered the embedded emissions of the structure. Also, we categorised the steel for rebar as part of the construction of reinforced concrete.

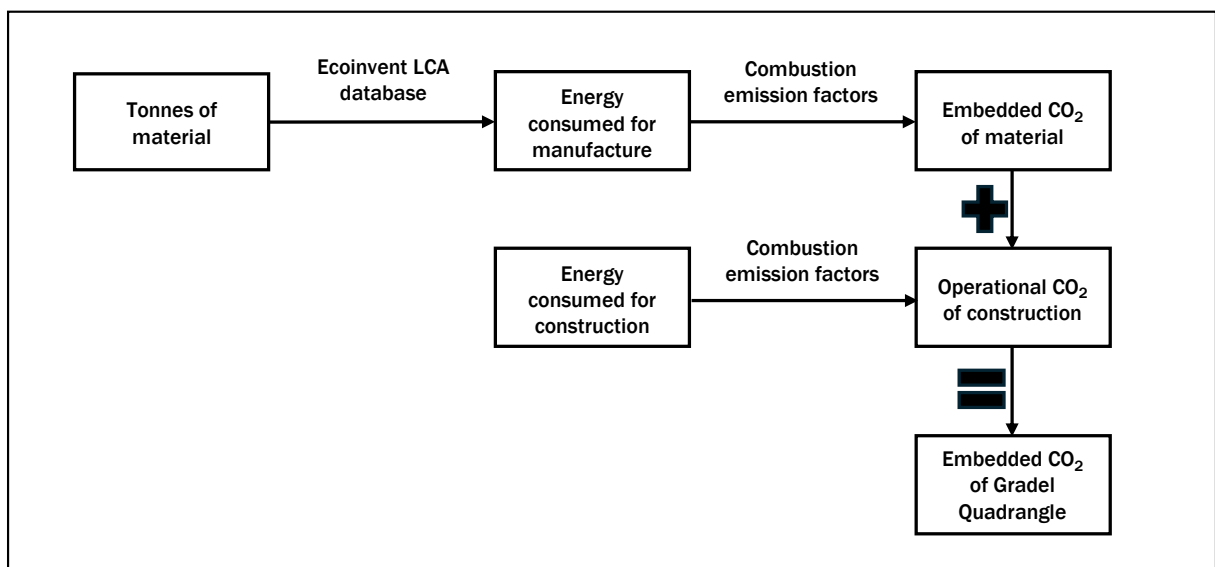


Figure 6-8 Process diagram for analysing our data. (Source: Author’s creation)

To calculate the EC of materials, we performed a cradle-to-gate LCA study using the Ecoinvent Building Materials (Ecoinvent, 2007) and Metals (Ecoinvent, 2009) databases as well as scientific literature for bitumen (Eurobitume, 2012) and timber (Bergman & Bowe, 2012; Wilson & Sakimoto, 2006). We traced each material back to the extracted mineral from the earth. For example, concrete has material inputs of Portland cement and gravel. Portland cement required clinker and steel as materials input, and clinker requires bauxite, lime, among other mined ore. For each material in the value chain, we summed the fuel consumed for manufacture, such as natural gas, electricity, diesel, among others. We excluded the transportation fuel between factories, as we were unable to estimate the distances between facilities. However, these could be easily added, if known. The energy values can be found in Table 6-14(B).

**Table 6-14 Energy and carbon dioxide conversion factors, as determined by a cradle-to-gate LCA studies. Data for bituminous material taken from (Eurobitume, 2012).**

**Panel A: Material conversion factors by weight**

(A) Material	(B) Energy (MJ/kg)	(C) Carbon Dioxide (kgCO <sub>2</sub> /kg)	(D) Methane (kgCH <sub>4</sub> /kg)	(E) Nitrous Oxide (kgN <sub>2</sub> O/kg)	(F) From calcination (kgCO <sub>2</sub> /kg)
Aluminium	58.84	3.378	0.0136	0.0176	
Bituminous Material	1.69	0.122	0.0002	0.0003	
Concrete (Normal)	0.37	0.026	0.0001	0.0001	0.0613
Concrete (GGBS)	0.21	0.015	0.0000	0.0001	0.0233
Concrete (Rebar)	14.29	1.524	0.0044	0.0077	
Copper wires	30.21	1.786	0.5257	0.5274	
Glass	8.80	0.530	0.0010	0.0009	
Plaster	0.22	0.014	0.0000	0.0001	
Rockwool	8.24	0.719	0.0019	0.0028	0.0583
Steel	17.52	3.986	0.0123	0.0249	
Stone and Gravel	0.05	0.003	0.0000	0.0000	
Stone for façade	5.19	0.304	0.0008	0.0029	

**Panel B: Material conversion factors by volume (Bergman & Bowe, 2012; Wilson & Sakimoto, 2006)**

Material	Energy (MJ/m <sup>3</sup> )	Carbon Dioxide (kgCO <sub>2e</sub> /m <sup>3</sup> )	Methane (kgCH <sub>4</sub> / m <sup>3</sup> )	Nitrous Oxide (kgN <sub>2</sub> O/ m <sup>3</sup> )
Natural Wood	1,007.19	54.415	0.1690	0.3523
Processed Wood	2,891.60	45.148	0.1481	0.1865

Table 6-15 Combustion emission factors for various fuels (UK DESNZ & UK DEFRA, 2023)

Fuel	Combustion emission factors			Units
	Carbon Dioxide	Methane	Nitrous Oxide	
Diesel (average biofuel blend, Gross CV)	0.24	0.00002	0.00310	per kWh
Hard coal coke (Coking coal, kWh (Gross CV))	0.36	0.00095	0.00136	per kWh
Hard coal mix (Coal, industrial, tonnes)	2,371.91	7.64	16.93	per tonne
Heavy fuel oil (fuel oil, tonnes)	3,216.38	5.39	7.12	per tonne
Heavy fuel oil (fuel oil, kWh (Gross CV))	0.27	0.00045	0.00060	per tonne
Light fuel oil (fuel oil)	3,216.38	5.39	7.12	per tonne
Light fuel oil (fuel oil)	0.27	0.00045	0.00060	per kWh
Natural gas (Natural gas, kWh (Gross CV))	0.18	0.00028	0.00009	per kWh
Petroleum coke (tonnes)	3,377.05	3.83	5.69	per tonne

To estimate energy-based emissions of CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O, we used the UK DEFRA combustion emissions factors (Table 6-15) (UK DESNZ & UK DEFRA, 2023). When combined with energy of manufacturing, we were able to generate conversion factors of CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O emitted per kg of material, as shown in Table 6-14(C-E). Emissions of CO<sub>2</sub> from calcination were obtained from the Ecoinvent Building Materials (Ecoinvent, 2007). These are shown in Table 6-14F. Next, we calculated the GHG emitted of energy consumed during the construction process. This included transportation of materials to the site as well as energy consumed for construction process. The transactions for transportation recorded the vehicle type, an estimate of the distance travelled (in miles), the emission factor, and carbon dioxide emitted due to transportation (in kgCO<sub>2</sub>). Energy was reported in kWh. By the end of the process, we generated a carbon dioxide, methane, and nitrous oxide value for every material delivery transaction and energy consumption transaction. We now had the transactional data to construct the statement of position and performance.

### 6.5.2. Constructing the statement of position: Recording embedding activities

Under financial rules, commercial start is when a building becomes operational. Activities and costs prior to a commercial start can be capitalised and recorded as an asset on the

*Table 6-16 Emission balance sheets of carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) for the Gradel Quadrangle*

(A) Carbon Dioxide Assets (tCO <sub>2</sub> ) January 1, 2024	(B) Methane Assets (tCH <sub>4</sub> ) January 1, 2024	(C) Nitrous Oxide Assets (tN <sub>2</sub> O) January 1, 2024
<b>CO<sub>2</sub> ASSETS</b>	<b>CH<sub>4</sub> ASSETS</b>	<b>N<sub>2</sub>O ASSETS</b>
Intrinsic CO <sub>2</sub>	Intrinsic CH <sub>4</sub>	Intrinsic N <sub>2</sub> O
Wood Products 13	-	-
EC for Exchange -	EM for Exchange -	ENO for Exchange -
EC for Use	EM for Use	ENO for Use
Gradel Quadrangle 2,461	Gradel Quadrangle 8.81	Gradel Quadrangle 14.20
Calcination of Concrete 303		
<b>Total CO<sub>2</sub> ASSETS 2,778</b>	<b>Total CH<sub>4</sub> ASSETS 8.81</b>	<b>Total N<sub>2</sub>O ASSETS 14.20</b>
<b>CO<sub>2</sub> RESPONSIBILITIES</b>	<b>CH<sub>4</sub> RESPONSIBILITIES</b>	<b>N<sub>2</sub>O RESPONSIBILITIES</b>
Responsibility of debtors -	Responsibility of debtors -	Responsibility of debtors -
Responsibility of owners 2,778	Responsibility of owners 8.81	Responsibility of owners 14.20
<b>Total CO<sub>2</sub> RESPONSIBILITIES 2,778</b>	<b>Total CH<sub>4</sub> RESPONSIBILITIES 8.81</b>	<b>Total N<sub>2</sub>O RESPONSIBILITIES 14.20</b>

balance sheet. Similarly, we will consider any GHG emitted prior to commercial start as embedded GHGs that is recorded on an emissions balance sheet.

As shown in Table 6-16(A), as of 1 January 2024, the Gradel Quadrangle released 2,778 tCO<sub>2</sub> during its construction. Note that the timber in the structure still has intrinsic CO<sub>2</sub> value of 13 tCO<sub>2</sub>, because of the optionality to convert it into electric energy at a waste-to-incinerator plant at end-of-life of the building. The value of EC for exchange is zero (0) as there is no inventory being exchanged. The EC of use, calculated from energy consumption, is 2,461 tCO<sub>2</sub>. Further, we can show that the EC of calcination, from the manufacture of concrete, is 303 tCO<sub>2</sub>. Panel (B) and (C) shows the equivalent statement of positions for embedded methane and embedded nitrous oxide.

Assuming the New College paid for the construction with cash-on-hand, and no new debt was taken out, New College is the full equity owner of the building. Therefore, the entirety of the embedded emissions is the responsibility of New College. Similarly, the methane and nitrous oxide responsibilities are allocated to New College. If there are debt holders, then the embedded attributes can be assigned to the financiers as well.

Table 6-17 Materials delivered for the Gradel Quadrangle construction. This table is the Assets of the Balance Sheet for upfront embodied attributes of the building.

Material	Tonnage	Embedded CO <sub>2</sub> (tCO <sub>2</sub> )	Embedded CH <sub>4</sub> (tCH <sub>4</sub> )	Embedded N <sub>2</sub> O (tN <sub>2</sub> O)
Aluminium	151,183	511	2.05	2.67
Bituminous material	9,198	1	0.00	0.00
Reinforced concrete				
<i>Normal concrete</i>	440,885	12	0.03	0.06
GGBS	11,178,310	171	0.41	0.90
Rebar	546,512	833	2.40	4.23
Copper wires	3,440	6	1.81	1.81
Glass	4,810	3	0.00	0.00
Plaster	276,000	4	0.01	0.02
Rockwool	267,202	192	0.52	0.76
Steel	26,240	105	0.32	0.65
Stone and gravel	3,297,670	10	0.03	0.08
Stone for façade	692,000	210	0.53	1.99
Timber				
<i>Natural wood</i>	252	14	0.04	0.09
<i>Processed wood</i>	711	32	0.11	0.13
Electricity		124	0.53	0.80
Transport		234		
EC from chemical reactions				
<i>Calcination from concrete</i>		287.37		
<i>Calcination from other</i>		15.59		
<b>GRAND TOTAL</b>	<b>16,894,413</b>	<b>2,764</b>	<b>8.81</b>	<b>14.20</b>

### 6.5.2.1. Itemising EC by material

Because the quantity of each transaction is known, we can itemise the categories by material, as shown in Table 6-17. From this table, one can identify materials that have the highest emissions footprint. For example, although GGBS is the majority of materials by tonnage, constituting 66% of the structure in terms of mass, it is only responsible for 7.12% of the structure's EC. On the other hand, although aluminium only constitutes 0.89% of materials by mass, it represents 24.42% of EC. The ability to differentiate whether a carbon dioxide footprint is due to quantity of usage (such as concrete) or due to intensity of manufacture (such as aluminium) may inform better decision-making of reducing carbon dioxide emissions via using less material, procuring less carbon dioxide intense material, or a combination of the two.

### 6.5.2.2. Periodic display of embedded carbon dioxide assets

Because each transaction also records the date, the EC data can be displayed periodically.

Table 6-18 presents the annual accumulation of EC of the Gradel Quadrangle over the years of construction. Figure 6-9 visualises the table into a chart.

Table 6-18 CO<sub>2</sub> assets by material and year (in tCO<sub>2</sub>)

	CO <sub>2</sub> Assets by year (in tCO <sub>2</sub> )		
	2021	2022	2023
<b>Intrinsic CO<sub>2</sub></b>			
<b>Timber</b>			
<i>Natural wood</i>	-	3.20	3.48
<i>Processed wood</i>	5.13	9.23	9.81
<b>EC of Use</b>			
Aluminium	-	39.20	510.70
Bituminous material	-	-	1.13
<b>Concrete</b>			
<i>Normal concrete</i>	1.22	7.10	11.68
<i>GGBS</i>	96.26	169.11	170.65
<i>Rebar</i>	363.40	833.10	833.10
Copper wires	-	-	6.14
Electricity	6.67	50.38	124.38
Glass	-	1.08	2.55
Plaster	-	2.19	3.96
Rockwool	-	55.50	192.00
Steel	-	100.60	104.58
Stone and gravel	5.50	6.88	10.07
Stone for façade	-	52.31	210.45
<b>Timber</b>			
<i>Natural wood</i>	-	12.62	13.74
<i>Processed wood</i>	16.78	30.19	32.11
Transport	55.93	160.94	234.02
<b>EC from chemical reactions</b>			
Calcination from concrete	149.69	274.43	287.37
Calcination from other	-	4.51	15.59
<b>GRAND TOTAL</b>	<b>700.57</b>	<b>1,812.56</b>	<b>2,777.51</b>

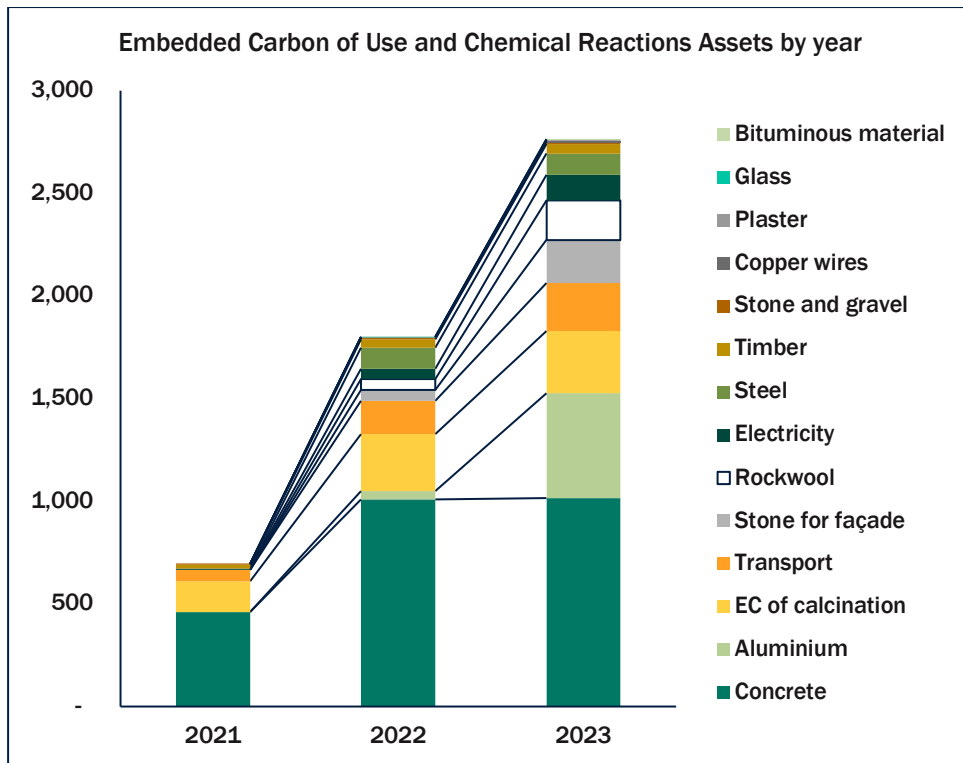


Figure 6-9 Graph depicting the annual embedment of EC assets by material

### 6.5.3. Constructing the statement of performance: Recording ongoing activities

The Gradel Quadrangle began commercial in January 2024 and Table 6-19 represents transactions that occurred in the first six months of operations. Transaction T-7 records the 35.16 tCO<sub>2</sub> released due to the consumption of electricity. The EC of Electricity, a Release category, is credited to represent an increase to the account. Simultaneously, the EC of Entity is increased with a debit recording. Transaction T-8 represents the withdrawals of due to natural processes, such as naturally occurring oceanic and biomass absorption. The calculation can be seen in Table 6-21. We assume CO<sub>2</sub> has an atmospheric lifetime of 500,000 years. As a result, the annual withdrawals are 0.005528 tCO<sub>2</sub>. In the first six months, half of this is withdrawn, or 0.00267 tCO<sub>2</sub>

Table 6-19 Transactions of activities between January and July 2024

Transaction	Journal Entry	Debit	Credit
(T-7) Purchase of Electricity	EC of Electricity (Release)		(+) 35.16
	EC of Entity (Embedded)	(+) 35.16	
(T-8) Withdrawals due to Natural Processes of Gradel Quadrangle	EC of Entity (Embedded)		(-) 0.00267
	Responsibility of Owners (Owned)	(-) 0.00267	

Table 6-20 Table of withdrawals due to natural processes

EC of Use Category	Initial EC Value (tCO <sub>2</sub> )	Salvage EC Value	Atmospheric lifetime (Years)	Annual EC withdrawn (tCO <sub>2</sub> )
EC of Gradel Quadrangle	2,461	0	500,000	0.004923
EC of Calcination	303	0		0.000606
Total annual withdrawals due to natural processes:				<u>0.005528</u>

Table 6-21 Statement of CO<sub>2</sub> Releases & Withdrawals

Jan - Jun 2024 (tCO <sub>2</sub> )		
<b>R&amp;W FROM OPERATING ACTIVITIES</b>		
Releases due to direct activities		
(+)	From fuel combustion	-
Releases due to indirect operational activities		
(+)	EC of Purchased Electricity	35.16
<b>Total Releases</b>		<b>35.16</b>
Withdrawals due direct activities		
(-)	Direct removals	-
<b>Total Withdrawals</b>		<b>-</b>
<b>R&amp;W FROM NON-OPERATING ACTIVITIES</b>		
(-)	Retired purchased offsets	-
(-)	Natural processes	0.00267
<b>R&amp;W from non-operating activities</b>		<b>0.00267</b>
<b>Net Releases (Withdrawals)</b>		<b>35.16</b>

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Table 6-21 depicts the statement of performance of the first six months, constructed with the transactions in Table 6-19 and Table 6-20. As the Gradel Quadrangle does not have any generation equipment, there is zero (0) emissions from fuel combustion. The Quadrangle also does not have any GHG removal equipment, nor does New College purchase emissions offsets, thus direct removals and retired offsets are also zero (0). The releases from purchased electricity and withdrawals from natural processes result in a Net Releases (Withdrawals) of 35.16 tCO<sub>2</sub>.

### **6.5.4. Updating the CBS**

Just like the Net Profit (Loss) of a financial statement is recorded as Retained Earnings on a financial balance sheet, we propose that the Net Releases (Withdrawals) is recorded back on the CO<sub>2</sub> balance sheet. As shown in T-9 in Table 6-22, the Net Releases (Withdrawals) is added to the Responsibility of Owners. Simultaneously, to maintain balance in the transaction, the same amount is also added to the EC of Entity.

As shown in Table 6-23, based on the initial EC values, the annual EC used is 36.86 tCO<sub>2</sub>. As per New College's depreciation policy, we use a useful life 75 years. Transactions T-10 and T-11 depict the usage of the Gradel Quadrangle over six months. EC of Gradel Quadrangle is decreased by 16.41 tCO<sub>2</sub>, which is half of 36.86 tCO<sub>2</sub>. EC of Entity is increased by the same amount.

Table 6-24 depicts the updated CBS after 6 months. It depicts an increase in total CO<sub>2</sub> assets due to energy consumption of the period. As the table demonstrates, the CBS can be regularly updated with new environmental activities, as they occur.

