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## The environmental smile curve: Input-output evidence on the pollution haven hypothesis

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# LEM

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### **The Environmental Smile Curve: Input-Output evidence on the Pollution Haven Hypothesis**

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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. Building on the "smile curve" framework (Mudambi, 2008; Meng et al., 2020), we show that developing countries specialize in low-value-added, high-emission production stages, while advanced economies capture high-value, low-emission activities like R&D and design (Riccio et al., 2025). Using OECD ICIO and CO<sub>2</sub> emissions data, we demonstrate that GVC integration exacerbates a "double harm": production workers—particularly in middle-stage manufacturing—face wage suppression, while these same stages exhibit higher carbon intensity per unit of value added. This aligns with the Pollution Haven Hypothesis (Cole, 2004), as emissions are displaced to regions with weaker regulations. 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 emissions data, we provide novel evidence of how GVCs structurally embed unequal ecological and economic burdens.

**JEL Codes:** F14; F18; F63; F64; O44; Q54; Q56.

**Keywords:** Smile Curve – Ecological Economics – Global Value Chain – Embodied emissions– Environmental & Income Inequality.

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## 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; Riccio et al., 2025). The rise of digital and green 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; UNCTAD, 2023).

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 specialisation patterns during development (Ciarli & Savona, 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, especially, GVCs—the EKC theory has increasingly been called into question (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 specialize in primary inputs and labour-intensive, low-value-added manufacturing—such as electricity generation, raw material processing and fabrication stages—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).

This dynamic challenges the conventional wisdom that trade liberalisation and GVC participation automatically lead to technology diffusion (Rodrik, 2018), convergence in incomes (Jangam et al., 2020) and environmental standards (Siewers et al., 2024). Instead, many scholars have argued, the current wave of technological and green transitions may exacerbate inequalities (Coveri et al., 2024; Duarte et al., 2022), with advanced economies capturing the lion's share of high-value, low-emission activities while relegating developing nations to polluting, low-wage segments of production.

The existing literature has largely treated wage suppression and environmental externalities as separate consequences of GVC integration. Yet, these phenomena are deeply intertwined. The "smile curve" of value capture in GVCs—where pre- and post-production stages (e.g., R&D, marketing) generate high returns while manufacturing generates minimal profits—has direct implications for both labour remuneration (Meng et al., 2020) and environmental outcomes (Dosi et al., 2025; ). When firms face squeezed margins in middle-stage production, they often cut costs either by suppressing wages and generating within countries inequality (Duarte et al., 2022), or offshoring production to low-income countries (Jeon & Kwon, 2021). However, since developing countries are characterised by weaker environmental regulations and dirtier technologies, the offshoring of these production segments to lower-income regions is likely to increase the environmental externalities of global production (Cole, 2004; Aichele & Felbermayr, 2015).

The Pollution Haven Hypothesis (PHH) provides a partial explanation, showing that stringent environmental regulations in advanced economies drive the offshoring of dirty industries (Porter & Van der Linde, 1995). This nexus is particularly evident looking at GVCs trade, where offshore production stages to 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 potentially upgrade technologically thanks to FDI within GVCs. Here, the role of the low-road strategy 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 cleaner 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 total low-cost strategies. Recent work by Riccio et al. (2024) underscores this point, demonstrating that GVC participation reduces wage shares for production workers across all income levels, but most severely in developing economies. This finding aligns with the broader critique of GVCs as engines of "social downgrading" (Szymczak, 2024, Milberg & Winkler, 2011), where economic gains are concentrated among capital owners and high-skilled, workers while the majority of the labour force bears the costs of precarious employment and environmental harm.

Still, few studies explicitly integrate PHH with GVC analysis to examine how production fragmentation redistributes emissions *along* value chains—not just *between* nations (Duan et al., 2021). This gap is striking given the central role of GVCs in modern trade and their stark distributional consequences. As highlighted by Pietrobelli et al., (2024), technological and green transitions are reshaping GVCs, creating new opportunities as well as new dependencies (e.g., critical minerals for renewables), while destabilizing old hierarchies. Yet, the environmental implications of these shifts remain opaque. Addressing whether GVC participation locks developing countries into high-emission specialisation patterns is still an open question, that deserves to be addressed with exhaustive empirical evidence. Related, tracing the emission contents within fragmented production networks, deriving from country patterns of sectoral specialisation and GVCs integration, allows to pinpoint in which segment of the production process the emission burden of GVCs is largely located, and ultimately to quantify the ensuing value added generated in that phase. If low value added and high-emission intensity phases tend to coexist, our conjecture is that there should exist an environmental smile curve symmetrical to the value added smile curve. Addressing these issues requires bridging GVC governance and upgrading literature with not only environmental economics, but also with the political economy of globalisation.

With such an aim, this paper investigates the "environmental smile curve" hypothesis, positing that GVCs concentrate high-emission activities in middle/low-income stages—often located in the Global South—while high-value, low-emission stages are mostly supplied by advanced economies. Using OECD Inter-Country Input-Output (ICIO) data from 1995–2018, we trace CO<sub>2</sub> emissions along production chains, linking them to sectoral specialisation, via Revealed Comparative Advantage (Balassa, 1956) and development levels. Our methodology combines Leontief-based emission accounting to quantify domestic and foreign emissions embodied in exports as well as propagation length metrics (Koopman et al., 2014) to locate production stages within GVCs. Furthermore, for each input supplied throughout the production process we account for its emission intensity. In particular, acknowledging that total emissions of each chain depend on the final production, we measure emissions as deviation from the sectoral average. Then, following Meng et al., (2020), for each value chain we test the existence and significance of an environmental smile curve, by estimating a quadratic relationship between the positioning metric and emission intensity of each stage, looking at intermediate inputs employed in the production process as unit of analysis. A recent contribution in this direction is provided by Schwarzbauer et al. (2025), who investigate the existence of an environmental smile curves to map CO<sub>2</sub> emissions in GVCs. However, their approach relies on a different measure of functional positioning than the seminal framework of Meng et al. (2020), which limits comparability. In this paper, we extend this line of research by focusing on foreign intermediates, thereby isolating the specific role of international trade in shaping emission. Moreover, by applying the upstreamness measure introduced by Meng et al. (2020, 2022), we are able to capture U-shape and inverse-U-shape relationships, rather than monotonic trends.

Our findings reveal a stark divergence: developing economies increasingly specialize in mid-stream, emission-intensive sectors (e.g., energy, metals, plastic products), while advanced economies dominate both upstream and downstream, cleaner activities (e.g., design, managerial activities, marketing, retail). Notably, focusing on foreign-sourced intermediates, that is those specifically traded via GVCs, amplifies these disparities. Our results challenge

optimistic narratives about GVC-led emission convergence, via spillovers from technological diffusion. While technological diffusion could theoretically decouple growth from emissions, according to the green growth approach, our evidence suggests that current GVC configurations reinforce a "double harm" on developing countries: economic downgrading (capturing less value) and environmental downgrading (absorbing more pollution).

