Carbon Without Borders: Emissions Embedded in Global Trade

C. Vezil[3,4] F. Vanni[1] M. Guerini[3,4,5,6] M. Napoletano[3,2,4]

[1]University of Insubria, Dept. of Economics
[2]Sciences Po, OFCE
[3]Université Côte d'Azur, CNRS, GREDEG
[4]Institute of Economics, Sant'Anna School of Advanced Studies
[5]University of Brescia
[6]Fondazione ENI Enrico Mattei

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The Economics of Networks

Network science provides a set of tools, techniques, and models for studying interconnected systems.

1. **Objective**: theoretical and empirical analysis of interaction structures modeled through mathematical objects called graphs or networks.
2. Graphs encode **information** on: – nodes: economic agents (firms, sectors, ports, countries, households) – edges: direct interactions (trade, supply links, communication, finance)
3. From a **GE perspective**: NS offers a framework to model externalities and interdependencies in decentralized economies.

Transportation Networks: Supply Chain Disruptions

Figure: Container ships anchored off the Californian coast wait to offload containers. Source: FT (2021)

Network and Tariffs

Figure: President Trump with a list of tariffs. Source: Axios (2025)

Natura non, nisi parendo, vincitur.

Francis Bacon (1607), *Cogitata et Visa*

Global CO_2 Emissions and GDP

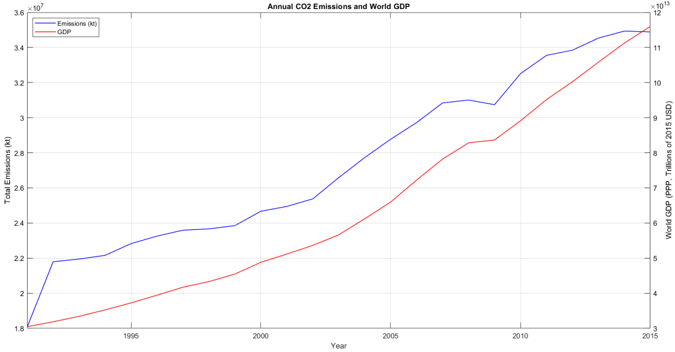


Figure: Annual evolution of global CO_2 emissions (left axis, blue line) and world GDP in PPP (right axis, red line).

A country perspective...

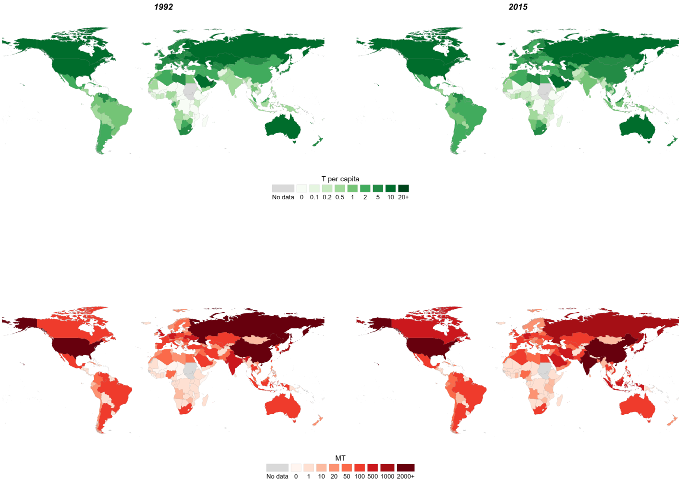


Figure: Global CO_2 emissions (bottom) and emissions per capita (top) in 1992 and 2015.

A sectoral perspective...

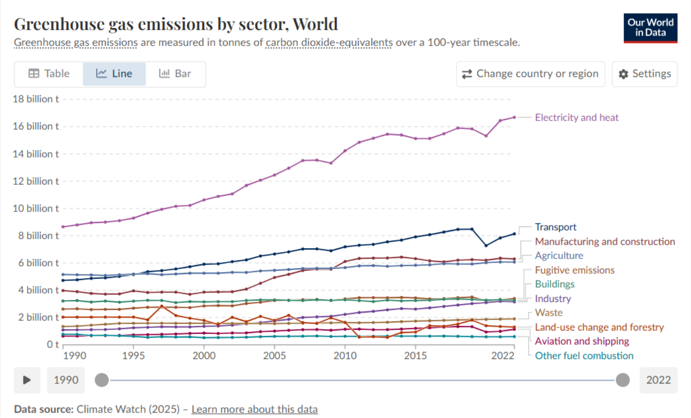
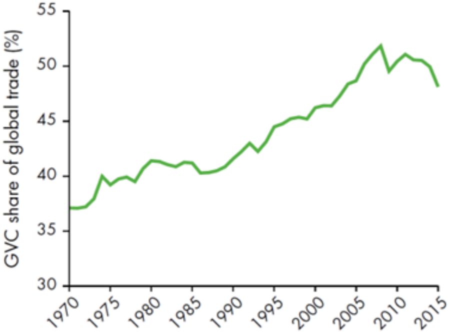


Figure: Global GHG emissions by sector. Source: OWD

The Age of GVC



Sources: WDR 2020 team, using data from Eora26 database; Borin and Mancini (2019); and Johnson and Noguera (2017). See appendix A for a description of the databases used in this Report.

