White Rose Research Online

eprints@whiterose.ac.uk
https://eprints.whiterose.ac.uk
Universities of Leeds, Sheffield and York

Deposited via The University of Sheffield.

White Rose Research Online URL for this paper:
https://eprints.whiterose.ac.uk/id/eprint/246373/

Version: Accepted Version

Article:
Brennan, S.J., Meng, F., Bolson, N.F. et al. (2026) Credible, scalable, actionable: principles for scope 3 emissions measurement and supply chain decarbonization. One Earth, 9 (9). 101782. ISSN: 2590-3322

https://doi.org/10.1016/j.oneear.2026.101782

© 2026 The Authors. Except as otherwise noted, this author-accepted version of a journal article published in One Earth is made available via the University of Sheffield Research Publications and Copyright Policy under the terms of the Creative Commons Attribution 4.0 International License (CC-BY 4.0), which permits unrestricted use, distribution and reproduction in any medium, provided the original work is properly cited. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/

Reuse
This article is distributed under the terms of the Creative Commons Attribution (CC BY) licence. This licence allows you to distribute, remix, tweak, and build upon the work, even commercially, as long as you credit the authors for the original work. More information and the full terms of the licence here: https://creativecommons.org/licenses/

Takedown
If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.

UNIVERSITY OF LEEDS
University of Sheffield
UNIVERSITY of York

Credible, Scalable, Actionable: Principles for Scope 3 Emissions Measurement and Supply Chain Decarbonisation

Spencer J. Brennan[1*], Fanran Meng[2*], Natanael F. Bolson[3], Miguel Mancera de Olloqui[1], Jobey P. Meacham[1], Ming Xu[4], Eric Masanet[5,6], Jonathan M. Cullen[1,7*]

[1] Neutreeno, Cambridge Institute for Sustainability Leadership, Cambridge, CB2 1GG, United Kingdom.
[2] School of Chemical, Materials and Biological Engineering, Faculty of Engineering, University of Sheffield, Sheffield, S10 2TN, United Kingdom.
[3] Sustainable Manufacturing Group, School of Engineering, University of Birmingham, Edgbaston, Birmingham, B15 2TT, United Kingdom.
[4] School of Environment, Tsinghua University, Beijing, 100084, China.
[5] Bren School of Environmental Science and Management, University of California, Santa Barbara, CA, USA
[6] Department of Mechanical Engineering, University of California, Santa Barbara, USA
[7] Department of Engineering, University of Cambridge, Trumpington Street, Cambridge, CB2 1PZ, United Kingdom.

*Correspondence: spencer.brennan@neutreeno.com; f.meng@sheffield.ac.uk; jmc99@cam.ac.uk

Scope 3 emissions dominate corporate carbon footprints, yet reported figures are often too uncertain to guide effective decarbonisation, creating a dangerous illusion of climate accountability. This problem is intensifying as AI tools speed up flawed estimates. We propose three bedrock principles, credible, scalable, and actionable, to make Scope 3 accounting trustworthy and, critically, accelerate decarbonisation. ~~Scope 3 emissions make up the majority of corporate lifecycle carbon footprints, yet most reported numbers are too uncertain to guide effective decarbonization—creating a dangerous illusion of climate accountability. This problem is intensifying as AI tools that match purchases to generic emissions-factor databases produce fast, seemingly precise figures that are in fact less accurate than the methods they are replacing, further divorcing reported numbers from the real production choices that determine emissions. We propose a set of bedrock principles—credible, scalable, and actionable—for trustworthy Scope 3 emissions accounting, defining how approaches, including AI-based ones, can improve product emissions measurement and accelerate effective decarbonisation.~~

~~Scope 3 emissions dominate corporate carbon footprints, yet reported figures are often too uncertain, creating a dangerous illustion of climate accountability. This problem is intensifying as AI tools may speed up flawed estimates. We propose three bedrock principles — credible, scalable, and actionable — to define how approaches, including AI-based one, can make Scope 3 accounting trustworthy and decarbonisation more effective.~~

Formatted: Font: Bold, Complex Script Font: Bold

Formatted: Font: Bold, Complex Script Font: Bold

Formatted: Font: Bold, Complex Script Font: Bold

Commented [JC1]: Proposed new text. Incorporates the issue of AI generated measurements. But keeps the last paragraph which we think is important.