By joining environmental economics with the political economy of globalisation, this paper advances two key contributions: Theoretically, it formalizes the "environmental smile curve" as a structural feature of GVCs, complementing existing work on value appropriation (Riccio et al., 2025; Buckley et al., 2022; Meng & Ye, 2022) and pollution havens (Duan et al., 2021; Cole, 2004). On the policy side, it identifies leverage points for just decarbonisation, such as targeting emission-intensive intermediates in trade agreements or fostering green upgrading in supplier industries. Overall, our findings also bear implication for the climate crisis: against naive techno-optimism, emissions, such as value distribution, are not only a structural variable but also a political choice and thus we urge for coordinated global policies to ensure that the "green" transition does not become another vector of uneven development.

The paper proceeds as follows: Section 2 details our data and methodology, linking the integration of emission accounting with GVC positioning metrics. Section 3 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 4 empirically tests the environmental smile curve and discusses the consequences for unequal development and environmental pollution. Section 5 concludes.

## 2. Data and Methodology

### 2.1 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<sub>2</sub> emissions intensity data from the OECD TECO<sub>2</sub> 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 10.1, 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. Appendix 1 and 2 provide countries' development level 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, allowing us to account for the complete supply chain of a specific industry, also encompassing highly polluting industries 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 export and emissions when we take into account their entire production chain. 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 that may not exhibit clearly identifiable upstream, midstream, and downstream stages that are essential for the position-based emission analysis that our study undertakes.

### 2.2 Constructing CO<sub>2</sub> 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 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.

To compute CO<sub>2</sub> multipliers, we pre-multiply the Leontief inverse  $L=(I-A)^{-1}$  by a diagonalized vector of sector-specific CO<sub>2</sub> emission per unit of output ( $EF$ ), yielding:

$$C = \hat{E}F(I-A)^{-1} \quad (1)$$

where  $C$  represents the matrix of CO<sub>2</sub> 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 diagonalized export vector ( $X$ ), thereby concentrating on the emissions attributable to international trade rather than domestic consumption.

$$CC = \hat{E}F(I - A)^{-1}\hat{X} \quad (2)$$

The matrix  $CC$  represents the global CO<sub>2</sub> emissions associated with exports at each stage of the production process. Specifically, summing the elements of a given column yields the total CO<sub>2</sub> emissions generated in the production of a particular good—for example, computers in China. These correspond to the backwards linkages for the production of a PC 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 correspondent row of the  $CC$  matrix, we can trace the emissions contributions from each input-providing industry. 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<sub>2</sub> 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 move the attention from the country-industry specificity, due to the sector of final production, to traded inputs which risk to be shaded by the much more concentrated domestic ones. In such a way, we intend to give importance to traded emissions along production processes, and accounting for the different characteristics of global 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.

### 2.3. 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 intermediaries which tracks the position of each inputs 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 systems like ISCO), which can be then 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 upstream and retail as downstream. 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 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 frameworks of Antràs et al. (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 final producer  $k$ . We define  $V_s = [00...v_s...0]$  the value-added input coefficient of industry  $s$  and  $X_k = [00...x_k...0]^T$  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  $V_s L X_k$ . 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:

$$D_{sk} = \frac{[V_s(I+2A+3A^2+4A^3+\dots)X_k]}{V_s L X_k} = \frac{V_s L^2 X_k}{V_s L X_k} \quad (3)$$

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<sup>1</sup>.

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 other analysis typically treats 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 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 calculate their distance from the final Automotive products using APL measures independently, effectively extending the value chain beyond the factory gate, equivalent to the final manufacturing production 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.

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

The concept of the "smile curve," firstly introduced by Shih (1996) in the context of the personal computer industry, illustrates how value-added is distributed asymmetrically across GVCs. The curve reveals that activities at the upstream stages of production, such as research and development, and downstream stages, such as retail and branding, tend to capture higher value-added, whereas midstream activities, like assembly, generate lower returns. Building on this idea, Meng et al. (2020) formalized the smile curve using input-output analysis, quantifying both the distribution of value-added and the distance of industries to final consumers within GVCs. To summarise the results, Meng and co-authors estimate a quadratic relation between the distributive variable (either value added

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



final output ratio or wages) and the length measure for each GVC, detecting either a U-shape (coefficient of the quadratic term,  $a_2 > 0$ ) or a hump-shape ( $a_2 < 0$ ) pattern.

In their contribution, Meng et al. (2020) focus on ICT sectors comparing the United States and China to show that the country's level of development and technological intensity of its industries fundamentally shape its participation in GVCs, and therefore its ability to gain from this participation. The contrasting functional forms—a persistent U-shape for developing economies and an inverted-U shape for advanced economies—serve as powerful structural diagnostics of asymmetric value capture and specialisation patterns driven by positioning of countries into international GVCs. These patterns illuminate the inherent tensions within global production networks and the distributional consequences of GVC integration.

Value chains whose final production stage takes place in developing economies consistently show the expected U-shape smile curve. Firms in such economies, exemplified by China's ICT producers/exporters, typically occupy the midstream position at the very bottom of this curve. While they capture the largest absolute share of the value-added generated within the chain, due to their role as final assemblers or exporters, their value-added ratio—the domestic value created per unit of output— or alternatively their wage paid to workers is markedly lower than the corresponding figure for advanced countries. This position reflects an initial integration strategy heavily reliant on static comparative advantages, particularly abundant low-cost labour for assembly and basic manufacturing. Consequently, their contribution generates significant employment and export volume but yields relatively thin margins. The rising arms of the U-shape illustrate where the bulk of high-margin value is captured: upstream by technologically-intensive foreign suppliers of high-value components, intellectual property, and R&D services, and downstream by foreign providers of distribution, marketing, and after-sales services in destination markets. This structure signifies a vulnerability termed the "low-end trap," where dependence on imported technology and intermediate inputs persists, and domestic firms face intense cost competition with limited pricing power or bargaining leverage. Upgrading towards higher value-added activities is constrained by significant barriers, including technology gaps and intellectual property regimes. China is one of the countries that over time has been able to overcome such barriers, but so far is more an exception rather than the rule.

Conversely, value chains led by firms within technologically advanced industries of developed economies exhibit a strikingly different pattern: an inverted-U shape. For instance, US ICT producers dominate the peak of their value curve. They capture not only an overwhelming and increasing share of the total value-added gain but also boast a very high value-added ratio, signifying substantial domestic value creation per unit of output. This inverted-U shape is the outcome of successful dynamic upgrading and the leveraging of knowledge-intensive comparative advantages. Advanced economy firms increasingly specialize in producing very high-value, complex final goods or critical high-tech intermediate inputs within their domestic borders, utilising high-skilled labour, advanced capital inputs, and proprietary technologies. Further, the specialisation in "intangible-intensive" goods—where physical goods serve primarily as vessels for embedded intellectual property, design, and specialized software—allows them to command premium prices and capture significant rents within the manufacturing stage itself.

Such firms internalize or tightly control the critical, high-value, technology-intensive production stages, leading to a flatter upstream segment and a concentration of value capture within what would traditionally be considered the midstream. This position signifies substantial bargaining power and the ability to set standards within the GVC, reflecting a successful escape from the low-value trap that characterizes the U-shape of developing countries. The inverted-U, therefore, represents a specialisation pattern achievable only by industries/countries possessing significant technological capabilities and the capacity to control core innovation and high-value transformation processes.

