



OPEN Tracing two decades of carbon emissions using a network approach

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According to the guidelines of the Intergovernmental Panel on Climate Change, carbon emissions are attributed to the *producers* of goods and services. This approach has been challenged by recent literature, advocating an attribution criterion based on *consumers*, i.e. accounting for the carbon embedded into the goods imported by each country. Quantifying the effectiveness of such a consumption-based accounting requires understanding the complex structure of the graph induced by the flows of emissions between world countries. To this aim, we have considered a balanced panel of a hundred of countries and constructed the corresponding Carbon Trade Network for each of the past twenty years. Our analysis highlights the tendency of each country to behave either as a 'net producer'—or 'net exporter'—of emissions or as a 'net consumer'—or 'net importer'—of emissions; besides, it reveals the presence of an unexpected, positive feedback: despite individual exchanges having become less carbon-intensive, the increasing trade activity has ultimately risen the amount of emissions directed from 'net exporters' towards 'net importers'. Adopting a consumption-aware accounting would re-distribute responsibility between these two groups, possibly reducing disparities.

Keywords Sustainable trade, Consumption-based accounting, Trade-embedded carbon emissions, Carbon trade network

Over the past two decades both the world GDP and total amount of CO₂ emissions have increased (see Fig. 5). With regard to GDP, Europe was surpassed by Asia in 2011 and in 2015. Overall, the Asian GDP has experienced the largest growth throughout the whole time-span (see Fig. 5). Regarding the emissions, the growth rate of Europe and North America remained close to zero until 2008 and became negative afterwards; Asia, instead, has displayed an increasing trend throughout the entire period (see Fig. 5). Although the 2008 financial crisis and the Covid-19 pandemic had clear consequences on both trends, the observations above suggest that reducing the environmental impact of economic growth remains a challenging goal.

As emissions from burning fossil fuels are the primary cause of global warming¹, the last decades have witnessed significant efforts to mitigate carbon emissions. At country level, the Intergovernmental Panel on Climate Change (IPCC) accounts emissions according to a 'production principle', i.e. by attributing them to countries *producing* goods and services^{2,3}.

Recent literature, however, has proposed to consider the adoption of a consumption-aware accounting, prescribing to focus on 'final consumers' as well^{4–7}: in other terms, this stream of literature advocates for accounting the carbon embedded into *imported* goods and services, hence re-distributing the responsibility for these emissions between producers and users.

Studies have estimated the extent of the out-sourcing phenomenon on the basis of regressions (solely accounting for country-specific factors such as GDP and energy efficiency^{8–12}—and invoking assumptions often leading to contradictory policy recommendations^{13–16}. Other authors have attempted to understand to what extent a 'consumption principle' may help reducing disparities in carbon accounting^{17,18}: in such studies, the amount of traded carbon is estimated via Multi-Regional Input-Output (MRIO) tables^{19,20} that, however, are very sensitive to the accuracy of the available data on trading sectors^{21,22}.

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As noticed by Caro et al.²³, data requirements can be relaxed by considering aggregate measures: specifically, the amount of carbon embedded into a country export can be simply quantified by multiplying it by the related *GDP-induced carbon intensity* (named *National Carbon Intensity* in²³), defined as

$$\text{GDP-CI}_i^y = \frac{[\text{CO}_2]_i^y}{\text{GDP}_i^y} \quad (1)$$

and measuring the kilograms of carbon, per dollar of GDP, released by country i , during a given year y (see also [Appendix A](#)): although less accurate, this method overcomes many of the aforementioned problems while keeping the uncertainty accompanying estimates in a suitable range for quantitative analysis (as the authors of²³ explicitly acknowledge, their ‘[...] systemic approach, in which carbon intensity plays the role of national indicator relative to production efficiency [...] is very easy, not labor-intensive to implement and no further data is needed beyond those already available at the national level’).

Inspired by the work of Caro and co-authors, we have adopted a complex network approach^{24–27} and constructed a Carbon Trade Network (CTN), i.e. a graph induced by the trade-embedded carbon exchanges between world countries, with the aim of investigating its complex architecture over the past two decades. More specifically, we have focused on (1) the evolution of the GDP-CI of each country and of its nearest neighbours; (2) the geographic distribution of the differences between production and consumption-based emissions at country scale; (3) the direction and magnitude of fluxes within and between groups of countries.

Data and methods

Construction of the carbon trade network

To construct the CTN, we have combined (1) data on trade flows from UN-COMTRADE (see <https://comtradeplus.un.org/>), (2) data on GDPs from the World Bank (see <https://data.worldbank.org/>), (3) data on CO₂ emissions from <https://ourworldindata.org/>. To consistently compare data over the years 2000–2020, we have selected a panel of 111 countries for which trade information was available for the entire period. To the best of our knowledge, the dataset employed to carry out the present study represents a quite unique example in the literature, for sample size, time span and granularity (OCSE reports usually focus on G20 countries over few years).

