Proc. of the European Safety and Reliability Conference (ESREL 2026)
Edited by José C. Matos, Paulo B. Lourenço, Michael Beer, Daniel Oliveira,
Edoardo Patelli, Hélder S. Sousa, Rui A. Silva and Monica Santamaria

doi: 10.3850/ESREL2026061419_esrel26-p29001-cd

A Systematic Evaluation of Uncertainty Quantification in Transport Carbon Accounting Standards

Mariana Gabriela Páez-Jiménez, Angus McIntosh, Marco de Angelis

Department of Civil and Environmental Engineering, University of Strathclyde, Scotland.
E-mail: {*mariana.paez, angus.mcintosh, marco.de-angelis*}*@strath.ac.uk*

Transport emissions represent 14% of global greenhouse gases (GHG), yet the reliability of reported emissions remains highly uncertain. This paper provides the first systematic evaluation of uncertainty quantification in transport carbon accounting standards. Four major frameworks: ISO 14083:2023, Global Logistics Emissions Council (GLEC) Framework, EN 16258:2012, and GHG Protocol Initiative, are assessed against the International Panel on Climate Change uncertainty principles across five dimensions: acknowledging uncertainty, characterization, quantification methods, propagation methods, and harmonization. Using systematic keyword searches and context analysis, we find a counterintuitive temporal pattern. The GHG Protocol Initiative (2001-2015), a general organizational-level framework, achieves higher scores across the five dimensions (73.3%), than transport-specific standards published up to 2023 (0-27%). This suggests a methodological regression rather than evolution. ISO 14083:2023 and EN 16258:2012 contain no uncertainty quantification-specific terminology, methods or guidance, while GLEC merely acknowledges uncertainty existance without offering quantification approaches. As a result, organizations can fully comply with the latest standards while providing no information on measurement uncertainty or data quality. The accounting level hypothesis offers partial explanation: organizational-level standards outperform product-level standards regardless of publication date. However, this creates a contradiction because product-level accounting "should" enable more precise uncertainty assessment through potentially more capacity to perform direct measurement. Across all frameworks, harmonization emerges as a universal weakness, particularly problematic for transport emissions that span multiple accounting levels. Overall, current standards permit emissions reporting without transparency on uncertainty, accuracy or reliability, undermining credible emissions reduction claims. Effective transport decarbonization requires trustworthy emissions data, current standards fail to ensure this.

Keywords: carbon accounting, transport emissions, uncertainty quantification, standards, greenhouse gases

1. Introduction

To address the climate crisis, the Paris Agreement commits signatory nations to limiting global temperature rise, requiring rapid reductions in greenhouse gas (GHG) emissions UNFCCC (2015). Achieving these reductions depends on accurate and transparent measurement and reporting of emissions, which are essential for tracking progress, informing mitigation strategies, and ensuring accountability Forster et al. (2025); Rawat et al. (2024). However, current carbon accounting systems face persistent challenges regarding transparency, comparability, and (critically) the embedded uncertainty in their quantification Bowen and Wittneben (2011); Marlowe and Clarke (2022).

Researchers use uncertainty to communicate the degree of confidence in their findings, to explicitly ascertain knowledge gaps, or to describe information that is inherently uncertain. Uncertainty quantification (UQ) enables the assessment of whether decision outcomes are influenced by incomplete information or remain stable in the presence of uncertainty, or in other words it is important to "know when a decision is and is not affected by whether we know something completely" Sence about Science (2013).

Due to the intrinsic complexity of many models, systematically assessing uncertainty requires robust analytical frameworks. UQ is the field that addresses this challenge by identifying, characterizing, and measuring all sources of uncertainty in a model to evaluate its reliability, communicate predictions, and ensure reproducibility and validation Volodina and Challenor (2021). UQ is inherently interdisciplinary, integrating statistics, numerical analysis, and computational mathemat-

Table 1. List of acronyms

CO_2e	Carbon Dioxide Equivalent
EF	Emission Factors
EN 16258:2012	European Standard. Methodology for Calculation and Declaration of Energy Consumption and GHG Emissions of Transport Services (Freight and Passengers)
GHG	Greenhouse Gases
GLEC	Global Logistics Emissions Council Framework (for this paper specifically Version 3.2)
GWP	Global Warming Potential
MCS	Monte Carlo Simulation
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
ISO 14064:2018	Greenhouse gases requirements
ISO 14083:2023	Quantification and reporting of greenhouse gas emissions arising from transport chain operations
UQ	Uncertainty Quantification

ics. Its primary objective is to provide trustworthy estimates of quantities of interest by, for example, propagating input-data uncertainties through model predictions, solving inverse problems to infer unknown parameters, or analyzing uncertainties intrinsic to the model itself University of Manchester (ND); The Alan Turing Institute (2026).