*Table 6-22 Transactions depicting CBS adjustments for January to June 2024. This includes both net R&W as well as adjustment for usage of the embedded carbon of the building.*

Transaction	Journal Entry	Debit	Credit
(T-9) Reconciling Net R&W	Retained R&W (Owned)		(+) 35.16
	EC of Entity (Embedded)	(+) 35.16	
(T-10) Usage of EC of Use	EC of Gradel Quadrangle (Embedded)		(-) 16.41
	EC of Entity (Embedded)	(+) 16.41	
(T-11) Usage of EC of Use	EC of Calcination of concrete (Embedded)		(-) 2.02
	EC of Entity (Embedded)	(+) 2.02	

*Table 6-23 Calculation of annual usage of EC of Use*

EC of Use Category	Initial EC Value (tCO <sub>2</sub> )	Salvage EC Value	Asset Lifetime (Years)	Annual EC Used (tCO <sub>2</sub> )
EC of Gradel Quadrangle	2,461	0	75	32.82
EC of Calcination	303	0		4.04
Total annual EC consumed and embedded into EC of Entity:				36.86

*Table 6-24 Statement of Position after first six months of operations*

	January 2024 (tCO <sub>2</sub> )	June 2024 (tCO <sub>2</sub> )
<b>CO<sub>2</sub> ASSETS</b>		
Intrinsic CO <sub>2</sub>		
Wood Products	13.29	13.29
EC of Use		
Gradel Quadrangle	2,461.26	2,444.85
Calcination of Concrete	302.96	300.94
EC of Entity	-	53.59
<b>Total CO<sub>2</sub> ASSETS</b>	<b>2,777.51</b>	<b>2,812.67</b>
<b>CO<sub>2</sub> RESPONSIBILITIES</b>		
Allocated to financial debtors	-	-
Allocated to equity owners	2,777.51	2,806.11
EC of Retained R&W	-	35.16
<b>Total CO<sub>2</sub> RESPONSIBILITIES</b>	<b>2,777.51</b>	<b>2,812.67</b>

## 6.6. Implications and insights: Specific situations

As GP-LCA is a general-purpose presentation of emissions data, it can be used to calculate emission values for specific purposes. In this section, we describe three possible applications of the emission statements generated from GP-LCA.

### 6.6.1. Forecasting operational carbon dioxide

With the above statements presenting environmental data based on normative rules, it is possible to then derive other applications from those values. One can project future emissions based on the values given. For example, Table 6-25 depicts a 75-year projection of the releases and withdrawals and CO<sub>2</sub> balance sheet for the Gradel quadrangle. For this example, we project the operations of Year 1 for the next 75 years to demonstrate how the CR&W and CBS could present data. Although this is a projection, the data can be updated in real time.

For the CR&W, line 6 models the additional CO<sub>2</sub> of electricity consumption of annual operations. Real data can replace the modelled values as the years progress to show how modelled assumptions match with reality of operations. Line 6 can also record changes to the CO<sub>2</sub> content of the electric grid as the system undergoes decarbonisation efforts. Line 11 and 15 represents offsetting activities by New College. Future investments in offsets and removals can be recorded here. Line 17 represents withdrawals due to natural processes of the planet. Line 18 thus represents the net release (withdrawals) per year. Net R&W is added to the CBS on line 34 EC of retained R&W, and line 27 EC of Entity.

For the CBS, lines 24 and 25 represent the EC usage of the Gradel Quadrangle. The value is added to EC of Entity, line 28. As we are assuming a 75-year depreciation policy, the EC of Use will be zero (0) by year 75, being fully transferred to EC of Entity. If New College decides to sell the building prior to year 75, the EC of Use of that year can transfer over to the new entity.

Table 6-25 A 75-year projection of CR&W and CBS.

	2024 (Year 1)	2025 (Year 2)	...	2098 (Year 75)
1 <b>R&amp;W OF OPERATING ACTIVITIES</b>				
2 Releases due to direct activities				
3 (+) From fuel combustion	-	-		-
4				
5 Releases due to indirect activities				
6 (+) EC of purchased electricity	70.33	70.33		70.33
7 (+) EC of purchased goods	-	-		-
8 <b>Total Releases</b>	<b>70.33</b>	<b>70.33</b>		<b>70.33</b>
9				
11 Withdrawals due to direct activities				
12 (-) Direct removals	-	-		-
13 <b>Total Withdrawals</b>	<b>-</b>	<b>-</b>		<b>-</b>
14				
15 <b>R&amp;W OF NON-OPERATING ACTIVITIES</b>				
16 (-) Retired purchased offsets	-	-		-
17 (-) Natural processes	0.01	0.01		0.01
18 <b>R&amp;W of non-operating activities</b>	<b>0.01</b>	<b>0.01</b>		<b>0.01</b>
19 <b>Net Releases (Withdrawals)</b>	<b>70.32</b>	<b>70.32</b>		<b>70.32</b>

	2023 Opening Balance Sheet	2024 (Year 1)	2025 (Year 2)	...	2098 (Year 75)
20 <b>CO<sub>2</sub> ASSETS</b>					
21 Intrinsic Carbon Dioxide					
22 Wood Products	13.29	13.29	13.29		13.29
23					
24 EC for USE					
25 Gradel Quadrangle	2,461.26	2,428.44	2,395.62		0.00
26 Calcination of Concrete	302.96	298.92	294.88		0.00
27					
28 EC of Entity	-	107.18	214.35		8,038.19
29					
30 <b>Total CO<sub>2</sub> ASSETS</b>	<b>2,777.51</b>	<b>2,847.83</b>	<b>2,918.15</b>		<b>8,051.49</b>
31					
32 <b>CO<sub>2</sub> RESPONSIBILITIES</b>					
33 Allocated to debt holders	-	-	-		-
34 Allocated to owners	2,777.51	2,777.51	2,847.83		7,981.17
35 EC of retained R&W	-	70.32	70.32		70.32
36 <b>Total CO<sub>2</sub> RESPONSIBILITIES</b>	<b>2,777.51</b>	<b>2,847.83</b>	<b>2,918.15</b>		<b>8,051.49</b>

The CBS enables one to make comparisons between time periods. Line 29 thus represents the lifetime CO<sub>2</sub> of constructing and operating the Gradel Quadrangle. By the 75<sup>th</sup> year, the building would have accumulated 8051.49 tCO<sub>2</sub>. We can thus calculate that the upfront CO<sub>2</sub> is 2777.51 and the lifetime operational CO<sub>2</sub> is 5273.98. Thus, roughly 34% of the CO<sub>2</sub> is due to construction activities and 66% is due to ongoing operations.

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As this example shows, GP-LCA enables both accounting and modelling activities. It can record the emissions related to historical and current activities. This data enables the modelling of future activities and adjusting the modelled futures when real data becomes available.

**Table 6-26 Alignment between GP-LCA and GPFS**

GP-LCA (Entity-level GHG accounting)	General Purpose Financial Statements (Entity-level financial accounting)
<b>CO<sub>2</sub> BALANCE SHEET</b>	<b>FINANCIAL BALANCE SHEET</b>
<b>EMISSIONS ASSETS</b>	<b>ASSETS</b>
Intrinsic Carbon of fuel	Current assets
Embedded Carbon of exchange	Current assets
Embedded Carbon of use	Non-current assets
Embedded Carbon of Entity	Intangible assets
<b>EMISSIONS RESPONSIBILITIES</b>	<b>LIABILITIES</b>
Responsibility of debt holders	Liability to debt holders
Responsibility of owners	Owner's equity
<b>CO<sub>2</sub> RELEASES AND WITHDRAWALS</b>	<b>PROFIT AND LOSS STATEMENT</b>
<b>RELEASES</b>	<b>REVENUE</b>
Direct activities	
Release from fuel combustion	Fuel-related expenses for combustion
Indirect activities from procurement	
Embedded Carbon Fuel	Fuel expenses for non-combustion activities
Embedded Carbon Electricity	Electricity-related expenses
Other purchases by the entity	All other expenses
<b>WITHDRAWALS</b>	<b>EXPENSES</b>
Direct activities	
Removals	Expenses related to removal activities
Indirect activities from sales	
Fuel	Revenue related to fuel sales
Electricity	Revenue related to electricity sales
Product	All other sales
Retired purchased offsets	Purchase of offsets
Absorption due to natural processes	Depreciation
<b>Net Releases (Withdrawals)</b>	<b>Net Profit (Loss)</b>

### **6.6.2. Calculating ratios of CO<sub>2</sub> and financial values**

Because GP-LCA is aligned with the information architecture of financial accounting, the categories of the two systems are closely aligned, as depicted in Table 6-26. Both systems were designed for entity-level accounting, and they share a common boundary. Both systems use the same transactions as the underlying measurement, with GP-LCA categorising them by their environmental attribute of the transaction while GPFS categorising them by their financial attribute. As such, GP-LCA categories can be further expanded to match its counterpart in GPFS.

Ratios can be developed between CO<sub>2</sub> and financial categories to identify emission hot spots of revenue and expenses. For example, if the cost of constructing the Gradel Quadrangle is known, then one could calculate the carbon dioxide intensity of costs (\$/tCO<sub>2</sub>) cost spent to create the embodied carbon dioxide content of the structure. Users can then model technology options based both on cost and carbon dioxide footprint, enabling a more informed choice based on two different indicators.

### **6.6.3. Support preparation of GHG Protocol disclosures**

The GHG Protocol is the dominant disclosure system in use today and GP-LCA can be used to support entities in fulfilling their GHG disclosure requirements. Table 6-27 aligns GP-LCA categories with those of the GHG Protocol.

As Table 6-27 shows, the GHG Protocol is an inventory of an entity's value chain, and many categories of an entity's emissions are not included in the inventory. For example, the GHG Protocol does not represent embedded emissions within assets, or accumulated stocks of emissions. The lack of representation of embedded emission assets makes it challenging to disclose financed emissions, by debtors or equity owners. However, the GP-LCA categories, Responsibility of Debt Holders and Responsibility of Owners, can be used to disclose financed emissions within the GHG Protocol system.

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The GHG Protocol is mainly concerned with flows of new emissions. Direct releases from fuel combustion fulfils Scope 1 disclosures and EC of Electricity fulfils Scope 2 location-based disclosures. Further, Scope 3 Category 3 Energy-related activities record the transmission and distribution losses in the delivery of electricity. Scope 3 Categories 1-6, and 8 are itemised emissions due to purchasing activities. We classify Scope 3 Category 2 Capital Goods as a purchasing activity because the category is used to account for the new purchases of capital goods, not the accumulated capital goods of previous periods. In fact, Category 2 requires accounting of emissions in the year of purchase. The GP-LCA can be itemised to fulfil the upstream Scope 3 categories.

Further, Scope 3 includes downstream categories that are beyond the reporting entity's control. For example, Categories 9, 10, 11, and 12 are concerned with modelling the downstream emissions of the sold product. Category 9 estimates the fuel involved with shipping and handling of the sold item, Category 10 model emissions of additional processing steps before sold to consumers, Category 11 models the operational emissions of a product's lifetime and Category 12 models the disposal of the product.

Category 14 Franchises is a special case. Sometimes, franchises are consolidated into Scope 1 and 2. For those that are not consolidated, then the Scope 1 and 2 emissions of franchisees are reported in Scope 3 Category 14. The GP-LCA rules for franchisees should follow the same mechanisms as found in financial accounting and is an area of future development.

Table 6-27 also shows the categories of an entity that are missing within the GHG Protocol framework. The GHG Protocol does not account for withdrawals, nor does it account for items that leave the reporting entity. Because of these gaps, the GHG Protocol lacks a connection between suppliers (upstream) and customers (downstream). For example, entities are required to quantify emissions of purchased products, but entities are not required to quantify emissions of products being sold.

Table 6-27 Alignment between GP-LCA and GHG Protocol. GP-LCA can be used to prepare Scope 1, 2, 3 disclosures.

GP-LCA (Entity-level accounting)	GHG Protocol (Entity-level inventory)
<b>CO<sub>2</sub> BALANCE SHEET</b>	
<b>EMISSIONS ASSETS</b>	None
Intrinsic CO <sub>2</sub> of Fuel	
Embedded CO <sub>2</sub> of Exchange	
Embedded CO <sub>2</sub> of Use	
Embedded CO <sub>2</sub> of Entity	
<b>EMISSIONS RESPONSIBILITIES</b>	Category 15 Financed Emissions
Responsibility of debt holders	
Responsibility of owners	
<b>CO<sub>2</sub> RELEASES AND WITHDRAWALS</b>	
<b>RELEASES</b>	
Direct activities	Scope 1
Release from fuel combustion	
Indirect activities from procurement	Scope 3* Upstream emissions of fuel is an optional category
Embedded CO <sub>2</sub> of Fuel	
Embedded CO <sub>2</sub> of Electricity	Scope 2
Other purchases by the entity	Scope 3 Category 3 Energy-related activities (T&D)
	Scope 3 Category 1 Purchased goods and services
	Scope 3 Category 4 Upstream transportation and distribution
	Scope 3 Category 5 Waste generated in operations
	Scope 3 Category 6 Business travel
	Scope 3 Category 8 Upstream leased asset
Scope 3 Franchises	
<b>WITHDRAWALS</b>	
Direct activities	None
Removals	
Indirect activities from sales	
Fuel	
Electricity	
Product	Scope 3 Category 9 Downstream transportation
Shipping and handling	
Retired purchased offsets	None
Natural processes	
Net Releases (Withdrawals)	None
<b>ADDITIONAL MODELING</b>	Scope 3 Category 7 Employee commuting Scope 3 Category 10 Processing of sold product Scope 3 Category 11 Use of sold products Scope 3 Category 12 End-of-life treatment of sold products

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*Table 6-28 Using GP-LCA to disclose Scope 1, 2, and 3 for the Gradel Quadrangle (in tCO<sub>2</sub>). The value for 2023 represents the construction of the building and in 2024 represents that year's operations.*

	2023	2024
Scope 1	0	0
Scope 2	0	70.33
Scope 3 Category 2: Capital Goods	2777.51	0

For New College, Table 6-28 is the Scope 1, 2, and 3 disclosures due to the Gradel Quadrangle for 2023 and 2024. Based on data from Table 6-25, in 2023, the building was completed, and the emissions of capital goods would be reported. Because the building was not operational, there was no Scope 1 or Scope 2. In 2024, the Gradel Quadrangle emitted 70.33 tCO<sub>2</sub> from purchased electricity, recorded as Scope 2. Scope 1 is zero because there is no fossil-fuel burning equipment on site. Because all capital goods must be reported in the year of purchase, and no new capital goods were purchased in 2024, there are no emissions for Capital Goods.

### **6.6.4. Alignment with whole life carbon assessment**

Further, GP-LCA may be used to calculate WLCA, as it is a model of 60-year cumulative emissions of a building. As shown in Table 6-29, within the GP-LCA, modules [A0] to [A5] are accounted for within EC of Use. Modules [B] and [C] can be obtained a 60-year projection of GP-LCA, as stylised in Table 6-25. As the future CBS already represents cumulative emissions, the WCLA is Total CO<sub>2</sub> assets (line 30) of Table 6-25 in year 60. The value of a WLCA of the Gradel Quadrangle is 6,996.70 tCO<sub>2</sub>.

Table 6-29 Alignment between GP-LCA and Whole life carbon assessment. GP-LCA can be used to support the preparation of an WLCA study.

GP-LCA (Entity-level accounting)	Whole Building LCA (Building-level inventory)
<b>CO<sub>2</sub> BALANCE SHEET</b>	
<b>EMISSIONS ASSETS</b>	
Intrinsic CO <sub>2</sub> of Fuel	None
Embedded CO <sub>2</sub> of Exchange	
Embedded CO <sub>2</sub> of Use	
	<b>EMBODIED EMISSIONS</b>
	Upfront emissions
	[A0] Pre-construction stage
	[A1] Raw material supply
	[A2] Transport
	[A3] Manufacturing
	[A4] Transport
	[A5] Construction process
	Modelled emissions, assuming a 60-year life
	[B1] In use
	[B2] Maintenance
	[B3] Repair
	[B4] Replacement
	[B5] Refurbishment
	Modelled emissions of end-of-life
	[C1] Deconstruction / demolition
	[C2] Transport
	[C3] Water processing
	[C4] Disposal
Embedded CO <sub>2</sub> of Entity	Modelled emissions for a 60-year life
	[B6] Operational energy
	[B7] Operational water
	[B8] Other operational
<b>EMISSIONS RESPONSIBILITIES</b>	
Responsibility of Debt holders	None
Responsibility of Owners	
<b>CO<sub>2</sub> RELEASES AND WITHDRAWALS</b>	
RELEASE	None
WITHDRAWALS	
NET RELEASES (WITHDRAWALS)	
<b>ADDITIONAL MODELING</b>	[D] Benefits and loads beyond the system boundary

## 6.7. Summary and future work

This paper proposed an entity-level environmental accounting system that is aligned with the information architecture of entity-level financial reporting. As a general-purpose framework, GP-LCA is a framework to present and periodically update data using normative rules. It synchronises emissions from combustion activities, usage of items whose emissions already

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occurred, and natural processes of planetary sciences. It allocates these emissions to products and entities in the economy.

We then applied the GP-LCA framework to develop a set of carbon dioxide statements for New College, Oxford, based on the activities of the newly constructed Gradel Quadrangle, a mixed-use educational facility. Based on the CO<sub>2</sub> statements, we then performed several additional operations, including projecting a 75-year emissions footprint, calculated the WLCA, and prepared sample GHG Protocol disclosures.

The GP-LCA model can continue to be refined to account for financed emissions. With the GP-LCA model, financed and facilitated emissions can be accomplished by examining the responsibility side of the CBS, rather than being a category of Scope 3. As such, a GP-LCA method of financed emissions would allocate all CO<sub>2</sub> assets to financial partners.

Withdrawal accounting within GP-LCA can also be further refined. It can potentially integrate the work of organisations that are quantifying high quality offsets, such as the Integrity Council for the Voluntary Carbon Market (ICVCM) and support the work of net zero guidelines (ISO, 2022). Further research can also be done to integrate into carbon market activities.

Additional work can also be done to connect GP-LCA to financial and economic impact of GHG emissions. As GP-LCA is aligned with financial accounting, improving the ability to cost GHG emissions may be an area of further development.

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# Chapter 7. A divergence of dynamics: Temporal issues between modelling forecasts of physical carbon emissions and monetary cost of damage

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## Abstract

While the relationship between greenhouse gas emissions and economic damage from climate change is well studied at the level of global policy making, this paper studies their relationship at the project level. A Passivhaus is a type of building that generally emits more upfront emissions due to construction to achieve lower emissions over the lifetime of the building's operations. Because both conventional financial cost benefit models and whole life cycle accounting are a summation of upfront and ongoing indicators, there lacks an analysis of the trade-off between the two. To fix this gap, this paper studies the effect of upfront and ongoing emissions with a payback analysis, showing how modelling physical emissions alongside financial costs can generate false positives (negatives) where the financial model suggests a project is (is not) worthwhile while physical emission models indicate otherwise. Second, we find that cost-benefit analysis can be more sensitive to upfront and ongoing emissions as compared to electricity prices and cost of carbon by an order of magnitude. Both the Passivhaus and the counterfactual benchmark building fall within one standard deviation of typical emissions values for construction. The results highlight the importance of relying on measurements to determine whether an emissions intervention is the lower carbon value, rather than rely on modelled assumptions.

## Keywords

Carbon accounting, climate change, cost of carbon, temporal analysis

## 7.1. Introduction

It has been well established that the release of anthropogenic greenhouse gases (GHGs) has been the driving force behind climate change (Myhre et al., 2013). Interest in the measurement and management of corporate GHG emissions have only increased over time, with over 80% of the global economy announcing net zero emissions targets (UNFCCC, 2022). Evidence suggests that even a 1°C rise in global temperatures can cause significant economic damage, with one study estimating climate damage would cost the US alone 1.2% of their GDP (Hsiang et al., 2017). In this paper, we follow the convention of referring to all Kyoto GHG's collectively as 'carbon'.

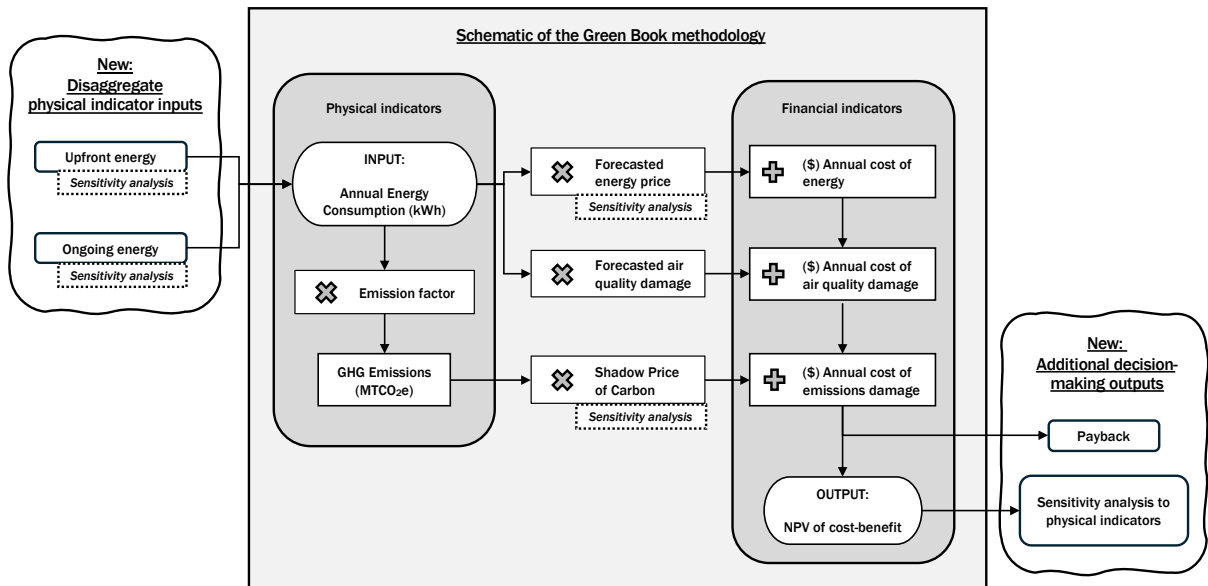
The UK Government issues guidance by HM Treasury on how to model financial cost-benefit of GHG emissions when evaluating policies, programmes, and projects, known as the Green Book (UK DESNZ, 2023b). Simultaneously, the government has a net zero emissions policy, a cap on physical emissions that will reduce emissions to net zero by 2050 (Burnett et al., 2024). As the UK Government owns the country's largest property portfolio, a collection of 300,000 properties (UK OGP, 2021), it is affected by both financial cost-benefit models of net zero policies as well as models of physical net zero emissions caps. This paper asks, are the financial indicators in cost-benefit analysis of carbon damage meaningful in achieving physical net zero? In other words, do the physical and financial models converge in informing achievement of climate policies? The question applies to a broader question of whether financial cost-benefit analysis of carbon damage is meaningful in achieving any net zero emissions goals.

