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The environmental smile curve: input-output evidence on the pollution haven hypothesis☆

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ABSTRACT

This paper examines how the fragmentation of production across Global Value Chains (GVCs) generates both economic and environmental inequalities. Integrating OECD ICIO and CO_2 emission data, our analysis reveals an *environmental smile curve*, where environmental and economic downgrading co-occur in middle segments of GVCs, reinforcing global inequalities. These disparities intensify with deeper GVC penetration, challenging the decoupling narrative of green growth. By integrating labour and emission data, we provide novel evidence of how GVCs structurally embed asymmetric power relations between production segments, generating unequal ecological and economic burdens across the globe. While the Global North has strategically benefited from GVCs, the Global South has experienced the heightening of its peripheral and subordinated position.

1. Introduction

The fragmentation of production across borders has fundamentally altered the relationship between economic development and environmental outcomes. Over the past three decades, the rise of global value chains (GVCs) has not only transformed the international division of labour but also reconfigured the geography of pollution (Peters, 2008; Meng et al., 2018). As production processes become increasingly fragmented across borders, the distribution of both economic gains and environmental externalities has grown more unequal, reinforcing long-standing disparities not only across countries, between advanced and developing economies, but also across different occupations within the same country (Timmer et al., 2019).

While traditional models of environmental economics assumed a straightforward link between income growth and emission reductions (Grossman & Krueger, 1995), the reality has proven far more complex (Wang et al., 2024). The Environmental Kuznets Curve (EKC) hypothesis—which posits that emissions initially rise and then decline with economic growth—was originally based on the experiences of advanced economies and largely reflects shifting patterns of specialisation during development (Savona and Ciarli, 2019). However, latecomer economies exhibit fundamentally different specialisation trajectories (Rodrik, 2016; Dosi et al., 2021), leading to highly divergent emission outcomes. When accounting for the structural asymmetries in these economies—rooted in their technological capabilities and further amplified by international trade and, in particular, GVCs—the EKC theory has increasingly been questioned (Stern, 2017).

The integration of developing economies into GVCs has often come at a dual cost: stagnant wage growth for workers (Szymczak & Wolszczak-Derlacz, 2022) and heightened environmental degradation (Krishnan et al., 2022). Given their technology gap and initial endowments, developing countries specialise in primary inputs and labour-intensive, low-value-added manufacturing—such as electricity generation, raw material processing, and fabrication, facing downward pressure on prices and wages due to global competition largely based on cost reduction (Jeon & Kwon, 2021). Simultaneously, these same sectors tend to be emission-intensive, locking nations into a "double harm" of economic and ecological downgrading (Dosi et al., 2025).

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The existing literature has largely treated wage suppression and environmental externalities as separate consequences of GVC integration. Yet, these phenomena are deeply intertwined. When firms face squeezed margins in middle-stage production, they often cut costs either by suppressing wages and generating within-country inequality (Duarte et al., 2022) or by offshoring production to low-income countries (Jeon & Kwon, 2021). However, since developing countries are characterised by weaker environmental regulations, the offshoring of these production segments to lower-income regions is likely to increase the environmental externalities of global production (Aichele & Felbermayr, 2015).

The Pollution Haven Hypothesis (PHH) provides a partial explanation, showing that stringent environmental regulations in advanced economies drive the offshoring of most polluting industries (Cole, 2004). This nexus is particularly evident in GVC trade, where offshore production stages in low-wage economies coincide with high-carbon-intensity segments per unit of value added (Althouse et al., 2023). However, the PHH alone cannot explain why these industries remain pollution-intensive, even as they could upgrade through technological spillovers within GVCs. Still, few studies explicitly integrate PHH with GVC analysis to examine how production fragmentation redistributes emissions *along* value chains—not just *between* nations (Duan & Jiang, 2021). This gap is striking given the central role of GVCs in modern trade and their stark distributional consequences. Tracing the emission contents within fragmented production networks, derived from country patterns of sectoral specialisation and GVC integration, allows us to pinpoint which segment of the production process bears the bulk of the GVC emission burden and, ultimately, to quantify the value added generated in that phase. If low-value-added and high-emission-intensity phases tend to coexist, we conjecture that there should be an environmental smile curve symmetric to the value-added smile curve. Addressing these issues requires bridging the literature on GVC governance and upgrading with environmental economics and the political economy of globalisation.

GVCs are not only the result of sectoral composition or national endowments, but also of governance structures and institutional asymmetries, that shape where capabilities accumulate and where externalities concentrate (Gereffi et al., 2005; Coe and Yeung, 2015; Dallas et al., 2019). Lead firms located in advanced economies typically coordinate dispersed supplier networks through standards, contractual requirements, and technological specifications, while lower-tier suppliers often operate under tight margins and limited autonomy, which constrains their capacity to undertake both productive and environmental upgrading (Pietrobelli and Rabellotti, 2011; Dallas et al., 2019; Krishnan et al., 2022; Colozza et al., 2024). Therefore, the role of the low-road strategy and governance structure assumed by multinational firms is critical: when labour costs are systematically depressed, and competition is based on cost-reduction, firms have little incentive to invest in less polluting production methods too, perpetuating a vicious cycle of low wages and high emissions (Distelhorst & McGahan, 2021). The coexistence of a low-road path in terms of both wages and lack of investments in environmental upgrading technologies might well be the result of managerial capabilities oriented toward cost compression strategies. For this reason, the environmental consequences of GVC integration cannot be read simply as a by-product of growth or trade intensity, but must be interpreted as part of a hierarchical organisation of production in which the same relations that shape value appropriation may also shape the distribution of environmental responsibilities and exposure to pollution-intensive activities (De Marchi and Gereffi, 2023; Bernhold and Selwyn, 2026).

Against this background, this paper examines whether the same stage-based hierarchy used to describe uneven value capture along GVCs also structures the distribution of emissions across production stages. We ask whether relative emission intensity along intermediate-input stages follows a systematic non-linear (inverted) U-shaped pattern and whether lower-value positions within value chains are also those that bear a disproportionate share of the emission burden, when production is internationally fragmented. In doing so, we bridge the smile-curve literature with research on pollution havens and trade-related environmental asymmetries by applying the propagation-length framework to environmental outcomes and making the stage-wise distribution of emissions directly comparable to that of value capture (Meng et al., 2020; Meng and Ye, 2022).

We employ OECD Inter-Country Input-Output tables and sectoral CO_2 data for the period 1995 to 2018 to trace emissions embodied in manufacturing value chains across countries, sectors, and production stages. We combine Leontief-based embodied-emission accounting with stage-position metrics and sector-normalised emission measures to examine how environmental pressure is distributed along the production process, and how this varies across development levels and sourcing structures. We focus on carbon intensity because it is the most harmonised and systematically measurable dimension of production-related environmental pressure in global input–output data, while acknowledging that it captures only one dimension of environmental inequality and does not exhaust broader questions of vulnerability, welfare, or climate justice across countries (Hickel et al., 2022). We distinguish between all intermediates and foreign-sourced intermediates to isolate the GVC-mediated component of environmental burden associated with cross-border fragmentation, rather than domestic production structure alone. Finally, by formally testing nonlinear relationships between positioning and relative emission intensity, we assess whether environmental burdens reproduce, invert, or diverge from the value-capture smile curve, thereby offering a precise account of how economic and environmental inequalities emerge as properties of the power structure within GVCs.

By joining environmental economics with the political economy of globalisation, this paper advances three key contributions: first, we show that the allocation of relative emission burden across intermediate-input stages exhibits a systematic non-linearity, such that the hierarchical distribution of value capture along GVC stages is mirrored by a hierarchical distribution of emission intensity along the identical stage metric. Second, we show that the environmental implications of GVCs are not reducible to national averages or sectoral specialisation alone, but are embedded in the functional architecture of global production itself, where economic and ecological inequalities reinforce one another along the same hierarchy. Third, our findings bear important implications for the climate crisis: against naive techno-optimism, emissions, such as value distribution, are not only a structural variable of production, but also a political choice. As their distribution across the globe is not random but reproduces ex ante inequalities, we urge coordinated global policies to ensure that the "green" transition does not become another vector of uneven development.

The paper proceeds as follows: Section 2 reviews the relevant literature and situates the paper within debates on smile curves, pollution havens, GVC governance, and unequal environmental burdens. Section 3 details our data and methodology, linking the integration of emission accounting with GVC positioning metrics. Section 4 presents the role of industry specialisation and country development levels in influencing global emissions, both looking at country-sector pairwise and exploiting the input–output world production network. Section 5 empirically tests the environmental smile curve and discusses the consequences for unequal development and environmental pollution. Section 6 concludes.

2. Smile curve in value capture, frown curve in emission production?

2.1. Asymmetry in value capture: country, sector and functional evidence

The smile curve provides a useful framework to empirically identify hierarchical value production and distribution along production chains. In its original formulation, the concept captured the idea that upstream activities, such as research and development, and downstream activities, such as branding, marketing, and distribution, tend to appropriate more value than fabrication and assembly tasks located in the middle of the chain (Shih, 1996; Mudambi, 2008). Subsequent contributions have extended this intuition beyond its original business-strategy formulation and shown that the hierarchical organisation of GVCs can be extended from specific multinational corporations to broader sectoral structures, through stage-based positioning metrics derived from input-output data (Timmer et al., 2019; Meng et al., 2020). This literature shows that the smile curve is not simply a stylised description of firm profitability, but a more general representation of hierarchical value capture under global fragmentation. At the sectoral level, GVC participation has been associated with increasingly uneven distributions of value added across industries and countries, with advanced economies concentrating in sectors and stages characterised by stronger rent appropriation. In contrast, developing economies remain more exposed to low-value, low-technology production segments (Baldwin & Ito, 2021). At the functional level, these asymmetries become even more visible. Timmer et al. (2019) show that richer economies are disproportionately specialised in R&D functions, while poorer economies are more heavily specialised in fabrication. Related work further shows that the distribution of labour compensation follows a similar pattern, with the gains from GVC participation accruing unevenly across occupations, sectors, and, most importantly, across countries at different levels of development (Riccio et al., 2025).

2.2. The hidden agency behind GVCs

A central mechanism driving this hierarchy is cost competition, which often takes the form of a downward pressure on labour compensation (Riccio et al., 2024). Participation in fragmented production systems frequently relies on the ability to supply narrowly defined tasks at low cost, especially in fabrication-intensive activities, so that competitive insertion into GVCs is often associated with wage compression rather than with movement into higher-value segments (Milberg and Winkler, 2011; Jeon and Kwon, 2021). Recent evidence shows that GVC integration is associated with lower labour compensation and weaker labour-market outcomes in more exposed segments, with particularly adverse effects for middle-income countries, manufacturing activities, and workers in production-related tasks, while higher-order functions are relatively more protected from these pressures (Szymczak and Wolszczak-Derlacz, 2022). Cost competition, therefore, does not simply accompany GVC integration; it is one of the mechanisms through which less-developed economies are locked into lower-value segments of the chain.

These dynamics have important distributive consequences, reinforcing both between-country divergence and within-country wage polarisation (Duarte et al., 2022; Coveri et al., 2024). Between countries, the smile-curve logic helps explain why global fragmentation has not generated a symmetric convergence in value capture, but has instead reinforced a hierarchical international division of labour in which advanced economies retain stronger positions in knowledge-intensive and rent-rich functions, while developing economies remain concentrated in fabrication and other lower-remunerated activities. Within countries, the same process contributes to widening wage gaps across occupational groups, since production workers bear the largest losses in labour share while higher-level occupational categories are relatively more sheltered (Riccio et al., 2025).

2.3. An emerging hierarchy of environmental burden across the globe

GVCs do not simply hierarchically assign value production and its distribution, but also encompass the corresponding environmental burdens across countries and stages of production (Peters, 2008). Within this perspective, the Pollution Haven Hypothesis remains a central starting point: stricter environmental regulation in advanced economies may induce the relocation of pollution-intensive activities toward lower-income countries, where regulatory constraints are weaker, and production costs are lower (Cole, 2004; Aichele and Felbermayr, 2015).

The strategic relocation of production stages is closely linked to evolving patterns of productive specialisation along development stages. Countries do not enter GVCs from symmetric positions, either technologically or institutionally, and environmental burdens are not distributed independently of the functions and sectors in which they specialise. Recent evidence shows that developing economies are more exposed to emission-intensive sectors, while advanced economies remain more concentrated in lower emission-intensive activities (Jeon and Kwon, 2021; Althouse et al., 2023). Dosi et al. (2025) push this argument further by identifying a double harm associated with GVC integration: the same cost-based strategy for competing in GVCs, that weakens productive upgrading favouring the emergence of the middle income trap, also intensifies environmental burdens. Emissions, therefore, cannot be read as a mere side effect of industrialisation, but understood within the structure of specialisation and the hierarchical position of economies in the world production system. Schwarzbauer et al. (2025) map CO_2 emissions across GVC positions and report initial evidence of frown-like patterns. Yet, the adopted framework is not directly comparable with the Meng-based positioning approach, usually conducted on value added.

