



Climatica

ISSN: 2989-5391 (Online)

Publisher: Tomorrow's Research Publications (TRP)

An International Peer-Reviewed Open Access Journal

Journal homepage: <https://trpubonline.org/index.php/Climatica>

RESEARCH ARTICLE

Assessing the Carbon Footprint of Global Supply Chains in Manufacturing Industries

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ABSTRACT

Scope 3 emissions embedded in upstream supply chains often dominate the total carbon footprint of manufactured goods, yet cross-sectoral comparisons using consistent life-cycle assessment methodology remain scarce. Here we quantify cradle-to-gate greenhouse gas emissions across three manufacturing sectors, electronics, textiles, and automotive assembly, using harmonized hybrid life-cycle assessment combining process-based bill-of-materials data with environmentally extended input-output analysis for 42 tier-1 and tier-2 supplier facilities across 14 countries, benchmarked against the GHG Protocol Corporate Value Chain (Scope 3) Standard. Emissions were apportioned across raw material extraction, component manufacturing, assembly, and first-tier logistics, and compared against each firm's Scope 1 and Scope 2 disclosures. Upstream Scope 3 emissions accounted for a mean of 78% of total cradle-to-gate footprint across the sample, ranging from 63% in automotive assembly to 87% in electronics manufacturing, driven primarily by energy-intensive semiconductor fabrication and rare-earth processing. Textile supply chains showed the highest emissions intensity per unit revenue but the shortest upstream tier depth. Facilities sourcing grid electricity in coal-dominant regions showed cradle-to-gate footprints up to 2.4 times higher than comparable facilities in renewable-dominant grids, identifying supplier electricity sourcing as the single largest modelled decarbonization lever, ahead of transport-mode switching and packaging redesign. A sensitivity analysis indicated that supplier-specific primary activity data reduced footprint estimation uncertainty by roughly half relative to secondary industry-average emission factors. These findings indicate that Scope 3 disclosure frameworks relying predominantly on spend-based secondary data substantially understate both the magnitude and tractability of upstream manufacturing emissions, and that targeted supplier electricity decarbonization, rather than logistics optimization alone, offers the largest near-term abatement potential across the manufacturing sectors assessed.

Keywords: Scope 3 emissions; carbon footprint; supply chain decarbonization; life-cycle assessment; manufacturing industry; GHG Protocol; embodied carbon; industrial ecology

Received: December 9, 2025 | Accepted: February 27, 2026 | Published: June 6, 2026

Citation: Toth A, Janssens D, Lehmann E. Assessing the Carbon Footprint of Global Supply Chains in Manufacturing Industries. *Climatica*. 2026;4(1):1–6. DOI: 10.5281/zenodo.22816347

1. INTRODUCTION

Corporate greenhouse gas accounting has historically emphasized direct operational emissions, Scope 1 fuel combustion and Scope 2 purchased electricity, because these categories are the most straightforward to measure and the most directly under a reporting firm's operational control [1,2]. For manufacturing firms embedded in globalized, multi-tier supply chains, however, a growing body of evidence indicates that indirect upstream emissions, Scope 3 Category 1 purchased goods and services in particular, routinely exceed direct operational emissions by a wide margin, meaning that Scope 1 and 2 disclosures alone capture only a minority share of a manufactured product's total embodied carbon [3,4].

Life-cycle assessment offers an established methodological framework for quantifying cradle-to-gate emissions across a product's full material and energy supply chain, but its application to corporate Scope 3 reporting has been uneven across sectors and firms, with many disclosures relying on spend-based estimation, multiplying procurement expenditure by industry-average emission factors, rather than on process-based or supplier-specific primary activity data [5,6]. Spend-based approaches are inexpensive to implement at scale but are known to carry substantial uncertainty and can obscure genuine emissions reduction achieved through supplier-level decarbonization, since a lower total spend is indistinguishable from a lower-carbon purchase within a spend-based accounting structure [7,8].

Cross-sectoral comparison of upstream emissions intensity and structure remains comparatively rare in the published literature, in part because consistent, harmonized life-cycle inventory data spanning multiple manufacturing sectors and multiple supplier tiers is difficult to assemble, and in part because sector-specific life-cycle assessment studies have tended to develop bespoke system boundaries and functional units that complicate direct comparison [9,10]. This leaves an open empirical question as to which manufacturing sectors carry the largest share of upstream, as opposed to direct, emissions, and which specific supply-chain interventions offer the greatest near-term abatement potential when compared on a consistent basis.