By studying physical carbon emissions alongside financial costs, this paper address three gaps, as summarised in Figure 7-1. First, current models do not distinguish between upfront embedded carbon to achieve net zero operational carbon goals. The methods of modelling cost-benefit and net zero both rely on summations over all time. The UK Green Book is a net present value (NPV) model, evaluating projected annualised costs of energy, carbon, and air

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quality. Meanwhile, physical emissions of buildings are modelled using whole life cycle accounting (WLCA), a method used by the Royal Institute of Chartered Surveyors (RICS). WLCA is also summation of total physical emissions over an asset's lifetime (RICS, 2024). Second, disaggregating upfront and ongoing emissions enables the modelling of additional decision-making indicators. While NPV and WLCA inform a decision maker on which option will have a lower total cost or carbon footprint, decision makers also use payback and years to break even to evaluate the trade-off between upfront and ongoing indicators. For example, payback can inform how long an upfront investment needs to operate before pursuing additional investments, such as retrofits, refurbishments, upgrades or additional investments. Much like how upfront capital investments can affect ongoing operational expenditures, this paper investigates how upfront embedded carbon emissions can affect ongoing carbon emissions. Third, there is a lack of modelling sensitivities to physical emissions characteristics. The cost-benefit analysis of the UK Green Book includes central-, high-, and low-price scenarios for sensitivity analysis for the shadow price of carbon and to the cost of electricity. However, real estate industry averages for physical emissions values can have a standard deviation of 30% (Simonen et al., 2017). Therefore, we investigate the relative importance of physical emissions characteristics against financial characteristics.

The contribution of this paper demonstrates the divergence between physical and financial models of emissions. As explained in our methodology section, we add periodicity into GHG emissions for the built environment, enabling alignment of models of physical GHG emissions and financial cost of damage. We show the importance of physical emissions on decision-making indicators, such as payback and cost-benefit analysis. The result of the analysis indicates the importance of measuring emissions per project rather than relying on industry averages in the operationalizing of net zero policies.



**Figure 7-1** The Green Book model takes in annual energy consumption as an input, and calculates GHG emissions, and three financial indicators, the cost of electricity, cost of air quality damage, and cost of emissions damage. The various costs feed into an NPV model for cost-benefit analysis. This research investigates the UK Green Book methodology by disaggregating physical inputs into upfront and ongoing energy and emissions, enabling additional outputs of payback analysis and a sensitivity analysis to physical indicators. (Source: Author's creation)

The paper is structure as follows. We first present methodology used for physical modelling of emissions and financial modelling of cost of damage of emitting carbon. We also present the dataset used in this paper, of a recently constructed Passivhaus. We then develop the hypothesis and explain the analyses to test the hypothesis. We then present the results and discuss their implications.

## 7.2. Methods

### 7.2.1. Summation of time in the real estate emissions

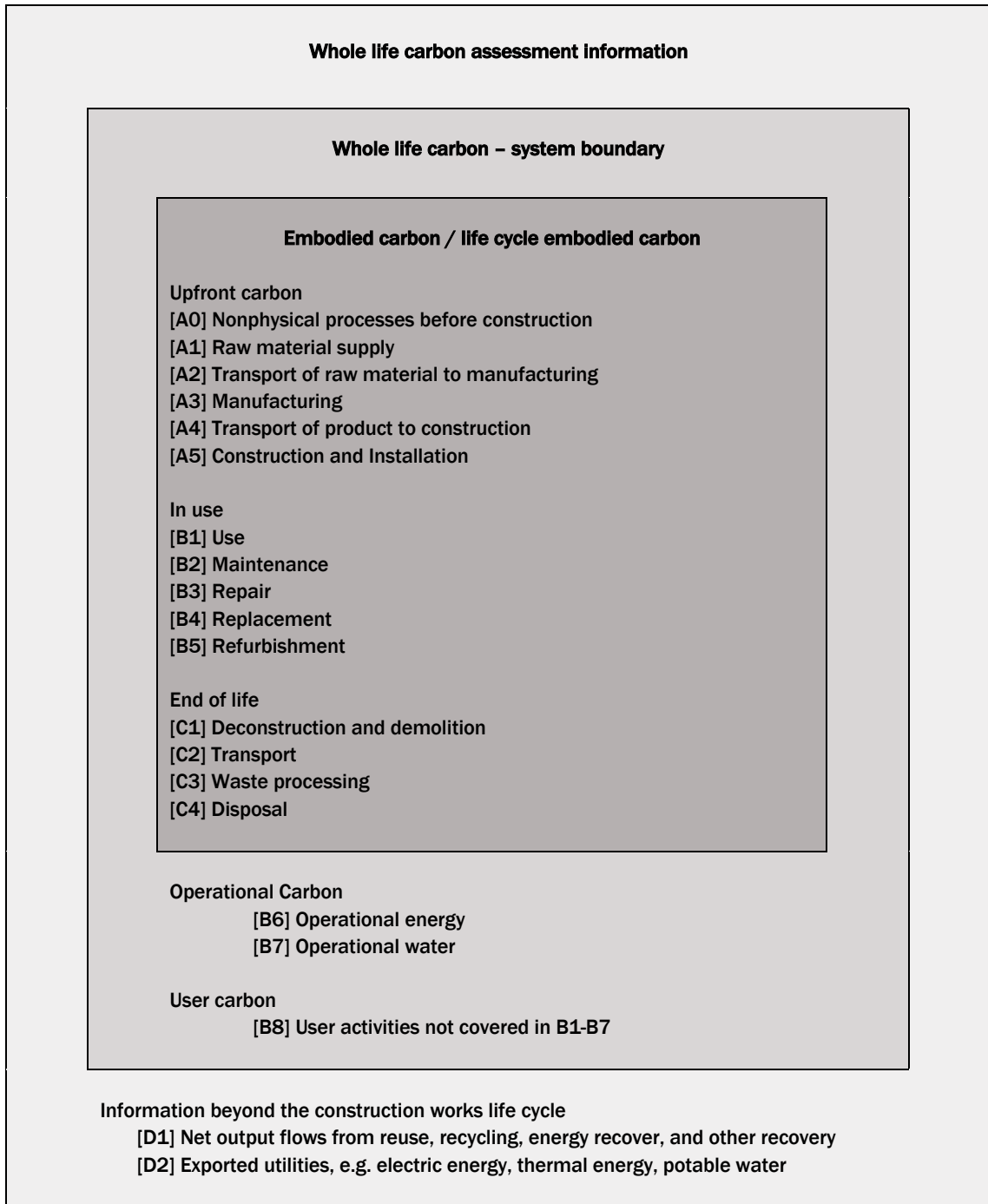
The real estate sector is responsible for roughly 40% of global emissions (Grazieschi et al., 2021). The emission can be categorized into upfront embedded emissions due to production of materials and construction of the building and ongoing operational emissions due to the usage of the building. The pursuit of net-zero operations within the real estate sector has primarily focused on reducing operational carbon (Giordano et al., 2017). However, as

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buildings and assets become more operationally efficient, the embedded carbon component becomes more important (Balouktsi & Lützkendorf, 2016). Furthermore, some operational carbon improvements come at the expense of increased embedded carbon emissions. For example, to increase the thermal performance of a building, one could add more concrete for insulation, install metal overhangs to reflect sunlight, or retrofit mechanical equipment (Azari & Abbasabadi, 2018; García-Sanz-Calcedo et al., 2021). While these technologies would decrease operational carbon emissions, they incur additional embedded carbon.

A Passivhaus is an example of such a trade-off, where additional insulation and weatherisation beyond a code compliant building reduces the consumption of primary energy and carbon emissions to operate the building (Passivhaus Trust, 2024). One study found roughly 30% additional upfront emissions due to increased material usage to achieve an average of 72% lower energy consumption as compared to a code compliant building (Williams, 2023). In essence, to achieve a lower overall carbon emission, a Passivhaus emits shifts future emissions to the present, by increasing embedded carbon emission of the present for a lower operational carbon emission of the future.

Temporal trade-offs in the real estate sector are well studied for financial indicators, such as managing the large upfront capital investments against the long-duration operational revenue and expenses. However, the current approach to carbon accounting does not facilitate temporal assessment of this trade-off. This is because WLCA is based on traditional life cycle assessment (LCA) approaches which lacks temporality (Chapter 6 / Paper 3). As shown in Figure 6-1, WLCA is a summation of embodied upfront emissions that arise from materials manufacturing and construction (module [A]), in use emissions of capital asset replacement and refurbishment (modules [B1-B5]), and end of life emissions related to disposal (module [C]). A whole life carbon assessment adds the emissions that arise from operating the building (module [B6-B8]). Module [D] represent optional emissions that are beyond the construction of the building. RICS recommends using a 60-year operational life



*Figure 7-2 Information architecture of whole life carbon assessment is based on the LCA supply chain. Figure adopted from RICS (RICS, 2024). Note that Embodied carbon includes upfront, ongoing, and end-of-use carbon, or is the sum of past, present, and future emissions.*

for a building to model a WLCA. Ideally, it is updated frequently during the concept, technical design, and construction phases. After a building becomes operational, a WLCA is updated only when there is a major refurbishment or when an update to the predictions is required. In

short, as WLCA is a summation of upfront and ongoing physical emissions values over time, it is not suitable to investigate the trade-off between them.

### 7.2.2. Summation of time in financial analysis

Foundational to financial analysis is the ability to make comparisons that are spread out over long periods of time (Berk & DeMarzo, 2020). Net present value (NPV) is a common methodology to conduct a financial cost-benefit analysis of a project. It incorporates the time-value of money that money today is worth more than money in the future. It is the sum of the present value of all future discounted cash flows:

$$NPV = \sum_{t=0}^n \frac{CF_t}{(1+d)^t} \quad \text{Equation 7-1}$$

CF is the cash flow of a given year  $t$ ,  $d$  is the discount rate,  $n$  is the last year of the project. Positive NPV generates value while a negative NPV reduces value. When comparing multiple projects, one should choose the one with the highest NPV. Although powerful and commonly used, NPV has several limitations. NPV is sensitive to the assumption of future cash flow (Ross, 1995). Uncertainty of the size and duration of the future cash flow can shift the NPV of a project. Therefore, it becomes a challenge to compare projects of different lengths. NPV is also requires a selection of a discount rate, and it is highly sensitive to the choice. In addition, the further into the future the cash flow, the higher it is discounted, reducing its contribution to the present value. A sensitivity analysis of input parameters can examine how NPV is affected, thus identifying areas of uncertainty.

As shown in Figure 7-1, the Green Book model is an NPV of three cashflows, annual cost of energy, annual cost of air quality damage, and annual cost of emissions damage. The NPV is conducted over the expected duration of a project. As the model includes forecasts, it enables the sensitivity analysis to forecasted energy prices and to the shadow price of

carbon (SPC). As shown, the Green Book model and WLCA model are both based on summation of upfront and ongoing emissions values over time.

To evaluate trade-offs between upfront and ongoing emissions, decision makers will use a payback analysis. A payback analysis quantifies the amount of time it takes to pay back an initial investment (Berk & DeMarzo, 2020). To find the payback period, one equates the time it takes for the initial investment to equal the sum of ongoing costs.

$$\text{initial investment} = \sum_{t=1}^{\text{payback time}} \frac{\text{Ongoing costs}_t}{(1 + d)^t} \quad \text{Equation 7-2}$$

A discounted payback takes into account that future costs are discounted by rate  $d$ . A simple payback would set the rate  $d$  equal to zero. Payback on its own is not as reliable as NPV as an investment indicator for financial analysis as it does not consider the time value of money. However, it provides useful information for how long an investment needs to be utilised before it is the lower cost option. Similarly, carbon payback can be evaluated to understand how long an investment needs to be utilised before it becomes the lower carbon option. Physical carbon emissions payback is therefore a viable tool to analyse the carbon footprint of real estate asset, which are often held for many decades, if not centuries.

### **7.2.3. Brief description of UK Green Book methodology**

The values used in the Green Book also has temporal assumptions. The analytical process used by HM Treasury to model carbon emissions of policies consist of seven steps, summarised in Table 7-1.

First, one identifies a baseline counterfactual for energy and emissions. We use the construction of a conventional building as the counterfactual. Second, one identifies the policy interaction. We use the decision to construct a Passivhaus as the policy interaction.

Table 7-1 Summary of steps to model GHG emissions and their economic value (UK DESNZ, 2021).

<ol style="list-style-type: none"><li>1. Identify energy and emissions counterfactual</li><li>2. Identify policy interactions</li><li>3. Quantify changes in fuel use<ol style="list-style-type: none"><li>a. Value the change in fuel use</li></ol></li><li>4. Quantify changes in emissions<ol style="list-style-type: none"><li>a. Value the change in emissions</li></ol></li><li>5. Identify and quantify any other impacts</li><li>6. Calculate cost effectiveness</li></ol>
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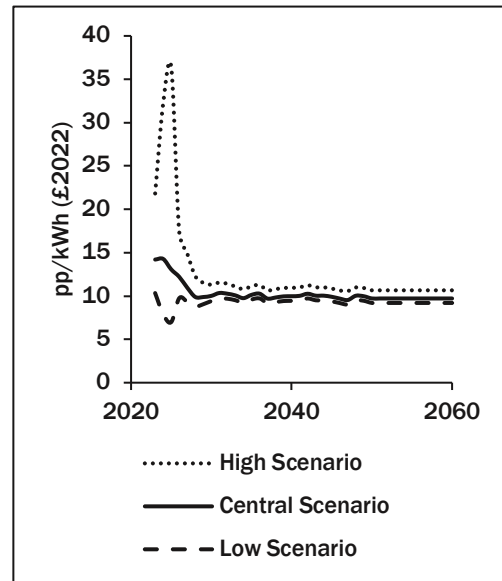
Next, one would quantify the change in fuel consumption between the two options on an annual basis. We describe the energy and emissions models for the Gradel Quadrangle in the next section. To value the change in fuel use (step 3a), one applies the long-run variable cost (LRVC) of energy supply. The LRVC only includes costs that represent actual costs to society, such as GHG costs, primary fuel, and variable costs of production. Non-variable costs, such as taxes or fixed costs, are not included. The estimates are based on expected wholesale prices, policy support costs, variable distribution and transmission costs, amongst other suggestions. Because the price of electricity is highly uncertain, the Green Book also provides a low and a high scenario for sensitivity analysis. Table 7-2 is a table of electricity prices used in the Green Book and Figure 7-3 graphs their long-term projection to 2060, where the price stabilises out till 2098.

From the change in energy, one quantifies the changes in emissions. The Green Book integrates changes to the power sector necessary to meet UK's net zero target by 2050. As shown in Table 7-3 and Figure 7-4, the emissions of electricity is projected to rapidly decline, reaching 0.015 kgCO<sub>2</sub>e/kWh by 2040, stabilising to 0.002 kg/kWh by 2050 (UK DESNZ, 2023a).

**Table 7-2 Central, low, and high electricity price scenarios**

Year	Cost of electricity (pp/kWh (£2022))		
	Low	Central	High
2023	21.83	14.20	10.33
2024	32.22	14.27	7.91
2025	36.43	13.07	6.98
⋮	⋮	⋮	⋮
2097	10.65	9.71	9.20
2098	10.65	9.71	9.20

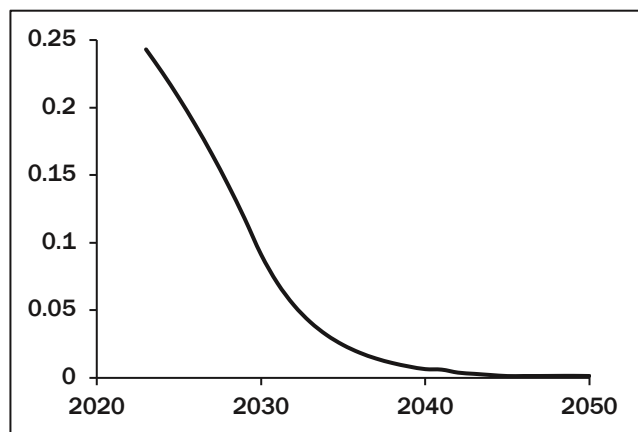
**Figure 7-3 Graph of central, low, and high electricity price scenarios**



**Table 7-3 Projected electricity emission factors (kgCO<sub>2e</sub> / kWh)**

Year	Carbon emission factors
2023	0.243050
2024	0.225761
2025	0.207184
2026	0.187226
2027	0.165782
2028	0.142742
2029	0.117988
2030	0.091393
2031	0.070139
2032	0.053829
2033	0.041311
2034	0.031704
2035	0.024331
⋮	⋮
2097	0.002455
2098	0.002455

**Figure 7-4 Graphical depiction of electricity emission factors (kgCO<sub>2e</sub> / kWh)**



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To value the changes due to emissions, one applies the cost of carbon. The UK uses a shadow price of carbon (SPC) that is a modification of the social cost of carbon (SCC). The SCC attributes to today the full global cost of damage over the lifetime of an incremental unit of GHG emissions (Price et al., 2007). It is defined as the net present value of the incremental damage due to the unit emission of GHGs (Tol, 2011). It represents a price signal of what society should do to avoid future damage. As the cost of damage increases with higher concentration of carbon in the atmosphere, the SCC usually increases over time (Evans et al., 2021).

- **Socioeconomic module**, which includes population and income, and emissions.
- **Climate module**, which describes how emissions affect physical climate variables, such as temperature.
- **Damages module**, which translates physical climate variables into costs of economic damage.
- **Discounting module**, which discounts the stream of future damages to the present value in the year in which the incremental unit of emissions was released.

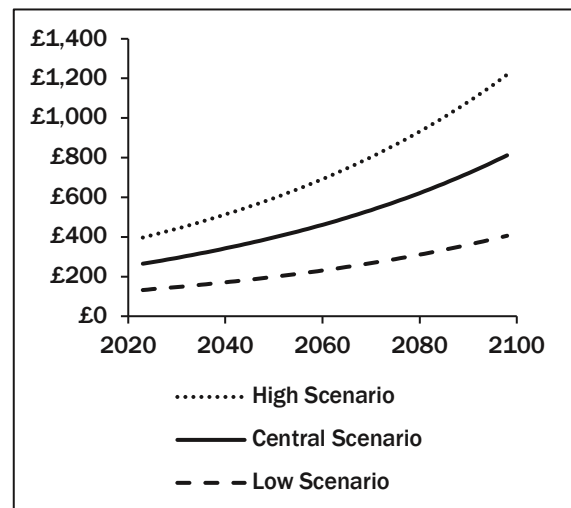
The value of the SCC over time is sensitive to small changes in discounting, due to the long time horizons (Evans et al., 2021). That report found that, by 2025, a discount rate of 2.5% would result in an SCC of \$152/tCO<sub>2e</sub> while a 5% discount rate would result in an SCC of \$25.7/tCO<sub>2e</sub>. Another report examined the sensitivity of the SCC based on a Monte Carlo simulation and found that the value can range from \$43,937/tCO<sub>2e</sub> to -\$55.2/tCO<sub>2e</sub> (Anthoff et al., 2009). This is because a higher discount rate results in a lower SCC value as future damages are weighed less (Evans et al., 2021). One limitation of the SCC model is that it only prices the cost of damage caused by climate change but does not enable policy alignments to net zero targets (Evans et al., 2021). For example, the SCC is not associated with any particular stabilisation goal for atmospheric carbon concentration (Price et al., 2007).

The UK adopted an SPC which addresses this limitation by enabling the inclusion of emission targets and other policy approaches to take into consideration the UK's carbon budget (UK DECC, 2009). While an SCC is a measure of the economic and social cost of damage of emitting an additional tonne of carbon, an SPC also includes a measure of the change in social welfare, or costs associated with implementing policies aimed at mitigating climate change (Dietz, 2007). The SPC includes a stabilisation trajectory as a function of global emissions as well as other factors that the UK may be willing to pay for the reduction of emissions (Price et al., 2007). The SPC is anchored on the median value of the range of climate model outputs to limit global warming to 1.5 °C target by 2100, from integrated assessment models (IAM) used by the Intergovernmental Panel on Climate Change (IPCC) (UK DESNZ, 2021). To capture the uncertainty in the model, the UK also publishes a low and high scenario that represents a 50% sensitivity range around the median value (UK DESNZ, 2021). As such, all three scenarios utilise the same discount rate. Table 7-4 and Figure 7-5 depicts the SPC values used in the UK Green Book. The starting value of the central scenario is £265.93, with an annual increase of 1.523% per year till 2040, and 1.5% per year increase 2041 onwards.

**Table 7-4 Annual values for UK SPC scenarios**

Year	SPC values (£2022 prices)		
	Low	Central	High
2023	£ 132	£ 265	£ 397
2024	£ 134	£ 269	£ 403
2025	£ 137	£ 273	£ 410
⋮	⋮	⋮	⋮
2097	£ 400	£ 800	£ 1,201
2098	£ 406	£ 812	£ 1,219

**Figure 7-5 Graph of UK SPC scenarios (£2022)**



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To value air quality impacts, the Green Book uses an impact pathway approach, which estimates how changes in air pollution emissions translates into damage costs for the UK as a whole (UK DEFRA, 2023). The model estimates pollutants such as particulate matter, nitrogen dioxide, and volatile organic compounds, and their cost impact on public health, the natural environment, and the broader economy. The results are presented as a cost per energy consumed (pp / kWh). The values are modelled automatically within the Green Book toolkit based on the estimated energy consumed.