At the same time, the environmental consequences of GVC integration cannot be reduced to a one-stage PHH strategic relocation problem. Relocation alone does not explain why relatively more polluting segments do not reduce their emissions, nor why participation in GVCs so often fails to generate meaningful environmental upgrading. Where competition is centred on low costs, the strategic headquarters' decisions may favour a low-road trajectory in which labour costs are compressed, and investment in less polluting technologies remains limited, thereby reinforcing the coexistence of low-wages and high-emission stages (Colozza et al., 2024; Pietrobelli et al., 2024). This suggests that the environmental burden of GVCs is not an occasional by-product, but is instead the result of strategic firm-level agency that operates exactly through GVCs, the latter being production processes that are fragmented across the globe and allow for the distribution of input mixes, final output, emissions and value, according to profit motives. In that respect, the extent to which a systematic co-location emerges between environmental-harmful i) input combinations and ii) output compositions, together with iii) compressed wage structure and iv) capital value capture, has been so far an open question.

2.4. Power in GVCs: effects for environmental inequalities

From a structure of governance perspective, GVCs act as amplification processes of power asymmetries: lead firms do not simply coordinate production; they shape the rules of participation, influence where capabilities accumulate, and affect how value and risks are distributed across suppliers (Gereffi et al., 2005; Coe and Yeung, 2015; Dallas et al., 2019). This matters for environmental performance because suppliers operating in lower tiers of the chain typically face tighter margins, stronger cost pressures, and more limited autonomy, conditions that can constrain both productive and environmental upgrading. As a result, the allocation of environmental burdens along GVCs must be interpreted through the hierarchical organisation of production and the asymmetric bargaining power between lead firms and dependent suppliers.

In this respect, the literature moves beyond the idea that GVC participation mechanically improves environmental outcomes through diffusion of standards or less polluting technologies (Siewers et al., 2024), and instead shows that environmental change is uneven, contested, and strongly mediated by governance. Krishnan et al. (2022) argue that environmental upgrading and downgrading should be analysed together, precisely because improvements in one part of a chain may coexist with deterioration elsewhere, and because productive upgrading does not automatically translate into broader environmental gains. Related work shows that lead firms may impose environmental requirements on suppliers without transferring the knowledge, finance, or organisational slack needed to implement lower emission intensity production in a sustained way, leaving weaker suppliers to absorb compliance costs while remaining locked into lower-value segments (Pietrobelli and Rabellotti, 2011; De Marchi and Gereffi, 2023).

A broader line of argument connects these dynamics to ecological unequal exchange. International trade allows wealthier economies to sustain high levels of consumption while externalising part of the material and environmental costs of production to poorer economies, which remain disproportionately specialised in resource- and pollution-intensive activities (Dorninger et al., 2021; Hickel et al., 2022; Althouse et al., 2023). In this respect, the uneven distribution of emissions across GVC stages reflects not only differences in technology or regulation, but also a hierarchical international division of labour shaped by cost competition, capability gaps, and asymmetric control over value-chain governance. Recent critical work has pushed this argument further by warning that accounts centred on successful cases of environmental upgrading may understate system-wide displacement effects, which are not side effects but structural features of the current capitalist mode of production (Bernhold and Selwyn, 2026).

2.5. Filling gaps in the literature

Taken together, these strands of literature suggest that environmental burdens are embedded in the same hierarchical structures that organise value capture and productive specialisation, yet they do not establish whether such burdens follow the same stage-based logic identified in the smile-curve literature. In this contribution, we extend this argument by showing that the unequal distribution of emissions is structurally embedded in the current international division of labour, and that these tendencies have intensified over the last twenty-five years. In this respect, our paper identifies a third loss associated with GVC participation: the same reorganisation of production that underpins specialisation downgrading and environmental burden also generates an unequal distribution of value added and wages across production stages, a dimension that has so far remained largely confined to the smile-curve literature.

In Table 1, we compare the closest contributions that analyse the smile-curve structure of GVCs in value capture, the environmental burden across production stages via emission multipliers, and the gap we intend to fill with this paper.

3. Data and methodology

3.1. Data

The analysis employs the OECD ICIO tables, covering 66 countries and 45 industries from 1995 to 2018, which provide a comprehensive mapping of global production networks. These tables are supplemented with CO_2 emission intensity data from the OECD TECO$_2$ database, which aligns perfectly with the ICIO sectoral classification and reports emissions from fuel combustion by industry and country. To account for economic development levels, real GDP per capita figures are drawn from Penn World Table 1, while country classifications follow the UN development categories (advanced vs. developing economies). In some analyses, industries are aggregated to the 1-digit level to preserve clarity. Appendices 1 and 2 provide the countries' development levels and detailed sector mappings, respectively.

This study focuses on manufacturing final products while accounting for all inputs involved in their production processes, including primary goods, utilities, and services, thereby enabling analysis of the complete supply chain of a specific industry, including highly polluting sectors such as electricity generation and transportation. The focus on manufacturing industries has a twofold explanation: first, they dominate global trade flows, both in terms of share of total exports and emissions, when we consider their entire production chains. Second, the smile curve framework we employ was originally developed to analyse manufacturing value chains and may not be directly applicable to other industries, such as services, which may not exhibit clearly identifiable upstream, midstream, and downstream stages, that are essential to the position-based emission analysis undertaken in our study.

3.2. Constructing CO_2 multipliers

Building on the work of Leontief (1936), our methodology extends the input–output framework to trace both direct and indirect emissions embedded in global production networks. The Leontief transformation enables us to account not only for the direct inputs required for production but also for the full cascade of intermediate goods needed across all upstream stages. By normalising the intermediate transaction matrix by total gross output, we derive the technical coefficient matrix A, which quantifies the input requirements per unit of output for each sector-country pair.

Table 1
Synoptic table comparing selected GVC contributions in the smile curve and environmental inequalities literature.

Dimension/advancement	Meng et al., 2020	Dosi et al., 2025	Schwarzbauer et al., 2025	This paper
Core object	Value added & wages mapped along GVC stages.	Specialisation patterns and emission multipliers along GVCs.	Emissions per worker & labour share mapped along GVC stages.	Emissions *stage-wise* mapped within the Meng smile-curve logic.
Positioning metric	Seminal framework: propagation length adapted to account for foreign post-production stages.	No smile-curve positioning identification.	Different positioning metrics derived from Antràs and Chor (2013), not directly comparable with Meng et al., 2020.	Meng's seminal framework on positioning, directly comparable with Meng et al., 2020.
Distribution/Pollution indicators	Value added, hourly wage, and monthly wage.	CO_2 multipliers (CO_2 emission per unit of final demand).	VA/ labour compensation (inverse of labour share) and emissions over labour compensation.	Deviation from sectoral emission intensity (accounting for sector-specific characteristics), monthly wage.
Unit of analysis	Country–industry intermediate inputs along all manufacturing worldwide value chains.	The world trade network is treated as a single GVC.	Multiple GVC mapping.	Intermediate inputs as units, within the manufacturing final products' value chain.
Explicit isolation of GVC-mediated component	No, whole value chain analysis (i.e., all intermediates). Partition of GVCs is not central.	Foreign backward linkages as determinants of double harm along GVCs (isolate trade/ GVC-mediated burdens).	No, whole value chain analysis (i.e., all intermediates). Partition of GVCs is not central.	Foreign intermediates alone vs all intermediates (isolate trade/ GVC-mediated burdens).
Formal "smile" identification	Quadratic identification of smile curves.	No smile curve analysis.	Mostly monotonic relations, either increasing or decreasing. No smile curve identified.	Quadratic identification and curve testing for U vs inverted-U using the Lind and Mehlum (2010) test.
Conceptual integration: PHH + smile-curve hierarchy + symmetry emission-value	Smile curve. No environmental dimension.	PHH + joint downgrading in emissions and specialisation "double harm".	Positioning in GVCs + symmetry emission-value. Mention of carbon leakage and PHH as future direction.	PHH and within-chain functional positioning. Assessement of value capture vs emission burden along identical stage metric.

To compute CO_2 multipliers, we pre-multiply the Leontief inverse L= $(I-A)^{-1}$ by a diagonalized vector of sector-specific CO_2 emission per unit of output ($\widehat{EF}$), yielding:

$$C=\widehat{EF}(I-A)^{-1} \tag{1}$$

where C represents the matrix of CO_2 multipliers. Each element in C captures the emissions generated worldwide per dollar of final production, with rows indicating the country-sector origins of emissions and columns representing the vertically integrated subsystems (i.e., the country-sector pairs where final production occurs). To isolate emissions driven by export production—our primary focus—we substitute final demand (Y) with a diagonalised export vector (X), thereby concentrating on the emissions attributable to international trade rather than domestic consumption.

$$CC=\widehat{EF}(I-A)^{-1}\widehat{X} \tag{2}$$

The matrix CC represents the global CO_2 emissions associated with exports at each stage of the production process. Specifically, summing the elements of a given column yields the total CO_2 emissions generated in the production of a particular good—for example, computers in China. These correspond to the backward linkages for the production of a personal computer in China, such as emissions from microprocessor production in Taiwan, screen manufacturing in Japan, and plastic or metal production in—say—Vietnam. By examining the corresponding row of the CC matrix, we can trace the emissions contributions from each industry that provides inputs. Then, the total emissions of an industry are determined by two key factors: on the one hand, the emission intensity (c_{ij}), a technological parameter reflecting the CO_2 efficiency of the supplying industry; on the other hand, the input requirements, that is the amount of each input demanded by the value chain, which depends on the production structure and technical interdependencies within the global supply network. Thus, the CC matrix captures not only the direct emissions from final production but also the embedded emissions from upstream activities, tracking how value chain integration shapes cross-border environmental impacts.

In addition to Meng et al. (2020), first, we single out the emissions generated in the foreign segment of the GVCs, then we classify foreign inputs by developmental origin (advanced vs. developing economies) and industrial sector, to reveal country- and sector-wise asymmetries in emission burdens. Taking into account only foreign inputs allows us to shift attention from country-industry specificity due to the sector of final production, to traded inputs, which, otherwise, risk being overshadowed by the much more concentrated domestic ones. In this way, we aim to prioritise traded emissions across production processes and account for the distinct characteristics of globally supplied inputs.

By multiplying the C matrix with export flows (rather than total final demand), we maintain consistency with Leontief's accounting identity, while highlighting the role of international demand in shaping global emission patterns. This framework not only quantifies the carbon footprint of exports but also tracks the origins of the emissions, showing how GVCs redistribute environmental emissions—a key contribution to debates on sustainable production, trade and climate justice. The sectoral and country classifications used in this decomposition are detailed in the Appendix, in Tables A1 and A2.

3.3. Positioning in global production networks

To analyse world production structures and their nexus with emission profiles, looking at input–output tables, the second crucial element involves positioning intermediate inputs along value chains. In the smile curve literature, recent approaches to locating industries within GVCs typically employ two alternative yet complementary strategies: one based on measures of input propagation lengths (Koopman et al., 2014; Borin & Mancini, 2019), calculating distances either from final consumers (downstreamness) or from producers (upstreamness) to establish an ordering of intermediates which tracks the position of each input along the chains. Another method leverages industries' occupational composition (Timmer et al., 2019; Riccio et al., 2025), examining shares of different worker categories (e.g., managers, R&D specialists, or assembly workers classified under occupational categories), which can then be used to infer the tasks and thus the positioning of that contribution along the chain.

The input propagation length, rooted in input–output linkages, quantifies an industry's position through its average-stage distance from final demand – clearly identifying, for instance, mining as an upstream industry and retail as a downstream one. While this provides a systematic and straightforward measure of sector-level positioning, it inevitably masks significant within-industry heterogeneity across occupational groups (e.g., high-skilled R&D workers in otherwise downstream electronics firms), especially when data are provided at a very aggregated level. Conversely, occupation-based measures reveal this internal stratification by directly linking positioning to labour roles (treating R&D engineers as upstream regardless of their sector). However, this method demands far more granular data that are not universally available and relies on sometimes questionable assumptions about occupational positioning (for example, whether retail managers should be considered upstream). Thus, while length metrics excel at economy-wide, and even world-wide "smile curve" mapping for policy analysis, occupational data provide finer-grained insights into distributional outcomes like wage disparities – making them complementary rather than competing approaches.

In this paper, we adopt the length metric to position industry along global value chains, employing a forward linkage-based upstreamness measure grounded in inter-country input–output analysis, extending the framework of Antràs and Chor (2013), as applied in Meng et al. (2020). This approach defines the Average Propagation Length (APL) D_{sk} from sector *s* (the value-added origin) to the final producer *k*. We define $V_s = [00\ldots v_s\ldots 0]$ the value-added input coefficient of industry *s*, and $X_k = [00\ldots x_k\ldots 0]^T$ the foreign demand for a final product *k*. Then, the contribution of sector *s* to the value-added generated by final demand for product *k* is measured as V_sLX_k. Thus, we can define the average propagation length D_{sk} from sector *s* (the value-added origin) to the final consumers of product *k* as the weighted sum of production stages:

$$D_{sk}=\frac{\left[V_s\left(I+2A+3A^2+4A^3+\cdots\right)X_k\right]}{V_sLX_k}=\frac{V_sL^2X_k}{V_sLX_k} \tag{3}$$

This distance metric captures the average number of production stages through which value-added from sector *s* traverses before being embodied in final product *k*. Higher *D* values indicate more upstream positioning (e.g., raw materials), while $D_{sk}=1$ signifies direct final demand linkage.[1]

In line with Meng et al. (2020), we first invert the scale for interpretability, with 0 representing value chain origins and increasing values approaching final consumers for pre- and production activities, then we incorporate post-production activities. While some other analyses typically treat the final production sector as the endpoint closest to consumers (e.g., Schwarzbauer et al., 2025), this approach overlooks critical downstream stages such as retail and transportation. To address this limitation, we explicitly account for these additional steps in our computations. For instance, looking at the Chinese Automotive sector

[1] The metric's ability to capture the weighted average of production stages stems from the inherent properties of L's power series expansion: L=$(I+A+A^2+\cdots)$ represents cumulative production requirements, while $L^2=(I+2A+3A^2+\cdots)$ explicitly weights each stage (0, 1, 2, …) by its distance from final demand. Consequently, the numerator $V_sL^2X_k$ sums sector's value-added contributions to product *k* multiplied by their respective stage weights, and the denominator V_sLX_k provides the total value-added without weighting. Their ratio D_{sk} thus computes the average number of stages value-added traverses.

exports to the US, in line with Meng et al. (2020), we add two post-production stages: retail & distribution and transportation to final consumers. Since input–output tables are compiled based on basic prices, these activities are reported separately. Thus, we independently calculate their distance from the final Automotive products using APL measures, thereby extending the value chain beyond the factory gate to the final manufacturing stages. We assume that the distance of the US retail and transportation sectors from imported Chinese Automotive products mirrors their distance to domestic US Automotive production.