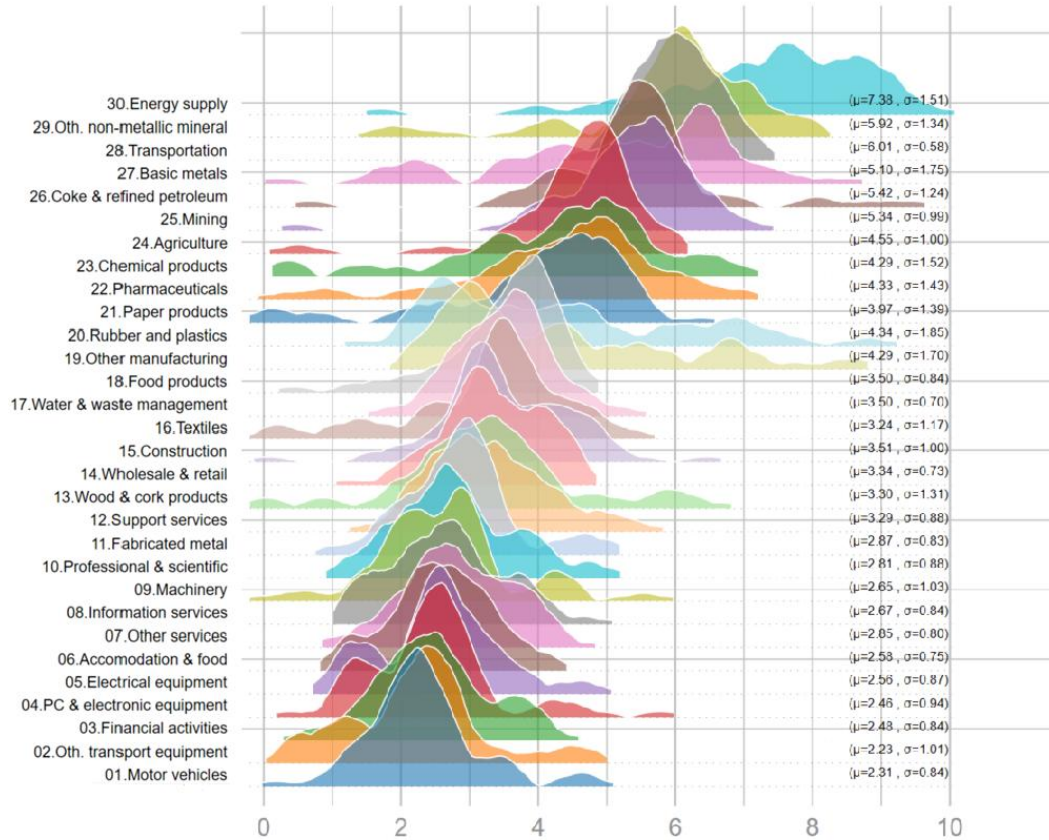
The divergence between the U-shape prevalent in developing economies and the inverted-U achievable by correspondent industries in developed countries is the core contribution of the smile curve analysis to empirically trace unequal exchange within GVCs. The very structure visualized by these curves creates an inherent asymmetry rooted in technological capabilities and countries' specialisation patterns, which, in turn, maps directly into the global development divide. This fundamental imbalance fuels what Meng et al., (2020) define a "*Paradoxical Pair of Concerns*": advanced economies fear industrial hollowing-out as standardized midstream activities potentially

relocate, while developing economies fear perpetual entrapment at the low-value base of the smile curve with limited prospects for equitable wage growth tied to global chain productivity, despite absolute gains in employment and poverty reduction. These concerns resemble the ones highlighted in the structuralist tradition and echoed in the premature deindustrialisation literature, that warn both advanced and developing economies on the distributive and growth consequences of the new international division of labour stemming from the hyper-globalisation, started with the fall of the Soviet Union (Rodrik, 2016)

While this framework provides a methodological foundation for analysing how economic gains propagate across production networks, its application could be extended beyond value-added. By adapting the same approach, we can instead examine the distribution of CO<sub>2</sub> emissions along GVCs. Just as technological and organisational dominance enables lead firms in advanced economies to capture disproportionate value, it also allows them to externalize environmental costs to developing nations. The forces driving both phenomena are fundamentally intertwined: technological and organisational hierarchies that perpetuate wage stagnation and industrial traps in the Global South similarly reinforce pollution-intensive specialisations. At the core of these dynamics lies the interplay between GVC-driven specialisation and environmental outcomes. Advanced economies, leveraging stricter environmental regulations and cleaner technologies, specialize in high-value, low-emission activities (e.g., design, finance), while developing nations—constrained by technological dependence and competitive pressures—are funnelled into midstream manufacturing or resource extraction. These sectors are not only less remunerative but also inherently more polluting due to their reliance on carbon-intensive processes (Althouse et al., 2023; Dorminger et al., 2021).

### 3. Development, industry composition and emissions patterns along GVCs

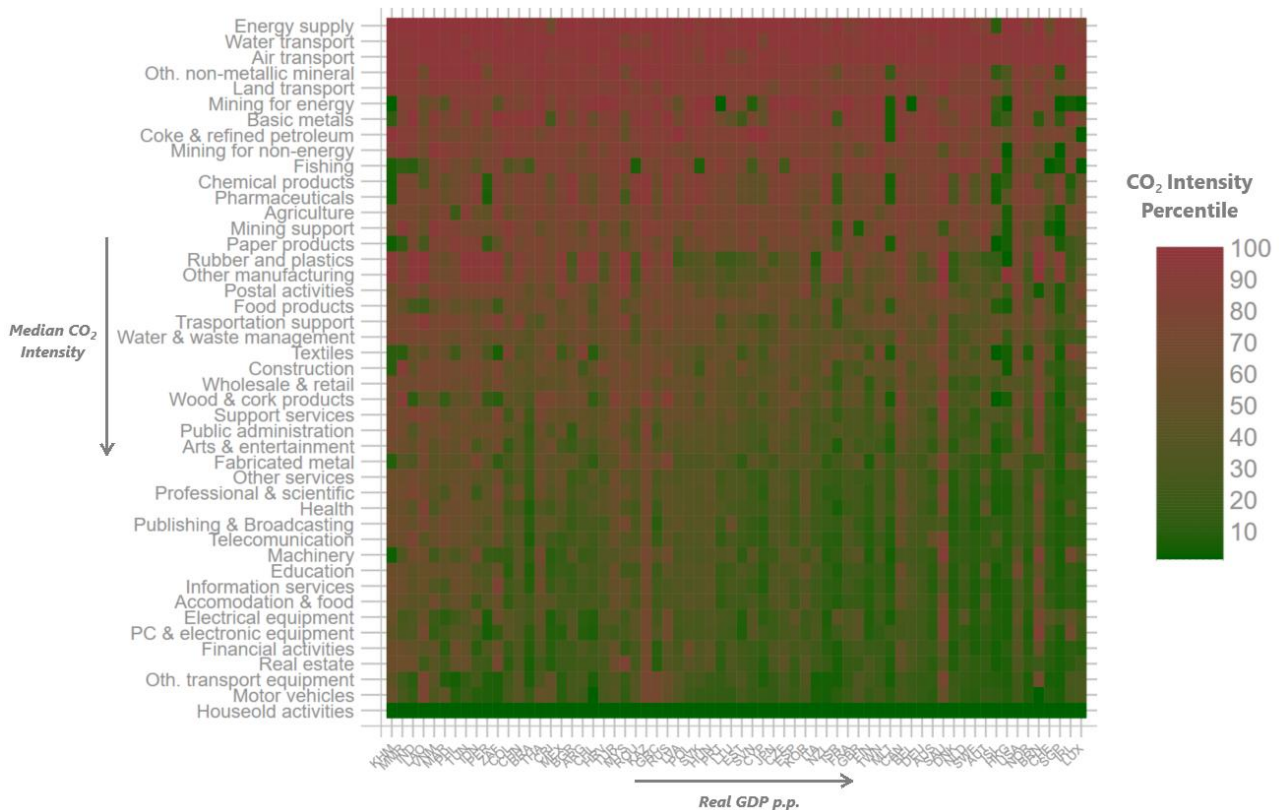
In line with such an evidence, Figure 1 underscores the dominant role of industrial composition in shaping global emissions, showing a striking sectoral heterogeneity. Sectors are ordered by median CO<sub>2</sub> intensity, from top to bottom.