Commented [SZ2R1]: Lovely! I really like the AI-element, thank you so much Jon! It's just that, we'd need to keep the Summary ideally below 50 words.

I've made some attempts in the version attached below. Let me fix with the Production team to have 60 words. Please do feel free to edit on that version further, as you see fit!

Despite record renewable energy growth and 80 carbon pricing mechanisms covering 28% of global GHG emissions, current mitigation policies and actions are struggling to keep pace with limiting climate warming to 1.5°C.[1,2] The sharpest gap lies in industry: over two decades, energy- and process-related CO_2 emissions have risen from 9.9 to 17.3 $GtCO_2$, equivalent to the rise of global emissions from 36% to 47%, with nearly all increases since 2005 stemming from making materials and products.[3,4] When these industrial emissions occur in upstream supply chain activities not directly owned by a reporting company, they are classified as Scope 3 emissions. Yet existing methods used to quantify Scope 3 emissions are often either too uncertain or too costly to guide meaningful decarbonisation.

As disclosure requirements tighten globally, prevailing approaches prioritise speed and cost to address the complety of Scope 3 emissions accounting, increasingly relying on AI assisted tools. However, in the absence of robust representativeness and granularity in emissions data, faster and cheaper Scope 3 emissions accounting risks creating a mismatch between the ambition of corporate climate commitments and the actual scale and scope of emissions that must be reduced —ultimately undermining mitigation efforts. The central question, then, is how to prevent corporate decarbonisation commitments from becoming detached from the procurement decisions, target-setting, and industrial interventions needed to deliver them.

Measruing and reducing Scope 3 emissions

The Greenhouse Gas Protocol[5] provides an agreed accounting method for allocating emissions, requiring companies to account for GHGs across 15 categories. Meanwhile, international standards, including ISO 14064-1:2018,[6] ISO 14067:2018,[7] and IFRS S2 Climate-related Disclosures (2023),[8] establish harmonised frameworks for emissions reporting and supply chain transparency. Under the Greenhouse Gas Protocol,[5] a company's emissions are classified into three scopes: Scope 1 covers direct emissions from owned assets and activities; Scope 2 covers purchased energy such as electricity and steam; and Scope 3 covers everything else: the upstream and downstream emissions embedded in the goods and services a company buys, uses, and sells.

Companies are therefore expected to report and reduce their Scope 3 emissions, which typically account for 75% or more of a company's total footprint, and in sectors like financial services, capital goods, and oil & gas can reach 90–99% or more. Currently, 96% of the world's largest 250 companies by revenue report on sustainability or ESG matters, with 78% using the Global Reporting Initiative,[9] and almost 10,000 companies have set science-based targets to reduce their emissions validated by the Science Based Targets Initiative.

Why Scope 3 emissions remain obscure

In practice, however, documenting Scope 3 emissions precisely poses a huge challenge to companies. Accurate measurement requires emissions factors tailored to real-world production activities, which depend on detailed knowledge of process technologies, locations, and operating efficiencies. Collecting such data is time-consuming, hindered by cumbersome questionnaires, reporting fatigue, and suppliers' reluctance to share sensitive information, leaving Scope 3 emissions as the least-understood share of a company's carbon footprint.

Presently, the standard method for quantifying Scope 3 emissions is to multiply an activity by an emissions factor (i.e. *emissions = activity (A) × emissions factor (EF)*[5]). For a steel component, this means multiplying the mass of steel purchased (in kg) by a factor representing

Commented [SZ3]: Edits proposed in this section are only attempting to make the narrative flows in a little more broadly accessible and compelling way. Please do feel free to edit further as you see fit.

Formatted: Space After: 0 pt, Line spacing: single

Commented [SZ4]: Headings can have up to 55 characters including spaces. We therefore made some edits throughout to take this formatting guidance into effects. We also proposed some new Section Heading to hopefully create effective 'breaks' to better navigate the reader throughout. Please do feel free to make further edits as you see fit.