UQ challenges are especially pronounced in the transport sector, which contributes for approximately 14% of global GHG and 20% of CO_2 emissions Statista (2023); UNDP (2025). Global freight demand is projected to double by 2050 ITF (2023), yet meeting 1.5°C pathways, requires transport emissions to fall by 59-80% by 2050 compared to 2020 levels Jaramillo et al. (2023).

In addition, transport emissions are especially challenging as emissions are dispersed across complex supply chains involving numerous actors, jurisdictions, and data sources. Activity data (e.g. fuel consumed) often come from providers with varying measurement accuracy, while EF differ by elements such as fuel type, vehicle technology, driving conditions, or geographic location Sirithian et al. (2022). Allocation across shared transport services adds further complexity. As a result, uncertainty ranges can be extremely wide, for example, light-duty diesel trucks show documented variability from -85% to $+182\%$ due to differences in testing methods and vehicle conditions Li et al. (2024).

1.1. *Background on transport carbon accounting standards*

Multiple international standards guide transport emission quantification. The GHG Protocol Initiative (first published in 2001, last updated in 2015) established the widely adopted Scope 1, 2, and 3 framework for organizational carbon footprints, with transport appearing across multiple scopes GHG Protocol et al. (2015). ISO 14064 (2006) covered organizational GHG accounting (including transport) ISO (2018). EN 16258:2012, provided one of the first official methodology to calculate CO_2 per shipment across transport modes (CEN, 2012). Then, the Global Logistics Emissions Council (GLEC) Framework created the harmonized methodology for calculating emissions across air, ocean, road, rail, and inland waterways Smart Freight Centre and GLEC (2023). Lastly, ISO 14083:2023 emerged as "the most comprehensive framework" for transport chain operations emissions across all modes ISO (2023) and represented an important milestone in standardizing emissions calculations for the transport sector.

These standards provide guidance on data collection, CO_2e calculation methods, and EF, yet do they address UQ? The Intergovernmental Panel on Climate Change (IPCC) Guidelines for National GHG Inventories have provided uncertainty assessment frameworks since 2006, including transport-specific guidance IPCC (2019), mandatory for national inventories under the Paris Agreement's Enhanced Transparency Framework (ETF). Yet whether corporate level transport standards have adopted comparable rigor is unclear.

This gap may have significant implications. A reported "10% emission reduction or increase" without uncertainty bounds could represent anything between 0–20% actual variation, or no statistically significant change if uncertainty ranges overlap. In such cases, investment decisions, carbon offset purchases, and regulatory compliance become unreliable. Allocation inconsistencies further exacerbate the issue: the same transport emissions can appear simultaneously in a carrier's Scope 1, a shippers' Scope 3, and a manufacturers' product footprints, risking double-counting Schmidt et al. (2022). Policymakers have been observed to favor "pretended certainty over nuance and detail" in climate decision-making Puig and Bakhtiari (2019) and transport standards may reflect this tendency.

This paper examines whether transport accounting standards consider uncertainty and how their requirements compare to IPCC principles. If current standards lack comprehensive UQ requirements, quantifying transport emission uncertainties becomes essential to assess whether its inclusion is needed to ensure reliable emissions tracking.

This paper provides the first systematic evaluation of uncertainty handling across four major standards: GHG Protocol Initiative Suite of Standards, EN 16258:2012, Global Logistics Emissions Council (GLEC) Framework, and ISO 14083:2023. This is done using five evaluation dimensions derived from IPCC's framework.

We make three contributions to the field. First, it provides the first systematic comparison of uncertainty handling in transport carbon accounting standards. Second, it translates IPCC uncertainty principles into five evaluation dimensions applicable to corporate and product-level standards. Third, it examines the factors that might explain observed gaps in uncertainty assessment.