Following²⁸, carbon emissions are embedded into trade exchanges by considering the yearly values of each country GDP-CI. In formulas, the CTN link weights read

$$c_{ij}^y = \text{GDP-CI}_i^y \cdot w_{ij}^y, \quad \forall i \neq j \quad (2)$$

with w_{ij}^y indicating the export, in US dollars, from country i to country j , during a given year y . While the out-strength of node i , defined as $t_i^{\text{out}} = \sum_{j(\neq i)=1}^N c_{ij}$ (where we have dropped the y index), quantifies the total amount of its exported emissions, the in-strength of node i , defined as $t_i^{\text{in}} = \sum_{j(\neq i)=1}^N c_{ji}$ (where we have dropped the y index), quantifies the total amount of its imported emissions. Then, the total weight $W = \sum_{i=1}^N t_i^{\text{out}} = \sum_{i=1}^N t_i^{\text{in}}$ quantifies the total amount of trade-embedded carbon emissions (see also [Appendix A](#)).

Nominal VS constant-price GDP

Evaluating the carbon intensity requires choosing a definition of GDP. Hereby, we compare the *nominal* with the 2015 *constant-price* one. As Fig. 12 shows, the differences between the nominal GDP-CIs and the 2015 constant-price GDP-CIs are larger during the first years of our dataset, while vanishing as we approach 2020 (see also below). Since employing the latter does not change the overall picture returned by our results, we follow²³ and stick to the nominal definition of GDP.

Results

The carbon released by a nation versus its GDP sheds light on the environmental impact of its economic development. For G20 countries, we observe two, different kinds of evolution (see Figs. 1 and 6): the first one characterises countries whose values of GDP and amount of emissions are positively correlated, i.e. Argentina, Brazil (although their trend shows an inversion in 2018 and 2014, respectively), China, India, Indonesia, the Russian Federation (although the overall amount of its emissions has risen at a much lower rate than others), Saudi Arabia, South Africa and Turkey; the second one characterises countries whose values of GDP and amount of emissions are negatively correlated, i.e. France, Germany, Italy, Japan, Spain, United Kingdom and the US. Finally, the Australian, Canadian, Korean and Mexican GDPs have risen as well: however, the amount of Canadian emissions has remained quite constant over time; the Australian and Korean ones have risen up to 2008 and 2011, respectively, and become flat afterwards; the Mexican one has risen up to 2012 and decreased afterwards.

As Fig. 12 shows, the effect of the inflation is larger for the first years of our dataset; as we approach 2020, however, the values of the GDP-CI calculated by employing the 2015 constant-price GDP become closer to the values of the GDP-CI calculated by employing the nominal GDP. This, in turn, leads to Fig. 13, closely resembling Fig. 1. More quantitatively, the average of the relative errors

$$\delta_{\text{GDP-CI}_i^y} = \left| \frac{\text{GDP-CI}_n - \text{GDP-CI}_{\text{cp}}}{\text{GDP}_n} \right|_i^y \cdot 100 \quad (3)$$

for the G20 countries, amounts at $\lesssim 40\%$ in 2000, $\simeq 15\%$ in 2010 and $\simeq 8\%$ in 2020.

The analysis carried out so far merely depicts the evolution of aggregate indicators (see also Fig. 7). To disentangle the role played by trade, the network representation of the carbon embedded into the exchanges between