**Figure 1.** Distribution of CO<sub>2</sub> emission intensity (log-transformed) across sectors in 2018. Sectors are ordered by median CO<sub>2</sub> intensity. On the right mean and variance of each distribution are presented. *Source:* Authors' elaboration using OECD TECO<sub>2</sub>.

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, Figure 2 shows the heat plot of CO<sub>2</sub> intensity for each sector-country pair in 2018. The graph reveals the relationship occurring between 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 cleaner production profiles and as such located in the lower triangular matrix—with the only exception being resource-dependent economies as oil-exporting countries, that, despite achieving high income levels, maintain emission intensities comparable to much poorer nations, demonstrating how natural resource endowments, and perverse economic structure, can distort and override expected development trajectories. The persistence of carbon-intensive production in these high-income, resource-rich economies suggests that specialisation patterns—not just development stage—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) determining, on the one hand, countries growth prospects, on the other, its dynamic environmental impact.



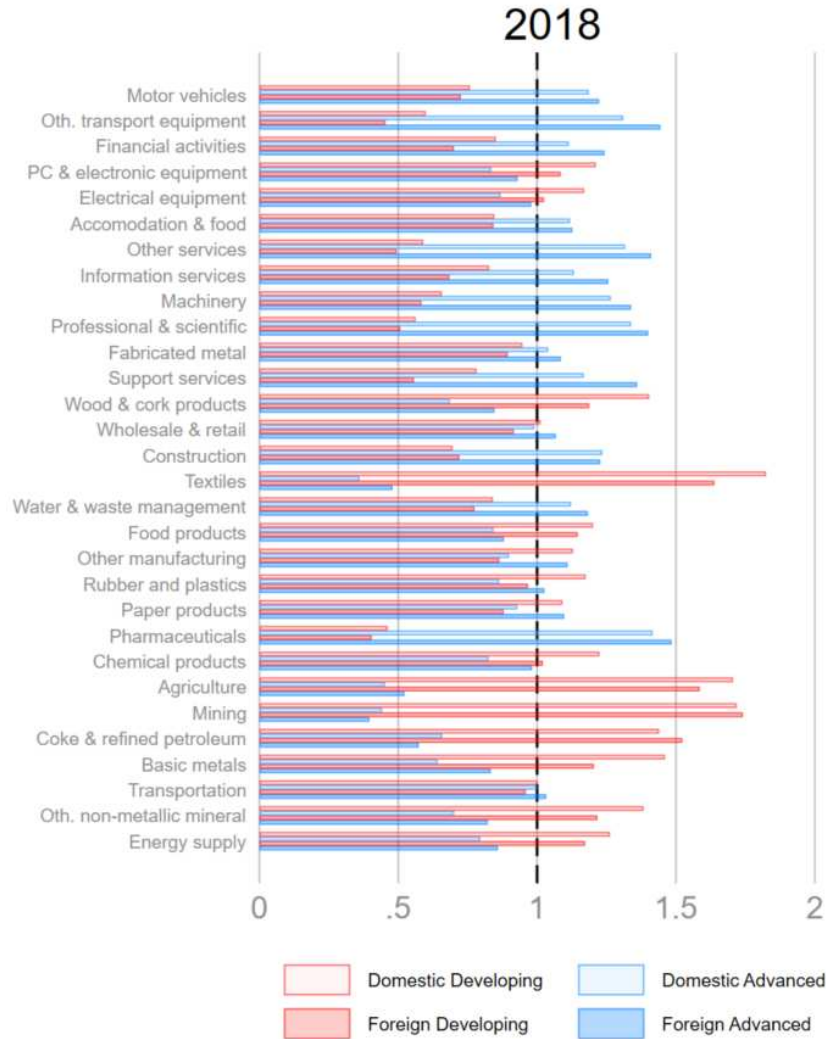
**Figure 2.** Heatplot of CO<sub>2</sub> Intensity for each sector-country pair in 2018. *Note:* Real GDP and Population data comes from PWT 10. Sectors are ordered by median CO<sub>2</sub> intensity while countries by Real GDP per capita. *Sources:* Authors' elaboration using OECD TECO<sub>2</sub> and PWT 10.1.

Building on the sectoral emission patterns revealed in Figures 1 and 2, Figure 3 examines how these carbon-intensive activities are distributed across countries at different development levels. Figure 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 world production network (see appendix A for industry-specific RCA distributions), and then we apply 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:

$$RCA_{i,j} = \frac{\frac{v_{i,j}}{\sum_i v_{i,j}}}{\frac{\sum_j v_{i,j}}{\sum_i \sum_j v_{i,j}}} \quad (4)$$

Where the numerator is the share of country  $i$  in the worldwide flows of intermediaries from industry  $j$ , while the denominator is the share of inputs provided by country  $i$  in world production. An  $RCA_{i,j} > 1$  indicates that country  $i$  is specialized 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.



**Figure 3:** Revealed Comparative Advantage (RCA computed for developing and developed countries) and evaluating domestic and foreign input. 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).

After having constructed country-industry measures of RCA for each of the GVCs, in Figure 3 we aggregate results by development levels.

Figure 3 shows a clear progression: developing economies demonstrate high specialisation ( $RCA_{ij} > 1$ ) in the most emission-intensive sectors like electricity, transportation, low and medium-tech manufacturing. Advanced economies, by contrast, specialize predominantly in low-emission sectors such as pharmaceuticals, electronics, and services. This pattern aligns closely with the emission intensity spectrum, but it adds a new information related to international production flows. Not only a neat correlation between sector-specific carbon footprint and the development level of its primary producers emerges, but also the country-level specialisation in international intermediaries reflects the same structure of relations. These results suggest that current trade structures allocate high-emission production to less developed nations while concentrating clean 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.

#### 4. 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 emissions 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<sub>2</sub> 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<sub>2</sub> emissions 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. Then, rather than tracking the value gain (i.e. economic benefits) accruing to different stages of production, we calculate the CO<sub>2</sub> emissions embodied in each value chain's input. Formally, given a specific value chain, the input-specific embedded CO<sub>2</sub> 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<sub>2</sub> 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 emissions intensity against GVC position reveals distinct patterns in how pollution is distributed across production networks. A traditional smile-shaped curve would suggest that CO<sub>2</sub> 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 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 characterize downstream activities.