Commented [JC5]: Actual text from the source.

how much CO_2 is released per kilogram of steel produced ($kgCO_2/kg$). For a food ingredient, it might mean multiplying the volume of wheat flour sourced (in tonnes) by an emissions factor for average wheat production. Yet, getting process-specific emission data is nevertheless challenging, so companies often apply average emissions factors, which can differ massively from reality. For example, across 63 sampled ethylene production processes, measured emissions factors span 0.23–7.3 $kgCO_2e/kg$, yet the global database average sits at 1.4–1.6 $kgCO_2e/kg$, misrepresenting a specific supplier's footprint by up to 600%.[10]

These 'convenience-led' accounting approaches conceal a deeper problem: they are overly simplified with huge uncertainties and therefore cannot properly guide the decarbonisation decisions Scope 3 emissions accounting is meant to inform. For example, a procurement team using average emissions factors cannot distinguish steel made from iron ore in a coal-fired blast furnace from steel made using scrap in an electric arc furnace running on renewables, or steel formed in a rod and bar mill from steel that is hot and cold rolled. Simply knowing the rolling/forming and steel-making processes can already narrow the cumulative uncertainty range by a factor of 3.27 for the simplest of products, made from a kilogram of steel (Figure 1); collecting process-level data at each stage of the value chain would narrow the range further. For more complex products than steel, assigning global average emission factors creates uncertainty that obscures low-carbon choices and effective decarbonization options.

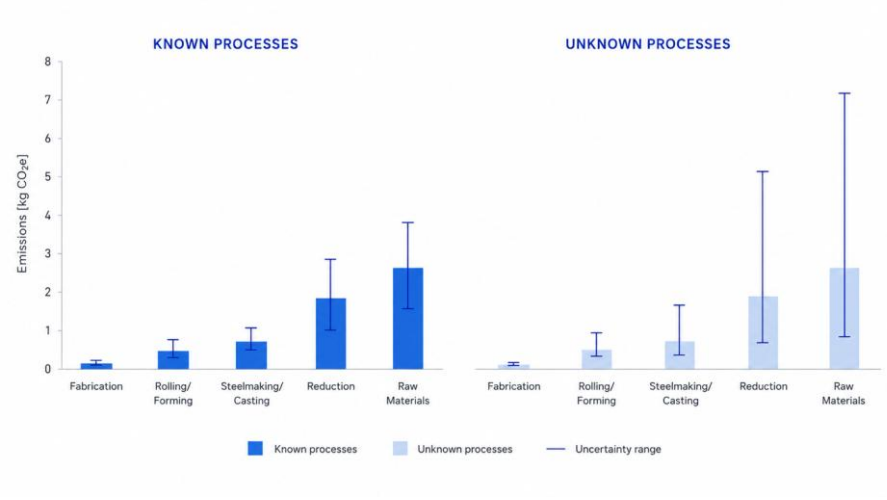


Figure 1. Cumulative emissions and uncertainty for producing one kilogram of steel product, shown at each process stage. When process-specific information is *known*, such as the proportion of rod and bar milling versus hot/cold rolling for *Rolling/Forming*, or the scrap steel rate for *Reduction,* the cumulative upstream uncertainty is narrower (1.7–3.7 kg CO_2e; left panel) than when this information is *unknown* (0.7–7.2 kg CO_2e; right panel). Data and ~~modelling~~calculation: Neutreeno's system with data from International Energy Agency, the UK Department for Energy Security and Net Zero and Gast et al.[11–13]

Commented [SZ6]: The narrative here reads a little convoluted, we thus proposed the edits to tidy things up a little. Please do edit further as you see fit.

Commented [JC7R6]: Thanks. I've tidied this up further.

Commented [SZ8]: This is an interesting example, but the way it is currently featured reads a little abrupt. We therefore moved it up to here and rephrase a little to fit the overall narrative. Please feel free to edit further as you see fit.

Commented [JC9R8]: agree.

Commented [SZ10]: Here should provide the link to the data source.

Commented [FM11R10]: Spencer/Jon to add the link if available.

Commented [JC12R10]: Can we make this "illustrative example"? The numbers are correct (and better than LCA databases) but would be a challenge to provided auditable data.