Lastly, one performs a cost-benefit analysis to determine if the policy is cost effective in achieving GHG reductions. The cost effective indicator (CEI) is net present value (NPV) of emissions saved divided by the carbon equivalent saved. If GHG savings is the primary objective of the policy, then the CEI is compared to a weighted average cost comparator. To calculate the NPV, one can use the green book default discount rate, set at a social discount rate of 3.5% for the first 30 years, and dropping to 2.5% by year 75.

The Green Book methodology has two major limitations, First, although the CEI can be used to rank multiple projects, the guidance states that it is only appropriate to compare projects that have the same length of time (UK DESNZ, 2023b). Second, there is no requirement to include upfront embedded emissions in the model. The reason is because the method only values marginal changes to the national emissions inventory. If the embedded materials are manufactured within the UK, then the emissions have already been modelled elsewhere. However, in calculating CEI, one is asked to include upfront costs, despite not being asked to include upfront emissions. Thus, there are misalignments in the assumptions of monetary and GHG flows.

As NPV models are highly sensitive to input variables, the Green Book provides information and guidance to performing sensitivity analysis for cost of electricity and cost of carbon. However, it does not provide information on performing a sensitivity analysis on changes to physical emissions that underlie the model. As shown in Figure 7-1, we build on the Green

Book model by disaggregating upfront and ongoing energy as inputs, thereby disaggregating emissions as well. This is described in detail in the next two sections. The disaggregation enables the analysis of payback time for achieving carbon break-even as well as the analysis of sensitivity of NPV to upfront and ongoing emissions

#### **7.2.4. Inserting temporality into carbon accounting**

The recently proposed general purpose lifecycle assessment (GP-LCA) addresses the temporality challenge by adopting the information architecture of double entry bookkeeping (DEBK), the system used by financial accounting (Chapter 6 / Paper 3). DEBK enables the synchronisation of short-term activities (revenue, expenses, etc.) and long-term activities (depreciation, capital assets, etc.) into a standardized set of periodic reports (Quattrone, 2005). Thus, financial statements provide periodic information to decision makers who can then evaluate the trade-off between past, present, and future activities. A balance sheet represents the accumulation of past activities (ignoring fair market adjustments), the profit and loss statement and cashflow statements represent present activities, and *pro formas* represent models of future scenarios.

Foundationally, GP-LCA recognised that flows of money are analogous to flows of emissions (Chapter 6 / Paper 3). Transactions of a purchase, such as buying a stapler, represents a monetary exchange as well as a carbon exchange. GP-LCA is aligned to several features within financial accounting, namely using the same boundary condition of an entity, formalising the financial transaction as the item to be counted, adopting the rules of recognition for when to count a transaction, and presenting the information using the same temporal periodicity as in financial accounting.

GP-LCA defines *Embedded Carbon* (EC) as emissions emitted as a result of past event from which one expects future carbon emissions/withdraws to flow. The definition is aligned with that of an asset, as per the IFRS (IASB, 2018). For example, the manufacture and

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construction of concrete, steel, and insulation would have embedded carbon values. Much like capital assets represent upfront costs, EC represents upfront emissions. *Operational carbon* (OC) is defined as carbon emissions that were released or withdrawn within the reporting period. The definition is aligned with that of expenses (IASB, 2018). For example, ongoing electric energy consumption and certain repairs would be classified as operational carbon.

The carbon categories are presented in the following reports, aligning temporal categories of carbon flows to financial flows:

- The *Carbon Balance Sheet* (CBS) The is the statement of position that represents the stock of emissions released to the atmosphere. Carbon assets include:
  - *EC for Exchange* or items in inventory that are exchanged between entities
  - *EC for Use*, or items found within fixed assets that are utilised for long periods of time. Real estate assets are represented as an EC for Use.
- The *Carbon Releases and Withdrawal* (CR&W) statement, represents the emissions performance of the entity due to direct activities of fuel combustion and indirect activities of sales, purchases and other trades that increase and decrease allocated emissions. It also records withdrawals from the atmosphere due to removal activities. Ongoing emissions of real estate assets are presented in the CR&W.

GP-LCA synchronises short-term operational carbon emissions with long-term embedded carbon emissions with a carbon balance sheet, to represent historical embedded carbon, Future emissions can be considered carbon lock-in (Unruh, 2000), or the quantity of emissions that are perpetuated in future periods based on investment decisions of the present period. An additional benefit of adopting DEBK into GHG accounting is an alignment of categories with financial accounting. Therefore, one can use GP-LCA and financial models

to model the divergence or convergence of physical and financial characteristics of the same activity.

### **7.2.5. The dataset: Emissions of the Gradel Quadrangle**

The GP-LCA model was previously used to disclose a carbon statement for the Gradel Quadrangle, completed in 2024, of New College, Oxford, founded in 1379. The Gradel Quadrangle is a mixed-used educational facility built to a Passivhaus standard, including natural ventilation, passive heating, ground source heat pump, among other design considerations. The complex has a four-story above-ground building with two basement levels and a four-story student accommodation building with a seven-story tower. The upfront, embedded emissions and ongoing operational emissions have been modelled in prior research (Chapter 6 / Paper 3).

The carbon data for the Gradel Quadrangle can be seen in Table 7-5, as derived from prior research (Chapter 6 / Paper 3). The *actual building* is based on the design specifications to a Passivhaus standard. The carbon balance sheet represents the upfront embedded emissions of a building. The total carbon assets of the actual building were previously calculated to be 2,778 tCO<sub>2e</sub>, using software that tracked energy consumed and exact quantities and nature of materials delivered to the site, and the means of transportation. The *benchmark building* is used as a counterfactual, modelled by design engineers to compare the actual building against a building constructed to the UK building code. The embedded carbon data for the benchmark building was estimated to be 30% less than the actual building, based on prior industrial research (Williams, 2023).

The carbon releases and withdrawals represent the ongoing emissions of the building. Operational carbon for both actual and benchmark buildings were taken from site planning reports, energy models, and analysis. As Table 7-5 (C) and (D) indicates, the ongoing carbon

Table 7-5 Carbon data from the Gradel Quadrangle. Upfront emissions are shown in the carbon balance sheet for (A) the actual building, constructed to a Passivhaus standard and (B) the benchmark building constructed to the UK benchmark, at 30% lower emissions. Ongoing emissions are modelled for (C) the actual building and (D) the benchmark building.

Actual building: Passivhaus standard (tCO <sub>2</sub> e)		Benchmark building: UK building code (tCO <sub>2</sub> e)	
(A) Carbon Balance Sheet January 1, 2024		(B) Modelled Carbon Balance Sheet January 1, 2024	
<b>CARBON ASSETS</b>		<b>CARBON ASSETS</b>	
<b>EC for USE</b>		<b>EC for USE</b>	
Gradel Quadrangle	2,475	Benchmark Building	2,137
<b>EC of Chemical Reactions</b>		<b>EC of Chemical Reactions</b>	
Calcination of Concrete	303	Calcination of Concrete	
<b>Total CARBON ASSETS</b>	<b>2,778</b>	<b>Total CARBON ASSETS</b>	<b>2,137</b>
(C) Carbon Releases and Withdrawals		(D) Carbon Releases and Withdrawals	
<b>CARBON RELEASES</b>		<b>CARBON RELEASES</b>	
Carbon of self-generation	0.00	Carbon of self-generation	0.00
Carbon of grid purchases	127.21	Carbon of grid purchases	176.73
<b>CARBON WITHDRAWALS</b>		<b>CARBON WITHDRAWALS</b>	
N/A	0.00	N/A	0.00
<b>Net Releases &amp; Withdrawals</b>	<b>127.21</b>	<b>Net Releases &amp; Withdrawals</b>	<b>176.73</b>

for the actual building, 127.21 tCO<sub>2</sub>e, is 28% lower than the ongoing emissions for the benchmark building.

Because the Green Book accepts inputs in units of energy, we convert the embedded carbon values Table 7-5 into its electricity equivalent. We did this by using the electricity emission factors of Table 7-3.

### 7.2.6. Uncertainty of physical emissions

Although the emissions of the Gradel Quadrangle are measured, studies have shown how embedded and operational characteristics of a building vary substantially. The Carbon Leadership Forum, in their survey of over a thousand buildings, found that larger buildings

had an average embedded carbon footprint of 1,612 kgCO<sub>2e</sub> / m<sup>2</sup> and smaller buildings 389 kgCO<sub>2e</sub> / m<sup>2</sup> (Simonen et al., 2017). However, the standard deviation is 543 kgCO<sub>2e</sub> / m<sup>2</sup> and 195 kgCO<sub>2e</sub> / m<sup>2</sup>, respectively, or 33% and 50% around the mean. Another study identifying carbon reduction potential during the design stage estimated that buildings had an average embedded carbon of 785 kgCO<sub>2e</sub> / m<sup>2</sup> with a standard deviation of 215 kgCO<sub>2e</sub> / m<sup>2</sup>, or 27% around the mean (Victoria & Perera, 2018).

Operational carbon faces the same challenge. In the UK, building performance are ranked by an Energy Performance Certificate (EPC) with *A* represent the most energy efficient and *F* being the least. However, according to a largescale survey, the distribution of energy use intensity across the different ratings categories broadly overlaps (BPP, 2023). Similar challenges are found in the US. In a study of over 178,000 buildings within the Los Angeles Department of Water and Power (LADWP) service territory, LEED certified buildings, awarded for sustainable practices in real estate, consumed 29.9% less energy than conventional buildings with a standard error of 10.95%, or 36% of the mean (Asensio & Delmas, 2017). Additionally, Energy Star rated buildings had a 19.3% lower energy consumption with a standard error of 5.81% or 30% around the mean. Because energy is directly proportional to carbon emissions based on an emission factor coefficient, these values also indicate a large variation of operational carbon. In short, studies indicate that it is common for both EC and OC to have a standard deviation of roughly 30%. Therefore, if one is modelling physical emissions and using a statistical average derived from literature, one should model the sensitivity of physical emissions to the variance.

### **7.3. Hypothesis development**

As described in the previous section, the current models for financial and physical emissions are summations of upfront and ongoing emissions over all time. In this paper, we disaggregate upfront and ongoing emissions, enabling the analysis of payback characteristics of both financial and physical models. As shown in Table 7-6, we build a

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simple model first, with each subsequent analysis adding complexity and to the prior. We use the dataset of the Gradel Quadrangle because the Passivhaus standard is both accepted for net zero government buildings as well as an exemplary policy that the government could pursue, resulting in a cost-benefit analysis for the UK economy. We therefore hypothesize:

- **(H1):** In buildings, the asset's financial cost of damage and physical emissions models will have similar payback characteristics.

To test H1, we perform a simple payback analysis of physical emissions, using the Gradel Quadrangle. We then apply the SPC to the physical emissions model to construct a simple payback analysis of the cost of damage. In analysis 1, the payback gap is calculated as the difference between the physical and financial payback. In analysis 2, we then test the sensitivity the payback gap, against variation of upfront emissions, ongoing emissions, and annual increase to SPC. We derive a set of continuous equations for the payback gap and analyse effects of one standard deviation changes to the inputs. Because the UK electric grid is planned to be decarbonised, we also conducted a payback gap analysis taking into consideration the changing electric grid emissions factors, analysis 3.

After analysing the effects of upfront and ongoing emissions to the payback gap, we analyse their effects to the NPV of the cost-benefit model. We hypothesize:

- **(H2.a):** In buildings, a cost-benefit analysis is more sensitive to financial characteristics, such as the cost of carbon and cost of electricity, rather than to physical emissions characteristics.

We test H2.a, in two steps, First, we construct a cost-benefit NPV that just includes the SPC, taking into consideration the decarbonisation in electricity emission factor, analysis 4.

Second, we use the full Green Book cost-benefit model, which includes a discounted SPC, price of electricity, and cost of air quality damage, analysis 5.

Table 7-6 Indicators used for each analysis in this paper.

	Physical characteristics			Financial characteristics			
	Upfront emissions	Constant operational emissions scenario	Decarb operational emissions scenario	SPC simple	SPC discounted	Electricity price	Air quality costs
Payback gap							
Analysis 1	x	x		x			
Analysis 2	x	x		x			
Analysis 3	x		x		x		
NPV, cost-benefit							
Analysis 4	x		x		x		
Analysis 5	x		x		x	x	x
Stylized example							
Analysis 6	x		x		x	x	x

Lastly, we generalize H2.a to non-real estate situations, hypothesizing,

- **(H2.b):** In general, cost-benefit analysis is more sensitive to the cost of carbon and cost of electricity rather than physical emissions, in buildings.

To test H2.b, we use a stylized example from a scenario used in the UK Green Book. We add to the scenario upfront and ongoing characteristics and analyse the results to the cost-benefit analysis.

## 7.4. Empirical analysis

### 7.4.1. Analysis 1: Simple payback gap of physical and financial emissions

We begin with a simple payback analysis, only taking into consideration physical emissions and the SPC. Table 7-7 is a 75-year model of the total emissions of the Gradel Quadrangle, assuming a constant energy consumption and the carbon footprint of electricity remains the same. The embedded carbon is accounted in Year 0 (row A, E) and operational carbon in the year it is emitted (row B, F). The total carbon accumulated from ongoing operations is in row

Table 7-7 Carbon lock-in model till 2080 of the Gradel Quadrangle, for both actual and benchmark building.

Period	0	1	2	3	...	74	75
Year	2023	2024	2025	2026	...	2097	2098
<b>Actual building carbon model (tCO<sub>2</sub>e)</b>							
(A) Embedded carbon	2,778						
(B) Operational carbon		127	127	127	...	127	127
(C) Annual carbon emissions (A+B)	2,778	127	127	127	...	127	127
(D) Carbon lock-in (Cumulative)	2,778	2,905	3,032	3,159	...	12,191	12,319
<b>Benchmark building carbon model (tCO<sub>2</sub>e)</b>							
(E) Embedded carbon	2,137						
(F) Operational carbon		177	177	177	...	177	177
(G) Annual Carbon (E+F)	2,137	177	177	177	...	177	177
(H) Carbon lock-in (Cumulative)	2,137	2,314	2,490	2,667	...	15,215	15,391

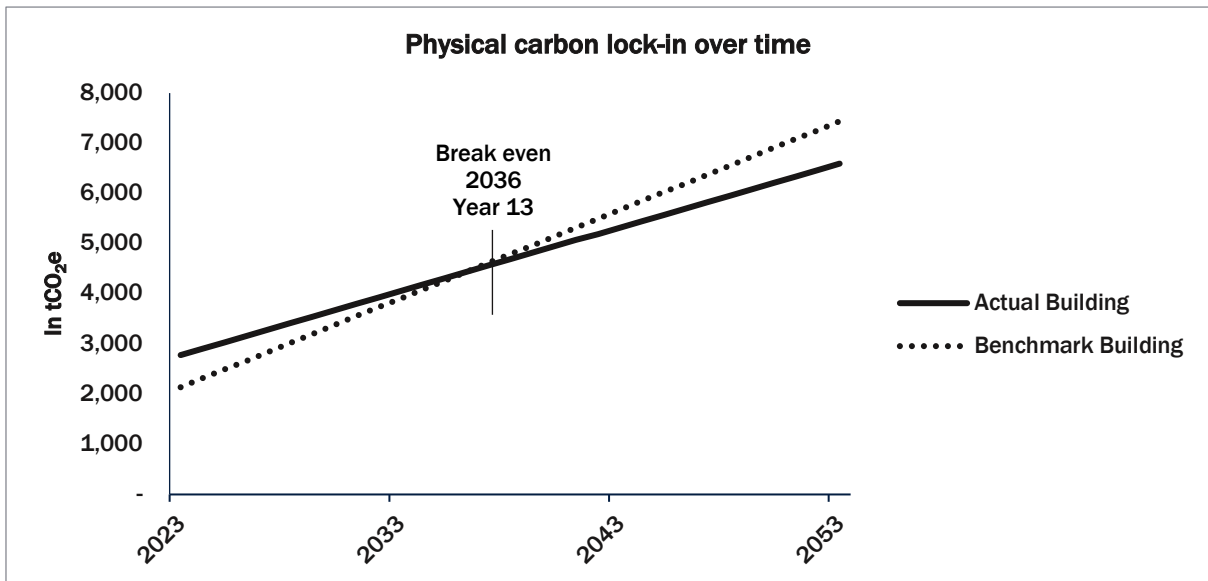


Figure 7-6 A chart depicting the simple payback of the physical carbon flow. The actual building has lower emissions after 2036, or 13 years after continuous operation.

D and H for the actual and benchmark building, respectively. By year 75, the actual building would have a lower footprint by 3,072 tCO<sub>2</sub>e.

The dynamic between the actual and benchmark building is depicted in Figure 7-6, showing the accumulation of carbon lock-in of each option over time. The simple payback of emissions for the actual building is 13 years, achieved in 2036. Until then, the actual building will be the higher total carbon option. The graph demonstrates how the choice between a Passivhaus and the benchmark building is a choice between emitting carbon upfront, during construction or in the future, during operations. If the structure had a lifetime of less than 13 years, following the UK building codes would be a better choice. However, if the structure is intended to have a lifetime of longer than 13 years, following a Passivhaus standard results in the lower carbon footprint.

To analyse the financial implications of the carbon options, we apply the UK SPC to the annual carbon emissions, as shown in Table 7-8. We multiple each year's physical emissions (Table 7-7 row C, G) with their respective cost of carbon (Table 7-8 row K). We then sum the cumulative costs in rows (M) and (O). To perform a sensitivity analysis, we repeat this analysis for low and high scenarios for the SPC. Figure 7-7 graphs the cumulative costs on an annual basis, illuminating the simple payback of the cost of carbon. In all three scenarios, actual building becomes financially the better option after 12 years of operations in 2035. This is because all three scenarios use the same discount rate, with their differences representing weights for uncertainty (UK DESNZ, 2023b), not different time-values of an event.

The analysis shows that the payback period of physical emissions does not equal the payback period for the cost of damage. The actual building is modelled to have lower economic damage one year before the physical emissions are lower. This implies that there is a 1-year period where the economic model is producing a 'false positive', or a situation where the financial model indicates an advantage before the physical model does. Although

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Table 7-8 The financial model for the cost of damage due to carbon emissions, using UK SPC central values. The same methodology is used to model other SPC values by replacing Line K with low and high scenarios.

Period Year	0 2023	1 2024	2 2025	...	74 2097	75 2098
<b>Cost of Carbon</b>						
(K) SPC Central (£2022/tCO <sub>2</sub> e)	£ 265	£ 269	£ 273	...	£ 800	£ 812
<b>Cost of damage, actual building</b>						
(L) SPC central x Annual carbon (K X C)	£ 736,170	£ 34,219	£ 34,727	...	£ 101,765	£ 103,292
(M) Cumulative cost of damage	£ 736,170	£ 770,389	£ 805,116	...	£ 5,335,586	£ 5,438,878
<b>Cost of damage, benchmark building</b>						
(N) SPC central x Annual carbon (K X G)	£ 566,285	£ 47,539	£ 48,246	...	£ 141,381	£ 143,502
(O) Cumulative cost of damage	£ 566,285	£ 613,824	£ 662,070	...	£ 6,956,188	£ 7,099,690

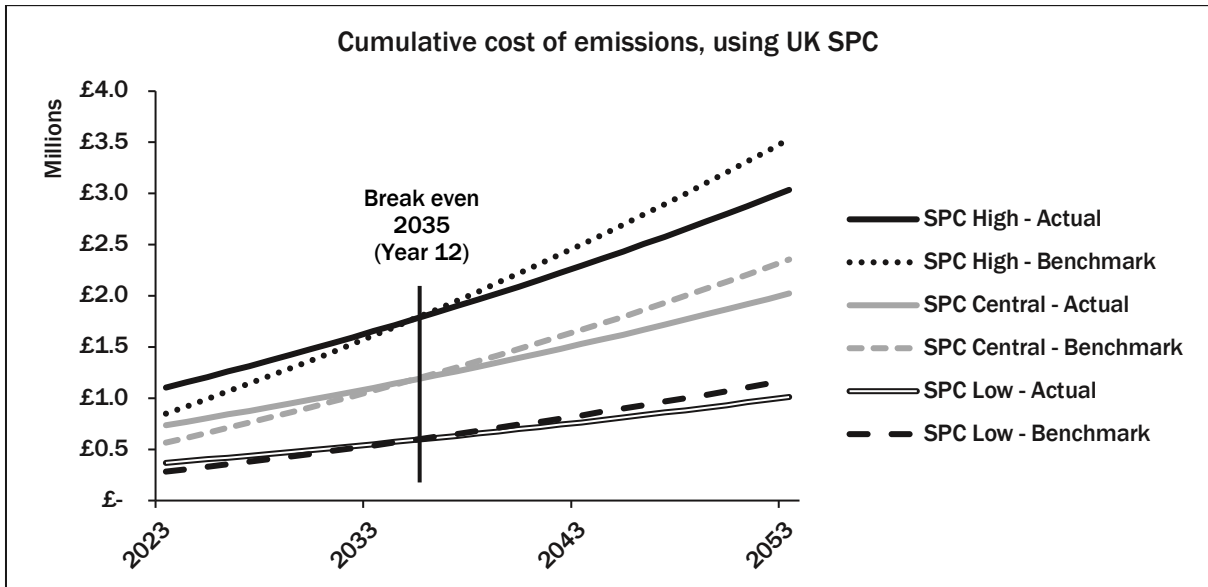


Figure 7-7 Simple payback of costs after applying the UK SPC to New College's emissions data. The actual building breaks even in year 12.

a 1-year gap is small. In our next analysis we investigate the sensitivity of the payback gap to different input variables.