Figure: GVC share of world trade. Source: Antras (2020, World Bank WDR) based on Borin and Mancini [2019].

Our contribution

We introduce a novel network-based framework for studying the environmental footprint of countries, capable of capturing the complex contribution of Global Value Chains (GVC) to global emissions dynamics.

1. First application of complex network methods to sectoral I-O data for both production and consumption based emission accounting.
2. Mapping of both direct and indirect emissions flows at the country-sector level.
3. New indexes of country systemic environmental impact and performance based on PageRank [Page et al., 1999]
4. Policy relevance: Identify "hotspots" for targeted international regulation.

Policy Implications in a Nutshell

- Advanced economies: Identify imported emissions activated by I-O channels
- Emerging economies: Tackle key central inefficient sectors (energy, heavy industry, transport) which drive emissions worldwide
- Insights helpful for the design of carbon border adjustments, climate clubs, targeted interventions [Nordhaus, 2021, OECD, 2025]

Motivation

Standard production-based accounting of CO_2 emissions [IPCC, 2006, UN, 2019] attributes all emissions to the country where they are generated, which overlooks the GVC nature of trade [Borin and Mancini, 2019].

Adoption of this accounting method in major climate agreements (e.g., Kyoto, Paris) may result in carbon leakage [Aichele and Felbermayr, 2012, King and van den Bergh, 2021].

- Environmentally-extended I-O that compute nations' *consumption-based* carbon footprints, tracing emissions embodied in trade [Davis and Caldeira, 2010, Davis et al., 2011].
- Simple carbon-weighted export network to account for embodied emission flows [Guidi et al., 2024].

Our approach: We move beyond traditional "isolated" accounting by explicitly modeling CO_2 emissions as a **network phenomenon**—mapping and quantifying the direct and indirect flows of carbon through global production networks [Grassi and Sauvagnat, 2019].

Data

Our analysis is based on the EORA26 environmentally extended multi-regional I-O database [Lenzen et al., 2013].

- **Coverage**: 189 countries, 26 harmonized sectors, annual data from 1990 to 2015.
- **Features**: Integrates multi-region I–O tables with environmental satellite accounts (f.i. CO_2, energy use).

This system lends itself naturally to a network representation:

- nodes → country-sector pairs
- edges → monetary I-O flows, weighted by associated emissions

Decoupling?

Countries differ in their emissions profiles. We apply a Kaya Identity [Yamaji et al., 1991, Raupach et al., 2007] to decompose the drivers of emissions:

$$CO_2 = \text{Population} \times \frac{\text{GDP}}{\text{Population}} \times \frac{\text{Energy}}{\text{GDP}} \times \frac{CO_2}{\text{Energy}}$$

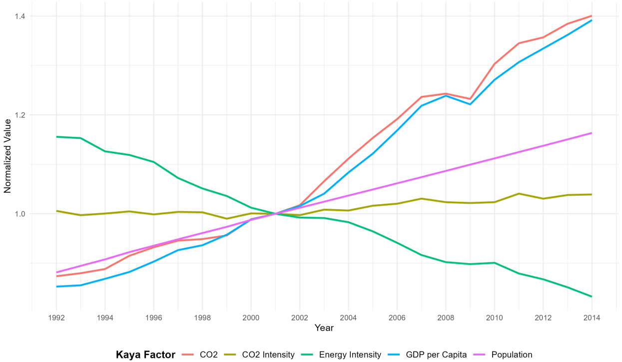


Figure: World Kaya decomposition (1992–2014).

Key Message → We still haven't decoupled economic growth and emissions!

Decomposition at the country level

Advanced economies have decoupled growth from emissions, while developing countries have not.

