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Scuola Superiore Sant'Anna

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Institute of Economics
Scuola Superiore Sant'Anna

Piazza Martiri della Libertà, 33 - 56127 Pisa, Italy
ph. +39 050 88.33.43
institute.economics@sssup.it

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Decarbonisation and Specialisation Downgrading: the double harm of GVC Integration

Giovanni Dosi [1]
Federico Riccio [1]
Maria Enrica Virgillito [1]

[1] Institute of Economics, Scuola Superiore Sant'Anna, Pisa,

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Decarbonisation and Specialisation Downgrading: the double harm of GVC Integration*

Giovanni Dosi[1]
Federico Riccio[1]
Maria Enrica Virgillito[1]

[1]Scuola Superiore Sant'Anna***

Abstract. This work assesses the double harm of Global Value Chain (GVC) integration. Firstly, we take a within-country structural change perspective and investigate how the internal structure of country production, and thus the ensuing emission profile, evolves across development phases. Assessing the structural change-emissions nexus is necessary to understand how to reconcile growth and sustainable development. Secondly, we look at the cross-country dimension, embracing how the changing geography of production affects the environment. We find evidence that the relocation of production toward developing countries via GVCs has negatively impacted worldwide emissions and document that GVCs are progressively becoming a carrier of industrial and ecological downgrading for developing countries.

Keywords: Structural Change · CO_2 Emissions · Global Value Chains

*** Institute of Economics and EMbeDS Department, Scuola Superiore Sant'Anna, Piazza Martiri della Liberta' 33, Pisa (Italy).
Corresponding author: `federico.riccio<at>santannapisa.it`

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1 Introduction

The relationship between capitalism and nature has historically been characterized by a unilateral pattern of dominance of the former over the latter. CO_2 emissions have in fact closely followed the non-linear accumulation path of physical production. Since the onset of the first industrial revolution, when the steam engine was invented, the exponential rise in GDP per capita has been coupled by a trajectory of similarly growing CO_2 emissions, at a pace and level that was unprecedented (Stern, 2013). However, technology use and input combination are not only a driver of industrial production but also of mechanization and automation. In that, they allow to produce more output more efficiently. Efficiency, or lack of it, in the production process, may result in CO_2 intensity reduction or, vice-versa, CO_2 intensity increase. Although flows of emissions have been non-linearly growing at the global scale, the amount of emissions largely differs across countries in terms of intensity (i.e., emissions per unit of production), as the emerging result of the technological level and the combination of inputs used, when looking at similar industries in the production of quality-comparable output. In this respect, the first major divide is between developed and developing countries as emitters per unit of output. Greater differences exist however across industries, comparing different types of production processes and the energy mix they entail. In this respect, the dimension that counts is the country-industry specialisation.

Country heterogeneity in the overall level of development and country-industry specialisation are two dimensions that have been classically studied by economic development, structuralist-evolutionary theories, and ultimately by dependency theory. However, the latter streams of literature have been relatively less oriented, beyond the analysis of the quality of specialisation (Dosi, Riccio, and Virgillito, 2022) and its distribution across productive units, towards the study and characterization of the productive structure by CO_2 emissions, as a further dimension to consider when addressing the patterns of country growth and specialisation. In fact, while usually emission levels are considered the results of final consumption activity, the most relevant contribution to overall emission levels stands in inter-industry production processes. In that, decarbonization paths are hard to be undertaken if not coupled with industry specialisation upgrading.

Inter-industry production processes, since the sixties, have been enormously transformed by the international flows of intermediate parts and components, but also by the flows of energy. In that, the rise in Global Value Chains (GVCs), and the consequent fragmentation of the production process across sectors and countries, has scaled up and increased the complexity of the overall emission chain, because of (i) transportation costs, and (ii) its ensuing articulation along the production process, in that making the tracking process even more difficult (Meng et al., 2018; Daudin et al., 2011). While GVCs have been acknowledged by the literature and international institutions as an opportunity of upgrading for development countries (Dimova, 2019), they have been less considered as a source of amplification of patterns of CO_2 emissions and therefore of ecological downgrading. In fact, if participation in GVCs for developing countries implies specialisation patterns in low-end value added phases, as largely acknowledge by the smile curve literature (Timmer, Erumban, Los, Stehrer, and De Vries, 2014; Meng, Ye, and Wei, 2020; Riccio, Dosi, and Virgillito, 2023), the very participation in GVCs is likely to redistribute the burden of emission exposure to less developed countries. In fact, GVCs are not only a mechanism of value added transmission, but also of CO_2 transmission.

Not by chance, similarly to the literature questioning the benefits of GVCs participation, a growing literature on Ecological Unequal Exchange (EUE) acknowledges the uneven distribution of environmental responsibilities among nations (Magacho et al., 2023; Althouse et al., 2023; Dorninger et al., 2020). Such a stream of literature recognises the existence of a hierarchically structured global system of production and exchange that engenders a vicious cycle, wherein peripheral countries specialise in resource-extractive and labour-intensive productions, marked by declining prices, while core countries in technologically intensive and more profitable goods. Inspired in essence by a Prebisch-Singer "ecological" hypothesis and the curse of natural resources, EUE underscores that the liberalization of trade and capital flows exacerbates and sustains such material inequalities, favouring the transference of CO_2 emissions through international trade, thus amplifying the environmental impact of globalization.

In parallel, taking an accounting-based perspective but corroborating such a hypothesis, Peters et al. (2011) evaluate that in 2007 one-quarter of global carbon emissions were generated through trade and that the net transfer of emissions (production minus consumption) via international trade from developing to advanced countries has increased fourfold from 0.4 Gt CO_2 in 1990 to 1.6 Gt CO_2 in 2008. The recent literature has inquired about these international dynamics by looking at trade patterns, not only in final goods but also in intermediate inputs (Peters, 2008; Manfred Lenzen and Munksgaard, 2004). Looking at GVCs progressively proves to be of pivotal importance to undertake a decarbonization path because GVC participation is ultimately among the main drivers of structural change modulating country-specific specialisation patterns (Coveri and Zanfei, 2023; Pahl and Timmer, 2019).

Given the extant literature, and embracing a hierarchical view in the responsibility of global emissions, in the following we address two set of questions. Firstly, we take a within-country structural change perspective and we investigate how the internal structure of country production, and thus the ensuing emission profile, evolves across development phases. Within-country structural transformations, triggered by technological progress and industry upgrading are necessary conditions for sustaining economic growth (Dosi et al., 2022). Assessing the structural change-emissions nexus is necessary to understand how to reconcile growth and sustainable development. Secondly, we look at the cross-country dimension, embracing how the changing geography of production affects the environment. Generally speaking, advanced countries are endowed with less pollutant production techniques and have enforced relatively more effective environmental laws, therefore, the relocation of production toward developing countries via GVCs might negatively impact worldwide emissions, a tendency labelled as the *Pollution Heaven Hypothesis*, PHH from hereafter (Cole, 2004).

To address our research questions we look at the evolution of the world production network and the CO_2 emissions intensity in the period 1995-2018, using OECD Input-Output tables. By accounting for the different components of the production process, we distinguish domestic and foreign inputs we characterize the sectoral origin of the inputs used in the production process and their development level (i.e., of the countries producing the inputs) and we undertake a shift-and-share structural decomposition analysis. According to our results, emission intensity presents a downward convergent trend across all industries however offset by a rising trend in the final demand. Second, the progressive participation of developing countries in GVCs, and the reshuffle of production embedding their participation, has a negative impact in terms of GVC emissions, due to the inclusion of higher-emission techniques of production. Third, we identify a few industries responsible for most of the emissions produced namely, the energy sector, scale-intensive industries, such as plastic and metals production, and transportation services, especially maritime transport, exactly the same industries in which developing countries are currently specialising more intensively. Our evidence brings therefore support to a PHP hypothesis because of i) unequal productive exchanges relocating high-intensive emission activities in developing countries, and ii) ensuing patterns of specialisation downgrading of the latter. We, therefore, find i) evidence of a bad specialisation/high-emission trap in which developing countries are progressively entered, but also ii) the need to embrace industrial and environmental policies in a coupled direction. In that, decarbonization paths will be hardly achievable without a full reconsideration of what and how countries produce and participate in international production.

In the following, we start by reviewing the literature we build upon (Section 2), while in Section 3 we present the data and I-O methodology applied. Section 4 proposes descriptive statistics on CO_2 emission intensity along GVCs, highlighting industry and country-specific dynamics, while Section 5 proposes a shift-share analysis able to disentangle the role of technology, demand and the changing geography of production. Section 6 discusses the results and concludes.

2 CO_2 emissions and income growth

Since carbon dioxide emissions are generated mainly through the production process, economic growth (i.e., the increase in output) has a strong positive effect on greenhouse gases, and in particular on CO_2 emissions. The environmental Kuznets curve (EKC) has been one of the most widespread approaches adopted to investigate aggregate pollution emissions and GDP per capita growth. Similarly to the Kuznets curve, its environmental version predicts that the early phases of a country's development are accompanied by a rise in per-capita polluting emissions. However, after a certain development level, the trend reverses generating an inverse U-shape function between emissions intensity and GDP per capita (Carson, 2010; Grossman and Krueger, 1991). The EKC is essentially an aggregate empirical phenomenon, that holds at the global level but country-specific estimates are not statistically robust due to the high heterogeneity in their productive structure and emission profiles (Churchill et al., 2018). Such mixed results are confirmed by the recent review by Stern (2017). Essentially, the turning point in the emission intensity for advanced countries is more influenced by the idiosyncratic internal composition of production and trade flows, rather than being a natural tendency (Marin and Mazzanti, 2021; Lazaric et al., 2020). The reduction in emission intensity after a given level of country development can be due to i) the emergence of new, and less pollutant industries (i.e., diversification in the productive structure), ii) the decarbonization of old mature industries via technological upgrading, iii) the substitution of domestic pollutant productions with foreign ones, through import of final and intermediate goods.

A related strand of the literature looks at whether per-capita emissions are converging over time and across countries and industries (Payne, 2020; Pettersson et al., 2014). If countries experience convergence in GDP per capita, emissions per capita should converge as well, assuming a monotonic relationship between the two variables, at least conditionally. Several contributions focusing both on advanced and developing countries have found that since the 1970s, emission intensity has shown unconditional convergence trends, at an unprecedented rate (Stern, 2013). However, more recent studies find contrasting results. Voigt et al. (2014) found a robust correlation between the initial level of emission intensity and emission reduction, particularly evident in Eastern European countries and China. Li and Lin (2013) investigate both absolute and conditional convergence in per-capita CO_2 emissions in a large panel of data covering 110 countries at different development levels, finding however absolute divergence among the full set of countries. Within each income classification, there is evidence of convergent patterns in per capita CO_2 emissions.

The lack of global convergence in CO_2 emission intensity points to enduring imbalances in technological capabilities and persistent structural differences among countries. In fact, a policy target meant at simply reducing the gap across countries could not be enough to reach the decarbonization target, as, even assuming convergence in emission intensity, developing countries' average CO_2 levels increase relatively rapidly, whereas developed countries' ones decrease at a slower pace (Borowiec and Papież, 2024).

2.1 Structural Change and CO_2 Emissions

Although the country-growth perspective is important, average emission intensity is the result of the sectoral composition of the industrial structure. Notably, IEA (2023) has clearly highlighted that emission variability by industry is higher than emission variability by country. Hence, decarbonization might be the result of a structural change process where low-emission industries grow and high-emission industries decline due to technological change, international trade and changing preferences (Semieniuk et al., 2021, Godin et al. 2023).