Commented [JC13R10]: We'll try to provide some data source here.

Commented [SZ14R10]: This sounds quite helpful, Jon. Let's stay with these references, sound very helpful. I only edited a little phrasing thing - i.e. change "modeling" to "calculation", just a tactic we use for Commentary articles, such that the piece is more of a science-based opinionated discussion, rather than presenting new analysis. Please, do definitely feel free to change further as you see appropriate!

Commented [SB15R10]: Hi Shanshan, the only thing is the calculation is done by Neutreeno's system with reference to these data. Is this a fine wording?

The problem becomes even more pronounced when emissions measurements are automated with the assistance of AI tools. These scan and match each line item to the nearest database average and produce a number within seconds, but that number provides no reliable or auditable basis for setting targets, selecting suppliers, or identifying where emissions reductions are actually achievable. This erosion of data quality, by moving from full LCAs to AI-assisted screening, obscures the supply chain interventions needed for genuine decarbonisation and undermines confidence in the emissions inventories that corporate climate commitments depend upon (Figure 2).

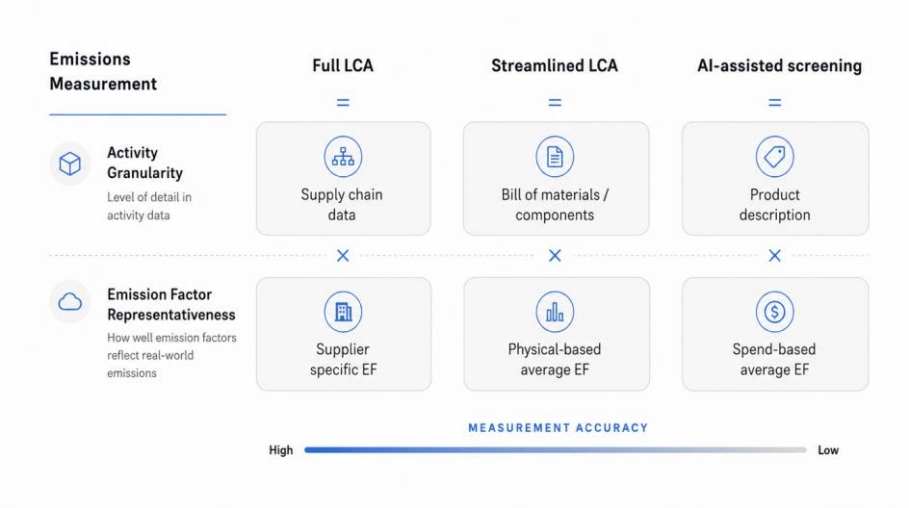


Figure 2: Measurement accuracy across LCA approaches. Emissions measurement accuracy decreases as methods move left to right, from Full LCA to Streamlined LCA to AI-assisted Screening, driven by compromises in both Activity Granularity and Emissions Factor (EF) Representativeness. This trade-off in measurement accuracy reflects the tension between methodological rigour and the practical demands of speed and cost.

Formatted: Font: Not Bold, Complex Script Font: Not Bold

The consequences of such systematic mismeasurement extend well beyond individual companies: they create a structural vacuum at the heart of industrial decarbonisation. Scope 3 emissions disclosed by European companies accounted for 92% of their reported footprints in 2022, yet decarbonisation actions targeting those sources covered only 37% of emissions on average,[14] and just 3% of companies use supplier-specific primary data for their baseline measurements.[15]

This is not a coincidence. When reported Scope 3 figures are built from averaged estimates rather than process-level data, they cannot identify which suppliers, materials, or production steps are driving emissions, cannot track whether interventions are working, and cannot support the procurement decisions that would shift market share toward lower-carbon producers. The result is that 93% of companies with publicly declared Net Zero targets will need to double their rate of decarbonisation by 2030 to meet them.[16] This is not because the physical solutions are absent, but because the measurement systems in place are not producing the decision-grade data needed to deploy them. The challenge is therefore not simply one of better reporting. It is one of replacing a measurement paradigm optimised for

convenience with one capable of revealing where industrial emissions truly arise and what it would take to reduce them.