3.4. The shape of smile curves: from value gains to emission damage

In their seminal work, Meng et al. (2020) focus on ICT sectors in the United States and China to show that a country's level of development and the technological intensity of its industries shape both its participation in GVCs and its ability to benefit from them. The contrasting functional forms they identify, a persistent U shape for developing economies and an inverted-U shape for advanced economies, provide a structural diagnostic of asymmetric value capture and specialisation patterns driven by countries' positioning in international GVCs.

When final production is located in developing economies, value chains tend to exhibit the standard U shape. Firms in these economies, such as Chinese ICT assemblers, occupy the low midstream point of the curve: they capture a large absolute share of value added because they assemble or export the final product, but their value-added ratio and wages remain low. This reflects GVC participation based on static comparative advantages, especially low-cost labour in assembly and basic manufacturing. The high-margin segments remain concentrated upstream, in foreign suppliers of advanced components, R&D and intangible assets, and downstream, in distribution, marketing and after-sales services. The result is a "low-end trap" characterised by dependence on imported technology and intermediates, intense cost competition, weak pricing power and limited bargaining leverage. China has partly mitigated this pattern, but it remains more the exception than the rule.

By contrast, value chains led by technologically advanced industries in developed economies display an inverted-U shape. US ICT producers, for example, capture both a dominant share of total value added and a high value-added ratio. This reflects dynamic upgrading and specialisation in knowledge-intensive, intangible-rich activities relying on skilled labour, advanced capital and proprietary technologies. Such firms internalise or tightly control the most valuable and technology-intensive stages, concentrating value capture within what would otherwise be the midstream. The inverted-U therefore reflects a specialisation pattern available only to countries and industries with strong technological capabilities and control over core innovation and transformation processes.

The divergence between the U shape of developing economies and the inverted-U of advanced ones is the core contribution of smile-curve analysis to the study of asymmetric exchange in GVCs. It reflects asymmetries in technological capabilities and specialisation that map directly onto the global development divide. This underlies what Meng et al. (2020) call a "Paradoxical Pair of Concerns": advanced economies fear industrial hollowing-out as standardised activities relocate, while developing economies fear persistent entrapment in low-value segments despite gains in employment and poverty reduction.

Although developed to analyse value-added propagation, this framework can be extended to emissions. The same technological and organisational hierarchies that allow advanced economies to capture disproportionate value also enable them to externalise environmental costs to developing countries. Advanced economies specialise in high-value, lower-emission activities, while developing economies, constrained by technological dependence and competitive pressures, are channelled into midstream manufacturing and resource extraction. These activities are not only less remunerative but also more polluting because they rely on carbon-intensive processes.

Our methodological advancements can be summarised as follows: first, we adapt the propagation-length framework originally designed for value-added attribution (Meng et al., 2020) to the environmental domain, preserving structural comparability. This is not simply a mechanical substitution of value added with emissions: we construct stage-level emission intensity as a deviation from sectoral averages, thereby preventing the curve shape from being driven by baseline sector composition and instead isolating relative within-chain allocation. Without this normalisation, any nonlinearity would be mechanically dominated by uniformly high-intensity sectors (e.g., energy, metals), thereby obscuring stage effects. Second, we isolate the GVC-mediated channel by restricting the analysis to foreign-sourced intermediates in addition to the full-input specification. This distinction is central to identifying whether emission burdens are shaped by cross-border fragmentation rather than domestic production structures. Existing studies either aggregate domestic and foreign contributions or decompose them at the macro level; we instead estimate stage-position relationships separately, showing that curvature and asymmetry intensify when focusing on foreign intermediates, consistent with a trade-mediated mechanism. Third, beyond descriptive mapping of emissions along stages, we formally estimate quadratic relationships between stage position and relative emission intensity for each manufacturing value chain and test for U-shaped versus inverted-U-shaped configurations within a consistent statistical framework, rather than relying on monotonic visual inspection. The identification is therefore inferential rather than descriptive, allowing us to determine whether environmental burdens replicate, invert, or diverge from the value-capture smile logic. Finally, by integrating Leontief-based embodied emission accounting, propagation-length positioning, foreign-intermediate isolation, and sector-normalised intensity construction within a single estimation framework, we generate an object not present in the prior literature: a stage-wise, Meng-comparable environmental hierarchy, that is structurally interpretable alongside value-added hierarchies.

4. Development, industry composition and emission patterns along GVCs

Fig. 1 underscores the dominant role of industrial composition in shaping global emissions, showing a striking sectoral heterogeneity. Sectors are ordered by median CO_2 intensity, from top to bottom.

Energy sector and heavy manufacturing industries not only exhibit the highest median emission levels but also display remarkable cross-country variation. Thus, while sector-specific production methods inherently constrain emission baselines (e.g., chemical processes in cement manufacturing), the wide variance within sectors demonstrates that country-level technological and organisational differences can substantially alter environmental footprints even for similar outputs. Such heterogeneity suggests that lagging firms or nations, given our dataset, could achieve significant emission reductions by adopting best practices already deployed by sectoral frontrunners, pointing to substantial untapped potential for targeted technological diffusion along GVCs.

Concurrently, Fig. 2 shows the heat plot of CO_2 intensity for each sector-country pair in 2018. The graph reveals the relationship between the development stages of an economy, measured by its GDP per capita, and the emission intensity of its production. The emergence of a neat distinction between an upper (red) and a lower (green) triangular matrix, confirms an overall inverse relationship between GDP per capita, increasing along the x-axis, and emission intensity, decreasing along the y-axis—with wealthier nations typically exhibiting less emitting production profiles and as such located in the lower triangular matrix—-with the only exception being resource-dependent economies such as oil-exporting countries, that, despite achieving high income levels, maintain emission intensities comparable to much poorer nations, demonstrating how natural resource endowments, and extractive economic structures, can distort and override expected development

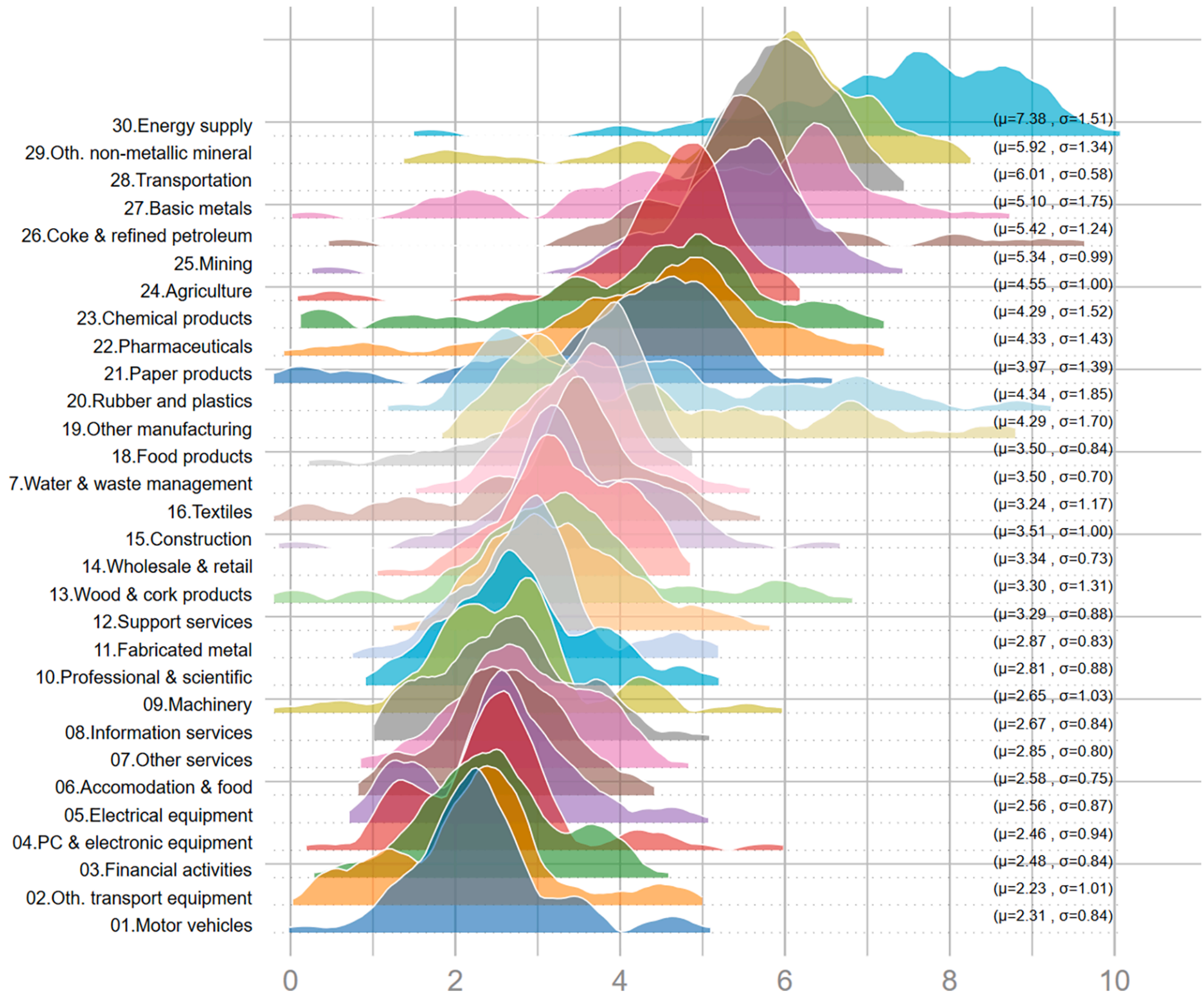

Fig. 1. Distribution of CO_2 emission intensity (log-transformed) across sectors in 2018. Sectors are ordered by median CO_2 intensity. On the right, mean and variance of each distribution are presented. *Source*: Authors' elaboration using OECD $TECO_2$.

trajectories. The persistence of carbon-intensive productions in these high-income, resource-rich economies suggests that specialisation patterns—not just development stages—are decisive in determining environmental outcomes. Their continued reliance on extractive and energy-intensive sectors creates a form of "carbon lock-in," where economic structure perpetuates high emissions regardless of national wealth (Unruh, 2000). This phenomenon underscores the limitations of relying on income growth alone as a pathway to decarbonisation. Conversely, it is the change in the production mix (i.e., specialisation) that determines, on the one hand, a country's growth prospects, and on the other, its dynamic environmental impact.

Building on the sectoral emission patterns revealed in Figs. 1 and 2, Fig. 3 examines how these carbon-intensive activities are distributed across countries at different development levels. Fig. 3 presents a series of histograms where industries are ordered from the lowest to the highest emission intensity, with each bar representing the Revealed Comparative Advantage (RCA) of a development group (advanced vs developing economies) in that particular sector, considering its participation in GVCs.

Drawing on Balassa's (1965) framework, we compute the RCA first for each country-industry group relative to the world production network (see Appendix A for industry-specific RCA distributions), and then we apply it to the input–output structure of the world economy. Thus, let $v_{i,j}$ denote the value-added flows originating from country i in sector j. The RCA of country i in sector j is defined as:

$$RCA_{i,j} = \frac{\frac{v_{i,j}}{\sum_i v_{i,j}}}{\frac{\sum_j v_{i,j}}{\sum_i \sum_j v_{i,j}}} \tag{4}$$

where the numerator is the share of country i in the worldwide flows of intermediates in industry j, while the denominator is the share of inputs provided by country i to world production. An $RCA_{i,j} > 1$ indicates that country i is specialised in sector j, as it supplies a share of intermediates in sector j more than proportional to its average contribution to global production. Conversely, an $RCA_{i,j} < 1$ suggests a lack of specialisation in the provision of such production input. Therefore, the indicator informs about comparative advantages at the GVC level.