### **7.4.2. Analysis 2: Sensitivity analysis of the payback gap**

To understand the dynamics of the analysis, we perform a sensitivity analysis of key indicators that can affect the payback gap. We examine the effects three variables – changing the upfront embedded energy, the ongoing operational energy, and the annual increase in SPC – on the duration of the payback gap. In 2023, the value of the central scenario is £264.93, with an annual increase of 1.522843% per year till 2040 and 1.5% increase each subsequent year afterwards (UK DESNZ, 2021). We begin by derive exact models for physical payback and economic damage payback before examining sensitivity.

#### *7.4.2.1. General formula for the payback of physical carbon emissions*

The payback time for physical carbon emissions can be found by setting the total carbon (TC) of the actual building equal to that of the benchmark building.

$$TC_{Actual}(t) = TC_{Benchmark}(t)$$

TC is a summation of upfront embedded carbon (EC) and cumulative operational carbon (OC) over time  $t$ . The OC is assumed to be a constant, so the only variable is time. The TC for the actual and benchmark buildings are thus,

$$TC_{Actual}(t) = EC_{Actual} + OC_{Actual}t$$

$$TC_{Benchmark}(t) = EC_{Benchmark} + OC_{Benchmark}t$$

Setting the two equations equal:

$$EC_{Actual} + OC_{Actual}t = EC_{Benchmark} + OC_{Benchmark}t$$

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Isolating time:

$$OC_{Actual}t - OC_{Benchmark}t = EC_{Benchmark} - EC_{Actual}$$

$$(OC_{Actual} - OC_{Benchmark})t = EC_{Benchmark} - EC_{Actual}$$

Solving for time:

$$t_{payback,physical} = \frac{EC_{Benchmark} - EC_{Actual}}{OC_{Actual} - OC_{Benchmark}} \quad \text{Equation 7-3}$$

We find that the time to achieve physical payback is a ratio of differences between embedded and operational carbon.

### 7.4.2.2. General formula for the payback of cost of damage of carbon emissions

The payback time for the economic cost of damages can be found by setting the total cost of damage (TCD) of the actual building equal to that of the benchmark building

$$TCD_{Actual}(t) = TCD_{Benchmark}(t)$$

The marginal cost of damage per year is found by multiplying the SCC value with that year's carbon emissions. For carbon values, the EC is used in the initial year and the OC(t) is used in subsequent years. We assume a constant OC, thus treating it as a coefficient.

$$\text{For the initial year: } EC \times SCC(0)$$

$$\text{For subsequent years: } OC \times SCC(t)$$

SCC(0) is the social cost of carbon in the initial year. SCC(t) increases each year,

$$SCC(t) = SCC(0)(1 + r)^t$$

where  $t$  is the time period, and  $r$  is the annual increase for the cost of damage. The total cost of damage is the sum of the cost of damage due to upfront embedded carbon and the cumulative cost of damage due to ongoing operational carbon.

$$TCD = EC \times SCC(0) + \sum_1^t OC \times SCC(t)$$

Substituting  $SCC(t)$ ,

$$TCD = EC \times SCC(0) + \sum_1^t OC \times SCC(0)(1+r)^t$$

The total cost of damage for the actual and benchmark buildings are:

$$TCD_{Actual}(t) = EC_{Actual} \times SCC(0) + \sum_1^t OC_{Actual} \times SCC(0)(1+r)^t$$

$$TCD_{Benchmark}(t) = EC_{Benchmark} \times SCC(0) + \sum_1^t OC_{Benchmark} \times SCC(0)(1+r)^t$$

Setting the two equations equal to each other:

$$\begin{aligned} EC_{Actual} \times SCC(0) + \sum_1^t OC_{Actual} \times SCC(0)(1+r)^t \\ = EC_{Benchmark} \times SCC(0) + \sum_1^t OC_{Benchmark} \times SCC(0)(1+r)^t \end{aligned}$$

Simplify by factoring out and dividing by  $SCC(0)$ :

$$EC_{Actual} + OC_{Actual} \sum_1^t (1+r)^t = EC_{Benchmark} + OC_{Benchmark} \sum_1^t (1+r)^t$$

Reorganise time to one side of the equation

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$$OC_{Actual} \sum_1^t (1+r)^t - OC_{Benchmark} \sum_1^t (1+r)^t = EC_{Benchmark} - EC_{Actual}$$

Factor the time term:

$$\sum_1^t (1+r)^t \times [OC_{Actual} - OC_{Benchmark}] = EC_{Benchmark} - EC_{Actual}$$

The general formula for payback is

$$\sum_1^{t_{Payback,SCC}} (1+r)^t = \frac{EC_{Benchmark} - EC_{Actual}}{OC_{Actual} - OC_{Benchmark}} \quad \text{Equation 7-4}$$

We see that the payback time of economic damage is related to the annual rate of increase  $r$  and the differences between embedded and operational carbon of the actual and benchmark buildings.

The payback gap can be represented as:

$$Payback\ Gap = t_{payback,physical} - t_{payback,sc} \quad \text{Equation 7-5}$$

As Equation 7-3 and Equation 7-4 shows, the simple payback for physical emissions is a constant value based on physical values, while the simple payback of the costs of carbon is an exponential function due to an annual increase in the SCC.

### 7.4.2.3. Results of the sensitivity analysis of a continuous function.

We performed a sensitivity analysis of  $EC_{Actual}$  and  $OC_{Actual}$ . We varied the physical variables in increments of 5% to evaluate their relative change. We also evaluated each variable for a one standard deviation (std dev) change, to account for the variable's normal variations. We used the real estate surveys that found EC and OC to have standard deviations of roughly 30% (Asensio & Delmas, 2017; Simonen et al., 2017). We also varied the annual increase  $r$ .

For the purpose of this calculation, we assumed that a standard deviation of the annual increase to be similar to that of the discount rate, or 1.62% (Drupp et al., 2018).

The sensitivity analysis shows that the payback gap is more sensitive to physical indicators than financial indicators by an order of magnitude (Table 7-9). The 1-year gap result from the previous section can be seen as the base case of the sensitivity analysis. A one std dev increase in EC results in 345% increase in the payback gap to 5.34 years and a similar increase in OC results in a 1221% increase in the payback gap to 15.86 years. However, a

**Table 7-9 Sensitivity analysis of the continuous function payback gap for (A) Embedded carbon of actual building (B) Operational carbon of actual building and (C) Rate of annual increase to SCC**

<b>(A) Sensitivity to embedded carbon, <math>EC_{Actual}</math></b>					
Input: Embedded carbon		Years to payback		Output: Payback gap	
% Input sensitivity	tCO <sub>2</sub> e	$t_{payback,physical}$	$t_{payback,SCC}$	Years	% Output sensitivity
(+1 std dev) 30%	3,611	29.78	24.43	5.34	345%
10%	3,056	18.56	16.25	2.31	92%
5%	2,917	15.75	14.03	1.72	43%
(Base case) 0%	2,778	12.95	11.75	1.20	0%
- 5%	2,639	10.14	9.37	0.77	-36%
- 10%	2,500	7.34	6.91	0.43	-65%
(-1 std dev) - 30%	1,945	- 3.88	- 3.97	N/A	N/A

<b>(B) Sensitivity to operational carbon, <math>OC_{Actual}</math></b>					
Input: Operational carbon		Years to payback		Output: Payback gap	
% Input sensitivity	tCO <sub>2</sub> e	$t_{payback,physical}$	$t_{payback,SCC}$	Years	% Output sensitivity
(+1 std dev) 30%	165	56.44	40.58	15.86	1221%
10%	140	17.42	15.36	2.06	72%
5%	134	14.85	13.31	1.55	29%
(Base case) 0%	127	12.95	11.75	1.20	0%
- 5%	121	11.47	10.50	0.97	-19%
- 10%	114	10.30	9.51	0.79	-34%
(-1 std dev) - 30%	89	7.31	6.88	0.43	-64%

<b>(C) Sensitivity of annual increase <math>r</math>, to the SPC</b>					
Input: Annual increase $r$		Years to payback		Output: Payback gap	
% Input sensitivity	$r$	$t_{payback,physical}$	$t_{payback,SCC}$	Years	% Output sensitivity
(+1 std dev) 106%	3.1428%	12.95	10.7484	2.20	83%
10%	1.6751%	12.95	11.6412	1.30	9%
5%	1.5990%	12.95	11.6931	1.25	4%
(Base case) 0%	1.5228%	12.95	11.75	1.20	0%
-5%	1.4467%	12.95	11.7987	1.15	-4%
10%	1.3706%	12.95	11.8525	1.09	-9%
(-1 std dev) -100%	0.0000%	12.95	12.9500	0.00	-100%

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one std dev increase in the annual rate of increase to SPC only results in an 83% increase in the payback gap, to 2.2 years. Therefore, analysis 2 shows that the payback gap is highly sensitive to physical attributes.

Our results show that the payback gap is highly sensitive to physical changes and less sensitive to economic changes. A one std dev increase of embedded carbon increases the payback gap to 5.3 years, or 345%. A similar increase in operational carbon increases the payback gap to 18.86 years, or 1,221% increase. However, a one std dev increase of annual increase  $r$  only results in an 83% increase of the payback gap, to 2.2 years. When normalising for statistical variations, one std dev change of physical emissions have a much larger effect than the high and low scenarios for the annual increase. Figure 7-8 depicts the input and output sensitivity trends for the three variables.

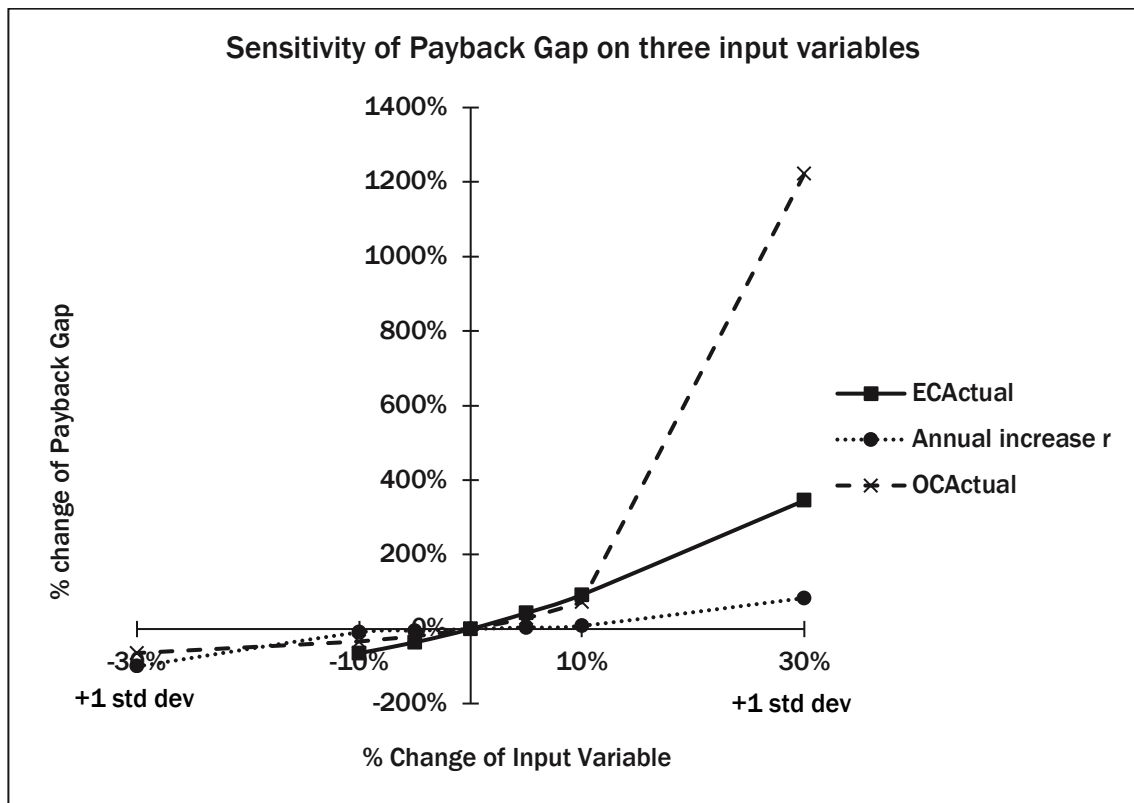


Figure 7-8 Spider chart of the sensitivity of the payback gap. The physical characteristics ( $EC_{Actual}$  and  $OC_{Actual}$ ) are more sensitive than the annual increase rate ( $r$ )

### 7.4.3. Analysis 3: Discounted payback gap and adding electric grid emission factors

We now add the expected decarbonisation of the UK grid and perform a discounted payback to the above analysis of physical emissions and SPC. Because the UK grid is on a decarbonisation pathway, the electricity consumed in the future will have a lower carbon footprint than today's consumption (UK DESNZ, 2023b). The Gradel Quadrangle consumes only electricity as its source of energy, for heating, cooling, ventilation, and plug loads. As a result, changes to the emission factor of the grid greatly affects the physical payback period.

As shown in Table 7-10, the operational energy of the Passivhaus building is 667,971 kWh/yr, as compared to a UK benchmark of 1,144,770 kWh/yr, found from documentation of the building's energy model. This represents a savings of 476,798 kWh/yr from the benchmark building. We assumed a 75-year lifetime for the building, aligning the analysis to the depreciation policy of New College. We applied the UK SPC central scenario and calculate the NPV of carbon emissions. We also used the Green Book default discount rate, which starts at 3.5% for the first 30 years, dropping to 3.0% between years 31 to 75, and to 2.5% beyond year 75.

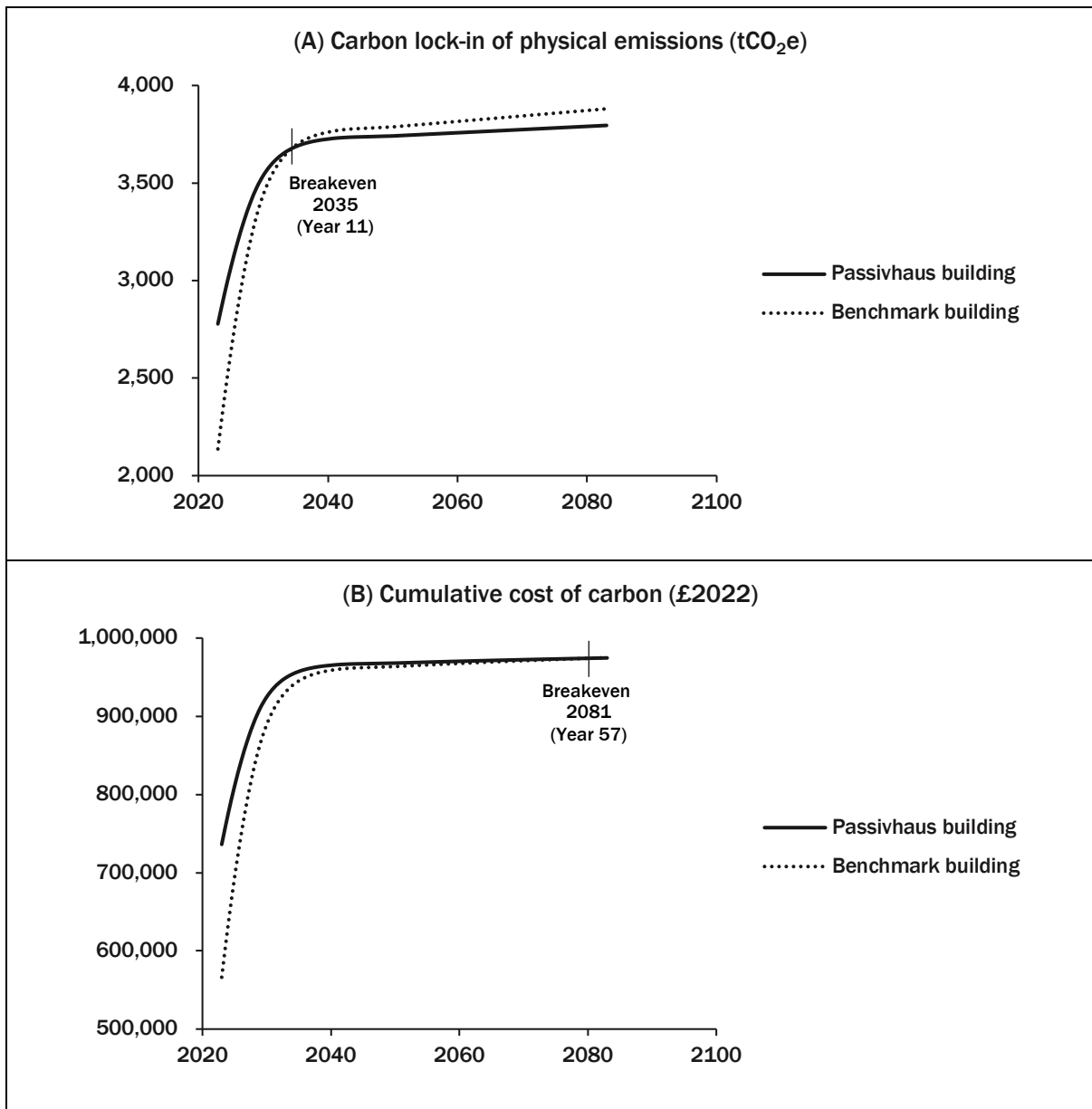
*Table 7-10 Input values for modelling the valuation of carbon emissions*

<b>Actual building (Passivhaus option)</b>	
Embedded carbon (EC <sub>Actual</sub> )	2,778 tCO <sub>2e</sub>
Operational energy (OE <sub>Actual</sub> ):	667,971 kWh/yr
<b>Benchmark building (UK benchmark)</b>	
Embedded carbon (EC <sub>Benchmark</sub> ):	2,136 tCO <sub>2e</sub>
Operational energy (OE <sub>Benchmark</sub> ):	1,144,770 kWh/yr
Building lifetime:	75 years (2023 – 2098)
Green Book default discount rate (d):	( < 30 years) 3.5% ( 31-75 years) 3.0% ( 75 years >) 2.5%

Table 7-11 Using SPC to model the value of emissions per year

Period Year	0 2023	1 2024	2 2025	3 2026	...	75 2098
<b>[A] Default values from UK Greenbook</b>						
[B] Electricity emission factor (kgCO <sub>2e</sub> /kWh)	0.24	0.23	0.21	0.19	...	0.0025
[C] UK SPC (£2022/tonne)	265	269	273	277	...	812
<b>[D] Discount rates</b>						
[E] Initial discount rate ( < 30 years)	3.50%					
[F] Middle discount rate (31 - 75 years)	3.00%					
[G] Long-term discount rate (75 years < )	2.50%					
[H] Annual discount rate (%)	0	3.5%	3.5%	3.5%	...	2.5%
[J] Discount Factor	1.00	0.97	0.93	0.90	...	0.10
<b>[K] Input: Ongoing operational energy (kWh)</b>						
[L] Passivhaus		667,972	667,972	667,972	...	667,972
[M] Benchmark building		1,144,770	1,144,770	1,144,770	...	1,144,770
<b>[N] Annual Physical Carbon Emissions (tCO<sub>2e</sub>)</b>						
[O] Passivhaus Carbon	2,778	151	138	125	...	1.64
[P] Benchmark Carbon	2,137	258	237	214	...	2.81
<b>[Q] Annual Cost of Carbon (Discounted)</b>						
[R] Passivhaus cost of carbon	£ 736,170	£ 39,194	£ 35,269	£ 31,245	...	£ 127
[S] Benchmark cost of carbon	£ 566,285	£ 67,171	£ 60,445	£ 53,548	...	£ 217
<b>[T] Simple payback, physical emissions (tCO<sub>2e</sub>)</b>						
[U] Cumulative Passivhaus emissions	2,778	2,929	3,067	3,192	...	3,820
[V] Cumulative benchmark emissions	2,137	2,395	2,633	2,847	...	3,923
[W] Years to break even	11 (2035)					
<b>[X] Discounted payback, cost of carbon</b>						
[Y] Cumulative Passivhaus cost of carbon	£ 736,170	£ 775,364	£ 810,633	£ 841,879	...	£ 976,697
[Z] Cumulative benchmark cost of carbon	£ 566,285	£ 633,455	£ 693,900	£ 747,448	...	£ 978,499
[AA] Years to break even	57 (2081)					

Table 7-11 depicts the model. We first calculated the ongoing energy consumption for both the Passivhaus [Row L] and the benchmark building [Row M] out till 2098. We then multiply the energy consumed by the electricity emissions factor [Row B], to calculate annual carbon emissions [Rows O and P]. We then multiply the cost of carbon [Row C] to calculate the annual cost of carbon. To calculate physical payback [Row T], we compare the cumulative emissions for the Passivhaus and the benchmark building. The payback year is 11<sup>th</sup> year of operation, or 2035. To calculate the financial payback, [Row X], we compare the cumulative cost of carbon for the Passivhaus and the benchmark building. The payback year is 57<sup>th</sup> year of operation, or 2081. Figure 7-9 shows the two payback profiles, showing how the emissions profile for the building flattens out by the 2040's due to the decarbonization of the electric grid of the UK. Although the passive structure becomes the lower emissions option by year 11 (2035), it does not achieve a cost of carbon payback until year 57 (2081). This indicates a false negative for 46 years, where the physical emission of the actual building is modelled to be lower, but the costs are modelled to be higher.