The remainder of this paper proceeds as follows. Section 2 describes our methodology. Section 3 presents comparative analysis in uncertainty treatment and provides recommendations while Section 4 concludes.

2. Methodology—evaluating transport standards against IPCC uncertainty framework

2.1. *Standards Selection*

Four standards were selected based on relevance to transport emissions, chronological span, and institutional interconnections. The GHG Protocol Initiative suite of standards GHG Protocol (2003, 2011); GHG Protocol et al. (2003, 2011, 2015) provide a widely adopted organizational-level GHG accounting framework used globally. EN 16258:2012 CEN (2012) established a standard for calculating emissions from transport services. The GLEC Framework Smart Freight Centre and GLEC (2023) offers a transport-specific emissions calculation methodology developed through global industry collaboration. Finally, ISO 14083:2023 is the current "most comprehensive framework" for quantifying GHG emissions across transport chains ISO (2023).

2.2. *IPCC Uncertainty Framework as analytical guideline*

The IPCC 2006 Guidelines (with 2019 Refinement) establish the mandatory standard for national GHG reporting under the Paris Agreement IPCC (2019). Their Vol. 1, Ch. 3 provides uncertainty assessment methods across three tiers of complexity: Tier 1 (default factors with error propagation), Tier 2 (country-specific data with MCS), and Tier 3 (facility-level measurements) IPCC (2006b). While Vol. 2, Ch. 3 addresses transport-specific uncertainty sources including fleet characteristics, combustion conditions, and emission control technologies IPCC (2006a). The framework requires systematic UQ, propagation, and reporting with 95% confidence interval (CI).

2.3. *Five evaluation dimensions*

We operationalize IPCC's framework into five evaluation dimensions applicable to corporate and product-level standards: **i) Acknowledging uncertainty** examines whether standards recognize that emission calculations contain uncertainty and require its disclosure; **ii) Uncertainty characterization** assesses whether uncertainty is systematically identified and characterized by type and source, including distinctions between types of error or sector-specific sources; **iii) Quantification methods** examines whether standards provide methods to calculate uncertainty; **iv) Propagation methods** assesses whether guidance exists for combining uncertainties through calculation chains, such as error propagation equations or MCS; and **v) Harmonization** examines whether uncertainties in allocation and aggregation across organizational or product boundaries are addressed to ensure completeness, consistency, and avoid double-counting.

2.4. *Analysis Process*

We conducted systematic keyword search across all four standards documents using six terms covering general uncertainty concepts and quantification methods: *"uncertainty, error, confidence, Monte Carlo, standard deviation* and *propagation"*. These keywords capture both acknowledgment of uncertainty (*uncertainty, error*) and technical methods for quantification (*CI, standard deviation, MCS, propagation*). Evidently, some keywords (*error, confidence*) could appear in both UQ and non-UQ contexts. To address this for each keyword found, we extracted surrounding context and assessed whether usage was related or not to UQ. For example, *confidence* in "stakeholder confidence" was classified as credibility language, while "95% confidence interval" was classified as UQ related. Relevant instances were mapped to the five evaluation dimensions. For each dimension, we assessed standards on a 4-point scale (Fig. 1). This produces a maximum score of 15 per standard, 3 per dimension, which involves interpretive judgment regarding whether content is referring to UQ.