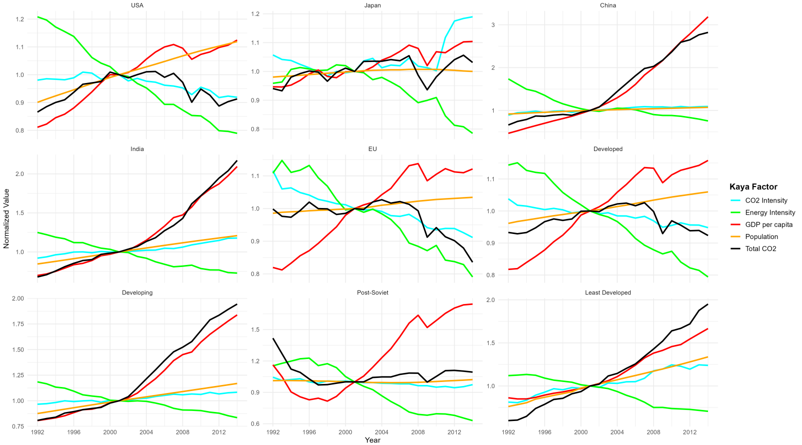


Figure: Kaya decomposition by geographical area. (1992–2014).

Lorenz Curves of CO_2 emissions

At the global level, four sectors are responsible for 20% of world output versus 80% of emissions. We also observe an increase of concentration over time in emissions production within countries as measured by Gini Emission Index Gini Emission Index World Lorenz Curve.

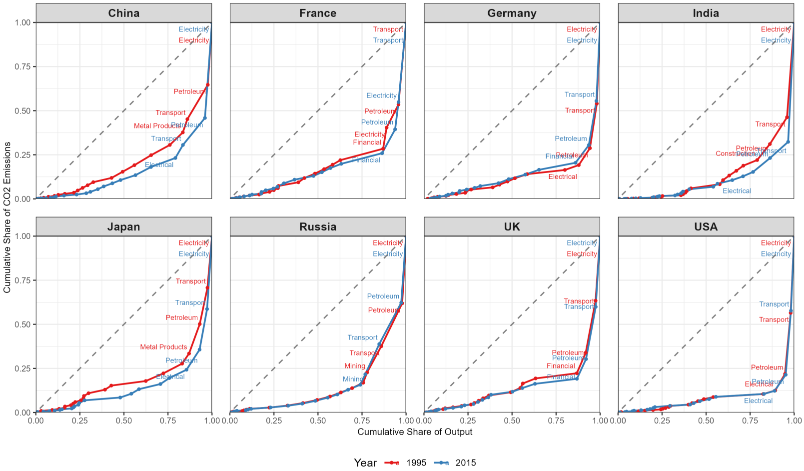


Figure: Lorenz curves of CO_2 emissions by sector for major economies (1995 vs. 2015).

Gini indices

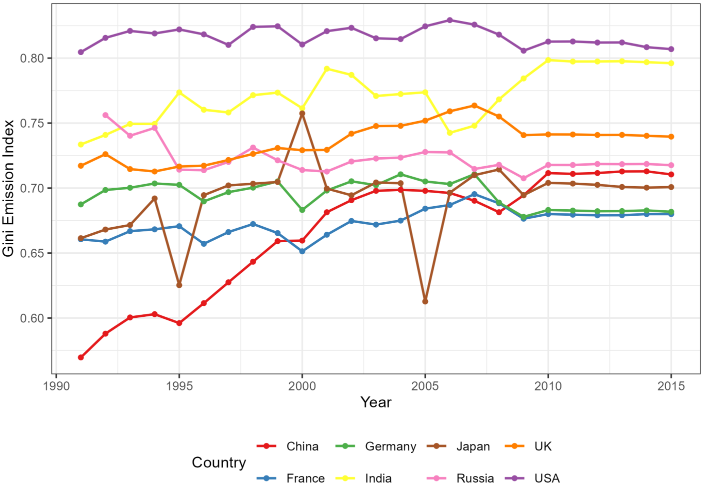


Figure: Gini index for emission concentration (1991–2015).

Sectoral Efficiency Measures

A small number of sectors (e.g. Electricity, Transport, Petroleum, Machinery) consistently account for the vast majority of emissions, despite varying contributions to output.

To evaluate this, we build a sectoral efficiency index $\xi_{C,i}$) which evaluates how effectively each sector produces economic output relative to its emissions of CO_2.

$$\xi_{C,i} = \frac{X_{C,i}}{\sum_{e,k} X_{e,k}} - \frac{Q_{C,i}}{\sum_{e,k} Q_{e,k}}$$

Aggregate sectoral efficiencies for country C:

$$\xi_C = \sum_i \xi_{C,i} \tag{1}$$

- Positive values: Sectors that are relatively emission-efficient (higher share in output than in emissions).
- Negative values: Sectors that are emission-intensive (higher share in emissions than in output).