*Figure 7-9 Cumulative graphs of (A) physical carbon lock-in and (B) cost of carbon for actual and benchmark models. Note that the year of achieving payback is different by 46 years.*

There are several implications. First, the physical and financial models are aligned in the long term. In our example, for time periods longer than 57 years, the two models agree that the Passivhaus is the lower carbon option. However, prior to that, the financial and physical model disagrees as to whether the Passivhaus or benchmark building is the lower carbon choice. The disagreement in payback period hinders decision maker's ability to determine when it is viable to perform retrofits or additional work. For a carbon optimizer, that choice is in year 11, but for a cost optimizer, that choice is in year 57. Given that both physical

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emission indicators and financial cost of emission indicators are used in modelling real estate assets, having the models differ by several decades is a challenge.

Further, the analysis is also subject to sensitivity of physical measurements. We calculated that a 4% increase of embedded carbon or a 10% increase of operational carbon means the Passivhaus option will never payback relative to the benchmark building. Both values are well within the 30% variance of one standard deviation of embedded or operational emissions. Thus, when relying on industry averages, it is indeterminate whether an average Passivhaus is better than an average benchmark building.

In summary, analysis 1, 2, and 3 shows that hypothesis H1 to be false. Analysis 1 showed that financial and physical emissions models diverge and analysis 2 showed that the sensitivities to physical emission assumptions are far greater than to financial cost of damage assumptions. Further, analysis 3 shows that this holds true, even after adding the expected decarbonisation pathway of the UK.

### **7.4.4. Analysis 4: NPV of SPC, with electricity emission factors**

We now vary the physical emissions characteristics and analyse its effects on the carbon lock-in and NPV of carbon costs. The results are presented in Table 7-12. A positive emissions value represents net additional emissions and a positive NPV indicates net economic damage. Panel A varies the upfront embedded emissions in increments of 5%, as well as in increment of a std dev. Panel B varies the ongoing operational energy, and thereby their associated emissions, by the same increments. A 5% increase of upfront emissions results in the actual building never paying off, having a higher carbon lock-in of 36.3 tCO<sub>2e</sub>. One reason is because the anticipated decrease of grid emission factors in the next decade means that consuming energy in the future is going to have a lower carbon impact than consuming energy today. Therefore, future operational carbon savings are not enough to negate the additional carbon emissions today. The change in the NPV of the cost of carbon

is even larger. A one std dev increase of EC results in a 17,678% increase of NPV damage. Similarly, in Table 7-12(B) a 10% increase in operational energy results in the actual building never paying off, having a higher carbon lock-in of 1.6 tCO<sub>2e</sub>.

**Table 7-12 Sensitivity analysis with SPC added to the model. (A) embedded carbon, (B) operational energy, and (C) the discount rate. Positive carbon lock-in represents additional carbon emitted. Positive NPV represents additional damage.**

<b>(A) Sensitivity to embedded carbon, <math>EC_{Actual}</math></b>					
Input: $EC_{Actual}$		Output: Difference in carbon lock-in		Output: Difference in cost of carbon	
% Input sensitivity	tCO <sub>2e</sub>	tCO <sub>2e</sub>	% Output sensitivity	NPV (£2022)	% Output sensitivity
(+1 std dev) 30%	3,611	730.8	812%	£ 219,602	17,678%
10%	3,056	175.2	271%	£ 72,368	5,893%
5%	2,917	36.3	135%	£ 35,559	2,946%
(Base case) 0%	2,778	-102.6	0%	-£ 1,249	0%
-5%	2,639	-241.5	-135%	-£ 38,058	-2,946%
-10%	2,500	-380.4	-271%	-£ 74,866	-5,893%
(-1 std dev) -30%	1,945	-936.0	-812%	-£ 222,100	-17,678%

<b>(B) Sensitivity to operational energy, <math>OE_{Actual}</math></b>					
Input: $OE_{Actual}$		Output: Difference in carbon lock-in		Output: Difference in cost of carbon	
% Input sensitivity	kWh	tCO <sub>2e</sub>	% Output sensitivity	NPV (£2022)	% Output sensitivity
(+1 std dev) 30%	868,364	209.9	305%	£ 70,676	5,757%
10%	734,769	1.6	102%	£ 22,726	1,919%
5%	701,371	-50.5	51%	£ 10,738	960%
(Base case) 0%	667,972	-102.6	0%	-£ 1,249	0%
-5%	634,573	-154.7	-51%	-£ 13,237	-960%
-10%	601,175	-206.8	-102%	-£ 25,225	-1,919%
(-1 std dev) -30%	467,580	-415.2	-305%	-£ 73,175	-5,757%

<b>(C) Sensitivity of discount rate <math>d</math></b>					
Input: Discount rate		Output: Difference in carbon lock-in		Output: Difference in cost of carbon	
% Input sensitivity	$d$	tCO <sub>2e</sub>	% Output sensitivity	NPV (£2022)	% Output sensitivity
(+1 std dev) 46%	5.12%	-102.6	0.0%	£ 13,348	1,168%
10%	3.85%	-102.6	0.0%	£ 2,250	280%
5%	3.68%	-102.6	0.0%	£ 529	142%
(Base case) 0%	3.50%	-102.6	0.0%	-£ 1,249	0%
-5%	3.33%	-102.6	0.0%	-£ 3,088	-147%
-10%	3.15%	-102.6	0.0%	-£ 4,993	-300%
(-1 std dev) -46%	1.88%	-102.6	0.0%	-£ 21,330	-1,607%

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We compare the sensitivity of physical characteristics to the sensitivity to varying the discount rate. We use 1.62% as the standard deviation of discount rates, as determined by a study that conducted a survey of expert economists (Drupp et al., 2018). This value represented a 46% change of the discount rate from the base case. As Table 7-12(C) shows, changing the discount rate does not have an effect of the physical emissions of the building as it affects the economic outcomes. A 5% change of the discount rate can have a 100% change in the NPV of the cost of carbon. Further, a one std dev change of EC and OC results in 17,678% and 5,757% change in the NPV, while a one std dev change of the discount rate only results in a 1,158% change in NPV. Due to the high sensitivity to physical emissions within a single standard deviation, it is difficult to conclude whether a Passivhaus is a lower emissions option. Having measured emissions data for a building is important to being able to make such a determination.

### **7.4.5. Analysis 5: The full Green Book model**

As shown in Figure 7-1, the full Green Book model includes the cost of electricity and the net change in air quality benefit in the NPV calculation. Because the toolkit is designed for marginal decision making, we calculated the increase in upfront emissions due to constructing to a Passivhaus standard and the decrease in energy consumption over the lifetime of the building. Table 7-13 depicts the construction of input values used for sensitivity analysis. We calculated the difference in EC between benchmark and actual building (Panel A). Because the toolkit only accepts energy values for input, the difference in EC was converted to an energy value using the emissions factor for electricity in 2023. For operational energy, Panel B takes the modelled energy footprint from the design model of the Gradel Quadrangle and varied the modelled energy for the actual building.

**Table 7-13 Deriving the input values for a full Green Book model sensitivity analysis. The difference in upfront carbon needs to be first converted to upfront energy for input into the model.**

<b>(A) For determining range of embedded carbon</b>					
Input sensitivity %	EC <sub>Benchmark</sub> (tCO <sub>2e</sub> )	EC <sub>Actual</sub> (tCO <sub>2e</sub> )	Difference in EC (tCO <sub>2e</sub> )	Conversion to energy in 2023 (kgCO <sub>2e</sub> /kWh)	Input to sensitivity analysis for increase in upfront energy (GWh)
(+1 std dev) 30%	2137	3,611.4	1,474.4	0.24305	6.066
10%		3,055.8	918.8		3.780
5%		2,916.9	779.9		3.209
(Base Case) 0%		2,778.0	641		2.637
- 5%		2,639.1	502.1		2.066
- 10%		2,500.2	363.2		1.494
(-1 std dev) - 30%		1,944.6	- 192.4		- 0.791
<b>(B) For determining range of operational carbon values</b>					
Input sensitivity %	OC <sub>Benchmark</sub> (kWh)	OC <sub>Actual</sub> (kWh)	Input to sensitivity analysis for decrease in in OC (GWh)		
(+1 std dev) 30%	1,144,770	868,362	- 0.276408		
10%		734,768	- 0.410002		
5%		701,370	- 0.443400		
(Base Case) 0%		667,971	- 0.476799		
- 5%		634,572	- 0.510198		
- 10%		601,174	- 0.543596		
(-1 std dev) - 30%		467,580	- 0.677190		

Table 7-14 shows the results of the sensitivity analysis. In comparing to Table 7-12, adding electricity prices and air quality benefits did not change the physical effects of emissions but the NPV sensitivities were reduced. However, despite these changes, the sensitivity to physical characteristics due to one standard deviation of change is still greater than that to changing the discount rate. Further, the built-in sensitivity analysis of energy and SPC scenarios are even smaller than one standard deviation change to the input variables.

Analysis 4 and 5 has shown hypothesis H2a to be false. When modelling NPV and cost benefit analysis, we have shown how NPV is more sensitive to physical attributes of embedded and operational carbon than to financial attributes of electricity and carbon prices.

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Table 7-14 Sensitivity analysis of the full UK Green Book model, on the performance difference between actual and benchmark buildings. Sensitivities evaluated for (A) Upfront emissions (B) Ongoing emissions (C) discount rate and built in scenarios for (D) electricity prices and (E) SPC prices.

<b>(A) Change to upfront emissions EC<sub>Actual</sub></b>					
Input: Change in upfront energy		Output: Difference in carbon lock-in		Output: Difference in NPV	
% Input sensitivity	GWh	tCO <sub>2</sub> e	% Output sensitivity	(£2022)	% Output sensitivity
(+1 std dev) 30%	6.07	730.70	- 811%	£396,242	- 60.43%
10%	3.78	175.10	- 270%	£799,698	- 20.14%
5%	3.21	36.20	- 135%	£900,562	- 10.07%
(Base Case) 0%	2.64	- 102.70	0%	£1,001,426	0.00%
- 5%	2.07	- 241.60	135%	£1,102,290	10.07%
- 10%	1.49	- 380.50	270%	£1,203,154	20.14%
(-1 std dev) - 30%	-0.79	- 936.10	811%	£1,606,610	60.43%

<b>(B) Change to ongoing emissions OC<sub>Actual</sub></b>					
Input: Change in ongoing energy		Output: Difference in carbon lock-in		Output: Difference in NPV	
% Input sensitivity	GWh	tCO <sub>2</sub> e	% Output sensitivity	(£2022)	% Output sensitivity
(+1 std dev) 30%	- 0.276	209.86	- 304%	£384,912	- 61.56%
10%	- 0.410	1.49	- 101%	£795,921	- 20.52%
5%	- 0.443	- 50.61	- 51%	£898,673	- 10.26%
(Base Case) 0%	- 0.477	- 102.70	0%	£1,001,426	0.00%
- 5%	- 0.510	- 154.80	51%	£1,104,178	10.26%
- 10%	- 0.544	- 206.89	101%	£1,206,930	20.52%
(-1 std dev) - 30%	- 0.677	- 415.27	304%	£1,617,940	61.56%

<b>(C) Change to discount rate d</b>					
Input: Change to discount rate		Output: Difference in carbon lock-in		Output: Difference in NPV	
% Input sensitivity	d	tCO <sub>2</sub> e	% Output sensitivity	(£2022)	% Output sensitivity
(+1 std dev) 46%	5.12%	- 102.6	0%	£610,173	-39.07%
10%	3.85%	- 102.6	0%	£896,400	-10.49%
5%	3.68%	- 102.6	0%	£947,161	-5.42%
(Base case) 0%	3.50%	- 102.6	0%	£1,001,426	0.00%
- 5%	3.33%	- 102.6	0%	£1,059,508	5.80%
- 10%	3.15%	- 102.6	0%	£1,121,753	12.02%
(-1 std dev) - 46%	1.88%	- 102.6	0%	£1,739,820	73.73%

<b>(D) Sensitivity to electricity prices (using Central SPC Scenario)</b>		
Input: Electricity price scenarios	Output: NPV of Benefits	% Output sensitivity
High scenario	£ 1,144,649	14.25%
Central scenario	£ 1,001,893	0.00%
Low scenario	£ 967,024	- 3.48%

<b>(E) Sensitivity to SPC scenarios (using Central Energy Prices Scenario)</b>		
Input: SPC scenarios	Output: NPV of Benefits	% Output sensitivity
High scenario	£ 1,003,182	0.13%
Central scenario	£ 1,001,893	0.00%
Low scenario	£ 1,001,366	- 0.05%

### 7.4.6. Analysis 6: A comparative case study

Finally, we investigate whether the characteristics identified in this study can be generalised to other decarbonisation policies that use the UK Green Book, or whether it is an artifact of the specific dataset used in this analysis, namely the carbon values of the Gradel Quadrangle as a Passivhaus structure. This addresses hypothesis H2b, generalizing the Passivhaus analysis to a broader category of carbon policies that may be pursued by the government.

We therefore perform a stylised sensitivity analysis of the Green Book toolkit using the scenario described in Box 3.5 of the HM Treasury guidance documentation (UK DESNZ, 2023b); specifically, a household energy efficiency programme. This programme assumes it achieves a 10 GWh reduction of household consumption relative to business-as-usual option between 2023 and 2043. As per the Green Book, the upfront emissions emitted to achieve this savings does not have to be considered as this is a marginal reduction. However, for completion, we model both zero (0) GWh and 60 GWh for embedded energy, and its associated embedded carbon. The duration of the Passivhaus was 75 years while that of the energy efficiency scenario is 11 years. In both scenarios, the Green Book default discount rate was used. Table 7-15 are input values for both the Passivhaus example used so far as well as the energy efficiency programme.

*Table 7-15 Comparison of the Passivhaus Example and Example 3.5 of the Green Book guidance documentation (UK DESNZ, 2023b).*

	Passivhaus example	Green Book Box 3.5 example
Additional upfront embedded energy	2.637 GWh	0 GWh and 60 GWh (*none specified)
Reduction in operational energy per year	0.477 GWh	10 GWh
Duration	75 years	11 years

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As shown in Table 7-16, a percentage change to the operational energy savings assumption results in the same percentage change to the outputs (Panel A). However, sensitivity to the discount rate is smaller, where a 40% change to the discount rate, or one std dev, results in a 12% change in the NPV (Panel B). However, a one std dev change of both ongoing carbon (Panel A) and discount rates (Panel B) are larger than the built-in sensitivity analysis scenarios for energy prices (Panel C) and SPC (Panel D).

**Table 7-16 Sensitivity analysis of Green Book example without upfront emissions. Unless indicated, central electricity and SPC scenarios were used.**

<b>(A) Sensitivity to ongoing operational carbon</b>					
Input: Reduction of energy		Output: Net emissions		Output: NPV of benefits	
% Input sensitivity	GWh	tCO <sub>2e</sub>	% Output sensitivity	(£2022)	% Output sensitivity
(+1 std dev) 30%	- 13.0	- 22,172	30.0%	£ 31,502,169	30.0%
10%	- 11.0	- 18,761	10.0%	£ 26,655,682	10.0%
5%	- 10.5	- 17,908	5.0%	£ 25,444,060	5.0%
(Base case) 0%	- 10.0	- 17,055	0.0%	£ 24,232,438	0.0%
- 5%	- 9.5	- 16,202	- 5.0%	£ 23,020,816	- 5.0%
- 10%	- 9.0	- 15,350	- 10.0%	£ 21,809,194	- 10.0%
(-1 std dev) - 30%	- 7.0	- 11,939	- 30.0%	£ 16,962,706	- 30.0%

<b>(B) Sensitivity to discount rate</b>					
Input: Chance in discount rate		Output: Net emissions		Output: NPV of benefits	
% Input sensitivity	d %	tCO <sub>2e</sub>	% Output sensitivity	(£2022)	% Output sensitivity
(+1 std dev) 46%	5.12%	- 17,055	0.0%	£ 21,290,951	- 12.14%
10%	3.85%	- 17,055	0.0%	£ 23,543,330	- 2.84%
5%	3.68%	- 17,055	0.0%	£ 23,883,897	- 1.44%
(Base case) 0%	3.50%	- 17,055	0.0%	£ 24,232,438	0.00%
- 5%	3.33%	- 17,055	0.0%	£ 24,589,185	1.47%
- 10%	3.15%	- 17,055	0.0%	£ 24,954,380	2.98%
(-1 std dev) - 46%	1.88%	- 17,055	0.0%	£ 27,881,870	15.06%

<b>(C) Sensitivity to electricity price scenarios (using Central SPC Scenario)</b>		
Input: Energy scenarios	Output: NPV of benefits	% Output sensitivity
High scenario	£ 30,831,856	27.2%
Central scenario	£ 24,232,438	0.0%
Low scenario	£ 21,006,736	- 13.3%

<b>(D) Sensitivity to SPC scenarios (using Central Energy Prices Scenario)</b>		
Input: SPC scenarios	Output: NPV of benefits	% Output sensitivity
High scenario	£ 26,248,474	8.3%
Central scenario	£ 24,232,438	0.0%
Low scenario	£ 22,216,533	- 8.3%

Finally, we add an assumption for upfront energy, of 60 GWh, needed to achieve the energy efficient outcome. This could be additional embedded energy due to the manufacture of improved energy efficient devices. As the results show in Table 7-17 (Panel A), the upfront emissions assumption reduces the overall emissions savings of the base case from 17,055 tCO<sub>2</sub>e to 1,217 tCO<sub>2</sub>e. It also reduces the NPV of total benefits from £24.2m to £3.32m. However, the sensitivity to changes of physical emissions increases. A one std dev increase of upfront emissions results in a net total emission of 3,534 tCO<sub>2</sub>e increase to atmospheric emissions, negating the effects of the energy reduction. This brings the total NPV of benefits to –£2.95m. A similar result occurs when varying operational assumptions (Table 7-17 Panel B). A one std dev decrease in annual savings, to 7 GWh, results in a net total emission of 3,899 tCO<sub>2</sub>e, or a negative benefit of –£3.95m.

Panel C shows how one std dev increase of the discount rate only results in a change of 88.5%, less than the sensitivity to changes in the physical attributes. This confirms the finding that physical emissions have a larger effect on carbon calculations than financial assumptions. Further, the built-in sensitivity tools of the toolkit continue to result in smaller changes than the sensitivity to physical characteristics or the discount rate.

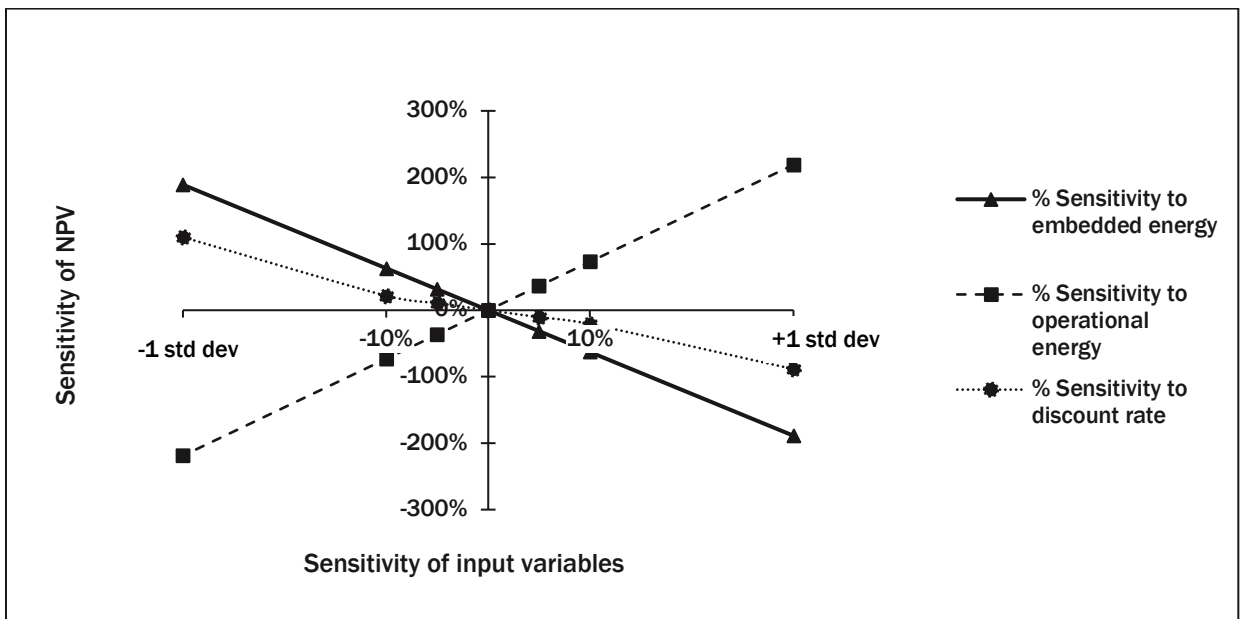


Figure 7-10 Sensitivity of NPV to embedded energy, operational energy, and discount rate

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Table 7-17 Sensitivity analysis of Green Book example *with* upfront emissions. Unless indicated, central electricity and SPC scenarios were used.