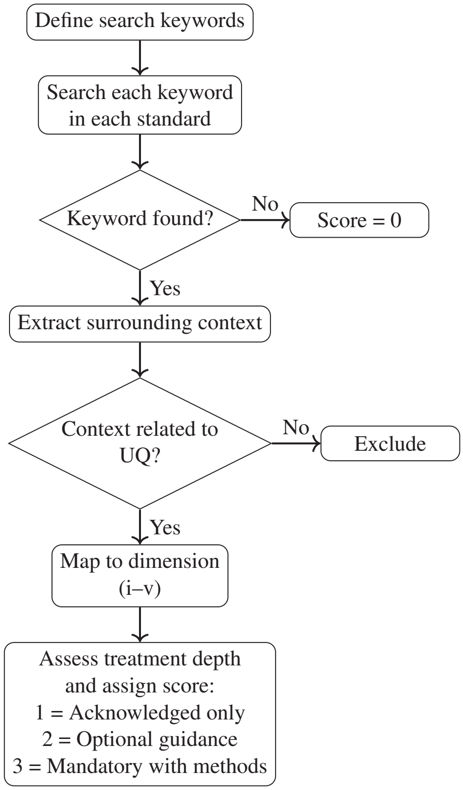

Fig. 1. Keyword Search and Scoring Methodology

3. Evaluation results and discussion

3.1. *ISO 14083:2023*

Published in March 2023 as the international standard for transport emissions, ISO 14083:2023 contains limited explicit uncertainty content. The word *uncertainty* appears only twice in more than 128 pages, both times in a bibliographic reference to IPCC Guidelines IPCC (2019) which is never cited in the text. Section 4.5 "Accuracy" states: "Reduce bias and uncertainties as far as is practical" using discretionary language. Its Section 2 states: "There are no normative references", meaning the standard does not reference ISO's own Guide to Uncertainty in Measurement JCGM/WG 1 (2023) or any other established framework. No transport-specific uncertainty sources are identified. Section 13.4.3 requires reporting data type (primary, modeled, or default) but no associated uncertainty ranges or confidence levels. Organizations using default EF vs direct measurements disclose different data sources but provide the same level of information about measurement confidence. Finally, searches for UQ-specific terminology yielded no results.

3.2. *GLEC*

Updated in 2023, GLEC positions itself as transport-specific guidance aligned with ISO 14083:2023, referencing ISO 110 times and listing IPCC guidance as a "harmonized source". GLEC mentions *uncertainty* fifteen times across 183 pages, primarily acknowledging qualitatively that uncertainty exists and increases with default data. The framework states that "Tier 1 applies simple activity data and default factors" and that default data should be used "with clear acknowledgment of the higher uncertainty it entails".

For sea transport, GLEC specifies using "median fuel consumption with addition of 10%, which equals the range between lower and upper quartile values, to avoid underestimation". By this, GLEC applies statistics to set conservative defaults (precautionary principle) rather than to deliver rigorous UQ. GLEC requires reporting data traceability but not uncertainty. Searches for UQ-specific terminology yielded no results.

3.3. *BS EN 16258:2012*

The withdrawn, EN 16258:2012, operating at the same product-accounting level than ISO and GLEC, contains no UQ content. None of the keywords appear in the standard. The standard's complete absence of UQ terminology is consistent with ISO and GLEC. Accounting level may explain the pattern of absent uncertainty guidance in product-level transport standards.

3.4. *GHG Protocol Initiative Suite of Standards*

The GHG Protocol is not a single document but a framework consisting of core accounting standards: "Corporate Standard" and "Scope 3 Standard", alongside separate technical UQ guidance documents: "GHG Uncertainty Guidance", and "Quantitative Uncertainty Guidance", as well as semi-automated Excel calculation tools to implement aggregation methods GHG Protocol (2003, 2011); GHG Protocol et al. (2003, 2011, 2015).

This structural separation means that while detailed UQ methods exist in supplementary guidance, uncertainty assessment remains optional within the core accounting standards. The Corporate Standard mentions "uncertainty" but defers quantification to supplementary materials. The Scope 3 Standard goes further, dedicating Appendix B to "Uncertainty in Scope 3 emissions", which provides a comprehensive framework distinguishing parameter uncertainty (direct emissions, activity data, EF and GWP values), scenario uncertainty (methodological choices) and model uncertainty (model limitations). However, even this appendix maintains optionality, stating: "Companies may choose a qualitative and/or quantitative approach". While propagation methods, such as MCS and Taylor series expansion are mentioned, their implementation is again deferred to supplementary guidance.

3.4.1. *Uncertainty classification framework*

The dedicated technical guidance documents, GHG Protocol (2003), establishes a GHG-specific taxonomy of uncertainties. It distinguishes *scientific* uncertainties (related to incomplete scientific knowledge of emission and removal processes) from *estimation* uncertainties (arising when quantifying emissions). Estimation uncertainties are further divided in *model* uncertainties (associated with the mathematical equations) and *parameter* uncertainties (associated with quantifying the input parameters, like EF). *Parameter* uncertainties are then split into *systematic* uncertainties (present when data is systematically biased; e.g. EF constructed from non-representative samples) and *statistical* uncertainties (resulting from random variability in sample data).