Sectoral efficiency: Output versus emission

Advanced economies ↑, but developing countries ↓

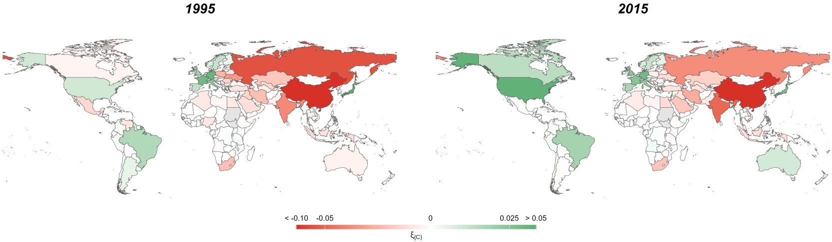


Figure: Country emission efficiency 1995-2015. Green indicates positive country efficiency, red negative values

Footprint Matrices

Production-driven (supply-to) network: Emissions assigned to producers

$$W = A\hat{Q}$$

where $\boldsymbol{A}$ is the technical coefficient matrix expressing input requirements per unit of output and $\boldsymbol{Q}$ the vector collecting the amount of emissions from that country sector.

Consumption-driven (demand-to) network: Emissions traced to final demand sectors

$$\boldsymbol{E} = \hat{Q}\boldsymbol{L}$$

where $\hat{\boldsymbol{Q}}$ is the diagonal matrix of emissions and $\boldsymbol{L} = (\boldsymbol{I} - A)^{-\mathbf{1}}$ is the Leontief inverse, which captures the total production response to final demand.

We apply PageRank centrality [Page et al., 1999] to measure systemic importance of sectors/countries for emissions propagation.

PageRank Centrality in Emission Networks

How do we identify nodes that are systemically relevant for global emissions via direct and indirect I-O channels? The PageRank algorithm [Page et al., 1999] provides a natural solution:

- **PageRank centrality** (ρ_i): Measures the systemic importance of each country-sector i in the emission network.

$$\rho_{i,t+1} = \frac{1-\alpha}{N} + \alpha \sum_{j \in N_i} \frac{w_{ij}}{S_j} \rho_{j,t}$$

  where w_{ij} is the weighted edge from j to i, S_j is the sum of outgoing weights from node j, α is the damping factor, and N is the total number of nodes.

- **Computation:** PageRank is computed as the stationary distribution of a random walk on the weighted I-O network, where each country-sector's centrality reflects the probability of reaching that node by following emission-weighted inter-industry links.
- **Interpretation**: A sector is central if it is connected to other central (high-emission) sectors via input-output linkages.
- **Average PageRank for a country** (ρ_C): Aggregates sectoral centralities for all N_s sectors in country C:

$$\rho_C = \frac{1}{N_s} \sum_{i=1}^{N_s} \rho_i$$

Emission Rank Demand-to – 1995

The centrality of a node/sector for global carbon emissions is shaped more by its position within GVC than by its economic size. Demand-driven emissions reflect the systemic importance of a sector as a trigger for emissions along supply chains.

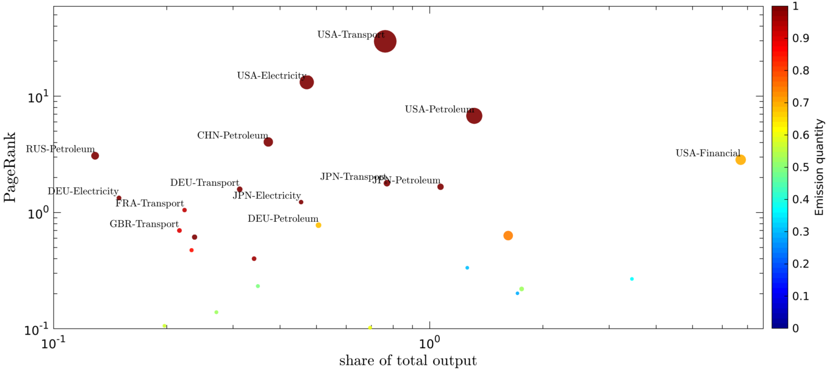


Figure: Sectoral PageRank (Demand-to network), 1995. Node size: node out-strength; color: emission scale.

Supply-to 1995

Emission Rank Demand-to – 2015

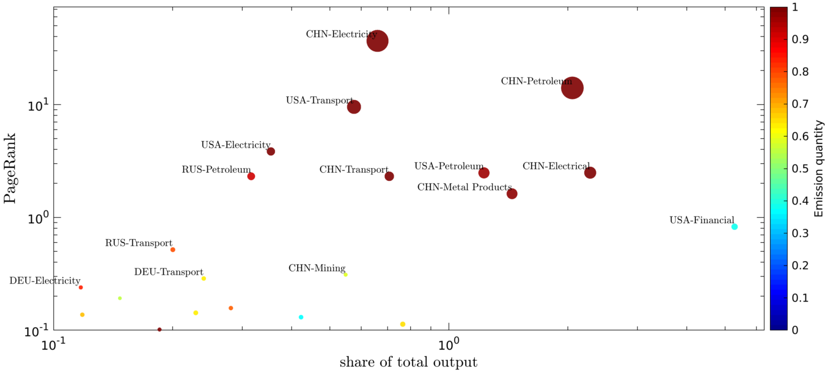


Figure: Sectoral PageRank (Demand-to network), 2015. Node size: node out-strength; color: emission scale.