The structural change-emission nexus implies the study of the stage and quality of economic development and its impact on the emission profile of a country. Country growth profiles are intimately linked to the evolution of the economic structure (Dosi et al., 2022; Diao et al., 2017; Hirschman, 1958). The early phase of the economic development process is characterized by the majority of the workforce employed in the primary sectors (i.e., agricultural and raw materials industries); as time goes by and countries accumulate the required technological and organizational capabilities, the productive structure progressively shifts towards elementary manufacturing activities. Since manufacturing industries ensure higher labour productivity and the setting up of economies of scale, as the workforce moves toward the manufacturing sector, the economy-wide productivity increases, ameliorating the growth pattern of the country (Rodrik, 2016; Chenery and Taylor, 1968; Fisher, 1939). At the same time, manufacturing activities show higher levels of innovation compared to non-manufacturing counterparts and thus, the industrial sector is widely considered the engine of economic growth (Szirmai, 2012). While playing a pivotal role in economic development, manufacturing is both directly and indirectly accountable for a significant portion of overall environmental pressure, accounting for one-fifth of overall carbon emissions, and more than 50% of energy usage. In this respect, the study of the country's specialisation patterns and the link with CO_2 emission is of primary importance.

A potential structural driver favouring the reduction in CO_2 intensity and overall emissions is the shift of employment and production towards the service sector, and the consequent dematerialisation of production. Commonly, it is assumed that such an economic shift would result in lower energy intensity and, consequently, a decline in emission intensity per unit of output. However, Henriques and Kander (2010), recalling the well-known Baumol's disease, challenges this optimistic perspective, asserting that the simple transition to a service economy may be somewhat illusory as a source of decarbonization. The primary drivers behind the reduction in emission intensity in developed countries have been the productivity gains in the manufacturing sector making more efficient the production activity, rather than the shift to a service-based economy. Similarly, Savona and Ciarli (2019) highlights tertiarization has not proven adequate in generating sustainable development patterns.

2.2 The Role of Trade and GVCs: the Pollution Heaven Hypothesis

A prominent factor influencing both growth and emission patterns is international trade. Trade increases consumer opportunities but also eases imitation and transfer of technologies favouring technical progress (Rodrik, 2018). In that, the trade-growth nexus is a well-known area of study. Less clear is the trade-emission relationship. Trade is in fact a driver of specialisation, which in turn determines countries' emission profiles. The trade-induced specialisation link might however result in a trap into bad specialisation, among the primary causes of the emergence of the middle-income trap (Dosi et al., 2022; Szirmai and Foster-McGregor, 2017). Arto et al. (2016, 2014) put forward the idea that bad specialisation has locked-in developing countries into the production of relatively more pollutant goods, impeding their transition to less energy-intensive production processes. Such an environmental-augmented Prebish hypothesis, termed as the '*environmental Prebisch deterioration*' (Rincón, 2006; Prebisch, 1950), assesses development not simply from a productive perspective but also in terms of an environmental upgrading process, from high-emission to low-emission intensive industries. If trade-induced specialisation favours the entry into a noxious industrialization trap (Bez and Virgillito, 2022), this will induce a joint environmental and economic risk for developing countries, due to the likely negative feedback dynamics between productive structure and emissions profile transformations.

The shift of production toward emerging markets triggered by globalization has increased the emissions embodied in imports from developing to advanced countries (Marin and Mazzanti, 2021; Xu and Dietzenbacher, 2014). Peters et al. (2011) find that net emissions embodied in exports from developing to developed countries increased fourfold between 2000 and 2008. Specifically, Jaunky (2011) highlights that advanced countries are changing their productive structure through trade and GVCs but not their consumption structure; hence, declining emissions per-capita in advanced economies might be due to relocation of dirty industries in developing countries, rather than to a worldwide reduction in emission intensities. In that, emissions can be shifted via international trade, a phenomenon known as carbon leakage.

Such tendencies have been labelled the "Pollution Heaven Hypothesis": trade liberalization and foreign direct investments have led developing countries to become pollution havens for the "dirty industries" of developed countries. This theory also suggests that advanced countries can comply with national environmental laws by relocating their pollution-intensive industries to developing nations (Cole, 2004). Consequently, developed countries will tend to specialise in incrementally less polluting goods, while developing countries in pollution-intensive goods.

If at the opposite we consider the prediction of a neo-classical trade model based on factor endowments (Helpman, 1984), capital-intensive firms (North) would invest in labour-abundant countries (South), while the opposite labour-intensive firms would do. Since the capital-intensive sector is typically associated with pollution-intensive activities, and capital-abundant countries often have more stringent environmental regulations, the Capital-Labour Hypothesis (KLH) predicts an increase in emission intensity in developed countries, a pattern clearly against the empirical evidence.

2.3 Fragmentation of Production and CO_2 Emissions

Since the 1990s, trade has moved from the exchange of final products to the exchange of intermediary inputs (Baldwin, 2011). The rise in GVC trade has accelerated the reconfiguration of the geography of production, affecting where and how the production process takes place, and in that making the tracking of emissions a complex endeavour. The literature has proposed a "consumption-based accounting", adjusting the standard territorial-based emission accounting by adding the emissions associated with exports and the ones connected to imports (Peters and Hertwich, 2008, 2006). In these endeavours, multi-regional input-output (MRIO) models are tools for tracking emissions in trade, and thus understanding the shared responsibility between producers and consumers (Meng et al., 2018; Peters, 2008).

GVCs offer opportunities for developing countries to enter more advanced production stages, specialising in elementary tasks and then upgrade towards more complex ones. However, an increasing amount of evidence is showing that GVCs, if not approached strategically, might pose risks to countries' development prospects. Indeed, the so-called *smile curve* literature highlights the existence of power relations in GVCs, which accelerate the specialisation process already taking place in international markets. Advanced countries take advantage of their more advanced technologies, keeping domestically the most "remunerative" part of the production process, such as R&D and Managerial activities, and outsourcing the least remunerative tasks, characterized by lower value-added contents, as fabrication (Riccio et al., 2023; Meng et al., 2020; Mudambi, 2008). Among the main causes of such downgrading paths enhanced by GVCs are the cost-reduction strategies that motivate offshoring decisions of advanced countries (Grodzicki and Skrzypek, 2020). Hence, the emergence of the risk of social downgrading within GVCs (Barrientos et al., 2011; Farole, 2016; Dosi et al., 2022) adds up to the potential productive downgrading hazard.

From an ecological perspective, the Ecological Unequal Exchange hypothesis defines GVCs as hierarchically structured entities that perpetuate the core-periphery dualism of the production activity, contributing to global environmental degradation and asymmetric development opportunities (Smichowski et al., 2021). Althouse et al. (2023) distinguish among various trajectories within GVCs, showing that developing countries often achieve, at best, an "ecologically perverse upgrading", characterized by productivity enhancements along GVCs coupled with deteriorating external environmental balances due to excessive exploitation of domestic natural resources. Conversely, most developing economies are stuck in the middle-income trap and experience "GVC marginalization", wherein substantial domestic ecological degradation fails to yield socioeconomic benefits. These experiences, typical of emerging economies, sharply contrast with the dynamics observed in high-income countries, where the "reproduction of the core", driven by their dominant position within the chain, ensures consistent socio-economic advantages and limited domestic ecological burdens.

Li et al. (2021) find that the international restructuring of production has an overall detrimental factor for the environment since the 1990s. Zhang and Peng (2016) show that approximately 20% of China's production-based emissions during 1995–2009 were induced by the production of goods and services satisfying final demand in developed economies. Participation degree in GVCs displays an inverted U-shaped relationship with per capita CO_2 emissions (Wang et al., 2019). These non-linear trends coupled with the evidence proposed by Espinosa-Gracia et al. (2023) highlight that more upstream positions are related to lower emissions per capita. This implies that specialising in activities closely linked to final demand, such as financial or high-technology services, can lead to emission reductions. Overall, developed nations, exhibit higher consumption-based emissions compared to territorial-based emissions. This indicates that they are net importers of emissions, deriving benefits from environmentally intensive production activities conducted abroad, while the opposite holds for developing nations (Meng et al., 2018). These joint dynamics unfolding through GVCs, matched with the trends discussed in the PPH literature, highlight the potential negative environmental and economic consequences related to GVC participation: there exists the risk of remaining stuck in a specialisation trap (productive downgrading), with lower potential for productive improvements (productive downgrading), wage improvements (social downgrading), increasing the environmental burden connected to the low-end activities conducted. (environmental downgrading).

3 Accounting Framework and Methodology

In the following, we employ the OECD Inter-Country Input Output (ICIO) tables covering 66 countries plus the rest of the world entity and 45 sectors in the period 1995-2018. We match these data with industry-level CO_2 intensity information provided by the OECD using the International Energy Association (IEA) and perfectly associated with the ICIO dataset. Input-output tables are essentially inter-industry, cross-country transactions organized in a square matrix; each column represents a vertically integrated subsystem and the entries are the contributions required by all country-industry pairs in the production process of that specific good (Pasinetti, 1977).

Applying the Leontief (1936) transformation, we can track not only the direct inputs required in the production process (first round of production) but also the intermediates required in the previous rounds of production (i.e., the intermediary goods to produce the inputs then used in the production process). After normalizing the matrix by the total gross output of the industry, we obtain the technical coefficient matrix which represents the amount and source of intermediate inputs needed in the production of one unit of gross output: the output multipliers. In addition, pre-multiplying the matrix of technical coefficients by a diagonalised vector of country-industry specific CO_2 emission intensity, we can compute the CO_2 emission multipliers, which account for the CO_2 emissions generated in the production process for one dollar of final demand.

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

Where A is the matrix of intersectoral linkages and $(I - A)^{-1}$ is the global Leontief inverse. $\widehat{EF}$ is the diagonalised vector of industry-country-specific emission factors and CC is the matrix of CO_2 multipliers. The rows in the CC matrix represent the country-industry origins of emissions; while columns represent vertically integrated subsystems, which are the country-industry pairs where final production takes place. Additionally, if interested in CO_2 level, it is possible to multiply the matrix CC by the vector of final demand fd.

Following the GVCs literature, we can trace emissions in a particular GVC (or subsystem) from downstream to upstream (Koopman et al., 2014). The production of a specific good, say a German car, may generate emissions in all upstream countries and sectors directly and indirectly involved in the production process, for instance, the import of wheels from China and engines from Japan which may use metal from Korea. Thus, summing up all elements of a column we account for the emissions generated worldwide in the production of inputs required by each chain:

$$C = \mathbb{1}CC \tag{2}$$

Where C is the vector accounting for all the CO_2 emissions generated along the backward linkages of each GVC and $\mathbb{1}$ is a row vector where each coordinate takes the value 1, which functions as a column-wise sum operator. Drawing upon Meng et al. (2018), we can classify intermediates flows in two roots:
ROUTE 1: Emissions generated from downstream to upstream in domestic segments of GVCs;
ROUTE 2: Emissions generated from downstream to upstream in foreign segments of GVCs.
Similarly, we can further classify these inputs based on their developmental (i.e., advanced vs developing countries) and industry origin.

In the following, we investigate the CO_2 emissions generated in world production looking at what is happening along backward linkages. Essentially, this means considering the entire global production as a single productive subsystem or GVC. This allows us to examine in detail the characteristics of the backward linkages employed worldwide. To aggregate information across columns of matrix CC, we weigh each entry by its corresponding total final demand provided by OECD, in so doing we maintain the accounting identity characteristic of Leontief's approach. Table A2 in appendix A presents the country's geographic and developmental attributes while table A3 the sectoral classification employed.