Importantly, the GHG Protocol et al. (2015) acknowledges that *scientific* and *model* uncertainties typically exceed the scope of most corporate inventory efforts, leaving *parameter* uncertainty (e.g. EF) as the only feasible focus for most companies. The guidance further notes that "uncertainty estimates for corporate GHG inventories will, of necessity, be imperfect" and "will have a subjective component", derived from the need to rely on expert judgment when complete information is not available. It explicitly states that "estimates of uncertainty for GHG inventories must themselves be considered highly uncertain".

3.4.2. *Quantification Methods and Guidance*

The Protocol provides UQ guidance only for *statistical* uncertainty through the "GHG Protocol Uncertainty Tool" and for *systematic* uncertainty through the "Managing Inventory Quality" chapter in the Corporate Module. In particular, to address *parameter* uncertainty, the Protocol presents two mathematical techniques: [1] using first-order error propagation formulas (applicable when parameter errors are normally distributed, estimator function are unbiased, estimated parameters are uncorrelated, and individual uncertainties are less than 60% of the mean) or [2] MCS (when these conditions are not fulfilled). However, the document does not expand on MCS methods, referring users to the IPCC Guidance for further information.

For the first-error propagation method, the document provides procedures for multiplying and adding uncertainties. The Protocol recommends this approach for statistical uncertainties using the dedicated calculation tool, which assists analysts with aggregation and ranking through five steps: (1) Preparatory Data Assessment, (2) Quantify identified uncertainties, (3) Combine uncertainty for activity data and EF, (4) Calculate aggregated uncertainty at site or company level, and (5) Document and interpret findings. The guidance describes MCS as a Tier 2 approach and provides well-known statistical procedures for CIs using lookup tables. Notably, the automated Excel tools GHG Protocol et al. (2003); Quantis (2003) implement only the first-order propagation method.

Despite providing a mathematical framework, the GHG Protocol still relies heavily on expert judgment, mandating only **qualitative** uncertainty assessment for the Product Standard (recommended for Value Chain Standard). Through its tools, users assign qualitative ratings (*very good*, *good*, *fair*, or *poor*) to activity data and EF across five data quality indicators using pedigree matrices. The guidance calculates geometric standard deviation as a 95% CI using "Eq. (1)"GHG Protocol (2011), focusing on activity data and EF.

$$SD_{g95} : \exp\left[\sqrt{\ln^2(U_1) + \cdots + \ln^2(U_5) + \ln^2(U_b)}\right] \quad (1)$$

where U_{1-5} represent uncertainty factors for precision, completeness, temporal representativeness, geographical representativeness, and technological representativeness, and U_b is a basic uncertainty factor. Finally, default basic uncertainty factors by emission category are provided: thermal energy and CO_2 emissions (1.05), methane and nitrous oxide emissions from combustion (1.50), transport services (2.00).

3.5. *Overall Results*

Figure 2 summarizes the score results across all four standards. In general there is inconsistent treatment of UQ and absence of rigorous quantitative methods across all standards.

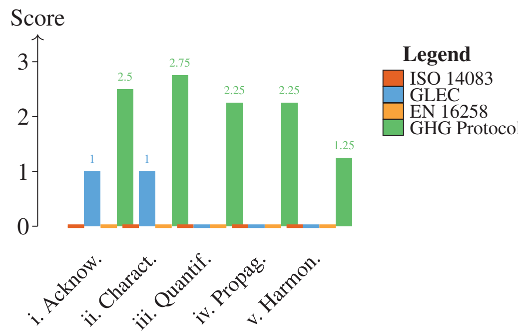

Fig. 2. Comparison of the four frameworks across the five uncertainty dimensions. Scoring: 0 = Not addressed; 1 = Acknowledged; 2 = Optional guidance; 3 = Required. Maximum score per dimension = 3. The GHG Protocol bar represents the average score obtained after evaluating each of its constituent standards (GHG Uncertainty Guidance; Quantitative Uncertainty Guidance; Scope 3 Standard; and Corporate Standard). See Section 2.3 for dimension definitions.