After having constructed country-industry measures of RCA for each of the GVCs, in Fig. 3 we aggregate results by development levels. Fig. 3 shows a clear progression: developing economies specialise ($RCA_{i,j} > 1$) in the most emission-intensive sectors like electricity, transportation, and low- and medium-tech manufacturing. Advanced economies, by contrast, specialise predominantly in low-emission sectors such as pharmaceuticals, electronics, and services. This pattern aligns closely with the emission intensity spectrum, but it adds new information related to international production flows. Not only does a neat correlation between sector-specific carbon footprint and the development level of its primary producers emerge, but also the country-level specialisation in international intermediates reflects the same structure of relations. These results suggest that current trade structures

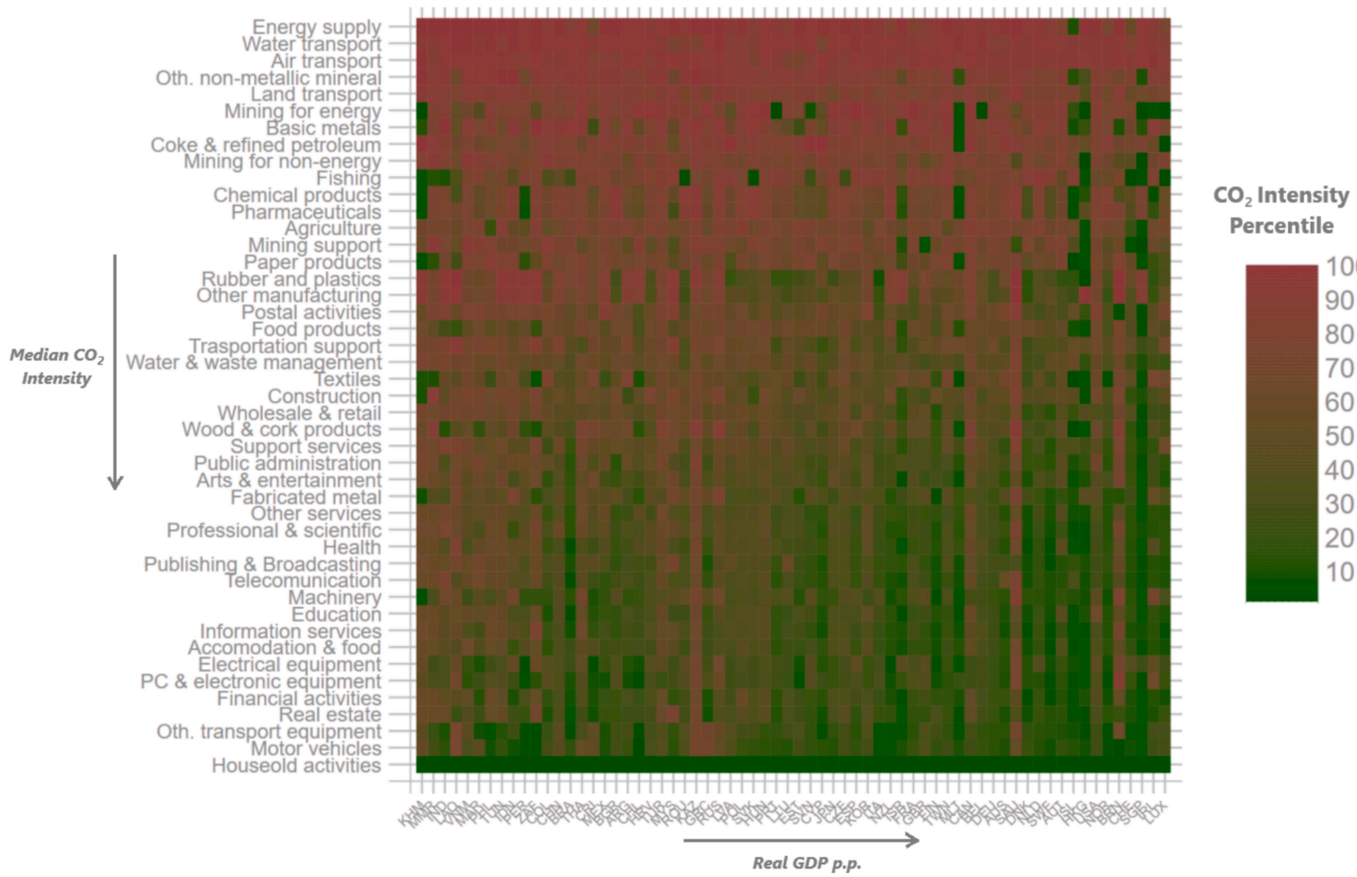

Fig. 2. Heatplot of CO_2 intensity for each sector-country pair in 2018. *Note:* Real GDP and Population data come from PWT 10. Sectors are ordered by median CO_2 intensity, while countries are ordered by real GDP per capita. *Sources:* Authors' elaboration using OECD TECO$_2$ and PWT 10.1.

allocate high-emission productions to less developed nations while concentrating the least polluting activities in advanced economies. The consistency of this delocalisation pattern across sectors implies more than coincidental specialisation – it reflects structural factors like technological disparities, capital availability, and the environmental regulations that shape global production networks. While this division may offer short-term competitive advantages, it risks creating long-term environmental and economic lock-in effects for developing countries, potentially hindering both their sustainable development and global decarbonisation efforts.

5. Is there any evidence of an environmental smile curve?

The environmental smile curve adapts the original value-based framework, transposing its analytical power to ecological asymmetries in global production. Where traditional smile curves map how value concentrates at GVC end-points, this transposition reveals how emission intensity varies at different stages of the production process within a specific value chain.

The modification is methodologically straightforward: we retain the x-axis positioning along value chains (from raw materials to final consumers) but replace value-added metrics with CO_2 intensity measurements. This substitution captures how environmental costs are distributed across the same production stages where value capture has been extensively studied. Since we acknowledge the major sectoral differences in emission productions (e.g., food vs coke production have inherently different CO_2 emission profiles), we apply a mean standardisation by dividing each country-sector emission intensity by the sector weighted average, so that the final index measures if that particular industry-country input is more ($>$1) or less ($<$1) pollutant than the average of its potential substitutes. Therefore, rather than tracking the value gain (i.e., economic benefits) accruing to different stages of production, we calculate the CO_2 emissions embodied in each value chain's input. Formally, given a specific value chain, the input-specific embedded CO_2 can be expressed as the product of that input's emission multiplier (c_{ij}) and the final demand vector of that value chain, in this case, export (X). Summing across all the inputs employed, we retrieve the total CO_2 emitted throughout the supply chain to produce a unit of output, capturing both direct and indirect contributions (see Section 2).

The rationale for the construction of the environmental smile curve stems from observed parallels between value distribution and ecological asymmetries in GVCs. Just as production hierarchies enable lead firms to capture disproportionate value, they also facilitate the displacement of emissions to supplier nations. The environmental smile curve makes these displacements visible, testing whether pollution follows the U shape pattern of value distribution or exhibits distinct behaviours. The framework's strength lies in its ability to connect specialisation patterns to environmental outcomes. By overlaying emission intensities with known value chain positions, it reveals whether developing countries' concentration in mid-chain manufacturing—already identified as low-value in traditional smile curves—also corresponds to peak pollution burdens.

Plotting emission intensity against GVC position reveals distinct patterns in how pollution is distributed across production networks. A traditional smile-shaped curve would suggest that CO_2 emissions are highest at both ends of the chain—for instance, due to energy-intensive R&D activities conducted upstream and carbon-heavy logistics conducted downstream—while midstream assembly exhibits lower emissions, perhaps because it relies on imported intermediates produced

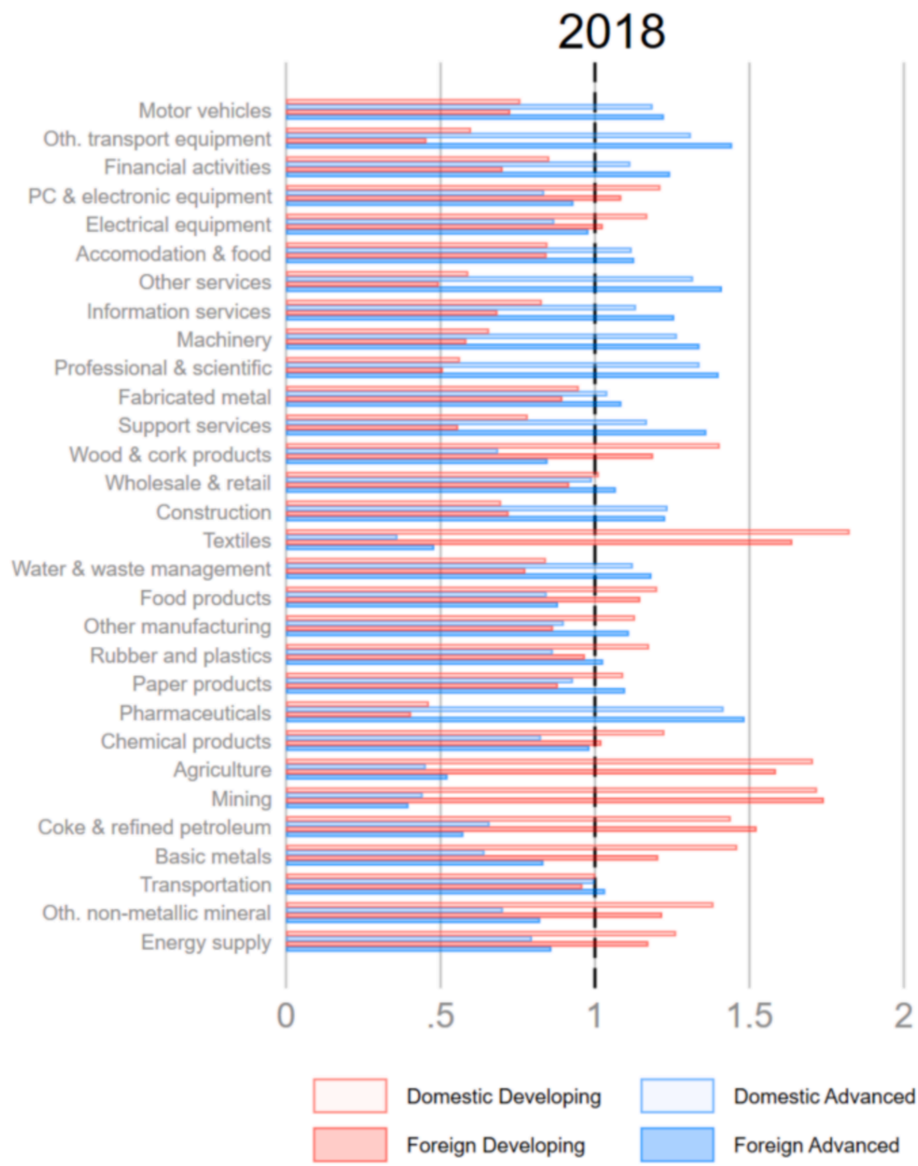

Fig. 3. Revealed Comparative Advantage (RCA computed for developing and developed countries) and evaluating domestic and foreign inputs. Sectors are ordered from the least to the most emission-intensive. *Note:* Countries' development level is reported in Table A1. *Source*: Authors' elaborations using ICIO – OECD (2021).

elsewhere. Alternatively, a "frown" curve could emerge if emissions are concentrated in midstream manufacturing, as seen in coal-intensive industrial hubs (Schwarzbauer et al., 2025). The shape of the curve is influenced by multiple factors, including the energy mix of upstream suppliers, the production technologies employed in midstream stages, and the transportation and consumption patterns that characterise downstream activities.

Our analysis begins by comparing value chain structures and emission patterns across selected industries in advanced (e.g., the USA) and developing (e.g., Vietnam) economies. The choice of the country is only representative of the different levels of development, that is high-income vs low-income countries. Following the smile-curve literature, we focus on two representative sectors, that we select on the basis of their inherent emission intensity: ICT (high-tech manufacturing), and steel (high-pollution manufacturing). This selection allows us to assess whether emission-intensity distributions vary systematically with technological sophistication and pollution levels.

For each sector, we examine two distinct versions of the smile curve. The first accounts for full production chains (domestic plus foreign linkages), which reflect the complete value-added structure and are heavily influenced by the characteristics of the final industry-country pair, therefore accounting for the majority of the value added. Additionally, we evaluate GVCs' foreign linkages only, which isolate the international division of production by excluding domestic inputs—focusing on how cross-border supply chain segments shape emission and value distributions. These complementary configurations are motivated by the fact that domestic inputs typically account for ~75% of total production, meaning that full-chain smile curves are predominantly shaped by the economic structure of the final production country. In advanced economies, this tends to generate inverted-U shapes, as their mid-chain production stages (e.g., assembly) exhibit higher wages and value capture than the foreign inputs they rely on. Conversely, developing economies typically exhibit U-shaped curves, as their mid-chain production remains low-wage, while depending on high-value inputs from advanced economies. By isolating foreign linkages, we can better discern the structural properties of international production networks, independent of final-stage country effects.

In the second part of our analysis, we explore sectoral heterogeneity and temporal dynamics, comparing how emission-intensity distributions differ based on technological and polluting characteristics of the final sector. Additionally, by examining changes between our baseline and final years, we assess whether globalisation phases (e.g., post-2008 slowdown, trade tensions) have altered these relationships. This allows us to evaluate whether the environmental smile curve has deepened, flattened, or shifted structurally over time—providing insights into the evolving interplay between GVCs and emissions. Thus, this multifold approach—cross-country, cross-sector comparisons and temporal analysis—helps disentangle the roles of sectoral and technological attributes, international specialisation, and GVC participation trends in shaping the distribution of both value and emissions along GVCs.