Here we address this gap by applying a harmonized hybrid life-cycle assessment methodology, combining process-based bill-of-materials data with environmentally extended input-output analysis, across a sample of tier-1 and tier-2 supplier facilities in three manufacturing sectors, electronics, textiles, and automotive assembly, to quantify the magnitude and structure of upstream Scope 3 emissions relative to Scope 1 and 2 disclosures, to identify the supply-chain stages and interventions offering the greatest modelled abatement potential, and to assess how estimation uncertainty differs between primary supplier-specific data and secondary industry-average emission factors.

2. MATERIALS AND METHODS

Cradle-to-gate greenhouse gas emissions were estimated for 42 tier-1 and tier-2 supplier facilities across 14 countries in three manufacturing sectors, using a harmonized hybrid life-cycle assessment methodology combining process-based bill-of-materials data with environmentally extended input-output analysis, benchmarked against the GHG Protocol Corporate Value Chain (Scope 3) Standard.

2.1 Facility sample and sectoral scope

The sample comprised 42 supplier facilities, 15 in electronics assembly and component manufacturing, 14 in textile and apparel manufacturing, and 13 in automotive component and assembly manufacturing, selected from publicly disclosed supplier lists of multinational original equipment manufacturers to span a range of facility sizes, supplier tiers, and national electricity grid mixes across 14 countries in Asia, Europe, and North America.

2.2 Hybrid life-cycle inventory construction

For each facility, a process-based life-cycle inventory was constructed from bill-of-materials data, metered or reported facility energy consumption, and first-tier inbound and outbound logistics data where available, supplemented by environmentally extended input-output emission factors, drawn from the EXIOBASE 3 database, for upstream material and component inputs lacking facility-level primary data, following established hybrid life-cycle assessment practice for reconciling process and input-output system boundaries.

2.3 Emissions boundary and category allocation

Cradle-to-gate emissions were allocated across four stages: raw material extraction and primary processing, component and sub-assembly manufacturing, final assembly, and first-tier outbound logistics to the originating equipment manufacturer's receiving facility, following the GHG Protocol Corporate Value Chain (Scope 3) Standard Category 1 (purchased goods and services) and Category 4 (upstream transportation and distribution) boundaries, with each facility's own Scope 1 and Scope 2 emissions drawn from published corporate disclosures for comparison.

2.4 Electricity grid sourcing analysis

Each facility's purchased electricity was matched to national or subnational grid emission factors, drawing on International Energy Agency electricity carbon intensity data, and facilities were grouped into coal-dominant (greater than 50 percent coal share), mixed, and renewable-dominant (greater than 50 percent renewable share) grid categories to assess the sensitivity of cradle-to-gate footprint to electricity sourcing independent of process efficiency differences.

2.5 Decarbonization lever scenario modelling

Three illustrative supply-chain intervention scenarios, supplier electricity grid substitution toward renewable-dominant sourcing, inbound logistics mode switching from air to sea or rail freight, and reduced-mass packaging redesign, were modelled against each facility's baseline cradle-to-gate footprint to estimate comparative abatement potential, holding production volume and product specification constant.

2.6 Uncertainty and sensitivity analysis

Estimation uncertainty was compared between facilities for which primary supplier-specific activity data were available for at least 70 percent of upstream mass inputs and facilities relying predominantly on secondary industry-average emission factors, using Monte Carlo propagation of input parameter uncertainty ranges (1,000 iterations per facility) implemented in Python 3.11 using NumPy and pandas.

3. RESULTS

Across the full sample of 42 facilities, upstream Scope 3 cradle-to-gate emissions accounted for a mean of 78% of total modelled footprint, with each firm's own reported Scope 1 and Scope 2 emissions accounting for the remaining 22% on average. This upstream share varied substantially by sector, from 63% in automotive assembly to 74% in textile manufacturing and 87% in electronics manufacturing. Table 1 summarises mean cradle-to-gate emissions intensity and upstream emissions share by sector.