Four patterns emerge from the evaluation. **1. Absence of quantitative methods across all standards:** No transport-related standard mandates quantitative UQ methods. ISO 14083 and EN 16258 contain no UQ-specific terminology. GLEC acknowledges uncertainty exists but provides no quantification methods. Even the GHG Protocol, which provides technical vocabulary and methods (pedigree matrices, error propagation equations, MCS guidance), mandates only qualitative uncertainty for its Product Standard. Organizations can report transport emissions with undisclosed uncertainty while maintaining full compliance across all frameworks. **2. Decline rather than improvement:** Standards published more recently provide less UQ guidance than older frameworks. The GHG Protocol (2001-2015), scores 11/15 (73.3%), while transport-specific standards published afterwards score dramatically lower: EN 16258 (2012) 0/15 (0%), GLEC (2023) 4/15 (27%), and ISO 14083 (2023) 0/15 (0%). This contradicts expectations that standards would incorporate advances, given improvements in computational methods, statistical techniques, and growing climate urgency. **3. Accounting level influence**: Product-level standards

(ISO, GLEC, EN 16258) score lower than the organizational-level GHG Protocol. Although this may reflect the intended user base (e.g. small logistics providers), it does not eliminate the systemic consequences: shipment-level uncertainty propagates upward into organizational and national inventories, regardless of the accounting level at which a standard operates. **4. Universal harmonization failure**: All standards score low on Harmonization (Dimension v), despite being designed for multi-stakeholder contexts. Yet no framework provides methods for combining uncertainties when one organization's emissions calculation depends on another organization's data. This gap prevents rigorous uncertainty assessment precisely where it matters most: when emissions cross organizational boundaries and data quality varies across actors.

3.6. *Potential Quantitative UQ Methods Applicable to Transport Standards*

Accurate carbon emission estimates require rigorous UQ, yet emission inventories remain among the most uncertain components of climate models Clappier and Thunis (2020); Lee et al. (2024). Quantitative UQ methods may clarify how uncertainties in activity data or EF propagate through GHG calculations Kimei et al. (2024).

Two well-established approaches could be integrated into transport standards, though they represent only a part of the available methods. **Error propagation** uses analytical expressions (e.g., Taylor series) to combine uncertainties through mathematical operations, and is already applied in the IPCC and the GHG Protocol Guidelines. **Probabilistic methods**, including MCS, characterize input uncertainty as distributions and propagate them through calculations to produce output distributions, an approach widely applied in GHG emission research Kimei et al. (2024); Ma et al. (2025). Beyond these, additional quantitative techniques, such as machine learning methods Yang et al. (2023), could also be adopted. These methods are computationally feasible and already implemented in national inventories, yet remain absent from corporate and product-level standards.

4. Conclusion

This evaluation reveals that transport carbon-accounting standards provide minimal guidance on quantitative UQ. The newest sector-specific standards, offer no UQ provisions, while the older and more general GHG Protocol, scores 11/15 and remains the only framework including technical UQ methods, though their use is optional and still relies heavily on expert judgment.

Across the three transport specific standards (ISO, GLEC, EN 16258), no quantitative UQ methods appear, enabling full compliance without reporting measurement confidence or data quality. Even the GHG Protocol, does not require mandatory rigorous UQ, despite referencing error propagation, MCS, pedigree matrices, and statistical procedures.

Harmonization emerges as the weakest dimension. All standards score 0/3 or 1.25/3, on combining uncertainties across organizational boundaries, allocation choices and mixed-data quality levels. This omission is particularly problematic because transport emissions span national inventories, corporate Scope 1 and 3, and product life cycles. Without harmonization methods, emissions reported from different organizational perspectives remain incomparable.

Despite these gaps, the field is well positioned to advance integrating more rigorous UQ approaches.

References

Bowen, F. and B. Wittneben (2011, 10). Carbon accounting: Negotiating accuracy, consistency and certainty across organisational fields. *Accounting, Auditing and Accountability Journal 24*, 1022–1036.

CEN (2012). Methodology for calculation and declaration of energy consumption and ghg emissions of transport services (freight and passengers). Technical report.

Clappier, A. and P. Thunis (2020, 12). A probabilistic approach to screen and improve emission inventories. *Atmospheric Environment 242*.

Forster, P. M., C. Smith, T. Walsh, and et al. (2025, 6). Indicators of global climate change 2024: annual update of key indicators of the state of the climate system and human influence. *Earth System Science Data 17*, 2641–2680.

GHG Protocol (2003). Ghg protocol guidance on uncertainty assessment in ghg inventories and calculating statistical parameter uncertainty. Technical report.