4 Descriptive Statistics

4.1 The rise in CO_2 emissions: the role of GVCs

Figure 1 introduces CO_2 emissions within the global production network by looking at the emissions embedded in the final productions of different regions (left axis). Note that in the final demand-based accounting framework not all emissions are generated within the geographic boundaries of that region; rather, they may come from foreign intermediate inputs situated elsewhere in the world. Further, figure 1 presents the evolution of CO_2 emissions at the world level and in two broad groups of countries based on their development stage.

Starting with the highest-polluting area, the Asian-Pacific region displays the highest level of CO_2 emissions embedded in final demand but also the most impressive rise, more than doubling the emissions in the period under examination. Similar rises are displayed by the other three developing regions (Latina America, Sub-Saharan Africa, and North Africa). Contrarily, North America and Europe, the second and third most emitting regions, maintained almost constant CO_2 emissions levels over twenty-seven years. However, if we consider emissions per capita, North America would emerge as the first emitting region followed by Europe. Looking at the broad aggregates (right axis), we see that the worldwide rise in CO_2 emission is driven by developing countries while advanced countries experience only a mild uptick during the period[1]. In 2008 emissions from developing countries crossed the hose of advanced ones. To identify shifts in the emission activity over time, we employ a Bai and Perron (1998) structural break identification procedure. In line with the findings in Espinosa-Gracia et al. (2023), we find a first structural break in 2002, while a second one in 2011, instead of 2008 as in the previous literature. The discrepancy in the second break identification is due to the different methodologies used to define the break identification since we imposed a minimum length for each segment of 7 years. The first phase (1995-2002) records an initial mild rise in CO_2 emissions,

[1] Appendix A reports countries' classifications

while the subsequent period (2002-2011) is characterised by a non-linear growing trend in pollution turning into an impressive rise in emissions. We recall that 2001 was the year of entry of China in the WTO. Notably, in this period the 2008 financial crisis occurred, accompanied by the so-called trade collapse, which temporarily curtailed CO_2 emissions, due to a reduction in final demand levels. However, CO_2 emissions were back to the pre-crisis trend in less than 2 years. Finally, the 2011-2018 period is characterised by smoother increases in overall carbon footprint; correspondingly, the same period is marked by a slowdown in intermediate trade (Timmer et al., 2021).

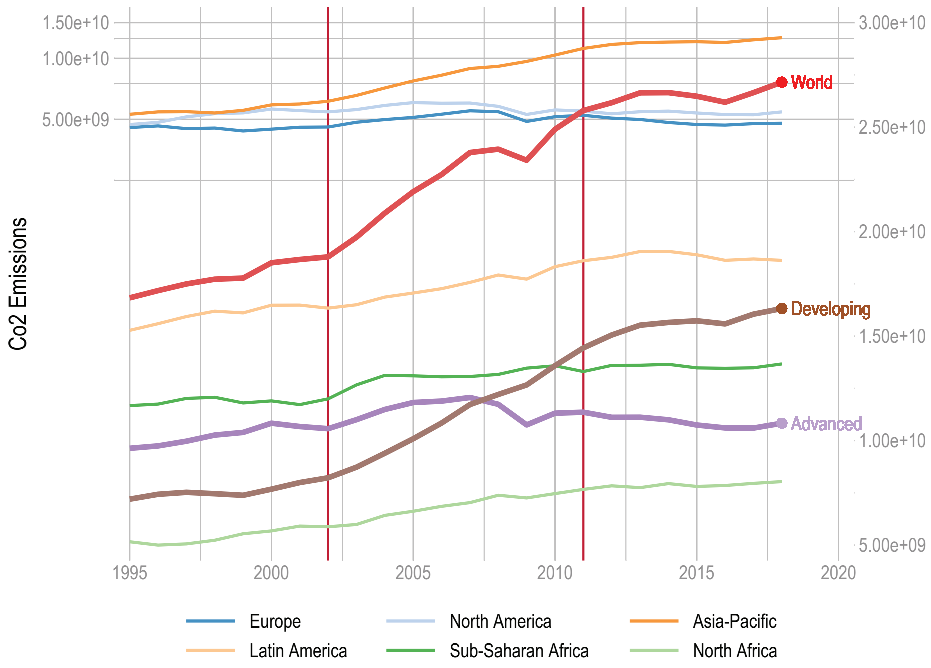

Fig. 1. Time evolution of CO_2 emissions embedded in final demand. The world production network is divided into 6 macro-regions (left axis) and 2 aggregates based on the country's development level plus the whole world (right axis). Table A2 presents country regional classification.

Employing the distinction between domestic and foreign stages, figure 2 investigates the sectoral and developmental origin of CO_2 emissions. Worldwide emissions are divided between those generated domestically, on the left panel, and those connected to international trade of intermediates, the middle panel. The right panel shows the ratio between foreign toward domestic emissions during the period of investigation. Emissions are classified into eight broad sectors making use of the Pavitt classification[2] and distinguished by their origin, between developed and developing origin countries. While not surprisingly the domestic component is much higher than the foreign component in total emission levels, what is notable is the absolute and relative growth dynamics in both aggregates. In terms of absolute growth in the period under scrutiny, domestic emissions grew by 43% while foreign ones by 135%. The share of CO_2 embodied in foreign inputs has grown from 18% in 1995 to 29% in 2018; as a consequence, the

[2] Appendix A presents the sectoral classification employed.

foreign-to-domestic CO_2 emission ratio has moved from 0.2 to 0.4 on average, and doubled in developing countries, from 0.32 in 1995 to 0.58 in 2018 (right panel). Second, a significant concentration in sectoral emissions emerges, with three macro-sectors collectively accounting for two-thirds of world production's carbon footprints. The energy sector alone accounts for 42% of total emissions, followed by the scale-intensive sector with 23% and transportation services that jointly account for 12% of CO_2 emissions. Interestingly, the distribution at the world level of sectoral emission shares is approximately constant in the period under analysis, except for the growing contribution of energy from developing countries. Finally, while in domestic stages developing economies account for 64% of total emissions, in foreign inputs they are even more relevant reaching 82% of total emissions.

This evidence starts to call for a further explanation of the link between patterns of GVC participation and emissions.

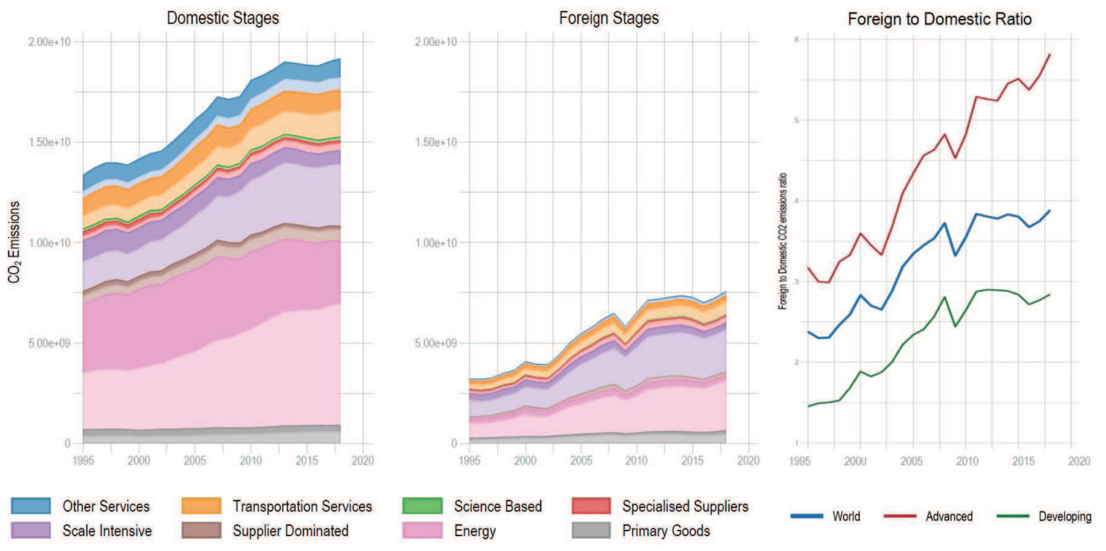

Fig. 2. Time evolution of CO_2 emissions embedded in final demand divided by developmental (darker/lighter colours) and sectoral origin. Emissions are divided into the ones generated in the domestic stages of production and the ones coming from foreign trade partners. Appendix A presents country and sectoral classification.

In an I-O framework, total emissions are the combined dynamics of CO_2 multipliers and final demand. Distinguishing between the two sources allows us to understand whether the total emission level is driven by the technical composition of the inputs used, or by the dynamics of final demand. Thus after having displayed the dynamics of CO_2 level we now focus on CO_2 multipliers.

The left panel of figure 3 presents the evolution of CO_2 emissions by development level and by domestic and foreign components embedded in final demand. Differently from figure 1, we split emissions across development levels leaving aside the sectoral dimension. From the I-O perspective is even clearer the role of developing countries in the overall rise in emissions. This is visible in the domestic segment but the trend is even more marked in foreign inputs from developing countries. On the contrary, advanced countries witness a mild decline in their domestic emissions while foreign emissions slightly rise. These trends are however the result of the concurrent dynamics of CO_2 multipliers and final demand. The middle panel shows a widespread decline in CO_2 multipliers, in all categories but particularly pronounced in domestic inputs in developing countries, while foreign components present returning-to-the-mean behaviours at the world level. Notably, the foreign component increases for developing countries while it decreases for advanced ones. The overall decline in multipliers means that emissions for units of output have declined consistently in the period under investigation, therefore hinting at a process of overall emission upgrading in terms of input usage and composition. However, the declining multipliers dynamics is more than compensated by the rise in final demand (right panel). Overall, these combined trends account for a worldwide increase in CO_2 emissions connected to production.

The comparison across multiplier levels is instead less direct because, by construction, the foreign production component is responsible for a lower production share. In this respect, in the following, we shall compare multiplier intensities.

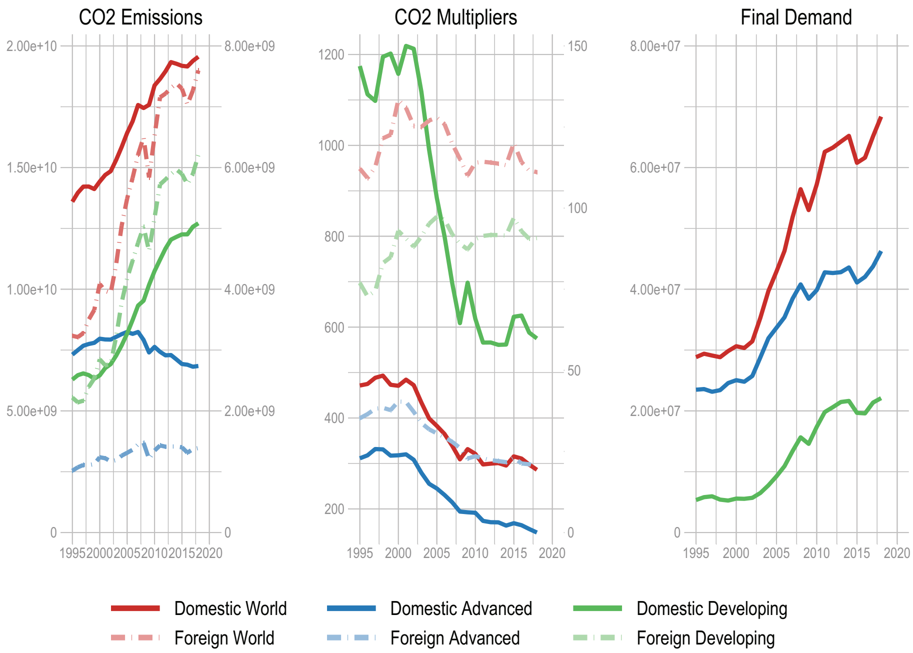

Fig. 3. Time evolution of CO_2 emissions embedded in final demand, CO_2 multipliers and final demand. The figure shows the dynamic in the World Production aggregate and in the two development groups. Further, we split production into domestic segments and foreign segments. Appendix A presents the country's classification.