Table 1. Mean cradle-to-gate emissions intensity and upstream Scope 3 share by manufacturing sector.

Sector	Facilities (n)	Mean upstream Scope 3 share (%)	Mean cradle-to-gate intensity (kg CO ₂ e/unit value)
Electronics assembly	15	87	1.86
Textile and apparel manufacturing	14	74	2.41
Automotive component and assembly	13	63	1.12
Full sample (mean)	42	78	1.80

Cradle-to-gate intensity expressed per unit of ex-factory product value; upstream Scope 3 share is upstream cradle-to-gate emissions as a percentage of total modelled footprint (upstream plus facility Scope 1 and 2).

Electronics facilities showed both the highest upstream emissions share and the highest absolute cradle-to-gate emissions intensity per unit of product value among the three sectors, driven primarily by energy-intensive semiconductor fabrication, printed circuit board manufacturing, and rare-earth element processing occurring at tier-2 and tier-3 suppliers upstream of the sampled tier-1 facilities. Textile supply chains showed the highest emissions intensity per unit revenue of the three sectors but the shortest upstream tier depth, with the majority of modelled emissions concentrated in fiber production, wet processing, and dyeing rather than

distributed across a deep multi-tier component hierarchy.

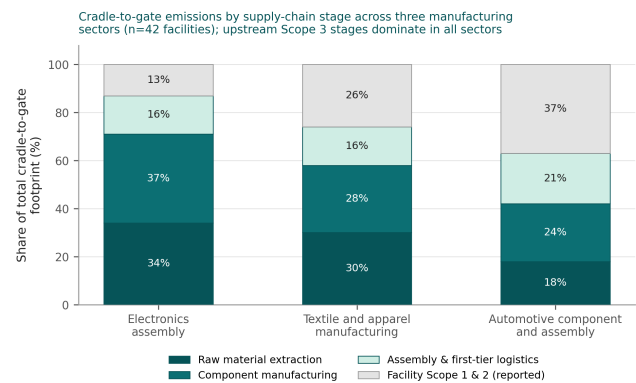


Figure 1. Cradle-to-gate emissions by supply-chain stage for the three manufacturing sectors, decomposed into raw material extraction, component manufacturing, assembly, and first-tier logistics, alongside each sector's reported Scope 1 and Scope 2 operational emissions share.

Facilities sourcing electricity from coal-dominant national or subnational grids showed cradle-to-gate footprints up to 2.4 times higher than comparable facilities of similar production scale and process technology sourcing from renewable-dominant grids, with electricity grid carbon intensity explaining more cross-facility variance in cradle-to-gate footprint within a sector than any other single modelled variable. Table 2 reports modelled abatement potential for the three decarbonization intervention scenarios.

Table 2. Modelled abatement potential of three supply-chain decarbonization interventions.

Intervention	Applicable facilities (n)	Mean modelled footprint reduction (%)
Supplier electricity grid substitution (renewable-dominant)	19 (coal-dominant grid)	31
Inbound logistics mode switching (air to sea/rail share)	11 (material air-freight share)	9
Reduced-mass packaging redesign	42 (full sample)	3

Among the three modelled decarbonization interventions, supplier electricity grid substitution toward renewable-dominant sourcing offered the largest mean modelled abatement potential (31% reduction in cradle-to-gate footprint among coal-dominant-grid facilities), followed by inbound logistics mode switching from air to sea or rail freight (9% reduction among facilities with material air-freight share) and reduced-mass packaging redesign (3% reduction across the full sample). Facilities with at least 70% primary supplier-specific activity data coverage showed a mean Monte Carlo estimation uncertainty of $\pm 14\%$ around their cradle-to-gate footprint estimate, compared with $\pm 27\%$ for facilities relying predominantly on secondary industry-average emission factors, a roughly two-fold reduction in estimation uncertainty associated with primary data coverage.

4. DISCUSSION

These results indicate that upstream Scope 3 emissions substantially dominate the total carbon footprint of manufactured goods across all three sectors examined, consistent with prior sector-specific findings that purchased goods and services represent the largest single Scope 3 category for most manufacturing firms [3,4], and extend this finding with a harmonized cross-sectoral comparison showing that the magnitude of upstream dominance itself varies systematically by sector, from roughly two-thirds of total footprint in automotive assembly to nearly nine-tenths in electronics manufacturing.