Supply-to 2015

Correlations Demand-to - 2015

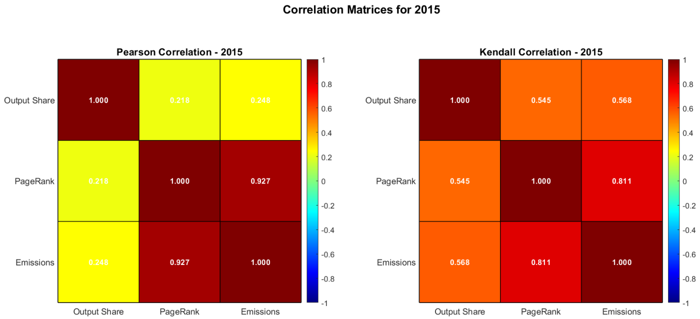


Figure: Pearson and Kendall's correlation coefficients among key variables for demand-to network for year 2015.

Correlations Supply-to - 2015

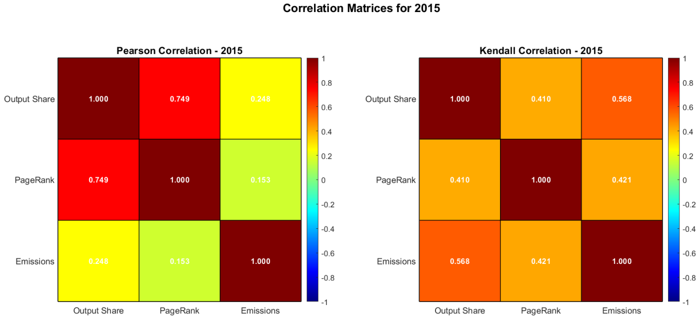


Figure: Pearson and Kendall's correlation coefficients among key variables for supply-to network for year 2015.

Dashboard Indicators

Figure: A car dashboard.

Complex Centrality Vector (Definition 1)

Definition: For each country-sector i, we define the **complex centrality vector** as:

$$Z_i = \rho_i e^{j\theta_i}, \quad i = 1, \ldots, N_s$$

where:

- ρ_i = PageRank centrality of sector i (systemic importance in the emissions network)
- $\theta_i = \frac{\pi}{2}\xi_i$ is the *efficiency angle*, with ξ_i the sectoral efficiency

Interpretation:

- $|Z_i| = \rho_i$ reflects the sector's centrality in propagating emissions.
- θ_i encodes whether the sector is efficient ($\theta_i > 0$) or inefficient ($\theta_i < 0$).
- Together, Z_i provides a polar (dashboard-like) representation of both systemic relevance and efficiency of a sector. Polar plot

Emission Rank Vector (Definition 2)

Environmental policies are formulated at the national level and often encompass multiple sectors rather than isolated industries → need for an indicator that captures the trade-off between a country's overall environmental impact and its productive efficiency. Polar mean plot

Definition: The **emission rank vector** for country c is the directional mean of its sectors' complex centralities Z_i:

$$Z_c = \frac{1}{N_s} \sum_{i \in \Omega_c} Z_i = \text{abs}(Z_c) \cdot e^{j \arg(Z_c)}$$

Aggregate measures:

$$A_c = \text{abs}(Z_c) \quad (\textit{Impact Strength})$$

$$I_c = \frac{2}{\pi} \arg(Z_c) \quad (\textit{Performance Phase})$$

Interpretation:

- A_c: Efficiency-adjusted systemic importance of a country in the global emissions network.
- I_c: Centrality-weighted average efficiency of the country's sectors.

Impact Strength and Performance Phase

Proposition 2 (Impact Strength):

$$A_c = \rho_C \sqrt{1 - \delta_c}$$

- A_c: Impact strength (national emission rank modulus)
- ρ_C: Average PageRank centrality of country C
- δ_c: Polarization coefficient (measures heterogeneity in sectoral efficiencies)

Implication: Impact strength is maximized when sectoral efficiencies are aligned (low heterogeneity) and minimized when they are polarized (high heterogeneity). A country can reduce its impact by either reducing its centrality or by compensating sectoral efficiency alignment.