Our analysis begins by comparing value chain structures and emission patterns across selected industries in advanced (e.g., the U.S.) and developing (e.g., Vietnam) economies. The choice of the country is only representative of the distinct 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, one accounting 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, which accounts for the majority of the value added. Additionally, we evaluate GVCs' foreign linkages only, which isolate the international division of labour by excluding domestic inputs—focusing on how cross-border supply chain segments shape emission and value distributions. These complementary reconfiguration is motivated by the fact that domestic inputs typically account for ~75% of total production, meaning 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-shape 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 technological attributes, international specialisation, and GVC participation trends in shaping the distribution of both value and emissions along GVCs.

#### **4.1 Case Studies: The Environmental Smile Curve in ICT and Basic Metals Sectors**

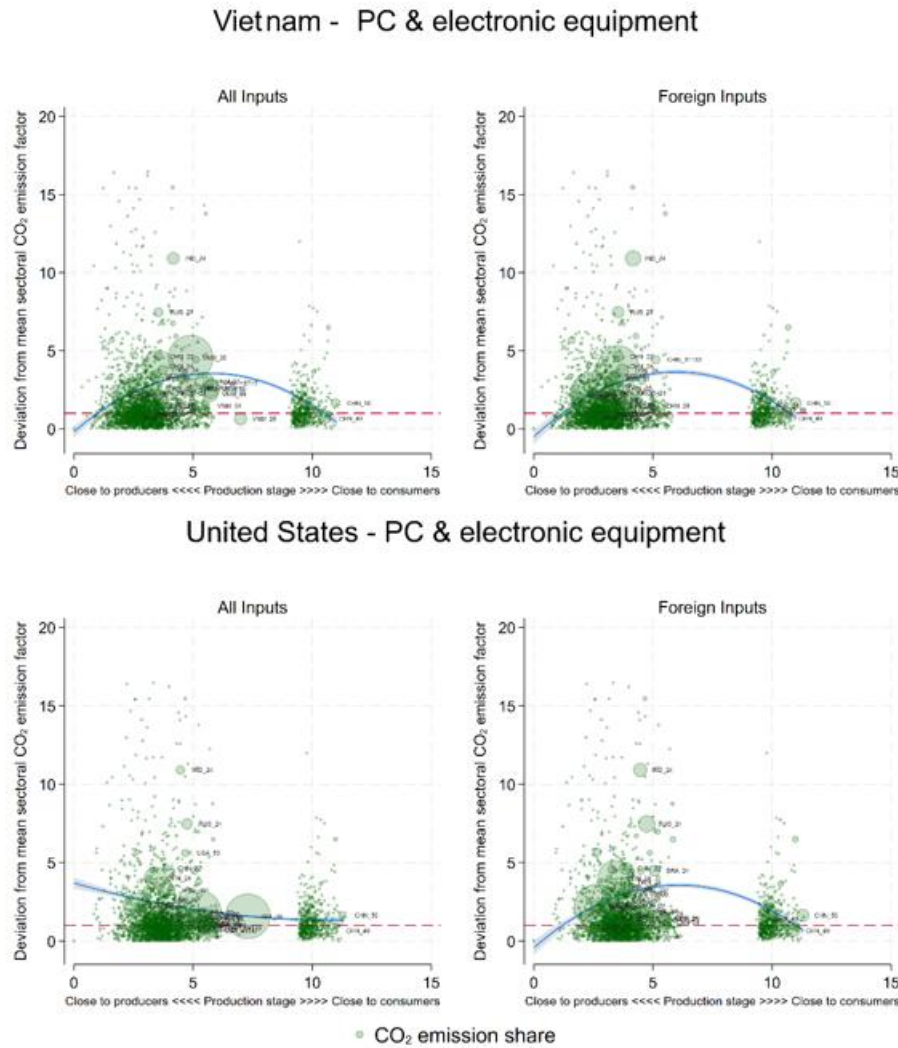
To empirically validate the environmental smile curve hypothesis, we initially focus on two archetypical sectors: Information and Communications Technology (ICT), representing an high-tech, low-emission production, and basic metals, a typical high-emission and low-tech industry. Following the methodological framework outlined in Meng et al. (2020), we trace CO<sub>2</sub> emissions and GVC positioning of all intermediates inputs along GVCs of these sectors, comparing Vietnam<sup>2</sup> (VNM) and the United States (USA), as two representative cases of one developing and one 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-shape or hump-shape (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.

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<sup>2</sup>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.

For Vietnamese ICT exports, the analysis reveals an inverse U-shape 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, specialize in assembly and basic manufacturing activities. These stages, characterized 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-shape 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 cleaner advanced countries.



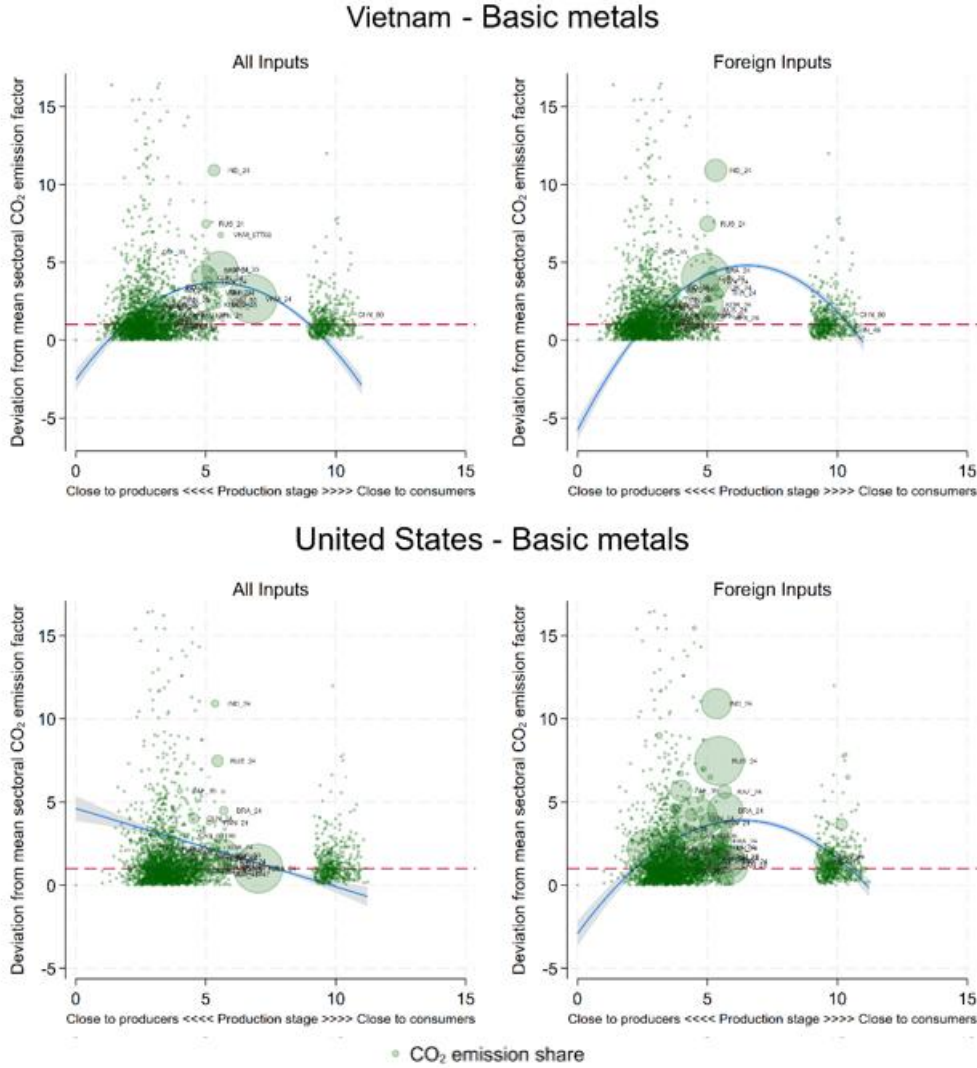
**Figure 5.**(Top) CO<sub>2</sub> embedded in Vietnam's ICT GVCs (2018); (Bottom) CO<sub>2</sub> embedded in USA's ICT. *Note:* Explanations of countries and industry codes are provided in Appendices A and B. *Sources:* Authors' elaborations using ICIO and TECO<sub>2</sub>.