To appreciate changes in the multiplier dynamics between domestic and foreign components, by sectoral and geographical origin, figure 4 zooms in the shift in CO_2 emission multipliers, with each dot representing the change of multipliers for inputs originating from specific sectors, in either advanced or developing countries, while the size of the dots is proportional to its final demand, to gauge the relative weight of each observation in world production. Dots below (above) the bisectors represent GVCs (worldwide sub-system levels) in which the Foreign CO_2 multipliers are increasing (decreasing) relatively more (less) than the domestic ones. If the foreign components' increase is higher than the domestic counterpart components this means that the emission intensity is gradually increasing because of GVC interactions. A dense distribution of the data points lies below the bisectors for the majority of sectoral origins of inputs, except for energy and the primary sector, which tend to be positioned above the bisector. Overall, the picture highlights a noteworthy trend of shifting emissions from domestic to foreign stages of production. Further information can be inferred by looking at the different quadrants. The majority of observations cluster in the third quadrant (southwest), indicative of a decline in both domestic and foreign emissions multipliers. Interestingly, the second most populated quadrant is the fourth (southeast), characterized by a decline in domestic emissions but an increase in foreign ones.

The figure also shows the non-parametric distributions of the change in multipliers. While domestic emissions of developing and advanced countries exhibit similar shapes, with a fatter right tail in developing countries, foreign emissions multipliers have positive mean and median variations, whereas variations are smaller and negative in developed countries.

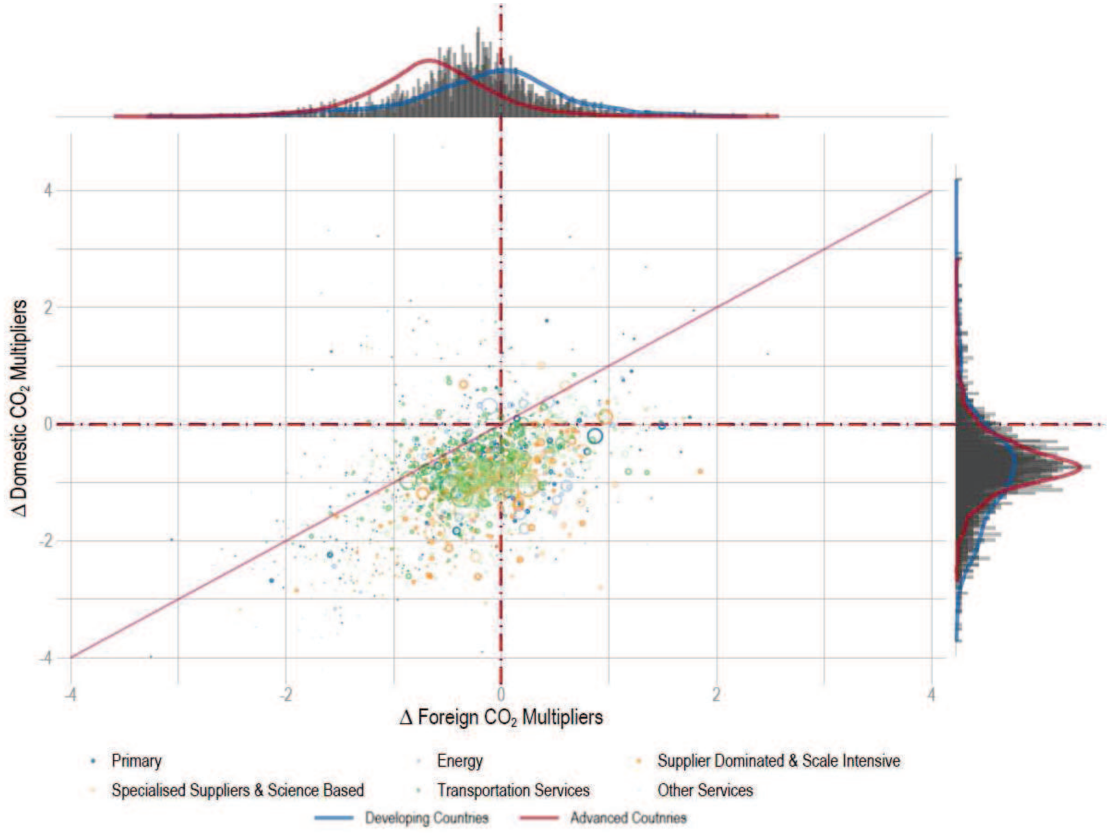

Fig. 4. Change in CO_2 emission multipliers in domestic vs foreign inputs in the period 1995-2018. Each dot represents a specific GVC and is classified based on the sector of final production. The size of the dots is proportional to its final demand. Additionally, we plot the distribution of the changes in emissions multipliers across chains in domestic and foreign stages dividing the chains based on the development stage of its final production stage. Appendix A presents the country's and sectoral classifications.

Having collected robust evidence on the pivotal role assumed by the foreign segments of the I-O relations, we now dig into the latter component. In order to normalize foreign multipliers emissions vis-à-vis output contribution of each foreign segment to overall value added, we contrast the information in Figure 5. The left panel of Figure 5 focuses on the sectoral origin of foreign inputs and their contribution to overall CO_2 emissions, within the world production network. As a counterpart, the right panel provides a contrasting examination based on the value-added contribution to final demands of each segment. We obtain the matrix of value added multipliers by applying the same methodology of eq. 1. The only difference is that we use a vector of value-added output ratios provided in the OECD ICIO tables. This dual approach allows us to dissect which industries contribute more than proportionally to CO_2 emissions vis-à-vis their value added contributions. Expressing both CO_2 emissions and value-added foreign inputs as a share of the total foreign contributions, the graph is divided between advanced and developing countries. The sum of these shares across both categories yields the total emissions/value added for a given year.

Figure 5 highlights a notable surge in both the CO_2 share of energy and inputs from the Supplier Dominated and Scale Intensive sectors originating from developing countries. In contrast, advanced countries have witnessed a widespread decline in their CO_2 emissions share across virtually all macro sectors. This implies a notable shift in the global distribution of emissions. With reference to value-added analysis, the increasing relevance of developing countries in the process of international production is confirmed. However, the highest growing sector in terms of foreign contribution to value added is the primary one. Notably, the most polluting sectors, energy and supplier dominated/scale intensive industries, contribute less than 10% total value added. These sectors turn out to be *"brown sectors"*. Conversely, foreign service sectors contribute to a progressively higher share of foreign value added, but to a negligible share in CO_2 emissions, therefore sectors which have an environmental contribution less than proportional than value-added contribution.

The role of sectoral contribution is crucial to shed light on the specialisation patterns.

Table 1 accounts for the sectoral specialisation patterns along foreign segments of GVCs. The literature shows that GVCs are an accelerator of countries' specialisation patterns. We thus computed the Reveal Comparative Advantage (RCA) for each macro industry across developmental classes (Balassa, 1965), according to the following specification:

$$RCA_j^{dev} = \frac{\sum_{i\in dev} v_{i,j} / \sum_{i\in dev}\sum_j v_{i,j}}{\sum_i v_{i,j} / \sum_i \sum_j v_{i,j}} \quad (3)$$

Where i represents countries, dev the development level group and j sectors, while v represents the value added flows of intermediate goods in the world production network. The index allows to compare the share of inputs from a particular sector in, say, advanced countries, to the share of the same inputs in the foreign segment of the world production network as a whole. RCA greater than one means that the developed group, or the group of countries under analysis, is specialised in providing that input.

Starting from the beginning of our period, in 1995 developing countries primarily specialised in the production of primary goods, construction, and energy sectors. By 2018, they significantly increased their relative specialisation in all manufacturing activities, achieving a comparative advantage, particularly in the low-Pavitt classes, specifically scale-intensive and supplier-dominated industries. In contrast, advanced countries, which initially specialised in manufacturing industries, maintained their RCA primarily in the upper Pavitt classes, such as science based and specialised suppliers. Alongside upper-Pavitt classes, advanced countries also diversified into services, intensifying their specialisation in these segments of production. Table 1 reveals a clear noteworthy trend, that is developing countries, which are relatively more emitting, are specialising in industries that are inherently more pollutant. These specialisation

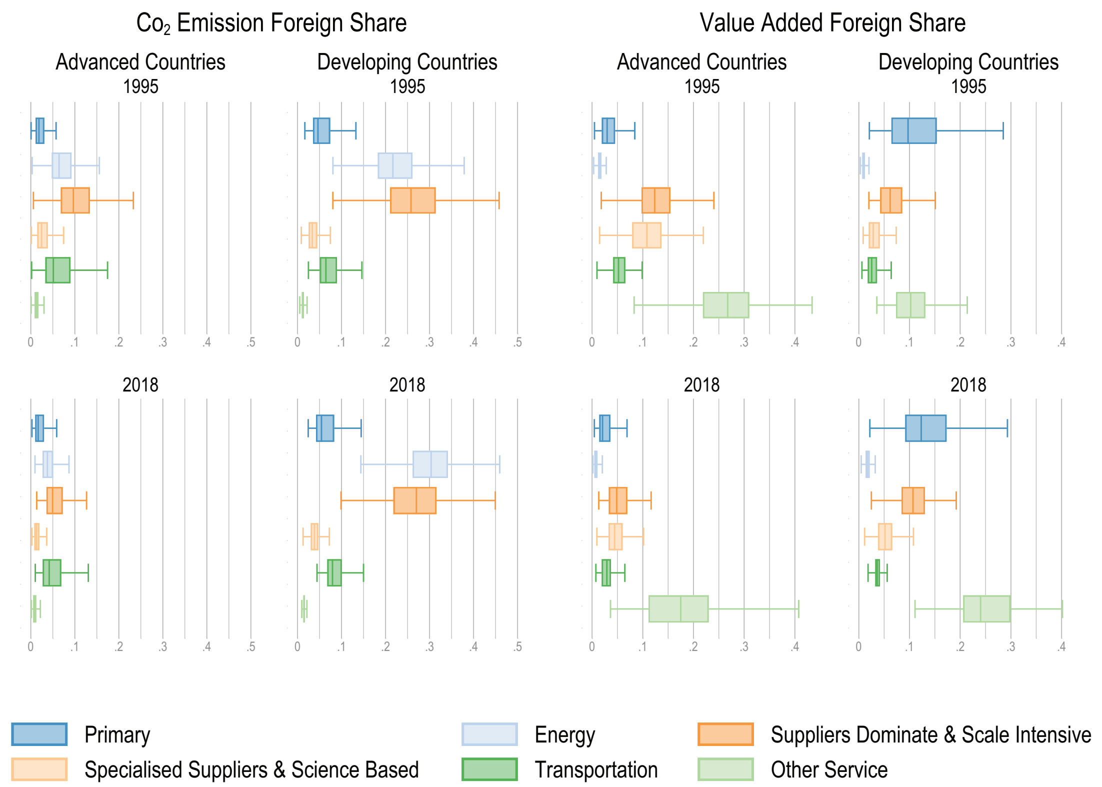

Fig. 5. CO_2 emission share and value added foreign share of inputs in 1995 and 2018. The unit of observation are single GVC and inputs are divided by their developmental and sectoral origin. Appendix A presents the country's and sectoral classifications.

patterns, reinforcing each other, underscore the importance of careful consideration when formulating trade and environmental policies. Tackling the vicious loop in the convergence of specialisation patterns in both emission-intensive and growth-diminishing productions in developing countries is fundamental for effectively achieving together environmental and growth sustainability.