Proposition 3 (Performance Phase):

$$I_c \approx \frac{\langle \rho \sin \theta \rangle}{\langle \rho \cos \theta \rangle + A_c}$$

- I_c: National performance phase (direction of average emission-impact vector)
- θ: Sectoral efficiency angle

Implication: The performance phase indicates whether a country's is on average more efficient ($I_c > 0$) or inefficient ($I_c < 0$), considering the centrality of its sectors.

Results: Impact Strength in Global Emissions

- **Divergent Trends:** Advanced economies (e.g., USA, UK, Germany, Japan) display a steady decline in impact strength over time, indicating a decoupling of domestic consumption from global emissions centrality.
- **Emerging Economies Rising:** China and India show a marked increase in impact strength, reflecting their growing systemic role as exporters of carbon-intensive goods and key nodes in global value chains.
- For advanced economies, the decline in impact strength is mainly driven by reduced centrality in the global input-output network, while sectoral polarization remains stable.
- In China and India, both centrality and sectoral polarization rise, signaling increasing dominance and internal heterogeneity in emission-intensive sectors.
- **Globalization Effect:** These trends are consistent with the *second unbundling* of globalization [Baldwin, 2016] and carbon leakage [Aichele and Felbermayr, 2012], where production and consumption are increasingly decoupled geographically, displacing emissions to emerging economies.
- **Implication** → Network-based accounting highlights the need for regulatory approaches which takes into account the differences in production versus consumption-based emissions:

Impact Strength and Polarization: Demand-to Network

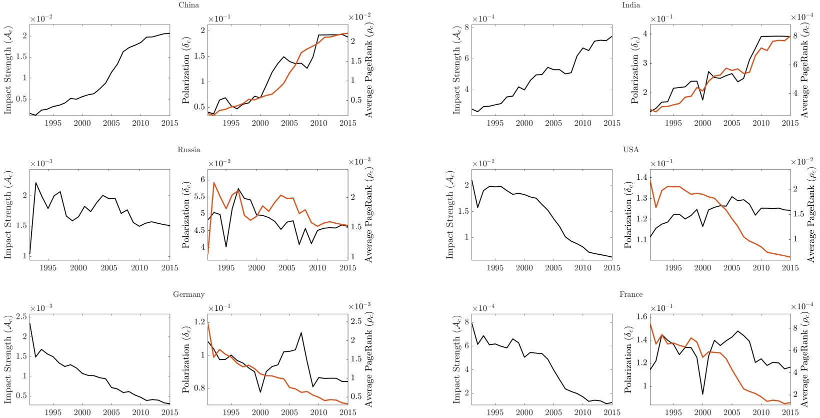


Figure: *Evolution of impact strength (left panel), polarization and average PageRank (red panel; black and red lines) for six major economies, 1991–2015. Heterogeneous trends reflect both differences in systemic emission impact and structural changes in global production networks.*

Supply-to results

Results: Performance Phase

The performance phase provides insight into the directional alignment of sectoral efficiencies, highlighting whether a country's production structure is becoming cleaner or more polluting in systemic terms.

- **Positive values**: indicate that a country's central sectors tend to be more emission-efficient
- **Negative values**: persistent reliance on polluting or misaligned sectors.

- **Advanced economies**: Persistent negative phases, decreasing impact strength and discrepancy —central sectors remain emission-intensive.
- **Emerging economies**: Volatile/increasing phases—greater misalignment and discrepancy and rising emission impact.

- Countries with negative performance phase but low discrepancy require broad-based regulatory efforts, as most sectors are misaligned.
- High discrepancy and negative phase call for targeted interventions in key polluting sectors.

Implication → For advanced economies, regulatory efforts should increasingly focus on emissions embodied in imports and I-O channels, while for developing economies, effective policies should target emission reductions in key domestic sectors (e.g. electricity).

Performance Phase

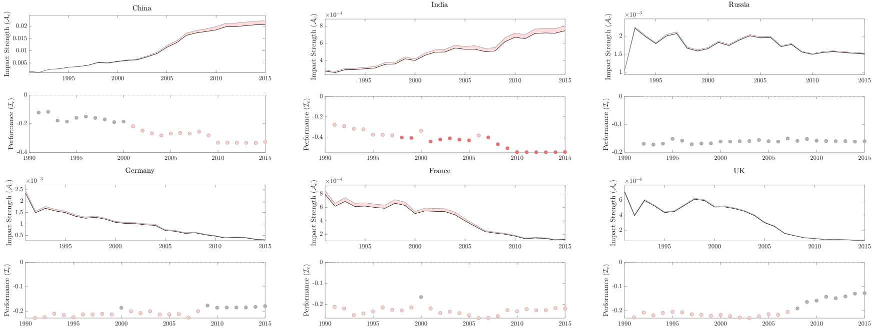


Figure: *Evolution of demand-driven impact strength (black line), average PageRank (grey line), and discrepancy (red area) for six major economies. Lower panels show the performance index, 1991–2015.*

Supply-to results

Conclusions

We have derived a novel network-based approach to jointly account for consumption- and production-based emissions in the global economy.