The US pattern in ICT value chain exhibits an opposite shape, a decreasing emissions 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 finalized (industry) impact the shape of the environmental curve as in the value curve hypothesized 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 cleaner 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 externalize 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 (Riccio et al, 2021). For Vietnam, the emissions 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.



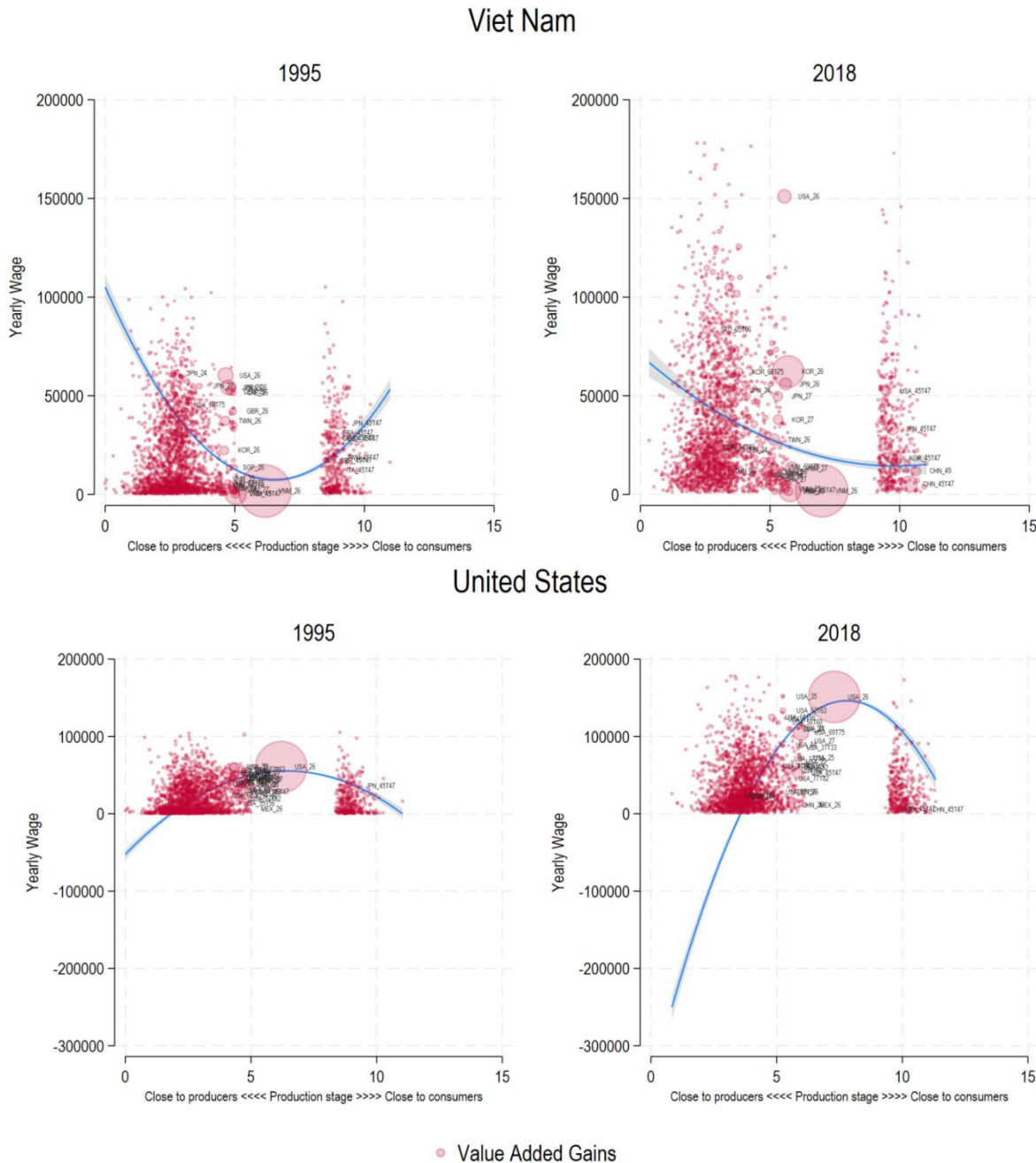
**Figure 6.**(Top) CO<sub>2</sub> embedded in United States' basic metal GVCs (2018); (bottom) CO<sub>2</sub> embedded in Vietnam's basic metal GVCs (2018). *Note:* Explanations of countries and industry codes are provided in Appendices A and B. *Sources:* Authors' elaborations using ICIO and TECO<sub>2</sub>.

The US basic metals chain, however, reveals declining emissions 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 reflects, being an advanced economy with the capacity to mitigate emissions through cleaner production methods and stricter regulations, even in traditionally dirty industries. Since advanced countries are able to appropriate much of the total production process, the final stage accounts for a relevant share of production and the same holds for CO<sub>2</sub> emission share. As a consequence, the results of domestic inputs heavily depend on the US final production, which is low-emission compared to similar productions in other countries (the observation lies below 1), but is also highly emitting for the very nature of the final production in itself, which is inherently highly polluting. Yet, foreign inputs



reintroduce the inverse U-shape, exposing the US's 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 labour.

**Figure 7.**(Top) Value Gains in Vietnam's ICT GVCs (1995 vs 2018); (bottom) Value Gains in 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 .



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 asymmetry between value capture and emission distribution—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" scenarios 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 green 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 Figures 7. The key distinction between Figures 5 and 6 and Figures 7 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<sub>2</sub> emission shares in the environmental curve. When looking at value capture, there is no distinction in terms of "all" versus "foreign" inputs chains, while the only distinction determining the different shapes applies to the level of development of the country: production stages conducted in high-income countries are always more remunerated than requested inputs in developing countries, for each given value chain. At the opposite, in the case of the developing country, the value appropriated in midstream production stages is the lowest, for each given chain.

#### 4.2 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 1 we report the instances where we detect a U-shape vis-à-vis an inverse-U quadratic relationship between positioning, measured via the downstream indicator, and CO<sub>2</sub> emission intensity. Table 1 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 weighting by the input-specific CO<sub>2</sub> share.