5.1. Case studies: the environmental smile curve in ICT and basic metals sectors

To empirically validate the environmental smile curve hypothesis, we initially focus on two archetypal sectors: Information and Communications Technology (ICT), representing a high-tech, low-emission production, and basic metals, a typical high-emission and low-tech industry. Following the methodological framework outlined in Meng et al. (2020), we trace CO_2 emissions and GVC positioning of all intermediate inputs along GVCs of these sectors, comparing Vietnam[2] (VNM) and the United States (USA), as two representative cases of a developing and an advanced economy, respectively. For each graph, we then draw a quadratic fit through a weighted OLS regression to gauge the concavity of the U shape and determine if the relationship is U-shaped or hump-shaped (inverse-U).

Our analysis distinguishes between emissions from all inputs required for the production of the final good, thus encompassing both domestic and foreign linkages, and those solely from foreign intermediates, allowing us to single out the impact of international production fragmentation in shaping global emission profiles.

For Vietnamese ICT exports (Fig. 4, top panel), the analysis reveals an inverse U-shaped curve when examining emissions from all inputs (left-panel). This indicates that the highest emission intensities occur in the middle stages of the value chain, where Vietnam and other developing countries as China and Russia specialise in assembly and basic manufacturing activities. These stages, characterised by lower value-added gains, as shown by Meng et al. (2020), and higher carbon intensity, align with the "double harm" hypothesis—economic and environmental downgrading co-occur in midstream segments. When isolating foreign inputs (right panel), the inverse-U persists, underscoring that Vietnam's position in GVCs systematically exposes it to emission-intensive intermediates in the midstream stages from other developing economies, such as raw materials and energy-intensive components, while requiring upstream and downstream stages from less emission-intensive advanced countries.

The US pattern in ICT value chain (Fig. 4, bottom panel) exhibits an opposite shape, a decreasing emission curve when all inputs are considered (left panel), with the final stage of ICT, which is placed at the end of the production activities and left before post-production (sale and transportation services), being the down peak since advanced countries own the least emission-intensive techniques of production, while emissions slightly increase moving to upstream stages which are mostly portrayed by developing countries, relatively more emission-intensive than similar suppliers in advanced countries (e.g., China). Thus, both the level of development of the country and the type of production finalised (industry) impact the shape of the environmental curve as in the value curve hypothesised by Meng et al. (2020).

However, when focusing solely on foreign inputs (right panel), the curve flips to an inverse U shape, mirroring Vietnam's results. This suggests that the US, while maintaining less emitting domestic production, depends on foreign-supplied intermediates that concentrate emissions in middle stages—often sourced from developing economies. The divergence between the two input structures highlights even more starkly how advanced economies externalise emissions through GVCs, while retaining low-emission, high-value activities domestically.

As a second example, we opted for the basic metals sector, among the most emitting industries requiring elementary technological capabilities but also proven to be fundamental for development (Dosi et al, 2021). For Vietnam (Fig. 5, top panel), the emission curve again resembles an inverse U shape across all inputs (left panel), with midstream processes generating the highest emissions. Foreign inputs on the right confirm this pattern, as Vietnam integrates emission-intensive intermediates like iron ore and coking coal from resource-rich, highly polluting economies. This reinforces GVCs' role as pollution drivers, where developing countries bear the brunt of carbon-heavy production for both developing and developed countries.

The US basic metals chain (Fig. 5, bottom panel), however, reveals declining emission intensity as we move closer to consumers, when all inputs are included. This is a consequence of the emission intensity that the US metal sectors reflect: the US is an advanced economy with the capacity to mitigate emissions through less emission-intensive production methods and stricter regulations, even in traditionally most-polluting industries. Since advanced countries can appropriate much of the total production process, the final stage accounts for a significant share of production, and the same holds for the share of CO_2 emissions. As a consequence, the results for domestic inputs depend heavily on US final production, which is low-emission relative to similar processes in other countries (the observation is below 1), but is also highly polluting by its nature. Yet, foreign inputs reintroduce the inverse-U shape, revealing the US reliance on high-emission intermediates from abroad. This duality underscores the limits and inherent contradictions of national decarbonisation efforts in a fragmented production system: while domestic processes may improve, global emissions remain entrenched in GVCs' unequal division of production and labour.

The consistent inverse U-shape observed in foreign-sourced emissions across both sectors and countries points to a systemic feature of GVCs: middle-stage activities, disproportionately located in developing economies, are structurally more emission-intensive. This aligns with the Pollution Haven Hypothesis and challenges the decoupling narrative of green growth. The country-level asymmetry between value capture and emission generation where advanced economies secure high-value, low-emission activities while offloading pollution-intensive stages—reveals the environmental smile curve as a mirror image of the traditional smile curve.

The divergence in shapes between "all inputs" and "foreign-only" segments highlights the centrality of final production countries in determining emission profiles. For developing economies like Vietnam, domestic production structures dominate, locking them into high-emission specialisations. For advanced economies like the US, domestic policies and technological advantages flatten emission curves, but their GVC integration perpetuates global inequalities by displacing emissions elsewhere. This spatial mismatch delays climate progress and calls for coordinated policies targeting emission-intensive intermediates in trade agreements, as well as support for technological upgrading in supplier industries.

The corresponding shapes in terms of value capture for each country and sector, according to the smile-curve paths, are presented in Fig. 6. The key distinction between Figs. 4, 5 and 6 lies in their y-axis: the environmental curve plots deviations from mean sectoral emission intensity, while the value curve uses average yearly sectoral wages. Additionally, the scatter size reflects value gains for a given input in the value curve, but CO_2 emission shares in the environmental curve. When looking at value capture, no distinction emerges in terms of "all" versus "foreign" input chains, while the only distinction determining the different shapes applies to the level of development of the country:

[2] The original paper by Meng et al., (2020) compares USA and China in 1995 and 2009 as example of advanced and developing economies, respectively. We opted for Vietnam as a representative of developing countries, since China is largely considered a special case of catching-up.

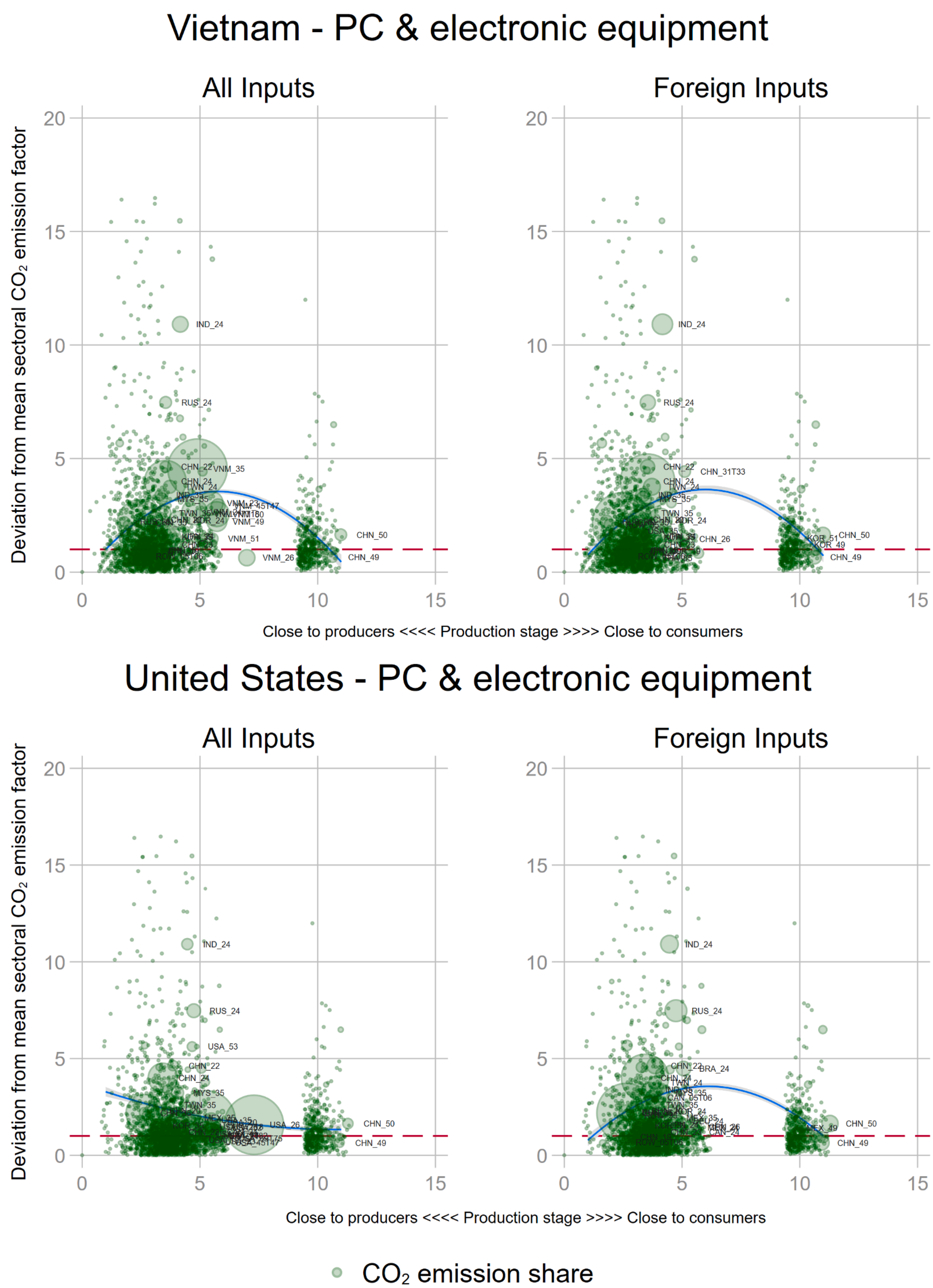

Fig. 4. (Top) CO_2 embedded in Vietnam's ICT GVCs (2018); (bottom) CO_2 embedded in the United States's ICT. *Note*: Explanations of countries and industry codes are provided in Appendices A and B. *Sources*: Authors' elaborations using ICIO and $TECO_2$.

production stages conducted in high-income countries are always more remunerated than required inputs in developing countries, for each given value chain. On the contrary, in the case of the developing country, the value appropriated in midstream production stages is the lowest, for each given chain.

5.2. The broader picture: sectoral and temporal heterogeneity in emission patterns

To investigate the environmental smile curve's recurrence and heterogeneity across GVCs and development levels, in Table 2, we report the instances where we detect a U-shape vis-à-vis an inverse U-shape quadratic relationship between positioning, measured via the propagation-length indicator, and CO_2 emission intensity. Table 2 compares emission-intensity distributions plotted against inputs' positioning for 20 manufacturing sectors in 1995 and 2018, distinguishing between advanced and developing economies as final producers, and evaluating emissions coming either from all inputs or foreign inputs only. For each GVC in the dataset, after plotting each backward linkage emission intensity against its positioning along the chain, we estimate a quadratic relationship weighted by the input-specific CO_2 share:

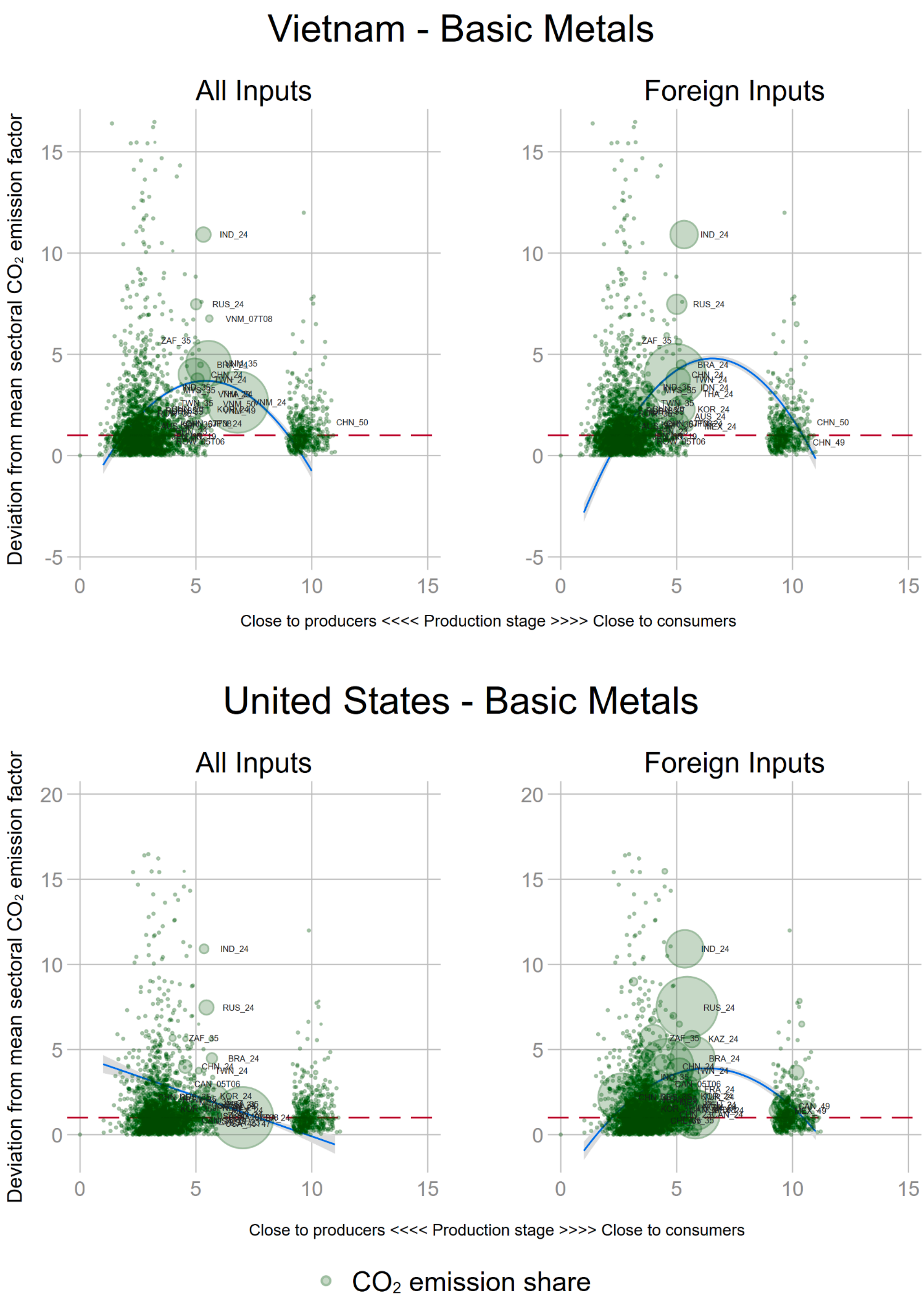

Fig. 5. (Top) CO_2 embedded in Vietnam' basic metal GVCs (2018); (bottom) CO_2 embedded in United States's basic metal GVCs (2018). *Note*: Explanations of countries and industry codes are provided in Appendices A and B. *Sources*: Authors' elaborations using ICIO and TECO$_2$.