Figure 6 summarises the information in figure 5, combining info on value-added and CO_2 emissions. The analysis involves segmenting the foreign contribution of each chain at the 2-digit industry level, distinguishing between developing and advanced countries. With 45 sectors, all chain-specific foreign contributions are disaggregated into 90 segments. For each segment, both value-added and emissions shares are computed, revealing the industry-specific relative emissions intensity.

$$CO_2RelIntensity_{i,j}^{dev} = \frac{\frac{\sum_{i \in dev} CO2_{i,j}}{\sum_i CO2_{i,j}}}{\frac{\sum_{i \in dev} va_{i,j}}{\sum_i va_{i,j}}} = \frac{co_2sh_{i,j}^{dev}}{vash_{i,j}^{dev}} \tag{4}$$

Where (i, j) represents the industry-country pairs providing inputs to each (h, k) GVCs, dev the development level of the country i providing inputs j. Essentially, for each chain (h, k) we are comparing the CO_2 and the value added share of each industry j aggregated by the 2 broad developmental classes. The plotted graph in figure 6 represents the relative CO_2 in-

Macro Sector	Foreign Inputs					
	Developed			Developing		
	1995	2018	Delta	1995	2018	Delta
Primary	0,42	0,53	0,11	2,01	1,23	-0,78
Energy	0,99	0,82	-0,17	**1,02**	**1,09**	**0,07**
Supplier Dominated	1,02	0,90	-0,12	**0,97**	**1,05**	**0,08**
Scale Intensive	1,09	0,92	-0,18	**0,84**	**1,04**	**0,20**
Specialised Suppliers	**1,24**	**1,36**	**0,12**	0,58	0,82	0,24
Science Based	**1,19**	**1,37**	**0,18**	0,68	0,82	0,14
Construction	0,58	0,25	-0,33	1,73	1,37	-0,36
Transportation Services	**1,09**	**1,26**	**0,17**	0,85	0,87	0,02
Other Services	**1,11**	**1,15**	**0,03**	0,80	0,93	0,13

Table 1. Revealed Comparative Advantage (RCA) across development levels and macro sectors in 1995 and 2018, and its change. RCA are computed using eq. 3. Sectors with RCA ≥ 1 and that witnessed RCA growth in the period are displayed in bold. Appendix A presents the country's and sectoral classifications.

tensity for developing countries against advanced countries for each (h, k) GVC. Observations above 1 indicate industries that contribute more than proportionally to CO_2 emissions compared to their value-added contributions. Therefore, dots in the I quadrant (north-east) represent "brown industries" contributing more than proportionally to global emissions in both advanced and developing countries. Conversely, dots in the III quadrant (south-west) represent "greening industries," inherently less pollutant. Industries in the II and IV quadrants can be either green or brown, contingent on their developmental origin. The focus narrows down to the 18 most emitting industries, shedding light on the nuanced dynamics of emissions in these sectors. This detailed analysis aids in identifying industries that play a significant role in shaping the global emissions landscape and understanding their relative contributions across different regions of the world. Table A4 in the appendix presents information for all the 45 sectors covered in the input-output tables. The figure illustrates that industries such as energy, basic metals, water and air transportation exhibit very high emission intensity in both advanced and developing countries, categorizing them as "brown" industries. Conversely, sectors including chemical production, rubber and plastic manufacturing, other manufacturing activities, and land transportation demonstrate relative emission intensity above one in developing countries and below one in advanced countries. This suggests that these sectors have the potential to be green but are currently produced in a sub-optimal manner in developing countries. Of particular interest is the case of electrical equipment, characterized by greener production in developing countries compared to advanced ones. Finally, all other sectors, and notably all services, can be considered green as they cluster in the III quadrant.

5 Shift Share analysis

As a last step, after having documented the increased role of developing countries and their mode of participation in GVCs as carriers of emissions, we try to disentangle the role of structural change, input recombination and technology, as they can be directly inferred from I-O analysis. In particular, on the technological dimension, the previous investigations do not discern whether declines in CO_2 multipliers are a result of industry-level reductions in emission

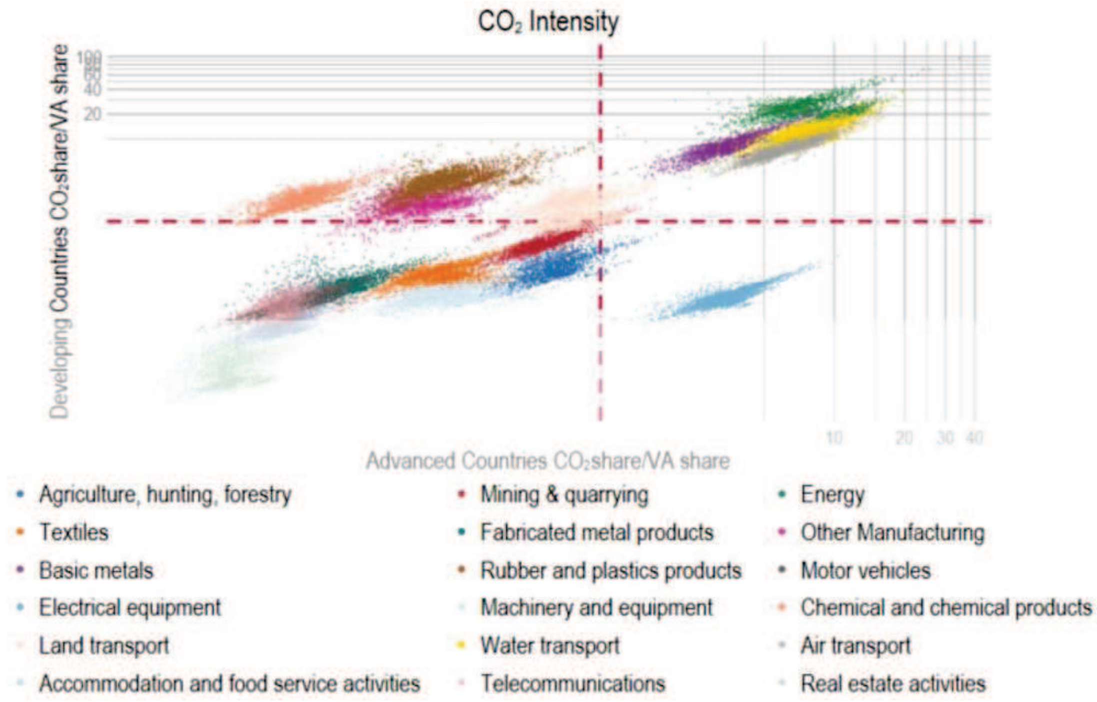

Fig. 6. relative CO_2 Emissions for the 18 most emitting sectors. Each dot represents the Relative CO_2 Emissions of Developing vs Advanced countries computed following eq. 4. Country classification can be found in appendix A.

intensities or, rather, technological shifts influencing production methods. Additionally, while we have observed a rise in emissions from the foreign segment of developing countries, it remains unclear how changes in the geography of production and shifts in demand structure contribute to the overall decline in CO_2 multipliers. As a textbook example, imagine the global automotive value chains witnessing a decline in emissions intensity. This decrease could stem from i) changes in production technologies, like Chinese metal producers adopting less polluting techniques of production, or ii) adjustments in the production "recipe" (Dosi, 2023) by automotive firms reducing metal usage and therefore the input mix, maintaining the other components of the I-O matrix unchanged. Another factor contributing to the reduction in CO_2 intensity could be iii) the shift in the import sources, for example, shifting wheel providers from Italy to, say, Japan, might reduce overall emissions if Japan is employing less pollutant techniques. Additionally, iv) changes in final demand can impact the emission profile. Suppose that the Korean Automotive Global Value Chain, inherently less emitting than the rest of the automotive GVCs, experiences a growth of demand in its inputs of production. This shift in final demand would contribute to an overall decrease in emissions.

All these represent potential drivers of shift in the structural decomposition analysis, that we intend to perform in the following. To single out the role of each potential driver, we perform a shift-share analysis on the average variation in CO_2 intensity of the world production network. We propose therefore a decomposition across four components:

- *Technical coefficients* tracking changes in the modes of production. This component gauges the effects of changes in production recipes, that is the contributions of different industries, whatever their origin, to final production. In that, it tracks the input-mix combination.

- CO_2 *intensity* accounting for improvements in input-specific CO_2 intensity per unit of output. This component accounts for country-industry-level improvements in emission profile keeping fixed all the other components. In that, it represents carbon-saving technical change.
- *GVCs reshuffling* measuring changes in the share of sectoral inputs delivered by each country-industry pair; in that, it represents a change in the input mix via relocation of production activities across the globe, and it is therefore the component intimately linking emissions to GVCs.
- *Final Demand composition* assessing the role of the changing structure of final demand in the overall emission dynamics. Since we are considering inter-industry trade, final demand represents the demand of inputs by the industry-destination country, and in that it informs about the type of specialisation path characterizing the destination country.

To focus on the developmental and sectoral origins of inputs, we investigate average CO_2 emissions multipliers in the world production network, without distinguishing across subsystems (GVCs). From a technical point of view, we are aggregating, weighting by the correspondent final demands, the whole matrix CC in a single column which synthesises world production, while we keep all information relative to the rows.[3]

$$\begin{aligned}
&\Delta CO_2Mult_t^{WLD} = CO_2Mult_t^{WLD} - CO_2Mult_{t-1}^{WLD} = \\
&= \Delta \sum_{(h,k)} \frac{fd_{h,k}}{fd_{wld}} \sum_{(i,j)} l_{i,j}\, CO_2ef_{i,j} = \Delta \sum_{(h,k)} \overbrace{\frac{fd_{h,k}}{fd_{wld}}}^{fdsh_{h,k}} \sum_{(i,j)} \overbrace{\frac{l_{i,j}}{l_J}}^{lsh_{i,j}} l_J\, CO_2ef_{i,j} = \\
&= \overbrace{\sum_{(h,k)} \sum_{(i,j)} \Delta \frac{fd_{h,k}}{fd_{wld}} \left(\widehat{l_J\, lsh_{i,j}\, CO_2ef_{i,j}} \right)}^{Final\ Demand\ Composition} + \overbrace{\sum_{(h,k)} \sum_{(i,j)} \Delta l_J \left(\widehat{\frac{fd_{h,k}}{fd_{wld}}\, lsh_{i,j}\, CO_2ef_{i,j}} \right)}^{Technical\ Coefficients} + \\
&+ \overbrace{\sum_{(h,k)} \sum_{(i,j)} \Delta lsh_{i,j} \left(\widehat{\frac{fd_{h,k}}{fd_{wld}}\, l_J\, CO_2ef_{i,j}} \right)}^{GVC\ Restructuring} + \overbrace{\sum_{(h,k)} \sum_{(i,j)} \Delta CO_2ef_{i,j} \left(\widehat{\frac{fd_{h,k}}{fd_{wld}}\, l_J\, lsh_{i,j}} \right)}^{Emission\ Intensity}
\end{aligned} \tag{5}$$

The notation (h,k) refers to GVCs, specifically the country-industry pair where the final production occurs, while (i,j) represents the inputs utilized in the production process coming from industry j in the country i. The CO_2 multipliers are initially broken down into country-industry specific CO_2 emissions per unit of output ($CO_2ef_{i,j}$), output multipliers ($l_{i,j}$), and then aggregated across the chain using final demand shares in worldwide final demand ($\frac{fd_{h,k}}{\sum_{h,k} fd_{h,k}}$). For each sectoral input j, we calculate the total input requirement in each specific chain (h,k), which is the sum of all inputs from sector j needed in the production process of (k,w). Subsequently, we determine the J's input share of country i in the (k,w) value chain by dividing output multipliers by the corresponding total input requirements $l_J = \sum_{j \in (h,k)} l_{i,j}$. To maintain equality, we multiply by l_J, representing the technical coefficients or requirements needed in production. Note that Δ denotes changes between the initial and final year of the variable, while the hat symbol represents transformations of averages between the initial and final year of the variables. For a detailed mathematical treatment related to the shift-share analysis, please refer to appendix C.