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

Where  $CO_{2(i,j,t)}$  denotes the deviation from the mean sectoral CO<sub>2</sub> emissions per unit of output in industry  $j$ , country  $i$ , at time  $t$ ,  $D_{i,j,t}$  represents the positioning metrics defined in Equation (3), while  $\delta_i$  captures country fixed effects to account for supplier-specific characteristics. Industry fixed effects are omitted because the dependent variable is already normalized 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 (2011) U-shape test to assess the statistical significance of the estimated relationship<sup>3</sup>.

First, the *all inputs* analysis reveals stark asymmetries tied to development levels of the production stage of the GVCs. Advanced economies predominantly exhibit U-shape emission curves (74% of the GVCs), where emissions down peak in the final stages of the production process, which are performed by advanced economies largely less polluting. While, as we move away from domestic final stages towards foreign contributions encompassing pre- and post-production activities as well, the weights of developing countries increase and emissions 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 dirty productions. Interestingly, U-shapes are numerous for advanced countries (roughly 75% of the cases), especially in value chains characterised by low technological intensity. On the contrary, in 2018 many medium-high tech, and low-emission, GVCs in the final stage switch to a U-shape resembling the structure of the GVCs finalized in developing countries. There, the contribution of the domestic final stage tends to decrease.

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<sup>3</sup>Lind and Mehlum (2011) 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.

On the other hand, GVCs finalized in developing economies display a majority of inverse U-shapes (hump), with emission peaks in midstream manufacturing. These dynamics underscore the role of developing countries as emissions heaven, with advanced countries supplying them pre- and post- production activities which are relatively less pollutant and thus generating declining parable arms. Here, the time dynamics shows an opposite behaviour with respect to advanced economies, with the instances where the hump-shapes are detected rising significantly from 1995 to 2018 (55% vs 76%), especially in medium and high tech GVCs. Jointed, these disparities underscore how GVCs structurally concentrate pollution-intensive stages in the Global South, while enabling advanced economies to externalize emissions.

Second, the dichotomy between all inputs and foreign inputs only unveils the role of GVCs' structure on their emission profile. When isolating foreign intermediaries, disparities across development and developing countries disappear and inverse U-shapes dominate across both 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, irrespectively 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 stages that are disproportionally 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 cleaner, high-value activities domestically. In advanced countries' value chains, considering all inputs, this tendency can be spotted looking at the rise of an inverted U shape from 1995 to 2018, which makes advanced countries' chains worryingly more similar in distributing CO<sub>2</sub> to developing countries.

In the foreign inputs' cases, the temporal dynamics between advanced and developing countries became similar as well, with an impressive increase in the instances where the hump-shapes are found 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 rise in the recent years of the incidence of these curves highlights that these patterns are consequences of the emergence of GVCs and where not built in at the beginning of the so-called second unbundling in the nineties, the beginning of the production fragmentation period.

Finally, GVCs heterogeneity further underscores the role of technological capabilities under three dimensions. First, at the same time and for the same industry there co-exist several production techniques and generally developing countries master the ones relatively more pollutant than the average. This pattern resembles the large evidence in the emergence of widespread heterogeneities in the techniques of production even at finer level of disaggregation, and the ensuing differences in terms of efficiency (Dosi, 2023). In sectors where the distribution is particularly wide and asymmetric (e.g. Coke and refined petroleum products) this feature might even generate perverse results, as a single country-industry pair might be responsible for an extremely high average and then influencing the other CO<sub>2</sub> intensities. Second, chains requiring higher amounts of 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 to their own industries less pollutant inputs. However, sector specificities emerge only analysing the entire GVCs, where domestic contributions cover the great majority of the intermediaries required in the production process. Looking at the entire value chain allows to disentangle the role of the 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.

GVCs	Year	Advanced Countries				Developing Countries			
		All Inputs		Foreign		All Inputs		Foreign	
		U		Hump		Hump		Hump	
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%

**Table 1.** Incidence of U or Hump shape curves by GVCs' sector of final production in 2018 and 1995. The analysis is performed evaluating all inputs along the chains (left) as well as only foreign inputs (right). U-test following Lind and Mehlhum (2011) are reported. *Note:* Explanations of countries codes are provided in Appendices. *Sources:* Authors' elaborations based on ICIO and TECO<sub>2</sub>.

## 5. Conclusions

Proponents of green growth argue that technological advancements—particularly in renewable energy and resource efficiency—will decouple economic activity from emissions (Freire-Gonzalez et al., 2024). Yet, this optimism overlooks how GVCs mediate the diffusion of green technologies (Lema et al., 2021). For example, while advanced economies invest heavily in R&D for clean energy and circular production models, developing nations often remain locked into supplying carbon-intensive intermediate products, such as steel for wind turbines or lithium for batteries (UNCTAD, 2023). The result is a paradoxical "green divide": the very technologies meant to mitigate climate change reinforce existing inequalities in the global division of labour. Further, the emergence

of geostrategic tensions adds another layer of complexity. As countries vie for dominance in green industries—from solar panels to electric vehicles—they are erecting trade barriers and subsidizing domestic production (Edler et al., 2023). This fragmentation risks creating parallel GVCs, where developing economies are even more excluded from high-value segments and relegated to polluting, commoditized roles (Gereffi et al., 2021). The case of rare earth minerals is illustrative: China's near-monopoly on processing has allowed it to capture value while outsourcing the environmental costs of extraction to Africa and Southeast Asia (Pietrobelli et al., 2024). Such fragmentation undermines the potential for systemic decarbonisation, as lead firms prioritize cost competitiveness over ecological upgrading.

Against the possibility of the decarbonisation transition resulting into a further lock-in process for developing countries, this paper reveals that the environmental consequences of global production follow a neat, distinct and troubling pattern when viewed through the lens of the smile curve framework. While traditional smile curves demonstrate how value concentrates at the upstream and downstream ends of global value chains, our environmental adaptation shows precisely the opposite dynamic—emissions peak in the middle segments of production, where developing economies specialize. This inverted U-shape distribution of pollution intensity stands in contrast to the U-shape distribution of value capture, creating a double asymmetry where poorer nations bear both economic and environmental disadvantages.

The sectoral heterogeneity in emissions profiles plays a crucial role in shaping these outcomes. Energy-intensive manufacturing and extractive industries, which dominate the export profiles of many developing countries, exhibit emission intensities an order of magnitude higher than knowledge-intensive sectors. This specialisation is not accidental but stems from deeper structural factors, including technological disparities, capital constraints, and the governance structures of global production networks. The pollution haven hypothesis finds strong support in these patterns, as emission-intensive production systematically shifts to jurisdictions with weaker environmental regulations and enforcement capacity.

In addition, these findings contribute to the literature on ecologically unequal production and exchange by demonstrating how environmental costs follow the same structural logic as economic value extraction in global capitalism. Advanced economies maintain cleaner domestic production profiles not solely through technological superiority, but also by strategically externalising pollution-intensive processes to supplier nations, through their governance of global value chains. The resulting spatial separation between value capture and emission generation creates fundamental challenges for both climate mitigation and equitable development.