CSA principles for Scope 3 stewardship

To meet policy requirements and emissions targets, corporations need robust technical solutions that integrate efficiently across value chains, without replicating resource-intensive accounting divisions. Scope 3 emissions accounting is fundamentally a data challenge, and digital systems must move away from generic, outdated databases and secondary emission factors toward supplier-specific, process-level data collection underpinned by consistent, science-based accounting methods. Here we propose three core principles — credible, scalable, and actionable — which we call the CSA Principles, drawing on research across multiple universities, including contributions to SBTi, the IPCC, and Industrial Ecology, as a feasible tool (Figure 3). Together, they define the minimum conditions for decision-grade emissions data – data that any company needs to make confident choices in product procurement, design and innovation. Without them, Scope 3 reporting risks becoming locked-in as a compliance exercise detached from real decarbonisation outcomes.

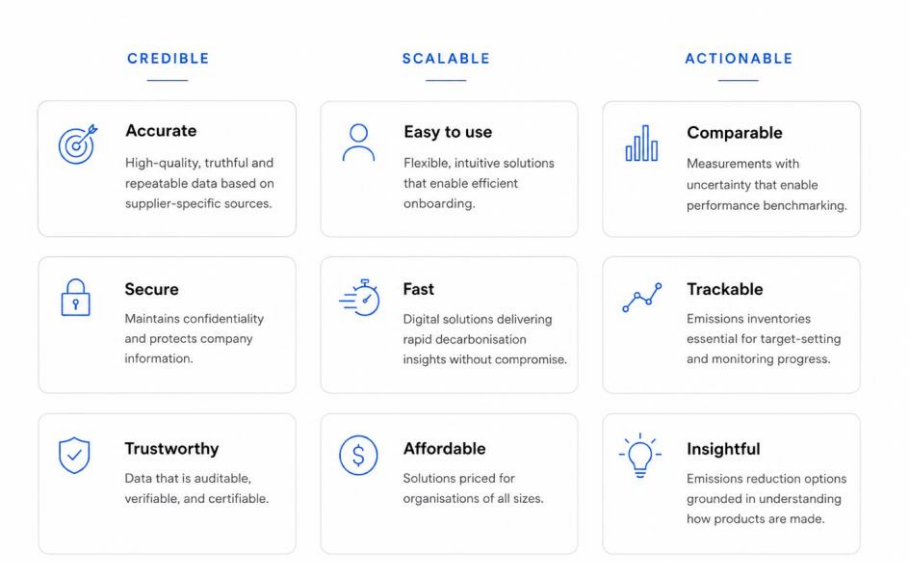


Figure 3: CSA Principles for guiding emissions measurement and decarbonisation. Effective Scope 3 ~~accounting~~emissions management must be *credible*, *scalable*, and *actionable*. It ~~should rely on~~requires auditable, supplier-level data~~, use digital tools to reach~~ that quantifies data trustworthiness and moves securely across the value chain, delivered through a fast and affordable digital system. ~~deep supply chains affordably, and provide~~It must provide comparablility~~e, trackable i~~ and direct decarbonisation insights ~~that support procurement, target-setting, and real emissions reduction~~that companies can act on and track over time~~s~~, rather ~~than purely driven by faster~~than simply faster reporting.

Formatted: Font: Not Bold, Complex Script Font: Not Bold

Formatted: Font: Italic, Complex Script Font: Italic

Formatted: Font: Italic, Complex Script Font: Italic

Commented [SZ16]: Sorry that this was off my radar last time. Our production team will ask for a Figure Caption here. Please do feel free to edit further as you see fit!

Credibility requires that emissions measurements accurately reflect how products are actually made, by whom, and where. This means moving beyond industry-average emissions factors toward primary data collected directly from suppliers at the process level, with gate-to-gate visibility of each production step. Credible data must also be secure, maintaining supplier confidentiality so that value chain partners are willing to share sensitive production information, and trustworthy, meaning auditable, verifiable against industry benchmarks, and certifiable by third parties. Without credibility, reported figures cannot support procurement decisions, target-setting, or regulatory compliance with confidence. Digital tools can support credibility by automating data collection from suppliers through structured, standardised input workflows that reduce reporting burden while enforcing data quality checks. Where primary data is unavailable, intelligent systems can flag gaps and quantify the resulting measurement uncertainty, rather than silently substituting a database average — giving decision-makers a clear view of where confidence is high and where it is not.