1. Our framework maps direct and indirect CO_2 flows across countries and sectors using input-output network analysis.
2. Results reveal a persistent—and in some cases, rising—concentration of emissions within a handful of structurally central sectors.
3. We highlight the role of network position and sectoral efficiency dispersion in shaping both emission footprints and regulatory leverage.
4. Regulatory efforts should focus in advanced economies on the imports channels, whilst in emerging economies on key polluting sectors.
5. This approach opens new directions for research, including policy evaluation, decomposition analysis, and extension to other environmental stressors.

Thank you!

Global Lorenz Curves

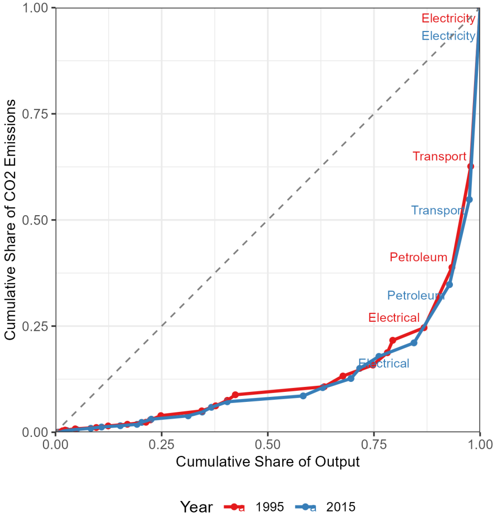


Figure: World Lorenz curves of CO_2 emissions by sector (1995 vs. 2015).

Emission Rank Supply-to - 1995

The supply-to impacts exhibit a strong correlation with a sector's share in total output for both 1995 and 2015. This suggests that the magnitude of a sector's CO_2 emissions impact is closely tied to its overall economic size. This is unsurprising, as the supply-to footprint is fundamentally linked to the volume of inputs a sector provides to other industries for production purposes.

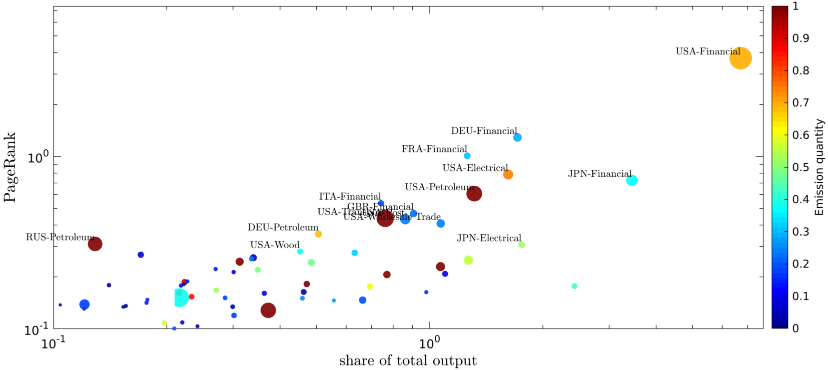


Figure: Sectoral PageRank (Supply-to network), 1995. Node size: node out-strength; color: emission scale.

Emission Rank Supply-to - 2015

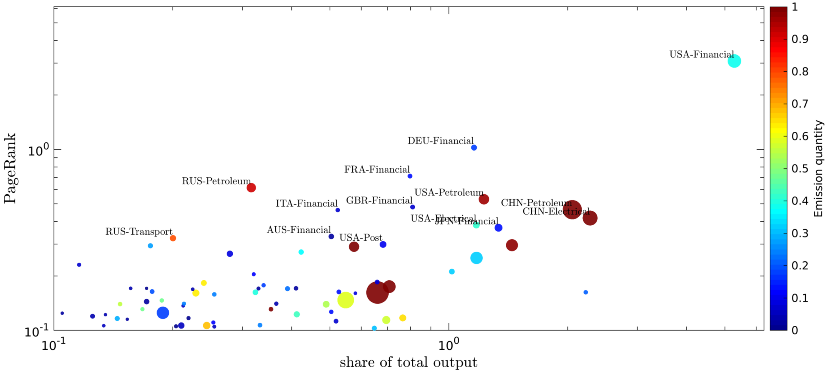


Figure: Sectoral PageRank (Supply-to network), 2015. Node size: node out-strength; color: emission scale.