<b>(A) Sensitivity to upfront embedded carbon (Central electricity and SCP scenarios)</b>					
Input: Change to upfront energy		Output: Net emissions		Output: NPV of benefits	
% Input sensitivity	GWh	tCO <sub>2</sub> e	% Output sensitivity	NPV	% Output sensitivity
(+1 std dev) 30%	78.0	3,534	- 390.35%	- £ 2,950,816	- 188.82%
10%	66.0	367	- 130.12%	£ 1,231,223	- 62.94%
5%	63.0	- 425	- 65.06%	£ 2,276,733	- 31.47%
0%	60.0	- 1,217	0.00%	£ 3,322,243	0.00%
- 5%	57.0	- 2,009	65.06%	£ 4,367,753	31.47%
- 10%	54.0	- 2,801	130.12%	£ 5,413,262	62.94%
(-1 std dev) - 30%	42.0	- 5,969	390.35%	£ 9,595,301	-218.82%

<b>(B) Sensitivity to savings of operational energy (Central electricity and SCP scenarios)</b>					
Input: Change to ongoing energy		Output: Net emissions		Output: NPV of benefits	
% Input sensitivity	GWh	tCO <sub>2</sub> e	% Output sensitivity	NPV	% Output sensitivity
(+1 std dev) 30%	- 13.0	- 6,334	420.35%	£ 10,591,974	218.82%
10%	- 11.0	- 2,923	140.12%	£ 5,745,487	72.94%
5%	- 10.5	- 2,070	70.06%	£ 4,533,865	36.47%
0%	- 10.0	- 1,217	0.00%	£ 3,322,243	0.00%
- 5%	- 9.5	- 364	- 70.06%	£ 2,110,621	- 36.47%
- 10%	- 9.0	488	- 140.12%	£ 898,999	- 72.94%
(-1 std dev) - 30%	- 7.0	3,899	- 420.35%	- £ 3,947,488	- 218.82%

<b>(C) Sensitivity to discount rate</b>					
Input: Change to discount rate		Output: Net emissions		Output: NPV of benefits	
% Input sensitivity	d %	tCO <sub>2</sub> e	% Output sensitivity	NPV	% Output sensitivity
(+1 std dev) 46%	5.12%	- 1,217	0.00%	£ 380,756	- 88.54%
10%	3.85%	- 1,217	0.00%	£ 2,633,135	- 20.74%
5%	3.68%	- 1,217	0.00%	£ 2,973,702	- 10.49%
(Base case) 0%	3.50%	- 1,217	0.00%	£ 3,322,243	0.00%
- 5%	3.33%	- 1,217	0.00%	£ 3,678,990	10.74%
- 10%	3.15%	- 1,217	0.00%	£ 4,044,185	21.73%
(-1 std dev) - 46%	1.88%	- 1,217	0.00%	£ 6,971,675	109.85%

<b>(D) Sensitivity to electricity price scenarios</b>		
Input: Electricity price scenarios	Output: NPV of benefits	% Output sensitivity
High scenario	£ 9,907,183	198.2%
Central scenario	£ 3,322,243	0.0%
Low scenario	£ 92,479	- 97.2%

<b>(E) Sensitivity to SPC</b>		
Input: SPC scenarios	Output: NPV of benefits	% Output sensitivity
High scenario	£ 3,279,365	4.41%
Central scenario	£ 3,322,243	0.00%
Low scenario	£ 3,381,091	- 4.22%

Hypothesis H2b stated that cost-benefit analysis would be more sensitive to cost of electricity and cost of carbon as compared to embedded and operational carbon. This has proven to be false. Analysis 6 found that the cost of electricity has the same order of magnitude sensitivity as embedded and ongoing physical emissions. The sensitivity to cost of carbon was less than that of physical attributes.

## **7.5. Implications**

This paper showed how models of physical emissions and financial cost of damage do not converge. The divergence is a critical one, as entities, such as the UK government is subject to both policies that affect physical emissions (net zero buildings policies) and the cost of damage (climate change policies). The implication is that to a decision maker, some decisions can vary by decades, depending on which model one follows. This demonstrates that there is a misalignment of policy-level indicators when applying to project-level decision making. Because of the misalignment, the government should clarify if the climate policy is to minimize cost of emissions damage, or minimize physical emissions into the atmosphere. This will indicate which set of decision indicators will follow. The government can also support research that closes the gap between the two models, thus aligning physical and financial climate scenarios.

At the project level, for net zero decision makers in both business and policy, this paper also showed the importance of temporal attributes in managing total carbon emissions of buildings in the real estate sector. Some of the options can take decades for the emissions to break even. As buildings are long term assets, decision made today can lock-in a long tail of emissions. If a building was designed to be sustainable, utilising higher upfront emissions, it needs to be utilised for a duration for those upfront emissions to payback. However, if the payback is many decades, future managers may not be aware of the constraint, hamper the efforts of sustainability should they decide to demolish a building before the emissions pays back. Small changes to the physical characteristics can have decadal changes to emissions

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break even. In some circumstances, the Passivhaus and a convention building are within one standard deviation of each other, making it indeterminate which is the better option. A tool, such as the GP-LCA accounting framework, can incorporate time into models of future GHG emissions, adding a new dimension to low-carbon decision making.

The results also show the importance of making measurements of physical carbon emissions, rather than relying on scientific studies, when evaluating lower carbon options. As this paper showed, within one standard deviation, a Passivhaus may or may not payback in their emissions savings. Financial inputs, such as discount rates, cost of carbon, and price of electricity, did not have as large of an effect as compared to physical characteristics. The results indicate the comparative importance of improving management of physical emissions. This could be through the improving of physical standards, such as UK energy codes and building regulations. We also urge the inclusion of upfront embedded energy into models of future emissions characteristics, as it can alter the outcome of an option.

Importantly, the results also indicate that the UK's projected decarbonisation of the electric grid may affect which long-term decisions are the lower carbon option. If the grid decarbonises per the government's plan, then it is better to consume energy in the future rather than today. As a result, the additional upfront emission today in constructing a Passivhaus may never be the lower carbon option. However, according to the most recent 2024 progress report, the UK is not on track to hit its targets of decarbonisation (CCC, 2024). This creates uncertainty for investors and businesses over which options are best. Research is needed to take into consideration management decision making into carbon modelling literature.

Future research can also be conducted to improve the accounting of embedded emissions within products. Upfront embedded emissions can vary based on construction practices, and operational emissions can vary based on how well maintained the facilities are. Individual buildings have a large range of possible upfront embedded emissions values that that good

intentions of constructing sustainable structures can be negated by lack of data verifying the intention was achieved. Several efforts are in their nascent stage to collect embedded carbon of buildings. GRESB, formerly the Global Real Estate Sustainability Benchmark, was created by investor community to create a framework for actionable environmental social and governance (ESG) data. Its 2023 standard added the reporting of embedded carbon for the first time (GRESB, 2023).

Buildings also have a large range of operational emissions. Operational drift is a well-documented effect where degradation and malfunctions of building systems contribute to an increase of up to 20% of energy consumption (Bigaud et al., 2019). Resetting a building to its design intention is known as commissioning, which has been shown to reduce energy consumption by a median of 9-14% (Crowe et al., 2020; Mills et al., 2004). These ranges are above the sensitivity threshold to alter the emissions characteristics of a building choice. Having an ongoing monitoring and measuring system that feeds into an emissions accounting system can help decision makers ensure the performance of a building towards decarbonisation intentions.

## **Acknowledgements**

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## Chapter 8. Conclusions

*If by chance I have omitted anything more or less proper or necessary, I beg forgiveness, since there is no one who is without fault and circumspect in all matters.*

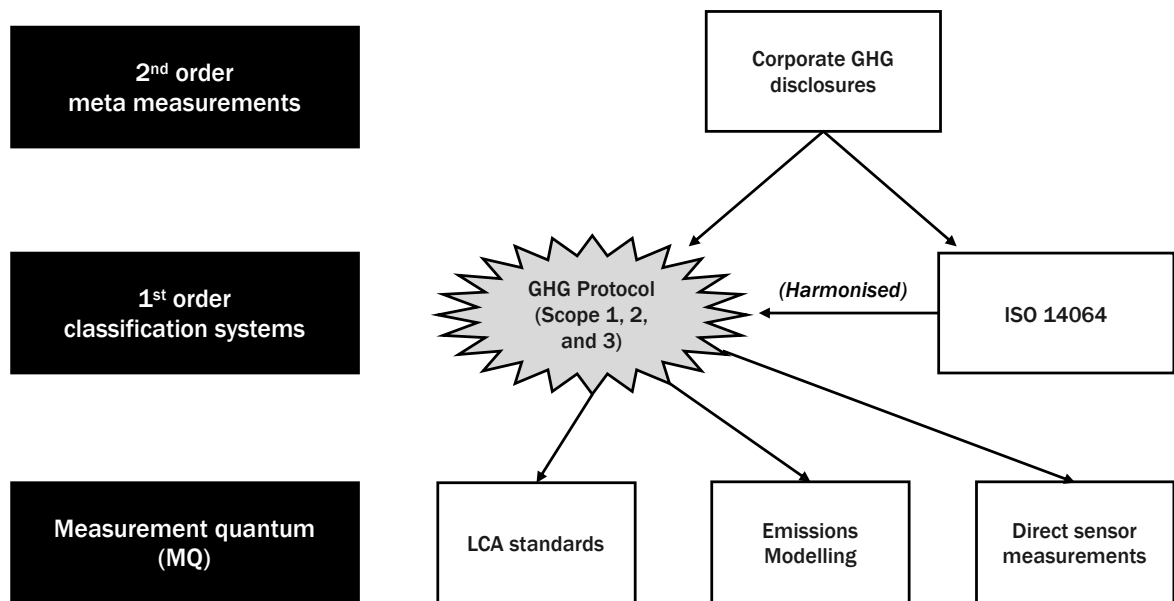
- Leonardo of Pisa (Fibonacci), Liber Abaci (1202)

This thesis studied the compatibility between physical GHG accounting and financial accounting. The research revealed details of the complex, non-linear dynamics at the intersections of the flow of money and physical GHG emissions. This chapter presents concluding remarks based on four academic papers presented in this thesis.

### 8.1. Summary of contributions

In paper one / chapter four, I performed a rapid review of GHG accounting standards to find that all standards are derivative works of the GHG Protocol. Figure 8-1 organises these standards based on Power's performance management system hierarchy. The work contributes to the GHG accounting field by creating a document database of standards, identifying the foundational standard amongst the derivative variations. The existence of multiple, yet similar, standards has created market confusion in deciding which standard to follow (Reinecke et al., 2012). However, there is a lack of convergence in the methodologies accepted to quantify GHG emissions, as LCA, emissions modelling, and direct sensor measurements are all accepted. Such lack of reliability creates challenges in quantitative evaluations of progress towards GHG emission reductions (Ruiz Manuel & Blok, 2023).

Power's hierarchy of performance measurement systems



*Figure 8-1 As found in paper one / chapter four, all GHG accounting standards are derivative works of the GHG Protocol. Further, GHG Protocol accepts GHG quantities found by LCA, emissions modelling, and direct sensor measurement methodologies. (Source: Author's creation)*

The paper discovered that all GHG accounting standards converge onto the GHG protocol. There is a 'false marketplace' where the abundance of standards do not represent true differentiation of ideas and approaches. For applications where the GHG Protocol is fit-for-purpose, the global standardisation community has an opportunity to reduce fragmentation and improve interoperability by directly referencing the dominant standard rather than creating derivative works. For situations where GHG Protocol is not fit-for-purpose, future research is warranted to design accounting systems that can ensure alignment between policy and practice. The results of paper 1, also enabled the focus of all subsequent research onto the GHG Protocol in this thesis.

One specific gap between GHG Protocol and other standards is the definition of comparability. To close this gap, paper two / chapter five examined the GHG Protocol for normative approaches to comparability. First, an empirical approach, with data from the CDP (formerly Carbon Disclosure Product), showed that Scope 1, 2, and 3 data does not conform

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to the principles of comparability, as used by the financial accounting sector. The importance of this finding is that GHG emission values might not be suitable for incorporating into capital allocation decisions, something the financial sector has already started to do.

A specific finding is that GHG Protocol lacks the ability to account for the passage of time, as Scope 1, 2, and 3 are designed to be summations over all time. To fix this problem, I proposed design criteria for temporal comparability for a GHG accounting system. The conditions of comparability were derived using methodologies suitable at each level of the performance management hierarchy, as shown in Table 8-1. To make the 2<sup>nd</sup> order level comparable, researchers can test for both input and output comparability. To make the 1<sup>st</sup>

*Table 8-1 Design criteria for entity comparability at each level of the GHG performance management system hierarchy, taken from paper two / chapter five. (Source: Author's creation)*

<b>Level</b>	<b>Recommendation</b>	<b>Example future research initiatives</b>
<b>2<sup>nd</sup> order systems:</b> <i>Input and output comparability</i>	Test for output comparability	Run empirical analyses of output comparability for any GHG accounting system.
	Test for input comparability	Run analyses of similarity and difference facet on any GHG accounting system
<b>1<sup>st</sup> order:</b> <i>Classification system comparability</i>	Harmonise the entity boundaries of GHG accounting and financial accounting.	Research the standardisation of GHG categories with financial accounting categories
	Harmonise the temporal boundaries, with similar treatment of past, present, and future data.	Research how DEBK can create temporal relationships between embodied and operational emissions.
<b>MQ: Unit comparability</b>	Use only measured emissions	Research adoption of methods that follow principles of an energy balance (combustion emissions) or mass balance (stoichiometric emissions)

order level comparable, the categories of the classification system need to be harmonised. This includes for both the spatial boundary, defining the entity, and the temporal boundary, making distinctions between the past, present, and the future. To make the measurement quantum level comparable, one needs to make distinct values that are measured from values that are modelled. The practical outcome is to unmix five attributes, measured, modelled, past, present, and future emissions, adding temporal comparability into GHG accounting.

Having proposed the design criteria for temporal comparability, paper three / chapter six followed them by contributing the information architecture of general-purpose life cycle assessment (GP-LCA). GP-LCA is designed for primary users of general-purpose financial statements, who are accustomed to viewing balance sheets for historical financial information, profit & loss statements for present financial information, and *pro formas* for forecasts of future financial performance. GP-LCA is a method that defines the boundary of analysis to that of the corporate entity, and a periodicity that is aligned to that of financial reports.

*Table 8-2 The emission balance sheet for CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O, taken from paper three / chapter six (Source: Author's creation)*

(A) Carbon Dioxide Assets (tCO <sub>2</sub> ) January 1, 2024	(B) Methane Assets (tCH <sub>4</sub> ) January 1, 2024	(C) Nitrous Oxide Assets (tN <sub>2</sub> O) January 1, 2024
<b>CO<sub>2</sub> ASSETS</b>	<b>CH<sub>4</sub> ASSETS</b>	<b>N<sub>2</sub>O ASSETS</b>
Intrinsic CO <sub>2</sub>	Intrinsic CH <sub>4</sub>	Intrinsic N <sub>2</sub> O
Wood Products		
13	-	-
Embedded CO <sub>2</sub> for Exchange	Embedded CH <sub>4</sub> for Exchange	Embedded N <sub>2</sub> O for Exchange
-	-	-
Embedded CO <sub>2</sub> for Use	Embedded CH <sub>4</sub> for Use	Embedded N <sub>2</sub> O for Use
Gradel Quadrangle	Gradel Quadrangle	Gradel Quadrangle
2,461	8.81	14.20
Calcination of Concrete		
303		
<b>Total CO<sub>2</sub> ASSETS</b>	<b>Total CH<sub>4</sub> ASSETS</b>	<b>Total N<sub>2</sub>O ASSETS</b>
2,778	8.81	14.20
<b>CO<sub>2</sub> RESPONSIBILITIES</b>	<b>CH<sub>4</sub> RESPONSIBILITIES</b>	<b>N<sub>2</sub>O RESPONSIBILITIES</b>
Responsibility of debtors	Responsibility of debtors	Responsibility of debtors
-	-	-
Responsibility of owners	Responsibility of owners	Responsibility of owners
2,778	8.81	14.20
<b>Total CO<sub>2</sub> RESPONSIBILITIES</b>	<b>Total CH<sub>4</sub> RESPONSIBILITIES</b>	<b>Total N<sub>2</sub>O RESPONSIBILITIES</b>
2,778	8.81	14.20

## **Chapter 8: Conclusions**

I applied GP-LCA to historical emissions data of the recently constructed Gradel Quadrangle at New College, Oxford. I showed how the framework can depict flows in and out of system as well as their accumulation into embodied attributes. As shown in Table 8-2, I generated balance sheets for carbon dioxide, methane, and nitrous oxide, demonstrating the flexibility of GP-LCA to incorporating multiple environmental flow. The paper further showed how disaggregating the data into individual GHGs also reveals details for what emissions are important for which materials. For example, aluminium and concrete are the highest intensity of all four attributes. However, copper wires become important for methane and nitrous oxide emissions. In separating out the gases, one can separately model their dynamics. For example, carbon dioxide has an atmospheric lifespan of 500,000 years (Lord et al., 2016), while methane, nitrous oxide has a lifespan of 11 years (Smith et al., 2021). Improved visibility of GHG attributes can target management techniques to each gas separately.

In showing how the GP-LCA can model historical flows, paper four / chapter seven expands on the findings by using the accounting system to model future scenarios. I studied forecasts of physical GHG emissions generated from GP-LCA and financial cost of emissions by using the HM Treasury Greenbook guidance on pricing emissions. My contribution is identification of non-linear dynamics between the two systems, where there are divergences between economic models and physical ones. This creates situations of 'false positives' where economic data indicates that an environmental choice has achieved less damage, while physical carbon data indicates otherwise. Further, the data showed that models are more sensitive to physical characteristics than to economic variables.

**Table 8-3 Sensitivity of NPV to emissions from electricity consumption and the discount rate, from paper four / chapter seven. (Source: Author's creation)**

<b>% Input sensitivity</b>	<b>Embedded energy on NPV sensitivity (%)</b>	<b>Operational energy savings on NPV sensitivity (%)</b>	<b>Discount rate on NPV sensitivity%</b>
<b>+1 std dev</b>	<b>- 189%</b>	<b>219%</b>	<b>- 89%</b>
<b>10%</b>	<b>- 63%</b>	<b>73%</b>	<b>- 21%</b>
<b>5%</b>	<b>- 31%</b>	<b>36%</b>	<b>- 10%</b>
<b>0%</b>	<b>0%</b>	<b>0%</b>	<b>0%</b>
<b>- 5%</b>	<b>31%</b>	<b>- 36%</b>	<b>11%</b>
<b>- 10%</b>	<b>63%</b>	<b>- 73%</b>	<b>22%</b>
<b>- 1 std dev</b>	<b>189%</b>	<b>- 219%</b>	<b>110%</b>

As shown in Table 8-3, net present value (NPV) calculations from the Greenbook are highly sensitivity to emissions from energy consumption, with a one standard deviation increase in embedded emissions resulting in a decrease in NPV of 189%, and a similar increase in operational energy savings resulting in a 219% increase to NPV. Meanwhile, a similar increase to the discount rate only decreases the NPV by 89%. Our result demonstrates the importance of measurement of physical attributes to support decision making because the results are highly sensitive to actual activities. Industry averages and scientific studies can inform decisions but are not specific to the situation at hand.

## **8.2. Core contributions of the thesis as a whole**

In addition to the individual contributions of each chapter, as a whole, the thesis contributes a method to synchronise the dynamics of non-financial indicators with financial indicators, a pressing need for conservation science (Feger et al., 2018). This thesis demonstrated how the financial, carbon, and energy fields can be synchronised, by separately studying and aligning attributes of the past, present, and future. As shown in Figure 8-2, GP-LCA can also be extended to other fields. Business, policy, financial, and other users of financial statements can research their temporal alignment with climate science, energy physics,

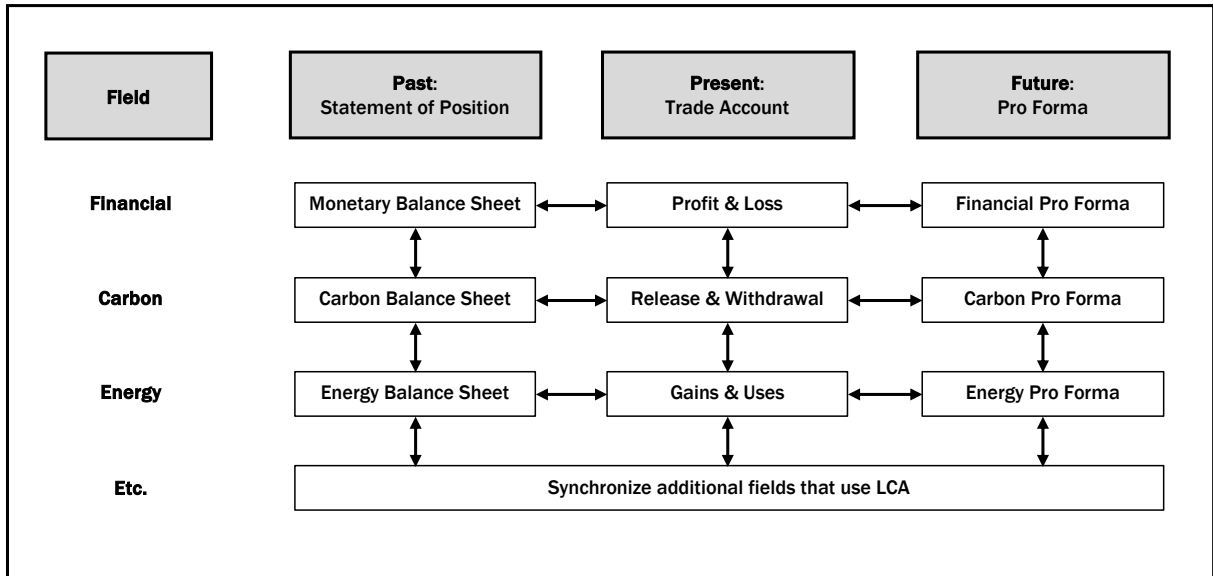


Figure 8-2 GP-LCA is a tool that can be used to synchronise activities of non-financial fields to that of financial accounting (Source: Author's creation).

product and project LCA, amongst other fields. Because GP-LCA is fundamentally an LCA-based technique, it is likely that any resource that is currently measured using LCA can be aligned temporally with the financial reports. Future research can be done to synchronise additional fields, and to understand the limitation of which fields cannot be included.