The policy implications are multifold and must be considered against the backdrop of two transformative forces reshaping global production: the green transition and growing geopolitical reconfigurations. Current approaches that focus narrowly on national emission inventories or sectoral efficiency gains fail to address these structural imbalances in global production. Effective solutions must recognise the embedded power asymmetries in global value chains while navigating the new realities of strategic decoupling and supply chain reconfiguration. This requires moving beyond technical solutions to confront the political economy of global production, including intellectual property regimes that restrict clean technology transfer, trade agreements that prioritise corporate flexibility over environmental standards, and financial systems that reinforce extractive specialisation in the Global South.

The green transition adds both complexity and urgency to these challenges. While it presents opportunities for technological leapfrogging in developing economies, current trajectories risk reinforcing existing asymmetries as advanced economies dominate clean technology sectors. Meanwhile, geopolitical tensions are driving strategic reconfiguration of production networks, with nations reshoring critical industries and forming new trade blocs - developments that could either exacerbate or alleviate environmental inequalities depending on how they are managed.

Ultimately, the environmental smile curve reveals how the current organisation of global production systematically disadvantages developing economies twice over - by relegating them to low-value activities while burdening them with disproportionate environmental costs. Addressing this dual asymmetry will require nothing less than a fundamental rethinking of how value and environmental responsibility are distributed in the global economy, one

that accounts for both the imperatives of decarbonisation and the realities of a fragmenting geopolitical landscape. Without such transformation, efforts to decarbonize industry will remain partial and unjust, reproducing the very inequalities that have brought us to the current climate impasse. The path forward must recognize that environmental justice and economic justice in global production are inextricably linked - neither can be achieved without addressing the structural power imbalances that shape both.

Limitations of our analyses directly connect with the future research paths that ultimately call for fine-grained studies on the control of value chains and the inherent choices of relocating both high-carbon intensive and low-value added production stages in low income countries. In particular, actual analyses on the quantification and diffusion of technologies along GVCs, their link with the power exercised by headquarter firms and the possibility to fragment production processes, the strategic decisions to relocate to low-income countries dirty productions, are lacking. The Global North, our work has shown, has progressively accumulated an environmental debt with the Global South. To stop such an accumulation, the South should be allowed to develop local in-house capabilities to look for solutions and technological autonomy able generate both internal gains and environmental sustainability. Studies should go in the direction of understanding which are the sources that might allow the Global South to gain technological autonomy. In addition, while our units of observations are countries, value chains are structured at sub-national levels, and the geography of articulation of such chains impacts upon the local development paths. In order to single out the role of local capabilities, sub-national analyses are needed (Pietrobelli & Rabellotti, 2011; Capello & Dellisanti, 2024).

After thirty years since the globalisation second unbundling and the growing evidence on the failure of hyper-globalisation, a new protectionist, military, anti-free trade stance is emerging with an unprecedented speed. Which will be the future of new production processes and whether regional development will finally take the place of global development remains an open question. Regionalisation would also entail lower emission contents in traded inputs, and China is progressively consolidating this strategy. Strategically, the need to secure critical inputs is pushing for the reduction of the length of the chains, together with opening new relationships based on higher trust with partners. Possibly, the era of low-road strategies of multinational enterprises, solely intended to secure value-capturing, squeezing developing countries, might come to an end, with the progressive regionalisation of production and exchange, particularly in far-east Asia.

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## Appendix

### A. Country Development Levels

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

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

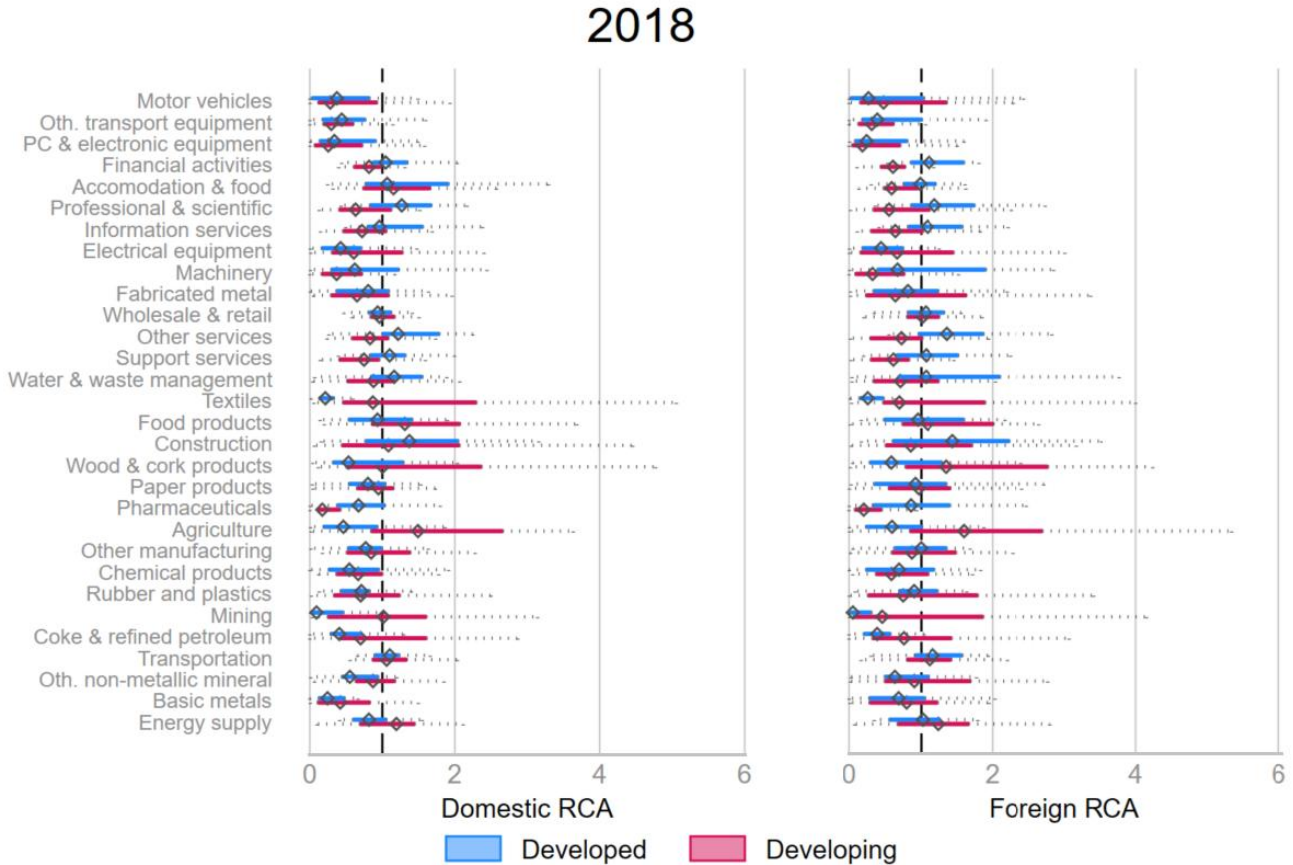
## Sector Aggregations

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

**Table A2.** Sectoral aggregation. *Source: Own Elaboration.*

## B. Specialisation Patterns

The analysis of revealed comparative advantage (RCA) confirms that advanced economies specialize 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.



**Figure 4:** RCA Distribution by Sector and Origin

RCA distributions 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.