Polar Representation of Complex Centrality Vectors

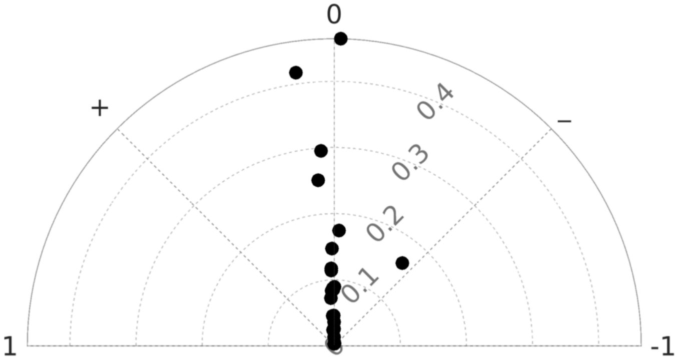


Figure: Polar plot of sectoral complex centralities. Each point represents a sector's complex centrality, with the radius indicating the systemic importance (centrality) and the angle capturing the balance between emission efficiency (left, +) and inefficiency (right, –).

Polar Representation of Mean Emission Rank

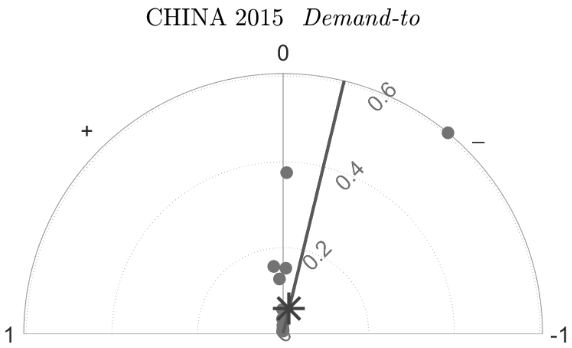


Figure: Polar plot of Emission Rank Centrality for China in the Demand-to network in 2015. The direction of the mean .

Impact Strength and Polarization: Supply-to Network

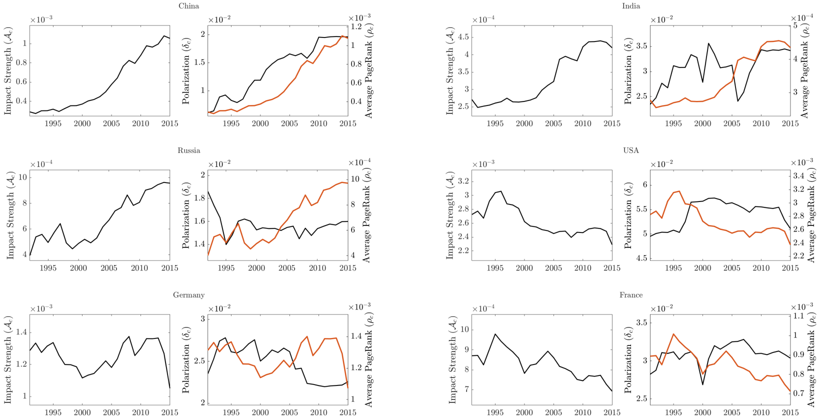


Figure: *Evolution of supply-driven impact strength ($\mathcal{A}_c$, black line), polarization (δ_c, red line), for six major economies, 1991–2015.*

Supply-to Network: Impact Strength and Performance

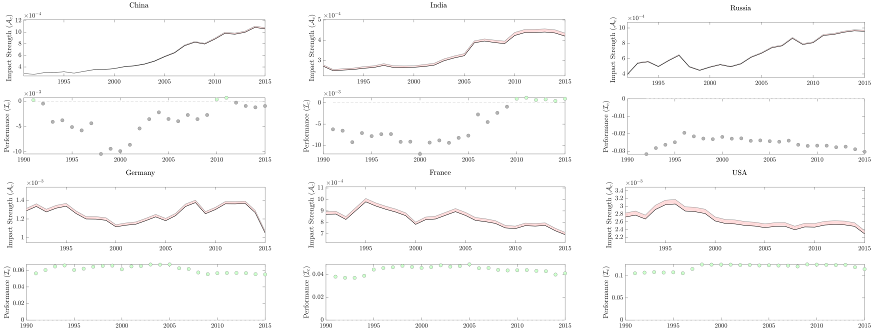


Figure: *Evolution of supply-driven impact strength ($\mathcal{A}_c$, black line), average PageRank (ρ_c, grey line), and discrepancy (red area) for six major economies, 1990–2015. Lower panels show the performance index ($\mathcal{I}_c$).*

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