GP-LCA can also be used to study gaps between fields. For example, the current approach to bringing the economics and climate fields together is to treat GHG as a cost, subsuming them into the economic perspective (Evans et al., 2021; Nordhaus & Sztorc, 2013). This approach ultimately sidelines the environmental indicator in the pursuit of financial returns (Milne & Gray, 2013). Using GP-LCA, researchers can gain a more sophisticated view to analyse the non-linear dynamics of the economic and GHG systems, identifying gaps and mismatches, and potentially finding better models to fix them. As more sectors become involved in the climate management field, it may become necessary to understand how one sector's assumptions and models align with those of another. Divergences between a field-specific assumptions and models can create false positives where, multiple fields contradict each other. Future research can be done to identify additional divergences, helping to improve models that influence decision making.

GP-LCA can also improve system-wide collaborations and interoperability by synchronising temporal characteristics across multiple fields. As shown in our work, policy makers are dependent on carbon accounting frame makers, who in turn depend on LCA scientists. Experts in each discipline will understand limitations of their own methods but may be less familiar with those of a different discipline. As a result, tools and methods may be adopted for use across disciplines that are not fit-for-purpose. GP-LCA creates a set of rules and principles that must be adhered to across all sectors, improving collaborations, and interoperability.

### **8.3. Limitations**

There are several limitations to this thesis. First, I only applied GP-LCA to three flows – carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O). There is a total of seven GHGs as determined by the Kyoto Protocol, include hydrofluorocarbon (HFCs), perfluorinated compounds (PFCs), sulphur hexafluoride (SF<sub>6</sub>), and nitrogen trifluoride (NF<sub>3</sub>) (WRI & WBCSD, 2013). Commonly, the environmental damages cause by all six gasses is normalised to that of carbon, measured in metric tonnes of carbon dioxide equivalents (tCO<sub>2e</sub>). As this research only analysed three gasses, I leave for future research the inclusion of the other GHGs into the accounting system. Also, this thesis does not analyse the impact of GHG emissions, the resiliency, or the adaptation and mitigation required to respond to climate change. Further work can be done to build upon the foundations of GP-LCA to derive impact, resiliency, and adaptation indicators.

This thesis takes a normative approach to the construction of the GP-LCA, aligning to existing financial and LCA standards. As a result, GP-LCA also shares the limitations of the LCA methodology and financial accounting systems. For example, some environmental indicators do not use LCA methodologies. Ecological services, which use techniques such as participant observations and surveys (Rasmussen et al., 2016), may not be suitable for synchronisation with financial accounts. Social and governance indicators also do not use

## **Chapter 8: Conclusions**

LCA, and they may not be suited to be harmonised using GP-LCA to the financial statements. There may also be limits even if a field uses LCA. For example, land use changes and biodiversity are pressing environmental topics of interest (Avery et al., 2024), and although LCA is commonly used, there are questions as to whether LCA is an appropriate methodology to quantify them (Bromwich et al., 2024).

GP-LCA is also subject to the limitations of financial accounting. GP-LCA aligns itself to the same boundary as that of financial reporting: the organisational entity. Therefore, items outside the entity may be difficult to account for. Further, GP-LCA is transaction based, much like financial accounting. If there is no transaction, then the activity is not recorded nor counted. For example, Scope 3 Category 7 accounts for the emissions of employee commuting (WRI & WBCSD, 2011). However, this activity is not recorded as a financial transaction because it does not fall within the corporate entity's boundary. As a result, GP-LCA would not account for that activity. One solution is to allow 'off balance sheet' items, as is sometimes used within financial accounting (IFRS, 2005).

There are also limitations to the GP-LCA model itself. It is intentionally designed for primary users of financial statements, making it fit-for-purpose for incorporating environmental information into financial decision-making. However, there are other viewpoints and situations where GP-LCA is not suitable. For example, Scope 1, 2, and 3 was designed from the viewpoint of environmental impact and the E-Liability system was designed to help consumers make better choices on the products they buy. There has also been a call to develop emissions accounting from the viewpoint of governments, as a way to manage planetary emissions (Barker, 2025). More research needs to be conducted to see if GP-LCA can be modified to also be used from those viewpoints.

## **8.4. Future Work**

Because GP-LCA is based on principles of financial and GHG accounting, there are additional areas of study that examines additional intersections not covered in this thesis. This section discusses three areas of future research, model refinement, linking to other disciplines, and developing case studies.

### **8.4.1. Model refinement**

The GP-LCA model can continue to be refined by adding capabilities to account for financed emissions. The Partnership for Carbon Accounting Financials (PCAF), launched in 2019, has developed standards for *Scope 3 Category 15 Financed Emissions* that have achieved the Built on GHG Protocol certification (PCAF, 2022). One limitation of the PCAF method is that it relies on Scope 1, 2, and 3, allocating those metrics emissions of a financial institution's portfolio to the financial institution. However, Scope 3 includes intentional double counting of a value chain. If a financial institution owns more than one company in a value chain, then there is potential double counting of their carbon footprint. Second, PCAF has a growing, but limited number of categories included in its guidance. This includes seven categories of financed emissions, or activities that are held for multiple years (PCAF, 2022), and five categories of facilitated emissions, or activities that are held for shorter than a year (PCAF, 2023). With the GP-LCA model, financed and facilitated emissions can be accomplished by examining the liability side of the carbon balance sheet. As financial liabilities are an allocation of ownership of assets to debt and equity holders, carbon liabilities could be interpreted as ownership of carbon assets by debt and equity holders. As such, a GP-LCA method of financed emissions would allocate all carbon assets to financial partners, not just a subset.

The model can also be extended to help synchronise accounting of carbon offsetting for the achievement of net zero. One challenge today is that emissions into the atmosphere may not

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be temporally matched to the withdrawals from the atmosphere. Carbon credits can be purchased and held, rather than retired, which is when the carbon removals are 'counted' towards emissions. As a result, there are challenges of the vintage of the carbon credit was generated, and the year in which the carbon credit is retired (Trencher et al., 2024). Because GP-LCA follows the matching rule in financial accounting, which states that activities have to be accounted for in the period in which it occurs, offsets would be automatically matched with emissions, making it clearer the accounting for net zero. Further, storage of carbon has different durations depending on the technology. The temporal permanence of storage may also be represented using a GP-LCA system. For example, carbon storage in forestry can have a 50-year cycle due to the trees being harvested (Dewar & Cannell, 1992), while geological storage can be for centuries, or even millennia (Bashir et al., 2024). As GP-LCA is designed to synchronise activities of different durations, the framework can be extended to account for the permanence of storage solutions.

GP-LCA may improve optimisations of climate-related financial decisions. Selecting a portfolio of climate-related investments can be considered a multi-objective optimisation problem, where one is minimising carbon flows while maximising financial flows (Calvo et al., 2012). The problem takes the same format as the Markowitz efficient portfolio with the so-called *efficient frontier* of solutions, where one is maximising returns while minimising risks (Markowitz, 1959). In treating climate finance as a multi-objective optimisation problem, it may be possible to explicitly optimise for climate tipping points, where there is a maximum amount of physical GHGs permitted to be emitted into the atmosphere. At the moment, climate finance is treated as a single objective optimisation problem, with physical emissions subsumed into economic models to generate a cost of carbon (Evans et al., 2021). This approach creates a gap for the inclusion of tipping points. Efforts to include tipping points still subsumes the physical emissions into economic models (Dietz et al., 2021), treating it as a single objective optimisation problem.

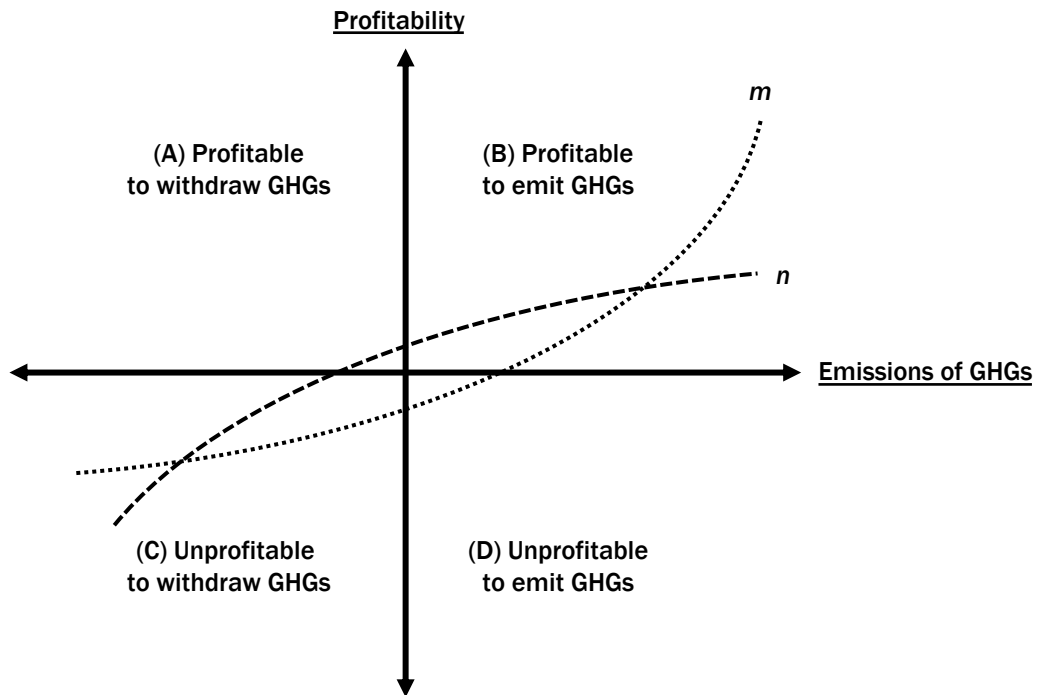


Figure 8-3 Stylised examples of a carbon/economic efficient frontier (Source: Author's creation).

Figure 8-3 gives a stylised example of the financial/carbon efficient frontier. The y-axis accounts for monetary flow while the x-axis accounts for GHG flows. One would therefore like to maximise the y-axis while minimising the x-axis. Quadrant (A) represent technologies that are profitable to withdraw GHGs, Quadrant (B) are those that are profitable and emit GHGs, Quadrant (C) are investments which are unprofitable but withdraw GHGs and Quadrant (D) are unprofitable yet still emit GHGs. Lines *m* and *n* are two stylised examples of an efficient frontiers of different technology portfolios and investment options. In line *m*, a marginal increase in GHG emissions greatly increases profits while in line *n*, the same increase can have a negligible increase in profits. Future research can be conducted to construct these efficient frontiers, enhancing policy and business decision maker's ability to maximise economic benefit while minimising climate harm.

### **8.4.2. Linking GP-LCA to other disciplines**

Future work can be conducted to link GP-LCA to the existing LCA field. There are two common approaches to LCA for GHG accounting – attributional and consequential LCA (Brander, 2015). Broadly, attribution LCA (aLCA) is a modelling approach that examines emissions attributed to a functional unit being analysed while consequential LCA (cLCA) is a modelling approach that examines the consequences across a system due to a change in demand for a functional unit (Brander et al., 2019). In other words, an aLCA study is analogous to the financial accounting of a single organisation while an cLCA study is analogous to consequences of an organisation on the broader economy. Because the GP-LCA information architecture disaggregates time and predetermines the boundary to be an organisation, it may be possible to construct both aLCA and cLCA studies. Theoretically, conducting an aLCA study of an organisation could be as simple as summing up those temporal categories. A cLCA study could also be conducted by summing up temporal categories across multiple organisations that are affected across a system. As such, GP-LCA could be an accounting tool that standardises the data from which environmental professionals can construct the model needed for their application.

Similarly, research can be conducted to link GP-LCA to existing carbon accounting frameworks. For example, many of the Scope 1, 2, and 3 categories are also summations over time. GP-LCA may be suitable as a foundational building block to generate an organisation's GHG disclosures. Further, it may be possible to link GP-LCA to other carbon accounting frameworks in use or being proposed. For example, E-Liability, carbon take-back obligations (CTBO), and emission trading schemes (ETS) may be specific use cases that GP-LCA can support. E-Liability has an intended outcome of tracking carbon of products for consumers (Brander & Gatzweiler, 2024), CTBO tracks carbon emissions and offsets for a producer (Lackner et al., 2023), and ETS accounts for emissions against a cap for how much an organisation is permitted to emit (Schultz & Swieringa, 2014). As GP-LCA is designed to

be a foundational set of disaggregated data, it may be able to reconstitute its data into these other accounting formats.

GP-LCA may be able to improve analysis of transition planning and carbon lock-in, two activities attributed to the future. A transition plan explains how an organisation will achieve their net zero targets and other climate pledges (TPT, 2022). Carbon lock-in is the concept that investments today will require a specific consumption level to operate that investment, hence locking in an expected level of consumption (Unruh, 2000). Within financial accounting, an asset is defined as that which is owned and controlled by the entity from which one derives future economic (cost) benefits. In essence, for an asset to appear on a balance sheet, it needs to be connected to ongoing revenues or expenses. In using GP-LCA, the upfront embodied carbon of an asset can also be linked to the ongoing operational carbon needed to operate it. As such, one can gain a more sophisticated view of transition planning by modelling if a replacement carbon asset is expected to reduce the ongoing carbon emissions. Similarly, one can also model the carbon lock-in of an asset by linking the expected future carbon emissions of an asset. Gaining more clarity in models that purport to achieve net zero goals will help us understand the assumptions required of future activities.

### **8.4.3. Develop case studies**

This thesis applied GP-LCA to a real estate case study, and future work can be done to develop additional case studies to demonstrate non-linear complexities due to differences in temporal dynamics between carbon, energy, and financial flows. As mentioned in the literature review, the Avedøre Power Station in Denmark consumes agriculture waste for the generation of thermal energy for district heating, electricity, and operate a carbon capture facility (Ørsted, 2024). The flows for money, energy, and carbon diverge, depending in the product being produced and sold, as shown in Table 8-4. GP-LCA could model each flow separately, enabling the examination of non-linear dynamics across the three systems.

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*Table 8-4 Non-linear financial, energy, and carbon flows at the Avedøre power plant in Denmark.  
(Source: Author's creation)*

Product	Financial flows	Energy flows	Carbon flows
Electricity generation	(+) Generates revenue	(-) Consumes energy	(+) Net releases
District heating	(+) Generates revenue	(-) Consumes energy	(+) Net releases
Carbon capture	(+) Generates revenue	(-) Consumes energy	(-) Net withdrawal

Case studies can also be developed to show how carbon ownership changes hands during different phases of a product's lifespan. Today, Scope 1 and 2 are defined based on ownership of an asset while Scope 3 is not. Further there is no guidance for how and if historic carbon emissions should be transferred upon sale of an asset. For example, when a property changes hands, should the historical emissions of the entity transfer to the new owners? A case study of medium- and heavy-duty trucks can help model the effects of carbon during ownership transfer. Trucks and other motor vehicles are carbon intensive to manufacture and require a high carbon footprint to operate. GP-LCA may be able to model the effects of carbon ownership as the vehicle changes hands both as a new vehicle and nearing the end-of-life.

### 8.5. Final remarks

Climate is complex. Climate change is a grand challenge facing our society (Beniston, 2013; Campbell-Lendrum et al., 2023; Reid et al., 2010). Many people, disciplines, and sectors are involved in its study. Many more people, disciplines, and sectors wish to use its results. However, grand challenges are problem oriented, but the solutions are discipline oriented. There is a need for transdisciplinary literacy, with an epistemic framing that is unique to each grand challenge. The financial sector may wish to incorporate emission indicators into investment decisions, but a decision-useful indicator is what needs to be adopted. As this thesis has shown, disciplinary frameworks need to be borrowed with care, ensuring compatibility with the intended use.

The study of frameworks is a study of systems (Jia, 2020). Frameworks are a mediating instrument, an infrastructure that enables multiple disciplines to interact with each other. Individual disciplines have foundational principles, some that are so ingrained that they are no longer mentioned. This thesis took care in merging the disciplinary frameworks only once the foundational principles were identified. The financial accounting system is built on the principle of a cash balance (Sangster et al., 2021), the energy thermodynamic system is rooted in the energy balance (Blundell & Blundell, 2009), and the engineering system is grounded in the mass balance (Ashby, 2013). By building an accounting framework that respected the epistemic foundation of balances, GP-LCA enabled the sharing of disciplinary knowledge, expertise, and insights that have been developed independently. As this thesis showed, it enabled the borrowing of temporal framing critical for the financial sector by the energy and engineering disciplines, which use a different temporal framing. Although this thesis developed a relationship between monetary units and mass units of GHG emissions, future research can demonstrate the connection to energy physics as well. When merging disciplines, the research should be grounded in the foundational principles of the disciplines under investigation.

Energy and carbon are intertwined. As mentioned in the literature review (Chapter 3), energy inputs are what create carbon outputs. To design the carbon accounting system, much of the foundational ideas were based on energy physics and thermodynamics. The concepts of embedded carbon are easily applied to embedded energy, and so forth. The transition to a low-carbon economy is a transition of the energy infrastructure, from its source, such as a mine or power plant, its transportation, via a grid, pipeline, or road, and its uses, in industrial, commercial, or residential settings. GP-LCA therefore enables the research of the non-linear dynamics between all three flows.

Physics has long influenced economics. The analogies between physics concepts and economics are well known (Mirowski, 1984), with early physicists and economists, such as

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Daniel Bernoulli, Irving Fisher, and Paul Samuelson, applying physics concepts to economic models (Cooper & Russell, 2006; Georgescu-Roegen, 1971; Stigler, 1950). This thesis took a different approach, examining the similarities between physics concepts and accounting. As accounting is a data source in the study of economic theory, in aligning the categories between the physics and accounting, GP-LCA may enable other environmental data sources to be compatible with economic research, opening new avenues to study the effect of climate factors on the micro- and macro- economy.

There are two category theories. In addition to the category theory used in this thesis, developed by social scientists to study the social and political context of the organisation of information (Bowker & Star, 1999), there is another category theory developed by mathematicians (Spivak, 2014). Mathematical category theory formalises different branches of mathematics into fundamental categories. Once formalised, the methods and techniques developed by one branch of mathematics can be applied and adopted by a different branch of mathematics. In other words, mathematical category theory is a way for tools and ideas developed for one field (i.e. topology) to be wholesale adopted by another (i.e., algebra), to form new fields (algebraic topology). In light of mathematical category theory, this thesis took great care not just to align the categories of financial and GHG accounting, but also the information architecture and the mathematics behind the two systems. Although not explored in this thesis, by aligning the underlying mathematical principles behind finance, energy, and GHG emissions, GP-LCA may enable wholesale sharing of models, methodologies, and techniques developed independently by these fields.

Ultimately, it's about time. What should we do, when to do it, and for how long? Philosophers have argued over the meaning and existence of time for thousands of years (Bardon, 2013). Thermal physics proved the existence of the 'arrow of time', pointing only in one direction and cannot be reversed (Blundell & Blundell, 2009). In finance, the interest rate is used to move present day money into the future and the discount rate is used to move future money

into the present (Berk & DeMarzo, 2020). Missing in our toolkit is how to push present day GHG emissions into their future equivalent or how to pull future GHG emissions into the present. As carbon dioxide will last in the atmosphere for countless generations, enabling accounting of time is of utmost importance.

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## Appendix – Co-authorship statements

### Authorship Statement, Paper 1 – Greenhouse gas accounting standards: A rapid review

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- **Jimmy Jia:** Contributed by leading the team, developing the research questions, designing the methodology, acquiring data, performing the analysis, and drafting and editing the manuscript.
- **Kaya Axelsson:** Supported data acquisition, performing the analysis, and editing the manuscript.
- **Abrar Chaudhury:** Contributed by developing the research questions, designing the methodology, and editing the manuscript.
- **Evan Taylor:** Supported acquiring data, performing the analysis, and editing the manuscript.
- **Jessica Thorn:** Contributed to designing the methodology and editing the manuscript.

All authors reviewed the results and approved the final version of the manuscript.

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- **Jimmy Jia:** Contributed by leading the team, conceptualising the research, designing the methodology, acquiring the data, performing the analysis, and drafting and editing the manuscript.
- **Abrar Chaudhury:** Contributed by supporting the conceptualisation, discussing the analysis, and reviewing and editing the manuscript.
- **Nicola Ranger:** Contributed by supporting the conceptualisation, discussing the analysis, and reviewing and editing the manuscript.
- **Evan Taylor:** Contributed by discussing the analysis and reviewing and editing the manuscript.

All authors reviewed the results and approved the final version of the manuscript.

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- **Jimmy Jia:** Contributed by leading the team, conceptualising the research, developing the research questions, designing the methodology, acquiring data, performing the analysis, and drafting and editing the manuscript.
- **Abrar Chaudhury:** Supported the analysis, validated the approach, reviewed and edited the manuscript.
- **Barbara Rossi:** Supported the data acquisition and data analysis, validated the approach, and reviewed and edited the manuscript.
- **Evan Taylor:** Contributed by supporting conceptualising the research, discussing the methodology, and reviewing the manuscript.

All authors reviewed the results and approved the final version of the manuscript.

## **Authorship statement, Paper 4 – A divergence of dynamics:**

### **Temporal issues between models of physical carbon emissions and monetary cost of damage**

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**The authors confirm contribution to the paper as follows:**

- **Jimmy Jia:** Contributed by leading the team, conceptualising the research, designing the methodology, acquiring the data, performing the analysis, and drafting and editing the manuscript.
- **Nicola Ranger:** Contributed by supported conceptualising the research, discussing the methodology and analysis, and reviewing and editing the manuscript.
- **Barbara Rossi:** Supported by discussing the analysis and reviewing the manuscript.

All authors reviewed the results and approved the final version of the manuscript.