$$CO_{2(i,j)} = a_0 + a_1 D_{i,j} + a_2 D_{i,j}^2 + \delta_i + \epsilon_{i,j} \quad (5)$$

where $CO_{2(i,j)}$ denotes the deviation from the mean sectoral CO_2 emissions per unit of output in industry j and country i, $D_{i,j}$ represents the positioning metrics defined in Eq. (3), while δ_i captures country fixed effects to account for supplier-specific characteristics. Industry fixed effects are omitted because the dependent variable is already normalised relative to sectoral averages. We estimate this regression separately for each GVC in the initial and final years (1995, 2018), presenting the results by GVC based on final production. Given the imposition of a quadratic functional form, we apply the Lind & Mehlum (2010) U-shape test to assess the statistical significance of the estimated relationship.[3]

First, the analysis of all inputs reveals stark asymmetries tied to the development levels of the production stage of the GVCs. Advanced economies predominantly exhibit U-shaped emission curves (see first column with %), due to emission decline at the final stages of

[3] Lind and Mehlum (2010) propose a widely used method for detecting U-shape relationships in regression models by testing whether the slope is significantly negative at the lower bound and significantly positive at the upper bound of the data range.

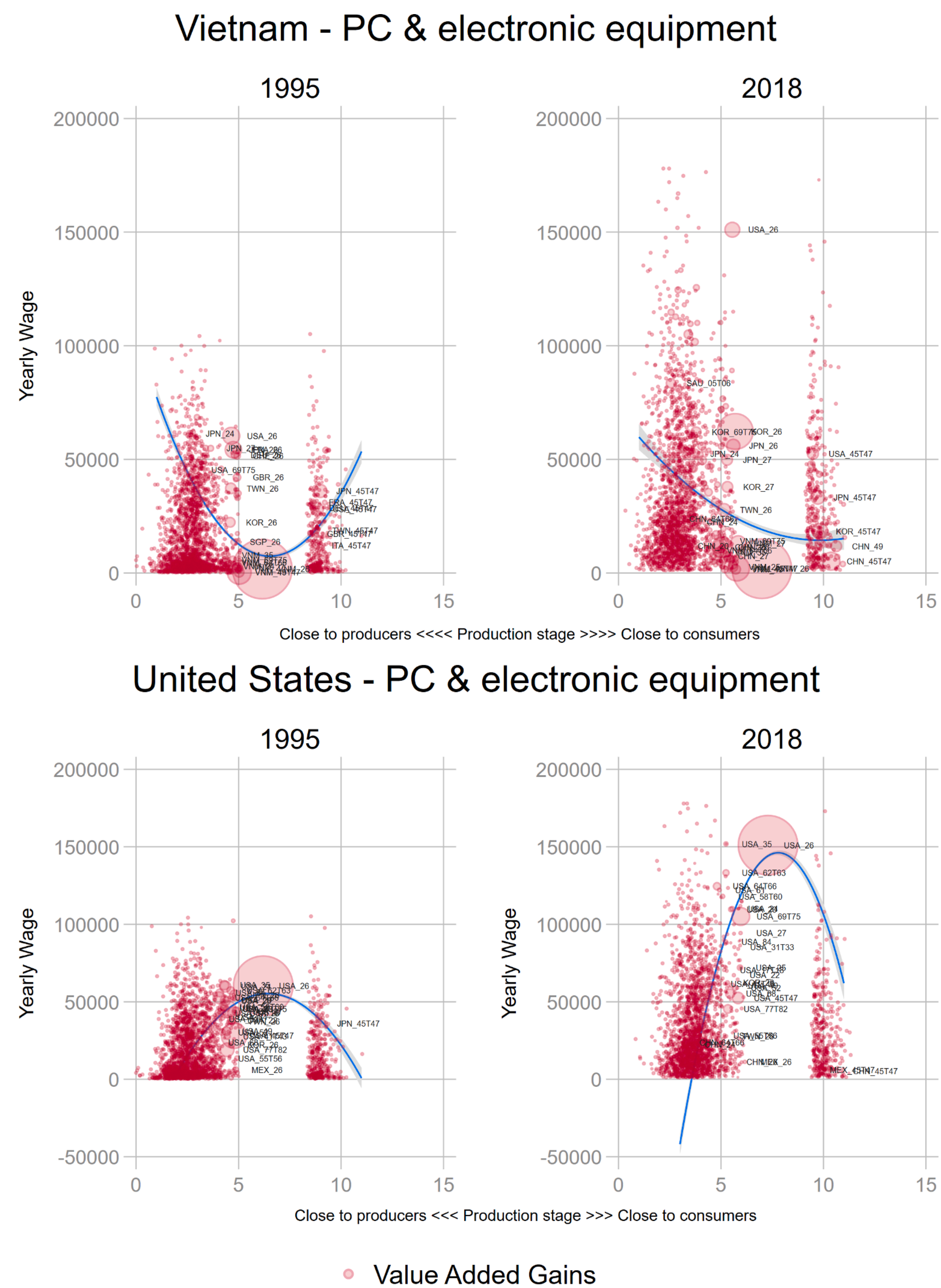

Fig. 6. (Top) Value Gains in Vietnam's ICT GVCs (1995 vs 2018); (bottom) Value Gains in the United States' ICT GVCs (1995 vs 2018). *Note*: Explanations of countries and industry codes are provided in Appendices A and B. *Sources*: Authors' elaborations using ICIO and TiM OECD.

production, which are performed by advanced economies that are largely less polluting. As we move away from domestic final stages toward foreign contributions encompassing pre- and post-production activities, the weight of developing countries increases and emission rise, generating the ascending arm of the parable. This aligns with advanced countries' specialisation in high-value, low-emission activities and their reliance on imported intermediates for more emission-intensive productions. At the beginning of the period, U shapes are numerous for advanced countries (on average roughly 75% of the cases), especially in value chains characterised by low technological intensity. In 2018, many medium–high-tech and low-emission GVCs in the final stage shifted to a hump-shape resembling the structure of GVCs finalised in developing countries. There, the contribution of the domestic final stage tends to decrease.

On the other hand, GVCs finalised in developing economies exhibit predominantly inverse U-shaped (hump) patterns, with emission peaks in midstream manufacturing. These dynamics underscore the role of developing countries as emission haven, with advanced countries supplying them pre- and post- production activities which are relatively less polluting and thus generating declining carbon arms. Here, the time dynamics show an opposite pattern to those observed in advanced economies, with the number of hump-shaped instances rising significantly from 1995 to 2018 (55% vs 76%), particularly in medium- and high-tech GVCs (fifth column with %). Jointly, these disparities underscore how GVCs structurally concentrate pollution-intensive stages in the Global South, while enabling advanced economies to externalise

Table 2
Incidence of U- or Hump-shaped curves by GVCs' sector of final production in 2018 and 1995. The analysis is performed by evaluating all inputs along the chains (left) as well as only foreign inputs (right), for advanced and developing countries. Among the identified U shapes and hump shapes, we perform the *U* test following Lind and Mehlum (2010). The second % column in each specification reports the share of confirmed U or inverse U among those already identified. Note: Explanations of country codes are provided in the Appendices. Sources: Authors' elaborations based on ICIO and $TECO_2$.

GVCs	Year	Advanced Countries				Developing Countries			
		All Inputs U shapes		Foreign Hump shapes		All Inputs Hump shapes		Foreign Hump shapes	
		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Food products	1995	96%	*93%*	18%	*0%*	36%	*57%*	54%	*67%*
	2018	86%	*67%*	96%	*81%*	59%	*57%*	97%	*89%*
Textiles	1995	100%	*93%*	21%	*17%*	41%	*50%*	62%	*54%*
	2018	61%	*24%*	96%	*89%*	77%	*70%*	97%	*92%*
Wood & cork products	1995	89%	*96%*	39%	*45%*	28%	*55%*	38%	*87%*
	2018	71%	*65%*	96%	*85%*	59%	*74%*	100%	*92%*
Paper products	1995	100%	*100%*	4%	*0%*	33%	*54%*	38%	*93%*
	2018	79%	*55%*	93%	*77%*	56%	*73%*	97%	*84%*
Coke & refined petroleum	1995	100%	*100%*	4%	*100%*	13%	*40%*	21%	*38%*
	2018	92%	*91%*	4%	*100%*	26%	*50%*	26%	*60%*
Chemical products	1995	89%	*100%*	7%	*100%*	21%	*38%*	28%	*91%*
	2018	86%	*71%*	75%	*33%*	56%	*55%*	85%	*73%*
Pharmaceuticals	1995	96%	*93%*	11%	*33%*	31%	*33%*	38%	*60%*
	2018	79%	*50%*	86%	*83%*	59%	*61%*	92%	*86%*
Rubber & plastics	1995	93%	*92%*	19%	*80%*	54%	*71%*	74%	*72%*
	2018	26%	*0%*	100%	*96%*	90%	*91%*	97%	*100%*
Other non-metallic mineral products	1995	100%	*100%*	0%	*0%*	21%	*13%*	23%	*78%*
	2018	93%	*85%*	61%	*47%*	38%	*80%*	72%	*61%*
Basic metals	1995	100%	*100%*	0%	*0%*	8%	*33%*	11%	*50%*
	2018	46%	*23%*	96%	*89%*	62%	*79%*	100%	*90%*
Fabricated metal	1995	100%	*100%*	0%	*0%*	13%	*60%*	10%	*25%*
	2018	14%	*25%*	100%	*100%*	97%	*79%*	100%	*100%*
ICT	1995	96%	*100%*	4%	*100%*	41%	*63%*	46%	*78%*
	2018	25%	*0%*	100%	*93%*	92%	*75%*	100%	*100%*
Electrical equipment	1995	100%	*93%*	7%	*0%*	26%	*60%*	33%	*69%*
	2018	4%	*0%*	100%	*100%*	97%	*92%*	100%	*100%*
Machinery	1995	100%	*100%*	0%	*0%*	26%	*60%*	31%	*58%*
	2018	11%	*33%*	100%	*100%*	97%	*84%*	100%	*100%*
Motor vehicles	1995	93%	*92%*	11%	*33%*	37%	*71%*	37%	*57%*
	2018	4%	*0%*	100%	*100%*	100%	*92%*	100%	*100%*
Other transport equipment	1995	100%	*100%*	0%	*0%*	36%	*64%*	33%	*69%*
	2018	14%	*0%*	100%	*100%*	97%	*92%*	100%	*100%*
Other manufacturing	1995	96%	*89%*	21%	*17%*	44%	*71%*	49%	*89%*
	2018	7%	*50%*	100%	*100%*	92%	*86%*	100%	*100%*

emissions.

Second, the dichotomy between all inputs and foreign inputs unveils the role of GVCs' structure on their emission profile. When isolating foreign intermediates, disparities across development levels disappear, and inverse U-shapes dominate across both advanced and developing economies. Interestingly, these hump shapes emerge in the period under analysis, as we detect 20% of hump-shapes in 1995, while this number jumps to a striking 91% in 2018, evenly distributed between advanced and developing countries. This convergence indicates that, once we exclude the final stage's country-industry specificities, environmental smile curves are fundamentally a feature of international production networks, irrespective of the final production or final country under analysis: regardless of the final producer's development level, foreign-sourced inputs disproportionately embed emissions in middle-production stages that are disproportionatelly executed in the Global South.