Scalability addresses the practical reality that Scope 3 spans thousands of suppliers, tens of thousands of purchased products, and multiple tiers of supply chains that no resource-intensive manual process can reach. Scalable solutions must be fast, delivering emissions measurements and decarbonisation insights without the months-long timelines of traditional life cycle assessment, and affordable, priced to enable engagement with suppliers of all sizes rather than only large Tier 1 partners. Ease of use is equally important: if data collection systems impose excessive burden through cumbersome questionnaires or require specialist expertise to operate, supplier participation will remain low, and coverage will be confined to the most accessible parts of the value chain. Modern digital platforms, including AI-assisted data ingestion, automated bill-of-materials parsing, and cloud-based supplier portals, can dramatically reduce the cost and time of emissions measurement while extending reach deep into supply chains and keeping confidential production data secret. The two-thirds of Scope 3 emissions that typically lie beyond Tier 1 suppliers will remain invisible until scalable digital infrastructure makes it practical to collect process-level data at that depth.

Actionability is the principle that distinguishes measurement from decarbonisation. Credible, scalable data only drives emissions reductions if it is presented in a form that enables decisions. It must be insightful, meaning that the data reveals the specific levers available within a given production process rather than offering only generic suggestions, and comparable, so that a company can benchmark a supplier's emissions performance against industry peers and identify best-in-class producers. Finally, it must be trackable, so that the impact of specific interventions — a process change, a material substitution, a switch to renewable energy — can be monitored over time and quantified as a reduction across the value chain.

The CSA Principles are starting to be validated by Neutreeno, a University of Cambridge spinout, working across 50+ companies spanning the built environment, automotive, aerospace, electronics, and chemicals sectors, including Danone, L'Oréal, National Grid, Sony, Specsavers, Velux, and AeroEdge. Across these applications, supplier-specific process data consistently reveals reduction opportunities that databases of average values fail to. A case study involving AeroEdge highlights the important co-benefits CSA can help yield: a full emissions measurement, completed within three weeks using supplier-specific process data, that identified manufacturing process changes generic databases had entirely overlooked. This yielded a potential 41.4% reduction in emissions and annual cost savings of several million euros from reduced material, energy, and processing inputs. With tailored CSA appropriately

applied, not only will Scope 3 emissions be more accurately monitored and transparently governed, but companies will also be more likely to provide granular process-specific data — meeting net-zero targets in a timely, cost-effective manner and unlocking tangible actions that make them more competitive in a fast-moving economy.

Closing theeing ~~the gap between~~ Scope 3 measurement and ~~emissions~~ reduction gap

The stakes of neglecting the measurement gap extend far beyond corporate balance sheets. Without accurate and transparent Scope 3 emissions data, financial institutions may lose the chance to effectively price the low-carbon transition and direct capital toward low-carbon producers. Regulators may miss the opportunity to enforce disclosure obligations and evaluate progress against national climate commitments. Trade mechanisms such as the EU Carbon Border Adjustment Mechanism[17] are unlikely to level the competitive playing field between high- and low-carbon producers across borders. Each of these functions is only as reliable as the emissions data underpinning it.

Policy- and decision-makers therefore have every reason to raise the bar for Scope 3 emissions accounting and reduction. That means standardizing primary data collection, creating incentives for supplier data sharing, and building disclosure frameworks that reward measurement quality and real emissions cuts, not just more reporting. Getting Scope 3 emissions accounting on the right path is not a technical side issue in climate policy; it is the backbone of any credible net-zero transition that governments, investors, and industries now claim to be pursuing. It also provides a competitive advantage to most corporations. With AI pushing the field toward faster and likely real-time emissions evaluation, the CSA Principles must serve as the guardrails to ensure Scope 3 emissions accounting delivers real value for both climate mitigation and long-term business resilience.

Commented [SZ17]: Apologise for the back and forth upon the heading here. The only reason that I proposed this further modification, is purely because of the formatting criteria - i.e. the production team will ask us to keep the length of the heading within 55 characters including spaces.