[3] The aggregation procedure strictly follows the methodology suggested by Miller and Blair (2021)

Figure 7 breaks down the change in global CO_2 multipliers into two technical change components (technical coefficients and C_O2 intensity usage) and two structural change components (GVCs reshuffling and final demand). The left panel provides a synthetic overview of this decomposition. The reduction in average CO_2 multipliers in world production is mainly attributed to improvements in CO_2 intensity, which represents the only component contributing to the decrease. This means that over time, production techniques have been adopting progressively carbon-saving techniques of production. However, such decline due to progressively polluting production techniques is offset by the other three components. Notably, both input-mix represented by the technical coefficients, GVCs restructuring and final demand components contribute to the rise in CO_2 intensity. Notably, changes in the composition of final demand compensate for almost half of the emission intensity gained through technical change, and GVC restructuring also has a positive impact, though of a smaller magnitude. This evidence militates in favour of a strong positive link exerted by the structuring of international production via GVCs in terms of overall contribution to emissions. In addition, it signals how specialisation strategies inducing shifts in final demand are acting against emission reduction.

Moving to the right-hand panel, we distinguish between two periods and split advanced and developing countries' dynamics. The phase 2002-2011 is the one characterised by higher dynamics in emissions, in line with our previous time trend observations, while the other two periods exhibit only moderate changes. Additionally, the two structural change components show opposite tendencies across development levels. Advanced countries contribute to the decline in CO_2 multipliers, while the opposite is observed for developing countries. Notably, the input mix positively contributes to emissions in both sets of countries, meaning the choice of the input requirements favouring an overall increase in emissions, while carbon-saving technical change, maintaining the basket of inputs unchanged, is the factor accounting for most of the decline over the entire period under analysis. However, carbon-saving technical change, given the patterns of worldwide rise in final demand, the country origin of the input mix, and the recombination in the input mix of production, independently from the country of origin, is not sufficient in allowing for emission reduction.

In line with our descriptive analysis, figure 8 dissects the overall change in emission multipliers, attributing it to either domestic or foreign inputs. Firstly, examining the left panel reveals that the dynamics of domestic CO_2 multipliers are predominantly influenced by advanced countries, contrasting with foreign CO_2 multipliers. Secondly, foreign inputs show a clear emission burden distribution between the two set of countries, with advanced countries declining and developing countries raising their contributions. Shifting the focus to the right panel, all components of developed countries, except for technical coefficients, contribute to a decrease in both domestic and foreign CO_2 multipliers. Conversely, developing countries contribute positively to emission multipliers across all components except for CO_2 intensity. Of particular interest is the case of GVCs restructuring component: while its impact is minimal in domestic production segments, it accounts for an increase in CO_2 emissions multipliers in foreign intermediates. Such a component is the one more connected to the pollution heaven hypothesis. Lastly, final demand composition, especially in developing countries, emerges as the primary counteracting force against the decline in global emissions multipliers. This underscores the significance of structural changes in consumption patterns and production structures throughout the developmental process. This component is the one mostly linked to the unequal ecological exchange hypothesis.

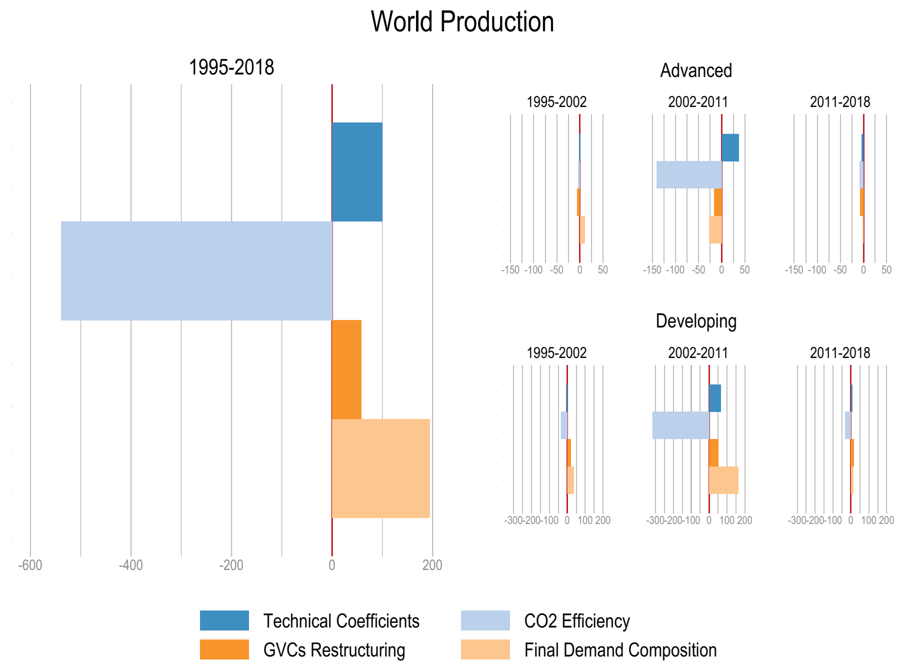

Fig. 7. Shift share analysis from 1995 to 2018 following eq. 5. Appendix A presents the country's and sectoral classifications.

Given the importance of the foreign segment, figure 9 conducts a shift-share analysis focusing only on the foreign segments of the production, where we observe a modest relative decline in C_O2 as the result of the contribution of developed and developing countries. Once again, even focusing on foreign inputs only, CO_2 intensity emerges as the sole factor inducing a reduction in CO_2 multipliers, while the other three components counterbalance such decline. Notably, GVC restructuring stands out as the predominant structural change component, suggesting that the reconfiguration of GVCs has contributed to an overall increase in CO_2 intensity. The importance of GVCs' international relocation of activities is significantly more than in the world production network as a whole. Notably, the changes in technical coefficients show a consistent positive trend, implying that changes in the mode of production within foreign segments favour greater emissions.

Shifting the focus to the right panel and distinguishing by countries and by sectors, we observe that the majority of the dynamics are driven by developing countries. Note that in the two technological components, both advanced and developing countries move in the same direction, with developing countries accounting for much of the variation. While in structural change components, they move in opposite directions, with developing countries consistently contributing to an increase in CO_2 emissions multipliers, whereas advanced countries contribute to a decrease, both via a transferring of emissions toward developing countries or rather via lock-in in carbon-intensive industry specialisation. Considering the sectoral dimension, the macro sectors with the greatest capacity to alter emission changes throughout the production process are energy and manufacturing ones, particularly scale-intensive industries. On the contrary, the service sector's dynamics exert a minor effect on the change in the foreign CO_2 multipliers. This can be understood as a relatively constant contribution of the emission share deriv-

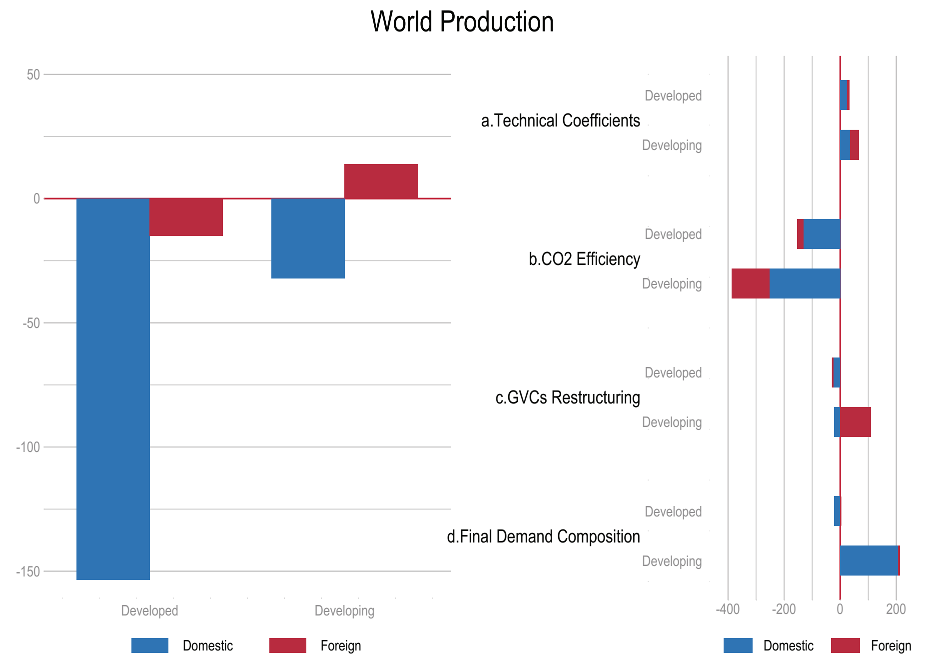

Fig. 8. Shift share analysis from 1995 to 2018 following eq. 5 highlighting Domestic vs Foreign contribution to the overall change in world CO_2 multipliers. Appendix A presents the country's classification.

ing from the service sector, by definition less subject to technical and structural change drivers of transformation.

6 Conclusions

In this paper we employed Input-Output tables to examine the network of GVC participation and CO_2 emissions, emphasizing how specialisation patterns within GVCs contribute to the escalation of CO_2 emissions and intensity in the global production network. Despite observing a general decline in CO_2 multipliers, we document a continual rise in emission levels attributable to a significant increase in final demand between 1995 and 2018.

In line with Meng et al. (2018), we have investigated how the recombination of domestic and foreign backward linkages contributes to the rise in CO_2 emissions. In particular, we confirm the convergence in CO_2 emission intensity between advanced and developing countries but only in domestic inputs. Although the decline in developing economies was sharp, the levels of emissions multipliers remain far above the ones of developed nations. Conversely, concerning foreign intermediate goods, we observed divergent patterns between advanced and developing countries' input contributions. While the former exhibited decreasing CO_2 multipliers, the latter displayed a concerning increasing trend.