The pervasiveness of hump-shaped curves for foreign inputs in the final year of the dataset suggests that GVCs reconfigure to allocate high-emission tasks to supplier nations—often developing economies—while high-income countries retain less-emitting, high-value activities domestically. In advanced countries' value chains, considering all inputs, this tendency is evident in the rise of an inverted-U shape from 1995 to 2018, which makes advanced countries' chains worryingly more similar in their distribution of CO_2 to developing countries.

In cases involving foreign inputs, the temporal dynamics between advanced and developing countries also became similar, with a marked increase in instances in which hump-shaped patterns are observed in the final year of the analysis. In most of the sectors, particularly the high-tech ones, these cases are close to the totality. The increase in the incidence of these curves highlights that such patterns are consequences of the rise in GVCs, and that, where not built in at the beginning of the so-called second unbundling in the nineties, the beginning of the production fragmentation period.

Finally, GVC heterogeneity further underscores the role of technological capabilities under three dimensions. First, within the same industry and in a given period, several production techniques coexist, but developing countries generally employ those that are relatively more polluting than the average. This pattern resembles the substantial evidence on widespread heterogeneities in production techniques, even at finer levels of disaggregation, and the ensuing differences in efficiency and productive capabilities across firms (Dosi, 2023). Second, chains requiring higher amounts of more-polluting backward inputs are more similar across advanced and developing countries, since the final production stage has lower importance in the overall emission footprint of the chain. Third, technological capabilities in the final country generate heterogeneity as well, with advanced countries able to demand less polluting inputs. However, sector specificities emerge only by analysing the entire GVCs, where domestic contributions cover the great majority of the intermediates required in the production process. Looking at the entire value chain allows us to disentangle the role of final production, and therefore to assess the extent to which sectoral specialisation in final production stages is less or more harmful for the environment. Once we exclude final production stages, the results appear homogeneous across chains, revealing that these environmental curves are not mere randomness but instead emergent properties of the joint effects of the uneven international division of production, labour and access to less-polluting production mixes. The evidence on the hump-shape suggests that emission inequalities are entrenched in the very architecture of global production, and tightly linked with economic inequalities, as discussed in Subsection 4.1.

6. Conclusions

This paper shows that the environmental consequences of global production follow a clear and troubling pattern when viewed through the smile-curve lens. Whereas traditional smile curves show value concentrating at the upstream and downstream ends of GVCs, our environmental adaptation reveals the opposite dynamic: emission intensity peaks in the middle stages of production, where developing economies are disproportionately concentrated. The result is a double asymmetry, in which poorer countries occupy positions associated with both lower value capture and higher environmental burdens. Sectoral heterogeneity is central to this pattern. Energy-intensive manufacturing and extractive activities, which feature prominently in the export profiles of many developing economies, display much higher emission intensities than knowledge-intensive sectors. This specialisation is not accidental, but reflects deeper structural factors, including technological gaps, capital constraints, and the governance of global production networks. In this sense, the evidence is consistent with the Pollution Haven Hypothesis, as emission-intensive production tends to shift towards jurisdictions with weaker regulatory and enforcement capacity.

More broadly, these findings contribute to the literature on ecologically unequal exchange by showing that environmental costs follow the same structural logic that organises value extraction in global capitalism. Advanced economies sustain lower-emission domestic production profiles not only through superior technologies, but also by externalising pollution-intensive stages to supplier countries through GVC governance. The resulting separation between value capture and emission generation creates a major challenge for both climate mitigation and equitable development.

There are multiple policy implications which must be read against two transformative forces reshaping global production: the green transition and growing geopolitical reconfiguration. Approaches focused narrowly on national emission inventories or sectoral efficiency gains are not enough, because they miss the structural imbalances embedded in global production. Effective responses must therefore address the political economy of GVCs, including power asymmetries, intellectual property regimes that restrict technology transfer, trade arrangements that prioritise corporate flexibility over environmental standards, and financial structures that reinforce extractive specialisation in the Global South.

Ultimately, the environmental smile curve shows that the current organisation of global production systematically disadvantages developing economies twice over: by concentrating them in low-value activities and by burdening them with disproportionate environmental costs. Addressing this dual asymmetry requires a rethinking of how value, technology, and environmental responsibility are distributed in the global economy, in ways that account for both the imperatives of decarbonisation and the realities of geopolitical fragmentation. Without such a shift, industrial decarbonisation risks remaining partial and unjust, reproducing the same structural inequalities that underpin the current climate impasse. Environmental and economic justice in global production are therefore inseparable.

This also has important implications for governance interventions. The rise of digital and decarbonisation technologies—now central to geopolitical competition as well—has further complicated this landscape, creating new opportunities for industrial upgrading while exacerbating concerns about carbon leakage, technological dependency, and environmental justice (Lema & Perez, 2024; Lema et al., 2021; UNCTAD, 2023). Trade-related environmental regulations, due diligence requirements, and industrial policies may help weaken the environmental smile curve, but only if they reduce technology gaps and actively support the diffusion of decarbonisation technologies and production practices along the chain. Where such interventions expand access to know-how and capabilities among lower-tier suppliers, they may loosen the alignment between low-value positions and high-emission burdens. However, where environmental standards are introduced without a corresponding redistribution of capabilities and resources, they may instead reinforce existing asymmetries, shifting adjustment costs onto weaker suppliers while preserving value capture and strategic control elsewhere. From this perspective, decarbonisation technologies should not remain subordinated to competitive advantage, bargaining asymmetries, or selective control by lead actors. If decarbonisation is to serve the common good rather than reproduce existing hierarchies, the diffusion of energy-saving and less-polluting mixes of production must become a priority above narrow market competition, so that environmental transition does not turn into another mechanism of structural lock-in for developing economies.

The limitations of our analysis point directly to future research paths, especially the need for fine-grained studies on value-chain control and on the choices underlying the relocation of high-carbon and low-value-added production stages to low-income countries. In particular, we still lack systematic analyses of the quantification and diffusion of technologies along GVCs, their relationship with the power exercised by headquarters firms, the role of production fragmentation, and the strategic relocation of high-emission-intensity activities to poorer economies. As our results suggest, the Global North has progressively accumulated an environmental debt vis-à-vis the Global South. Halting this process requires allowing the South to develop local capabilities, search for its own solutions, and build the technological autonomy needed to generate both domestic gains and environmental sustainability. Future work should therefore investigate the sources through which the Global South may achieve such an autonomy. In addition, although our units of observation are countries, value chains are articulated at sub-national scales, and their territorial organisation affects local development trajectories. To identify the role of local capabilities more clearly, sub-national analyses are needed (Pietrobelli & Rabellotti, 2011; Capello & Dellisanti, 2024). In addition, the evaluation of the asymmetric burden for different countries and territories, as mediated by context- and institutionally-dependent conditions, would require the development of local metrics of vulnerability to GVC exposure, which can represent future avenues of research. Certainly, while we have documented a global process of allocation of environmental *burden* via carbon emissions, a thorough evaluation of the environmental *value* created or destroyed through GVCs would require the development of local matrices and indicators, based on expectations, needs, experiences and contexts that communities may experience. Bridging GVCs and local-development analyses would certainly represent an interesting avenue of future research, to couple not only the environmental burden of GVCs but, potentially, contrasting loss *vs* generation of local environmental value.

Forty years after the second unbundling of globalisation, and in the face of growing evidence on the failures of hyper-globalisation, a new protectionist, military, and anti-free-trade stance is emerging with unprecedented speed. What this will mean for future production structures, and whether regional development may increasingly replace global development, remains an open question. Regionalisation could also reduce the emission content of traded inputs, and China is progressively consolidating such a strategy. At the same time, the need to secure critical inputs is pushing firms and states to shorten value chains and to build new relationships based on greater trust. It is therefore possible (and desirable) that the era of low-road strategies led by multinational enterprises, aimed primarily at maximising value capture while squeezing developing economies, may gradually give way to more regionalised patterns of production and exchange, particularly in East Asia. The emergence of new productive cores and multipolar orders might also affect the distribution of the environmental burden.

CRediT authorship contribution statement

Giovanni Dosi: Supervision, Resources, Funding acquisition, Conceptualization, Writing - review & editing, Formal analysis. **Federico Riccio:** Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Maria Enrica Virgillito:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing, Formal analysis.

Declaration of competing 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.

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Appendix 1

A. Country Development Levels

Table A1
Country, ISO3 country code and development level. Source: UN Statistics Division.

Country	ISO3	Code	Development Level	Country	ISO3	Code	Development Level
Argentina	ARG	032	*Developing*	Morocco	MAR	504	*Developing*
Australia	AUS	036	*Developed*	Myanmar	MMR	104	*Developing*
Austria	AUT	040	*Developed*	Netherlands	NLD	528	*Developed*
Belgium	BEL	056	*Developed*	New Zealand	NZL	554	*Developed*
Brazil	BRA	076	*Developing*	Norway	NOR	578	*Developed*
Brunei	BRN	096	*Developing*	Peru	PER	604	*Developing*
Bulgaria	BGR	100	*Developing*	Philippines	PHL	608	*Developing*
Cambodia	KHM	116	*Developing*	Poland	POL	616	*Developing*
Canada	CAN	124	*Developed*	Portugal	PRT	620	*Developed*
Chile	CHL	152	*Developing*	Rest of the World	ROW	–	*Developing*
China	CHN	156	*Developing*	Romania	ROU	642	*Developing*
Chinese Taipei	TWN	158	*Developed*	Russia	RUS	643	*Developing*
Colombia	COL	170	*Developing*	Saudi Arabia	SAU	682	*Developing*
Costa Rica	CRI	188	*Developing*	Singapore	SGP	702	*Developing*
Croatia	HRV	191	*Developing*	Slovak Republic	SVK	703	*Developing*
Cyprus	CYP	196	*Developed*	Slovenia	SVN	705	*Developing*
Czechia	CZE	203	*Developing*	South Africa	ZAF	710	*Developing*
Denmark	DNK	208	*Developed*	Spain	ESP	724	*Developed*
Estonia	EST	233	*Developing*	Sweden	SWE	752	*Developed*
Finland	FIN	246	*Developed*	Switzerland	CHE	756	*Developed*
France	FRA	250	*Developed*	Thailand	THA	764	*Developing*
Germany	DEU	276	*Developed*	Tunisia	TUN	788	*Developing*
Greece	GRC	300	*Developed*	Turkey	TUR	792	*Developing*
Hong Kong	HKG	344	*Developed*	United Kingdom	GBR	826	*Developed*
Hungary	HUN	348	*Developing*	United States	USA	840	*Developed*
Iceland	ISL	352	*Developed*	Viet Nam	VNM	704	*Developing*
India	IND	356	*Developing*				
Indonesia	IDN	360	*Developing*				
Ireland	IRL	372	*Developed*				
Israel	ISR	376	*Developed*				
Italy	ITA	380	*Developed*				
Japan	JPN	392	*Developed*				
Kazakhstan	KAZ	398	*Developing*				
Korea	KOR	410	*Developing*				
Lao P.D.R.	LAO	418	*Developing*				
Latvia	LVA	428	*Developing*				
Lithuania	LTU	440	*Developing*				
Luxembourg	LUX	442	*Developed*				
Malaysia	MYS	458	*Developing*				
Malta	MLT	470	*Developed*				
Mexico	MEX	484	*Developing*				

Sector Aggregations

Table A2
Sectoral aggregation. Source: Own Elaboration.

Industry	Industry Definition	Industry Aggregation	Definition
01T02	*Agriculture, hunting, forestry*	A	Agriculture
03	*Fishing and aquaculture*	A	Agriculture
05T06	*Mining and quarrying, energy producing products*	B	Mining
07T08	*Mining and quarrying, non-energy producing products*	B	Mining
09	*Mining support service activities*	B	Mining
10T12	*Food products, beverages and tobacco*	10 T12	Food products
13T15	*Textiles, textile products, leather and footwear*	13T15	Textiles
16	*Wood and products of wood and cork*	16	Wood & cork products
17T18	*Paper products and printing*	17T18	Paper products
19	*Coke and refined petroleum products*	19	Coke & refined petroleum
20	*Chemical and chemical products*	20	Chemical products
21	*Pharmaceuticals, medicinal chemical and botanical products*	21	Pharmaceuticals
22	*Rubber and plastics products*	22	Rubber and plastics
23	*Other non-metallic mineral products*	23	Oth. non-metallic mineral
24	*Basic metals*	24	Basic metals
25	*Fabricated metal products*	25	Fabricated metal
26	*Computer, electronic and optical equipment*	26	PC & electronic equipment
27	*Electrical equipment*	27	Electrical equipment
28	*Machinery and equipment, nec*	28	Machinery
29	*Motor vehicles, trailers and semi-trailers*	29	Motor vehicles
30	*Other transport equipment*	30	Oth. transport equipment
31T33	*Manufacturing nec; repair and installation of machinery*	31T33	Other manufacturing
35	*Electricity, gas, steam and air conditioning supply*	D	Energy supply
36T39	*Water supply; sewerage, waste management*	E	Water & waste mgt
41T43	*Construction*	F	Construction
45T47	*Wholesale and retail trade; repair of motor vehicles*	G	Wholesale & retail
49	*Land transport and transport via pipelines*	H	Transportation
50	*Water transport*	H	Transportation
51	*Air transport*	H	Transportation
52	*Warehousing and support activities for transportation*	H	Transportation
53	*Postal and courier activities*	H	Transportation
55T56	*Accommodation and food service activities*	I	Accomodation & food
58T60	*Publishing, audiovisual and broadcasting activities*	J	Information services
61	*Telecommunications*	J	Information services
62T63	*IT and other information services*	J	Information services
64T66	*Financial and insurance activities*	KL	Financial activities
68	*Real estate activities*	KL	Financial activities
69T75	*Professional, scientific and technical activities*	M	Professional & scientific
77T82	*Administrative and support services*	N	Support services
84	*Public administration & defence; compulsory social security*	SPQROT	Other services
85	*Education*	SPQROT	Other services
86T88	*Human health and social work activities*	SPQROT	Other services
90T93	*Arts, entertainment and recreation*	SPQROT	Other services
94T96	*Other service activities*	SPQROT	Other services
97T98	*Activities of households as employers*	SPQROT	Other services

B. Specialisation patterns

The analysis of revealed comparative advantage (RCA) confirms that advanced economies specialise in low-emission sectors, such as high-tech manufacturing and services, while developing economies concentrate in high-emission activities like energy and basic metals. This bifurcation aligns with the “smile curve” hypothesis, wherein low-value, high-pollution production stages are disproportionately located in the Global South. Interestingly, the distinction between domestic and foreign intermediates is minimal at this level of aggregation, indicating that specialisation patterns are structurally embedded rather than solely driven by intermediate trade dynamics.