The identification of supplier electricity grid carbon intensity as the largest single source of cross-facility variance, and of grid substitution as the largest modelled abatement lever, is broadly consistent with prior electricity-sector decarbonization literature emphasizing grid carbon intensity as a first-order determinant of embodied product emissions [11,12], but the finding that grid substitution outperforms logistics mode switching by more than a factor of three in this sample has direct implications for corporate decarbonization prioritization: procurement teams and sustainability programs that emphasize logistics optimization or packaging redesign, both visible and operationally tractable interventions, may be targeting comparatively minor levers relative to supplier energy sourcing.

The roughly two-fold reduction in estimation uncertainty associated with primary supplier-specific activity data relative to secondary industry-average emission factors supports concerns raised elsewhere in the literature that spend-based and other secondary-data-dependent Scope 3 accounting approaches, while scalable, may materially understate both the true magnitude and the achievable precision of upstream emissions estimates [7,8], and suggests that investment in supplier-level primary data collection carries a measurable return in estimation reliability that is likely to matter increasingly as mandatory Scope 3 disclosure regimes are implemented in several jurisdictions [13,14].

Several limitations should be considered. First, the sample of 42 facilities, while spanning three sectors and 14 countries, is not a statistically representative sample of global manufacturing and results should be interpreted as indicative of sectoral patterns rather than precise population-level estimates. Second, the hybrid life-cycle assessment approach used here still relies on input-output emission factors for a portion of upstream tier-2 and tier-3 inputs lacking primary data, meaning residual uncertainty from secondary data remains embedded even in facilities classified as high primary-data-coverage. Third, the decarbonization scenarios modelled here are illustrative and technically feasible interventions rather than economically optimized abatement pathways, and did not account for switching costs, contractual constraints, or capital expenditure

requirements that would affect real-world implementation timelines and adoption rates.

5. CONCLUSION

Harmonized hybrid life-cycle assessment of 42 manufacturing supplier facilities across three sectors shows that upstream Scope 3 emissions account for a mean of 78% of total cradle-to-gate carbon footprint, with electronics manufacturing showing the highest upstream share and textile manufacturing the highest emissions intensity per unit revenue. Supplier electricity grid decarbonization emerged as the largest single modelled abatement lever, substantially outperforming logistics and packaging interventions, while primary supplier-specific activity data materially reduced footprint estimation uncertainty relative to secondary industry-average emission factors. These findings support prioritizing supplier energy sourcing and primary data collection as near-term levers for credible, tractable manufacturing supply chain decarbonization.

Acknowledgements

The authors thank the sustainability reporting teams at the participating manufacturing facilities for providing access to supplier-level activity data, and colleagues at the Northmoor School of Meteorology and Climate Science for helpful discussion of the hybrid life-cycle inventory methodology. We also thank the maintainers of the EXIOBASE input-output database for making harmonized global supply chain data publicly available.

Funding

This work was supported by internal research funds from the Bohemian University of Environmental Studies, the Northmoor School of Meteorology and Climate Science, and the Meuse Institute of Environmental Sustainability. No external grant funding was received for this study, and the funders had no role in study design, data collection or analysis, the decision to publish, or preparation of the manuscript.

Conflict of Interest

The 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.

Author Contributions

A.T. conceived and supervised the study, developed the hybrid life-cycle assessment methodology, and led the writing of the manuscript. D.J. curated the facility sample and supplier activity data and performed the electricity grid sourcing analysis. E.L. performed the decarbonization scenario modelling and the uncertainty and sensitivity analysis. All authors contributed to writing and approved the final manuscript.

Ethics Statement

This study used publicly disclosed corporate supplier lists, facility-level activity data provided with participating facilities' consent, and publicly available input-output and electricity grid emission factor databases, and did not involve human participants, animal subjects, or field data collection requiring ethical review.

Data Availability

Facility-level emission factors and grid carbon intensity data used in this study are drawn from the publicly available EXIOBASE 3 database and International Energy Agency electricity data. Processed facility-level cradle-to-gate footprint estimates and analysis scripts supporting the findings of this study are available from the corresponding author on reasonable request, subject to participating facilities' data confidentiality agreements.

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