Please do edit further, as you see fit, upon these changes.

Commented [SB18R17]: How does this look now Shanshan?

Commented [SZ19]: We feel this paragraph intends to convey something quite important, but the current narrative reads a little ambiguous and disconnected to the central thread. We therefore proposed some tweaks, to help improve connectivity and intended message. Please do feel free to edit further as you see fit.

Commented [SZ20]: We slightly rephrase this ending remark to help shining out the takeaways in a more compelling way. Please feel free to edit further as you see fit.

Acknowledgements

The authors would like to acknowledge support from: C-THRU: Carbon Clarity in the Global Petrochemical Supply Chain, www.c-thru.com; Transfire (EP/V054627/1) www.transfire-hub.org; Royal Society ISPF - International Collaboration Awards (ICA\R1\231046); Tsinghua - Cambridge Joint Research Initiative Fund.

Competing interests

Spencer Brennan, Jonathan Cullen, Miguel Mancera de Olloqui, Jobey Meacham and Fanran Meng report a relationship with Neutreeno that includes employment. Neutreeno is a Cambridge-based start-up, engineering a new decarbonisation paradigm, www.neutreeno.com. The other authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. World Bank. *State and Trends of Carbon Pricing 2025*. (2025) doi:DOI:10.1596/978-1-4648-2255-1.
2. UNEP. *Emissions Gap Report 2025: Off Target - Continued Collective Inaction Puts Global Temperature Goal at Risk*. (United Nations Environment Programme, Nairobi, 2025). doi:10.59117/20.500.11822/48854.
3. IEA. *Energy Technology Perspectives 2008*. (International Energy Agency, Paris, 2008).
4. IEA. *World Energy Outlook 2023*. (International Energy Agency, Paris, 2023).
5. Schmitz, S. *et al.* The Greenhouse Gas Protocol - A Corporate Accounting and Reporting Standard, Revised Edition. *The GHG Protocol Corporate Accounting and Reporting Standard* **9**, (2004).
6. ISO. *ISO 14064-1:2018(E):Greenhouse Gases-Part 1: Specification with Guidance at the Organization Level for Quantification and Reporting of Greenhouse Gas Emissions and Removals*. (2018).
7. ISO. *ISO 14067:2018(E): Greenhouse Gases-Carbon Footprint of Products-Requirements and Guidelines for Quantification*. (2018).
8. IFRS Foundation. IFRS S2 Climate-related Disclosures, International Financial Reporting Standards Foundation. (2025).
9. GRI. A bird's eye view on reporting regulations and the SDGs. *Global Reporting Institute* (2024).
10. Cullen, L., Meng, F., Lupton, R. & Cullen, J. M. Reducing uncertainties in greenhouse gas emissions from chemical production. *Nature Chemical Engineering* **1**, 311–322 (2024).
11. International Energy Agency. *Electricity 2026: Analysis and Forecast to 2030*. (2026).
12. Department for Energy Security and Net Zero. *UK Government GHG Conversion Factors for Company Reporting: Full Set, 2025 (Version 1)*. (2025).
13. Gast, L., Cabrera Serrenho, A. & Allwood, J. M. What Contribution Could Industrial Symbiosis Make to Mitigating Industrial Greenhouse Gas (GHG) Emissions in Bulk Material Production? *Environ. Sci. Technol.* **56**, 10269–10278 (2022).
14. CDP & Capgemini Invent. *From Stroll to Sprint: A Race Against Time for Corporate Decarbonization*. (2023).
15. Science Based Targets initiative (SBTi). *Aligning Corporate Value Chains to Global Climate Goals*. (2024).
16. Luu, F. & Aizenberg, A. Nearly All Companies Will Miss Net Zero Goals Without At Least Doubling Rate of Carbon Emissions Reductions by 2030, Accenture Report Finds. *Accenture* (2022).

Formatted: Indent: Before: 1 cm

17. *Regulation (EU) 2023/956 of the European Parliament and of the Council of 10 May 2023, Establishing a Carbon Border Adjustment Mechanism (CBAM). Official Journal of the European Union* (2023).