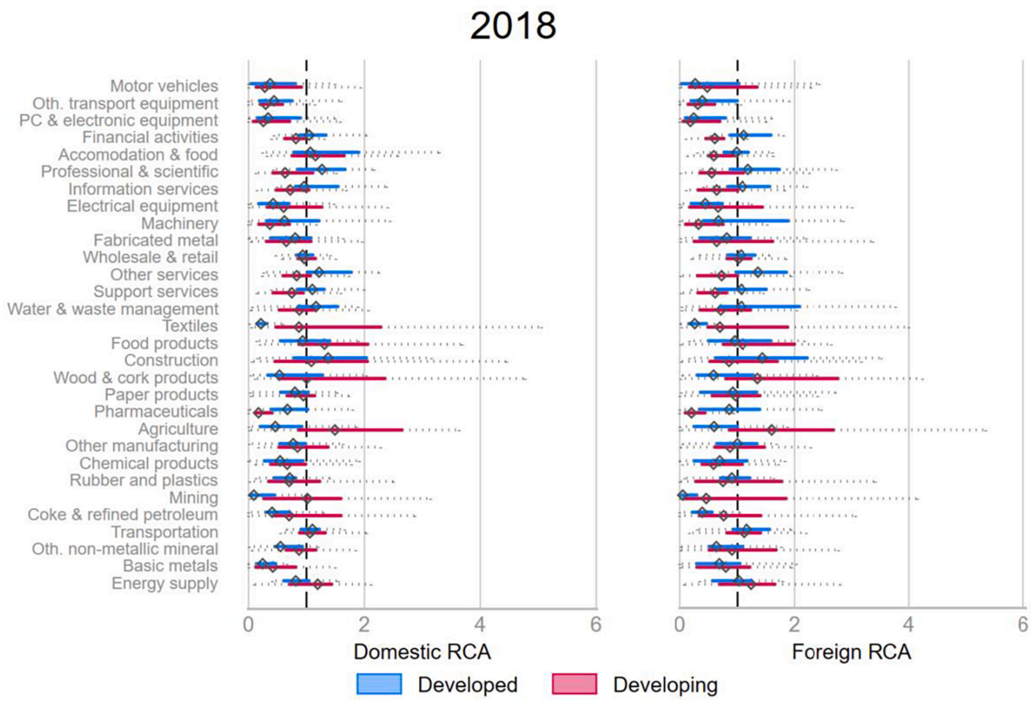

Fig. A1. RCA Distribution by Sector and Origin.

RCA distribution reveals extreme concentration in global value chains, with a few dominant players accounting for the bulk of high-emission production. This hyper-specialisation creates pockets of “pollution havens,” particularly in developing countries supplying raw materials and intermediate goods. When disaggregated by origin, foreign-sourced inputs exhibit even greater concentration than domestic ones, suggesting that GVC participation exacerbates environmental disparities. The skewed distribution implies that decarbonisation efforts must address not only sectoral emissions but also the structural imbalances in global production networks, where a handful of economies bear the brunt of pollution-intensive activities.

Data availability

Data used in the analysis are already available online.

References

Aichele, R., & Felbermayr, G. (2015). Kyoto and carbon leakage: An empirical analysis of the carbon content of bilateral trade. *The Review of Economics and Statistics, 97*(1), 104–115.

Althouse, J., Cahen-Fourot, L., Carballa-Smichowski, B., Durand, C., & Knauss, S. (2023). Ecologically unequal exchange and uneven development patterns along global value chains. *World Development, 170*, Article 106308.

Antràs, P., & Chor, D. (2013). Organizing the global value chain. *Econometrica, 81*(6), 2127–2204.

Balassa, B. (1965). Trade liberalisation and revealed comparative advantage. *The Manchester School, 33*(2), 99–123.

Baldwin, R., & Ito, T. (2021). The smile curve: Evolving sources of value added in manufacturing. *Canadian Journal of Economics / Revue canadienne d'économique, 54*(4), 1842–1880.

Bernhold, C., & Selwyn, B. (2026). Capitalism's systemic barriers to environmental upgrading in global value chains. *Journal of Economic Geography*.

Borin, A., & Mancini, M. (2019). Measuring what matters in global value chains and value-added trade. Policy Research Working Paper 8804. Washington, DC: The World Bank.

Capello, R., & Dellisanti, R. (2024). Smile-and-go: Regional performance through global value chains in Europe. *Papers in Regional Science, 103*(2), Article 100018.

Coe, N. M., & Yeung, H.-W.-C. (2015). *Global production networks: Theorizing economic development in an interconnected world*. Oxford University Press.

Cole, M. A. (2004). Trade, the pollution haven hypothesis and the environmental Kuznets curve: Examining the linkages. *Ecological Economics, 48*(1), 71–81.

Colozza, F., Pietrobelli, C., & Vezzani, A. (2024). Do global value chains spread knowledge and pollution? Evidence from EU regions. *Journal of Cleaner Production, 444*, Article 141180.

Coveri, A., Paglialunga, E., & Zanfei, A. (2024). Global value chains and within-country inequality: The role of functional positioning. *Structural Change and Economic Dynamics, 70*, 382–397.

Dallas, M. P., Ponte, S., & Sturgeon, T. J. (2019). Power in global value chains. *Review of International Political Economy, 26*(4), 666–694.

De Marchi, V., & Gereffi, G. (2023). Using the global value chain framework to analyse and tackle global environmental crises. *Journal of Industrial and Business Economics, 50*(1), 149–159.

Distelhorst, G., & McGahan, A. (2021). Socially irresponsible employment in emerging-market manufacturers. *Organization Science, 33*(6).

Dorninger, C., Hornborg, A., Abson, D. J., von Wehrden, H., Schaffartzik, A., Giljum, S., Engler, J.-O., Feller, R. L., Hubacek, K., & Wieland, H. (2021). Global patterns of ecologically unequal exchange: Implications for sustainability in the 21st century. *Ecological Economics, 179*, Article 106824.

Dosi, G. (2023). *The foundations of complex evolving economies*. Oxford: Oxford University Press.

Dosi, G., Riccio, F., & Virgillito, M. E. (2021). Varieties of deindustrialization and patterns of diversification: Why microchips are not potato chips. *Structural Change and Economic Dynamics, 57*, 182–202.

Dosi, G., Riccio, F., & Virgillito, M. E. (2025). Decarbonisation and specialisation downgrading: The double harm of GVC integration. *World Development, 194*, Article 107047.

Duan, Y., & Jiang, X. (2021). Pollution haven or pollution halo? A Re-evaluation on the role of multinational enterprises in global CO2 emissions. *Energy Economics, 97*(C). Elsevier.

Duarte, R., Espinosa-Gracia, A., Jiménez, S., & Sánchez-Chóliz, J. (2022). New insights on the relationship between the involvement of countries in global value chains, and intra- and inter-country inequalities. *Structural Change and Economic Dynamics, 63*, 320–329.

Gereffi, G., Humphrey, J., & Sturgeon, T. (2005). The governance of global value chains. *Review of International Political Economy, 12*(1), 78–104.

Grossman, G. M., & Krueger, A. B. (1995). Economic growth and the environment. *The Quarterly Journal of Economics, 110*(2), 353–377.

Hickel, J., Dorninger, C., Wieland, H., & Suwandi, I. (2022). Imperialist appropriation in the world economy: Drain from the global South through unequal exchange, 1990–2015. *Global Environmental Change, 73*, Article 102467.

Jeon, Y., & Kwon, C.-W. (2021). Offshoring, the threat effect, and wage inequality. *International Journal of Economic Theory, 17*, 135–150.

Koopman, R., Wang, Z., & Wei, S.-J. (2014). Tracing value-added and double counting in gross exports. *American Economic Review, 104*(2), 459–494.

Krishnan, A., De Marchi, V., & Ponte, S. (2022). Environmental upgrading and downgrading in global value chains: A framework for analysis. *Economic Geography, 99*(1), 25–50.

Lema, R., & Perez, C. (2024). The green transformation as a new direction for techno-economic development. UNU-MERIT Working Paper 2024–001.

Lema, R., Pietrobelli, C., Rabellotti, R., & Vezzani, A. (2021). Deepening or delinking? Innovative capacity and global value chain participation in the ICT sectors. MERIT Working Paper 2021-007, United Nations University – Maastricht Economic and Social Research Institute on Innovation and Technology (MERIT).

Leontief, W. W. (1936). Quantitative input and output relations in the economic systems of the United States. *The Review of Economics and Statistics, 18*(3), 105–125.

Lind, J. T., & Mehlum, H. (2010). With or without U? The appropriate test for a U-shaped relationship. *Oxford Bulletin of Economics and Statistics, 72*(1), 109–118.

Meng, B., & Ye, M. (2022). Smile curves in global value chains: Foreign- vs. domestic-owned firms; the U.S. vs. China. *Structural Change and Economic Dynamics, 60*, 15–29.

Meng, B., Peters, G. P., Wang, Z., & Li, M. (2018). Tracing CO_2 emissions in global value chains. *Energy Economics, 73*, 24–42.

Meng, B., Ye, M., & Wei, S.-J. (2020). Measuring smile curves in global value chains. *Oxford Bulletin of Economics and Statistics, 82*(5), 988–1016.

Milberg, W., & Winkler, D. (2011). Economic and social upgrading in global production networks: Problems of theory and measurement. *International Labour Review, 150* (3–4), 341–365.

Mudambi, R. (2008). Location, control and innovation in knowledge-intensive industries. *Journal of Economic Geography, 8*(5), 699–725.

Peters, G. P. (2008). From production-based to consumption-based national emission inventories. *Ecological Economics, 65*(1), 13–23.

Pietrobelli, C., & Rabellotti, R. (2011). Global value chains meet innovation systems: Are there learning opportunities for developing countries? *World Development, 39*(7), 1261–1269.

Pietrobelli, C., Casaburi, G., & Iizuka, M. (2024). Capabilities, sustainability, and innovation in mining value chains. *Industrial and Corporate Change, 33*(4), 918–921.

Riccio, F., Cresti, L., & Virgillito, M. E. (2024). The labour share along global value chains: Perspectives and evidence from sectoral interdependence. *Review of World Economics, 160*(3), 635–684.

Riccio, F., Dosi, G., & Virgillito, M. E. (2025). Functional specialisation and income distribution along global value chains. *Economic Systems Research, 37*(1), 116–147.

Rodrik, D. (2016). Premature deindustrialization. *Journal of Economic Growth, 21*(1), 1–33.

Savona, M., & Ciarli, T. (2019). Structural changes and sustainability: A selected review of the empirical evidence. *Ecological Economics, 159*, 244–260.

Schwarzbauer, W., Bittó, V., Koch, P., & Steininger, J. (2025). Mapping CO_2 emissions in global value chains: Does a value-added smile curve imply an emissions frown curve? *Structural Change and Economic Dynamics, 75*, 332–348.

Shih, S. (1996). *Me-too is not my style: Challenge difficulties, break through bottlenecks, create values*. Taipei: The Acer Foundation.

Siewers, S., Martínez-Zarzoso, I., & Baghdadi, L. (2024). Global value chains and firms' environmental performance. *World Development, 173*, Article 106395.

Stern, D. I. (2017). The environmental Kuznets curve after 25 years. *Journal of Bioeconomics, 19*(1), 7–28.

Szymczak, S., & Wolszczak-Derlacz, J. (2022). Global value chains and labour markets – Simultaneous analysis of wages and employment. *Economic Systems Research, 34*(1), 69–96.

Timmer, M. P., Miroudot, S., & de Vries, G. J. (2019). Functional specialisation in trade. *Journal of Economic Geography, 19*(1), 1–30.

Unctad. (2023). *Technology and innovation report 2023*. United Nations.

Unruh, G. C. (2000). Understanding carbon lock-in. *Energy Policy, 28*(12), 817–830.

Wang, Q., Li, Y., & Li, R. (2024). Rethinking the environmental Kuznets curve hypothesis across 214 countries: The impacts of 12 economic, institutional, technological, resource, and social factors. *Humanities and Social Sciences Communications, 11*, 292.