We further explore the asymmetry between foreign and domestic contributions by examining specialisation patterns along the chains. Firstly, we pinpoint a handful of highly pollutant sectors —namely, the energy sectors, scale-intensive manufacturing, and transportation services— that collectively account for the majority of worldwide CO_2 emissions. Secondly, we show that developing countries, which are relatively the most emitting, exhibit increasing specialisation trends in these highly emitting industries. These ongoing trends reveal dynamic

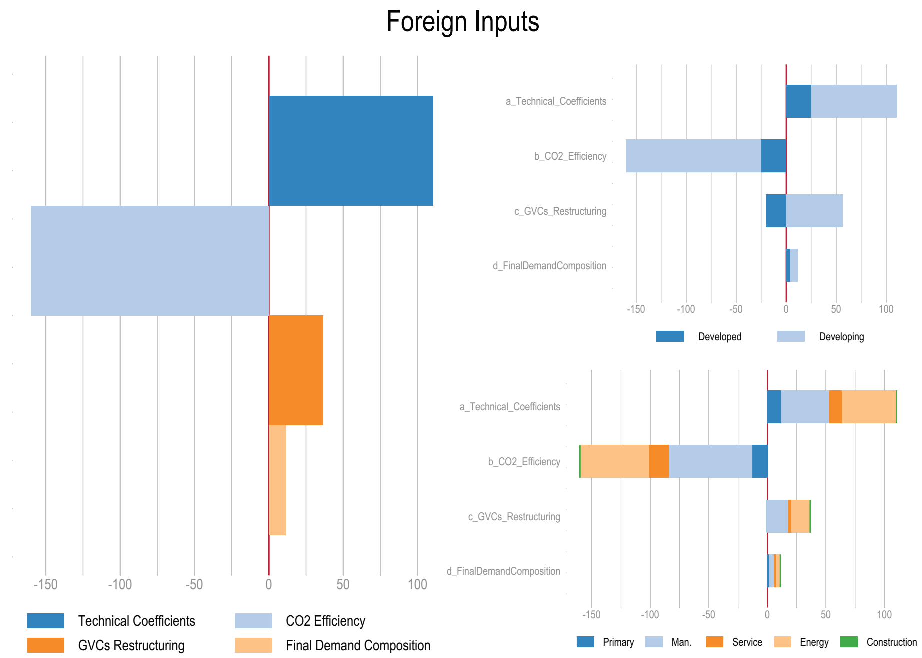

Fig. 9. Shift share analysis from 1995 to 2018 following eq. 5. Appendix A presents the country's and sectoral classifications.

risks to the sustainability of the world production network, particularly in foreign contributions.

Finally, we analyze the change in CO_2 emissions multipliers in domestic versus foreign contributions using a shift-share analysis, which decomposes the overall change into four components. These include two technological components accounting for improvements in country-industry-specific CO_2 emission factors and two structural change components. Two components measure changes in the structure of production (i.e., technical coefficients and emission intensity), while the other two reflect international reshuffling in GVCs composition (from the supply side), and changes in final demand composition (from the demand side).

Our findings reveal that the reduction in emissions, keeping constant the origin of sectoral and country input requirements, is the sole component showing significant decreasing trends across all segments and development levels, that is carbon-saving technical change. Conversely, the other three components contribute to an increase in CO_2 multipliers in both domestic and foreign contributions. Particularly noteworthy is the change in final demand composition, which is the primary counteractive force against technological improvements in emission intensity in domestic segments. Note here that demand represents inter-industry demand and, in that, reflects the country's specialisation paths. GVCs reshuffling (recombining the country origin of the same input requirements) and changes in the structure of production (recombining the input requirements across different industries) emerge as the most influential drivers in the rise of foreign inputs emissions, offsetting technological improvements (i.e., emissions intensity).

These findings document the double harm of GVC participation for developing countries. The very sectors that contribute to an increase in emissions intensity are also those challenging growth-promoting structural change paths in developing countries. These sectors typically exhibit relatively low levels of innovation and limited opportunities for productivity upgrading (energy, supplier dominated and scale intensive industries). On top of the bad specialisation strategy in terms of growth potential, the smile curve literature has shown that within these sectors, developing countries tend to specialise in fabrication occupations, which are associated with both higher emission intensity and less chance of social upgrading. Consequently, a dual harm arises, that is achieving a growth-promoting specialisation strategy, while simultaneously reducing the environmental impact and the consequent risk of being blocked not only in a developmental trap, well known in the structuralist-evolutionary literature, but also in an environmental trap.

In these respects, this article contributes to understanding the sectors that require targeted environmental, trade and industrial policies, as coexisting and multi-targeted policies. Moreover, it underscores the need of either rethink the participation of developing countries in GVCs, favouring their industrial, ecological and social upgrading, or facilitating the transfer of frontier technologies, less polluting, from advanced countries to mitigate overall emission intensity in alignment with UN environmental goals. Notably, our results can be extended to final levels of disaggregation, including not only countries but also territories characterized by environmental degradation and industrial decay, such as the so-called left-behind places whose discontent is progressively leading to protectionist and authoritarian political choices, also as a result of the unbridled effects of globalization.

Finally, from a theoretical-based perspective, our contribution calls for a common framework including the classical structural-dependency theory in the development of productive capabilities of developing countries and the ecological unequal exchange and pollution heaven hypothesis. Until recently, too often the two streams of literature have been considered as separated, however the factual empirical analysis of the developing country mode of participation into GVCs connects the trap of bad specialisation induced by trade-endowment factors, and the shift of the environmental burden towards developing countries. In particular, our empirical setting has allowed to verify both the pollution heaven hypothesis, via the GVCs restructuring component highlighting the transfer of emissions toward developing countries, and the unequal exchange hypothesis emphasizing how the periphery of the world is progressively subject to both socio-material and environmental degradation.

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Appendix

A Country and Sectoral Classifications

A.1 Country classifications

Country	ISO3	CountryCode	Development Level	Region
Argentina	*ARG*	032	Developing	Latin America
Australia	*AUS*	036	Developed	Asia-Pacific
Austria	AUT	040	Developed	Europe
Belgium	BEL	056	Developed	Europe
Brazil	BRA	076	Developing	Latin America
Brunei Darussalam	BRN	096	Developing	Asia-Pacific
Bulgaria	BGR	100	Developing	Europe
Cambodia	KHM	116	Developing	Asia-Pacific
Canada	CAN	124	Developed	North America
Chile	CHL	152	Developing	Latin America
China	CHN	156	Developing	Asia-Pacific
Chinese Taipei	TWN	158	Developed	Asia-Pacific
Colombia	COL	170	Developing	Latin America
Costa Rica	CRI	188	Developing	Latin America
Croatia	HRV	191	Developing	Europe
Cyprus	CYP	196	Developed	Asia-Pacific
Czechia	CZE	203	Developing	Europe
Denmark	DNK	208	Developed	Europe
Estonia	EST	233	Developing	Europe
Finland	FIN	246	Developed	Europe
France	FRA	250	Developed	Europe
Germany	DEU	276	Developed	Europe
Greece	GRC	300	Developed	Europe
Hong Kong	HKG	344	Developed	Asia-Pacific
Hungary	HUN	348	Developing	Europe
Iceland	ISL	352	Developed	Europe
India	IND	356	Developing	Asia-Pacific
Indonesia	IDN	360	Developing	Asia-Pacific
Ireland	IRL	372	Developed	Europe
Israel	ISR	376	Developed	Asia-Pacific
Italy	ITA	380	Developed	Europe
Japan	JPN	392	Developed	Asia-Pacific
Kazakhstan	KAZ	398	Developing	Asia-Pacific
Korea	KOR	410	Developing	Asia-Pacific
Lao	LAO	418	Developing	Asia-Pacific
Latvia	LVA	428	Developing	Europe
Lithuania	LTU	440	Developing	Europe
Luxembourg	LUX	442	Developed	Europe
Malaysia	MYS	458	Developing	Asia-Pacific
Malta	MLT	470	Developed	Europe
Mexico	MEX	484	Developing	Latin America
Morocco	MAR	504	Developing	North Africa
Myanmar	MMR	104	Developing	Asia-Pacific
Netherlands	NLD	528	Developed	Europe

Country	ISO3	CountryCode	Development Level	Region
New Zealand	NZL	554	Developed	Asia-Pacific
Norway	NOR	578	Developed	Europe
Peru	PER	604	Developing	Latin America
Philippines	PHL	608	Developing	Asia-Pacific
Poland	POL	616	Developing	Europe
Portugal	PRT	620	Developed	Europe
Rest of the World	ROW	.	Developing	Rest of the world
Romania	ROU	642	Developing	Europe
Russian Federation	RUS	643	Developing	Europe
Saudi Arabia	SAU	682	Developing	Asia-Pacific
Singapore	SGP	702	Developing	Asia-Pacific
Slovak Republic	SVK	703	Developing	Europe
Slovenia	SVN	705	Developing	Europe
South Africa	ZAF	710	Developing	Sub Saharan Africa
Spain	ESP	724	Developed	Europe
Sweden	SWE	752	Developed	Europe
Switzerland	CHE	756	Developed	Europe
Thailand	THA	764	Developing	Asia-Pacific
Tunisia	TUN	788	Developing	North Africa
Turkey	TUR	792	Developing	Asia-Pacific
United Kingdom	GBR	826	Developed	Europe
United States	USA	840	Developed	North America
Viet Nam	VNM	704	Developing	Asia-Pacific

A.2 Sector classifications

Sector	**Description**	**Broad Sector**
01T02	Agriculture, hunting, forestry	Primary Sector
03	Fishing and aquaculture	Primary Sector
05T06	Mining and quarrying, energy-producing products	Primary Sector
07T08	Mining and quarrying, non-energy producing products	Primary Sector
09	Mining support service activities	Primary Sector
10T12	Food products, beverages and tobacco	Supplier Dominated
13T15	Textiles, textile products, leather and footwear	Supplier Dominated
16	Wood and products of wood and cork	Supplier Dominated
17T18	Paper products and printing	Scale Intensive
19	Coke and refined petroleum products	Scale Intensive
20	Chemical and chemical products	Specialised Suppliers
21	Pharmaceuticals, medicinal chemical and botanical products	Science Based
22	Rubber and plastics products	Scale Intensive
23	Other non-metallic mineral products	Scale Intensive
24	Basic metals	Scale Intensive
25	Fabricated metal products	Supplier Dominated
26	Computer, electronic and optical equipment	Science Based
27	Electrical equipment	Specialised Suppliers
28	Machinery and equipment, nec	Specialised Suppliers
29	Motor vehicles, trailers and semi-trailers	Scale Intensive
30	Other transport equipment	Specialised Suppliers
31T33	Manufacturing nec; repair and installation of machinery and equipment	Supplier Dominated

Sector	Description	Broad Sector
35	Electricity, gas, steam and air conditioning supply	Energy Sector
36T39	Water supply; sewerage, waste management and remediation activities	Energy Sector
41T43	Construction	Construction
45T47	Wholesale and retail trade; repair of motor vehicles	Other Services
49	Land transport and transport via pipelines	Transportation Services
50	Water transport	Transportation Services
51	Air transport	Transportation Services
52	Warehousing and support activities for transportation	Transportation Services
53	Postal and courier activities	Transportation Services
55T56	Accommodation and food service activities	Other Services
58T60	Publishing, audiovisual and broadcasting activities	Other Services
61	Telecommunications	Other Services
62T63	IT and other information services	Other Services
64T66	Financial and insurance activities	Other Services
68	Real estate activities	Other Services
69T75	Professional, scientific and technical activities	Other Services
77T82	Administrative and support services	Other Services
84	Public administration and defence; compulsory social security	Other Services
85	Education	Other Services
86T88	Human health and social work activities	Other Services
90T93	Arts, entertainment and recreation	Other Services
94T96	Other service activities	Other Services
97T98	Activities of households as employers	Other Services

A.3 Pavitt Sectoral Taxonomy

To make sense of the documented heterogeneity across manufacturing industries, we employ the well-known Pavitt sectoral taxonomy (1984) which highlights the underlying technological and learning regimes. Thus, the 17 manufacturing industries available are divided into four groups.