GHG Protocol (2011). Quantitative inventory uncertainty. Technical report.

GHG Protocol, WRI, and WBCSD (2003). Aggregating statistical parameter uncertainty in ghg inventories - calculation worksheets september 2003. Technical report.

GHG Protocol, WRI, and WBCSD (2011). Corporate value chain (scope 3) accounting and reporting standard - supplement to the ghg protocol corporate accounting and reporting standard. Technical report.

GHG Protocol, WRI, and WBCSD (2015). A corporate accounting and reporting standard. Technical report.

IPCC (2006a). *Energy*, Volume 2.

IPCC (2006b). *General Guidance and Reporting*, Volume 1.

IPCC (2019). Decision ipcc/xliv-5. sixth assessment report (ar6) products, outline of the methodology report(s) to refine the 2006 guidelines for national ghg inventories. Technical report.

ISO (2018). Iso 14064-1. greenhouse gases - part 1: Specification with guidance at the organization level for quantification and reporting of ghg emissions and removals. Technical report.

ISO (2023). Iso 14083 greenhouse gases — quantification and reporting of ghg emissions arising from transport chain operations. Technical report.

ITF (2023, 5). *ITF Transport Outlook 2023*. OECD Publishing.

Jaramillo, P., S. K. Ribeiro, P. Newman, and et al. (2023, 8). *Transport*, pp. 1049–1160. Cambridge University Press.

JCGM/WG 1 (2023). Guide to the expression of uncertainty in measurement - part 1: Introduction. Technical report.

Kimei, E., D. Nyambo, N. Mduma, and S. Kaijage (2024, 3). Review of sources of uncertainty and techniques used in uq and sensitivity analysis to estimate ghg emissions from ruminants. *Sustainability (Switzerland) 16*.

Lee, K., J. Ko, and S. Jung (2024, 5). Quantifying uncertainty in carbon emission estimation: Metrics and methodologies. *Journal of Cleaner Production 452*.

Li, D., F. Yu, R. Zhang, M. Zhu, S. Liao, M. Lu, J. Guo, L. Wu, and J. Zheng (2024, 8). Real-world ghg emission characteristics from in-use light-duty diesel trucks in china. *Science of the Total Environment 940*.

Ma, H., Y. Zhu, W. Long, and et al. (2025, 7). Probabilistic, measurement-informed ghg emissions from global liquefied natural gas supply chains reveal wide country-level variation.

Marlowe, J. and A. Clarke (2022). Carbon accounting: A systematic literature review and directions for future research. *Green Finance 4*, 71–87.

Puig, D. and F. Bakhtiari (2019, 3). Incorporating uncertainty in national-level climate change-mitigation policy: possible elements for a research agenda. *Journal of Environmental Studies and Sciences 9*, 86–89.

Quantis (2003). Uncertainty assessment template for product ghg inventories. Technical report. Accessed: Jan. 08, 2026.

Rawat, A., D. Kumar, and B. S. Khati (2024). A review on climate change impacts, models, and its consequences on different sectors: a systematic approach. *Journal of Water and Climate Change 15*, 104–126.

Schmidt, M., M. Nill, and J. Scholz (2022, 7). Determining the scope 3 emissions of companies. *Chemical Engineering and Technology 45*, 1218–1230.

Sence about Science (2013). Do we even need more certainty?

Sirithian, D., P. Thanatrakolsri, and S. Pongpan (2022, 10). Co2 and ch4 emission factors from light-duty vehicles by fuel types in thailand. *Atmosphere 13*.

Smart Freight Centre and GLEC (2023). Global logistics emissions council framework v3.2. Technical report, Smart Freight Centre.

Statista (2023). Distribution of ghg emissions worldwide in 2023, by sector.

The Alan Turing Institute (2026). Uncertainty quantification.

UNDP (2025). Whats is sustainable transport and what role does it play in tackling climate change?

UNFCCC (2015). The paris agreement. Technical report, UN.

University of Manchester (ND). Uncertainty quantification.

Volodina, V. and P. Challenor (2021, 5). The importance of uncertainty quantification in model reproducibility. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 379*.

Yang, L., Y. Hu, H. Wang, and et al. (2023, 6). Uncertainty quantification of co2 emissions from china's civil aviation industry to 2050. *Journal of Environmental Management 336*.