Two technologically downstream Pavitt classes whose rate of technological change depends upon innovations generated in other sectors:

- *Supplier dominated industries (SD)*, wherein innovation is mainly driven by exogenous change in intermediate capital inputs and learning largely entails learning-by-using.

- *Scale intensive industries (SI)*, whose innovative abilities derive both from technological adoption of capital inputs but also by capabilities to internally develop complex products and manage complex organizations. Learning is cumulative and its effects are reinforced by economies of scale.

And two technological upstream Pavitt classes, more involved in the innovation process:

- *Specialised suppliers industries (SS)*, that provide capital equipment, instruments, and components to a wide range of "downstream" industries. Learning is based on innovative efforts via formal R&D expenses as well as on tacit knowledge about artefact design and user requirements.

- *Science based industries (SB)*, whose technological advances are strongly related to the ones in basic and applied research. They have often contacts with research laboratories and learning rates are typically quite high.

B Sectoral CO_2 Intensities

	Foreign							
	Advanced				Developing			
Industry	CO2sh	Vash	Rel Intensity	RCA	CO2sh	Vash	Rel Intensity	RCA
01T02	0,38%	0,48%	0,79	1,000	1,02%	3,72%	0,27	1,000
3	0,05%	0,07%	0,72	0,831	0,08%	0,39%	0,2	1,083
05T06	2,25%	1,53%	**1,47**	0,917	3,71%	6,59%	0,56	1,041
07T08	0,24%	0,42%	0,56	0,970	1,04%	1,15%	0,91	1,015
9	0,04%	0,10%	0,38	0,844	0,10%	0,30%	0,35	1,077
10T12	0,14%	0,39%	0,35	1,044	0,36%	1,72%	0,21	0,978
13T15	0,03%	0,11%	0,23	0,704	0,17%	0,74%	0,22	1,146
16	0,05%	0,15%	0,35	1,056	0,10%	0,31%	0,32	0,972
17T18	0,27%	0,41%	0,65	1,120	0,34%	0,62%	0,55	0,941
19	1,19%	0,35%	**3,39**	0,790	2,52%	1,15%	**2,2**	1,103
20	1,02%	1,18%	0,86	1,140	3,29%	1,86%	1,77	0,931
21	0,21%	0,62%	0,33	1,571	0,43%	0,48%	0,91	0,719
22	0,14%	0,46%	0,31	1,050	2,17%	0,68%	**3,21**	0,975
23	0,49%	0,24%	**2,04**	1,042	4,78%	1,31%	**3,65**	0,979
24	2,38%	0,66%	**3,61**	1,018	16,52%	2,04%	**8,08**	0,991
25	0,05%	0,64%	0,08	1,018	0,16%	1,05%	0,15	0,991
26	0,05%	0,94%	0,06	0,931	0,18%	1,47%	0,12	1,034
27	0,03%	0,43%	0,07	0,948	0,10%	0,83%	0,12	1,026
28	0,06%	0,95%	0,07	1,010	0,12%	0,97%	0,12	0,995
29	0,03%	0,56%	0,06	0,969	0,10%	1,00%	0,1	1,015
30	0,02%	0,34%	0,05	1,044	0,02%	0,21%	0,09	0,979
31T33	0,11%	0,49%	0,23	1,013	1,24%	0,62%	**2**	0,994
35	3,77%	0,46%	**8,27**	0,934	32,41%	1,45%	**22,34**	1,033
36T39	0,02%	0,20%	0,12	1,103	0,05%	0,33%	0,14	0,949
41T43	0,05%	0,31%	0,15	0,863	0,08%	3,33%	0,02	1,068
45T47	0,35%	4,36%	0,08	1,061	0,60%	7,17%	0,08	0,970
49	0,95%	1,00%	0,96	1,070	2,70%	2,15%	**1,26**	0,965
50	1,39%	0,18%	**7,58**	1,030	2,66%	0,22%	**12,3**	0,985
51	2,33%	0,36%	**6,42**	1,122	2,23%	0,30%	**7,35**	0,940
52	0,12%	0,76%	0,16	1,176	0,40%	0,68%	0,58	0,913
53	0,11%	0,26%	0,44	1,117	0,07%	0,21%	0,36	0,942
55T56	0,01%	0,23%	0,05	1,031	0,04%	0,82%	0,05	0,985
58T60	0,04%	0,72%	0,05	1,158	0,03%	0,33%	0,08	0,922
61	0,02%	0,39%	0,05	0,874	0,06%	0,58%	0,1	1,062
62T63	0,06%	1,34%	0,04	1,240	0,08%	1,68%	0,05	0,882
64T66	0,19%	3,36%	0,06	1,451	0,14%	4,39%	0,03	0,778
68	0,03%	1,00%	0,03	1,157	0,05%	3,55%	0,01	0,922
69T75	0,18%	3,80%	0,05	1,176	0,29%	2,06%	0,14	0,913
77T82	0,20%	2,51%	0,08	1,238	0,42%	2,26%	0,19	0,883
84	0,03%	0,31%	0,1	0,966	0,01%	2,18%	0	1,017
85	0,01%	0,18%	0,06	0,971	0,01%	1,61%	0	1,014
86T88	0,00%	0,08%	0,04	1,047	0,00%	0,90%	0	0,977
90T93	0,01%	0,13%	0,06	1,098	0,01%	0,28%	0,02	0,952
94T96	0,01%	0,12%	0,05	0,931	0,01%	0,75%	0,02	1,034
97T98	0,00%	0,00%	0	.	0,00%	0,00%	0	.

C Shift Share Analysis

Commonly used shift share decompositions disaggregate overall shift in two components: a within component that accounts for the dynamics inside the unit of observation keeping fixed the composition, and a between component that tracks the role of changes in the composition assuming constant within sector variation.

In this case, we aim to decompose the CO_2 multipliers shift in four components thus we need a slightly revised decomposition. In what follows, to lighten the exposition we will refer to final demand and input share as fd and l respectively, while we relabel the total input requirements as L and the CO_2 emission factor as c. Further, we define the final period variable as $'$. Finally, since the world wide decomposition is the summation of all within-inputs decompositions we propose the formula that holds for each input (i, j) used in the production process of (h, k).

Note that we do not aim at deriving the shift-share but just to deliver the full formula.

$$
\begin{aligned}
&\Delta CO_2Mult = CO_2Mult' - CO_2Mult = (fd'\, l'\, L'\, c') - (fd\, L\, l\, c') = \\
&= (fd' - fd)\,\frac{1}{4}\Big[\frac{(c'l'L') + (clL)}{2} + \Big(\frac{(L'c') + (Lc)}{2}\,\frac{(l' + l)}{2}\Big) + 2\Big(\frac{(l' + l)}{2}\,\frac{(L' + L)}{2}\,\frac{(c' + c)}{2}\Big)\Big] + \\
&+ (c' - c)\,\frac{1}{4}\Big[\frac{(fd'l'L') + (fdlL)}{2} + \Big(\frac{(l'fd') + (lfd)}{2}\,\frac{(L' + L)}{2}\Big) + 2\Big(\frac{(l' + l)}{2}\,\frac{(L' + L)}{2}\,\frac{(fd' + fd)}{2}\Big)\Big] + \\
&+ (l' - l)\,\frac{1}{4}\Big[\frac{(c'fd'L') + (cfdL)}{2} + \Big(\frac{(L'c') + (Lc)}{2}\,\frac{(fd' + fd)}{2}\Big) + 2\Big(\frac{(fd' + fd)}{2}\,\frac{(L' + L)}{2}\,\frac{(c' + c)}{2}\Big)\Big] + \\
&+ (L' - L)\,\frac{1}{4}\Big[\frac{(c'fd'l') + (cfdl)}{2} + \Big(\frac{(l'fd') + (lfd)}{2}\,\frac{(c' + c)}{2}\Big) + 2\Big(\frac{(fd' + fd)}{2}\,\frac{(l' + l)}{2}\,\frac{(c' + c)}{2}\Big)\Big]
\end{aligned} \tag{6}
$$

D China's Effect

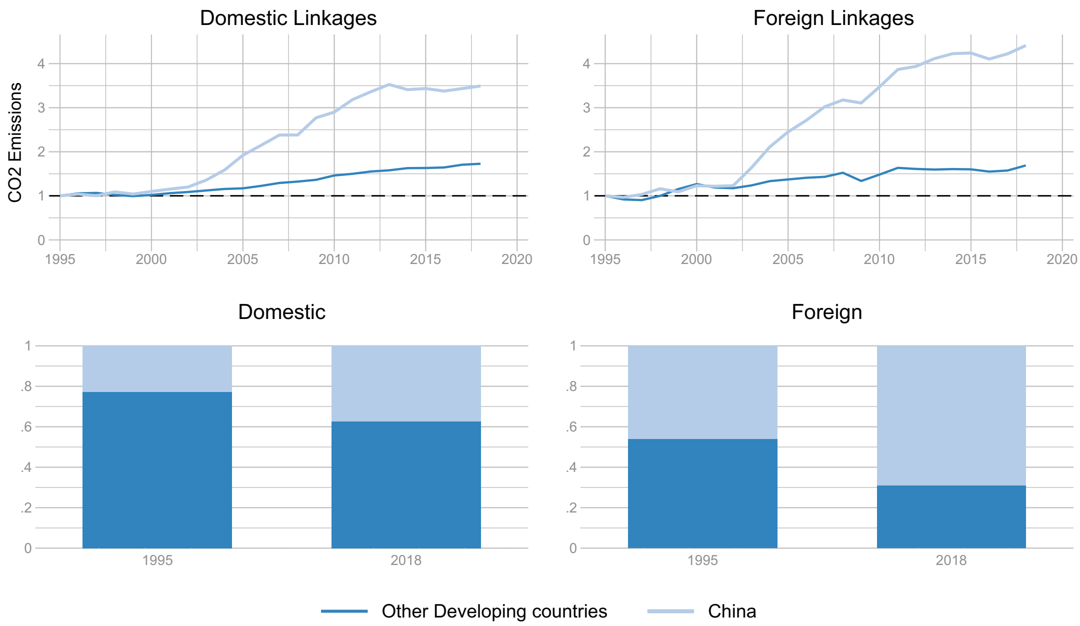

Fig. A1. Top panel: Evolution of CO_2 emissions in domestic and foreign linkages comparing China with the other developing countries. Bottom panel: Share of domestic and foreign CO_2 emission of China vis à vis the other developing countries in 1995 and 2018.

In this section, the evolution of CO_2 emissions of China is extrapolated from developing countries' trends to net out the impact of the extraordinary Chinese experience from the overall trend. The top panels show that in the period analysed Chinese CO_2 domestic emissions grew by 3.5 times while less than double in developing countries (left panel). On the other hand, foreign emissions grew by 4.5 and 1.7 times respectively. As a consequence, China's share of developing countries' CO_2 emissions moved from 20% in 1995 to 40% in 2018 in terms of domestic emissions, while from almost 50% to 60% in foreign CO_2 emissions (bottom panels). As such, the acknowledgement of the overall participation of China in GVCs since its accession into the WTO has to be pivotal in understanding the overall GVCs emission restructuring.