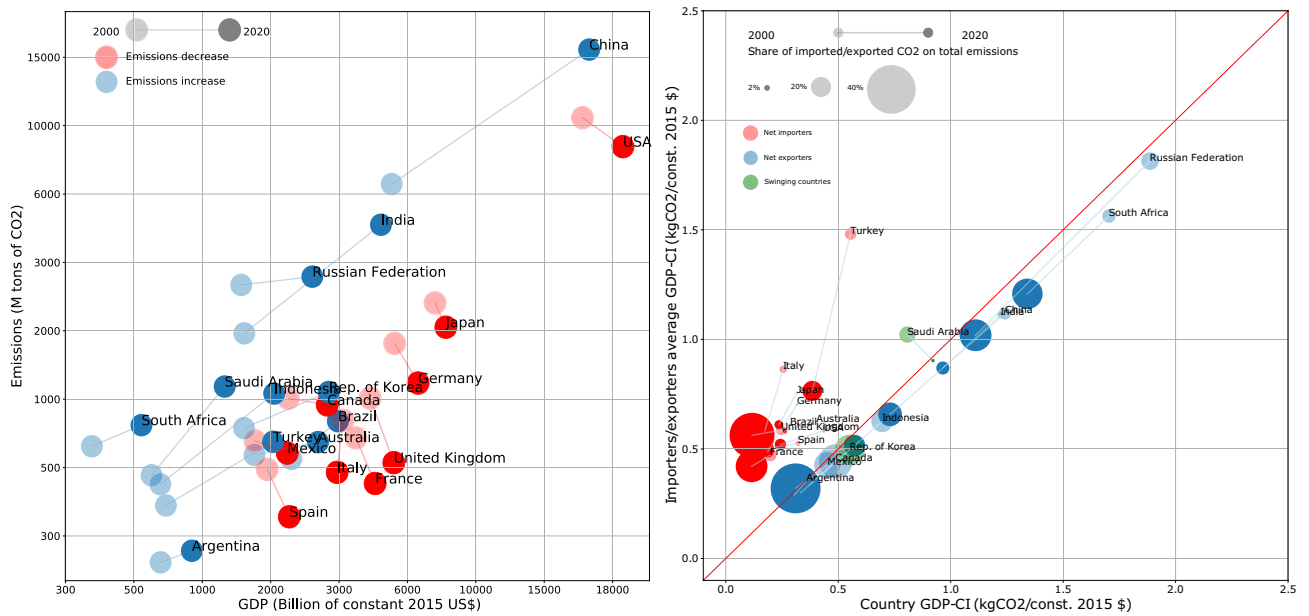


Figure 1. Left panel: the ‘economic-environmental trajectory’ of each country emerges upon scattering the tons of carbon released by it versus its GDP, in a yearly fashion. For G20 countries, two tendencies can be identified: the one characterising countries whose GDP and amount of emissions are positively correlated (i.e. Argentina, Brazil, China, India, Indonesia, Korea, the Russian Federation, Saudi Arabia, South Africa and Turkey—moving towards the top-right of the plane) and the one characterising countries whose GDP and amount of emissions are negatively correlated (i.e. France, Germany, Italy, Japan, Spain, United Kingdom and the US—moving towards the bottom-right of the plane). Right panel: scattering the weighted mean of the GDP-CIs of each country exporting partners versus its own GDP-CI reveals that many ‘net exporters’ are less economically efficient than the countries they export to; analogously, many ‘net importers’ are more economically efficient than the countries they import from. Overall, this leads us to conclude that countries whose export exceeds the import, export towards ‘cleaner’ countries; equivalently, countries whose import exceeds the export, import from ‘less clean’ countries. The size of ‘net exporter’ i is proportional to $[t^{out}]_i^y / PE_i^y$, i.e. the amount of exported emissions over the amount of produced emissions; the size of ‘net importer’ i is proportional to $[t^{in}]_i^y / PE_i^y$, i.e. the amount of imported emissions over the amount of produced emissions. Numbers are plotted on a doubly logarithmic scale. Names of countries indicate the last year covered by our dataset, i.e. 2020.

world countries provides more insights. As Fig. 8 shows, the total weight of the CTN has decreased throughout the second half of our time span, a result indicating that, from 2011 onwards, the impact of trade on world emissions has progressively diminished: one may be, thus, tempted to conclude that the rising trend in Fig. 4 is solely due to the carbon emitted for internal production; as we will see, this is only partially true.

In order to unambiguously classify each country on the basis of its trading behaviour, let us follow Caro et al.^{23,28} and re-write the amount of consumption-based emissions (or ‘consumed emissions’—the two terms will be used interchangeably) by country i , during the year y , as $CE_i^y = PE_i^y + [t^{in}]_i^y - [t^{out}]_i^y$ (see also Appendix B), where CE and PE are the acronyms for ‘consumed emissions’ and ‘produced emissions’, respectively. As a consequence, the difference between the amount of consumed and produced emissions by it is

$$CE_i^y - PE_i^y = [t^{in}]_i^y - [t^{out}]_i^y \equiv \Delta_i^y, \tag{4}$$

a relationship allowing us to distinguish ‘net importers’ of emissions, characterised by $\Delta_i^y > 0$ (equivalently, $CE_i^y > PE_i^y$), ‘net exporters’ of emissions, characterised by $\Delta_i^y < 0$ (equivalently, $CE_i^y < PE_i^y$), and countries that have reached the ‘trade-embedded carbon neutrality’, characterised by $\Delta_i^y = 0$ (equivalently, $CE_i^y = PE_i^y$). According to Eq. (4), ‘net importers’ (‘net exporters’) can be also classified as ‘net consumers’ (‘net producers’) of emissions. Figure 2 depicts the distribution of the set of values $\{\Delta_i^{2020}\}$, i.e. of the differences between out-strength and in-strength for each country, during the year 2020: as our analysis reveals, France, Germany, Italy, Japan, the UK and the US are among the top ten ‘net importers’ while China, India, the Russian Federation and South Africa are among the top ten ‘net exporters’.

As an additional consistency check, the estimates of the emissions computed by using our method have been compared with the estimates of the ‘CO₂ emissions embodied into the domestic, final demand’, computed by OECD as the amount of carbon that is emitted for domestic production plus the amount of carbon that is emitted abroad and embodied into imports (see <https://stats.oecd.org>). More quantitatively, the average of the relative errors

2020

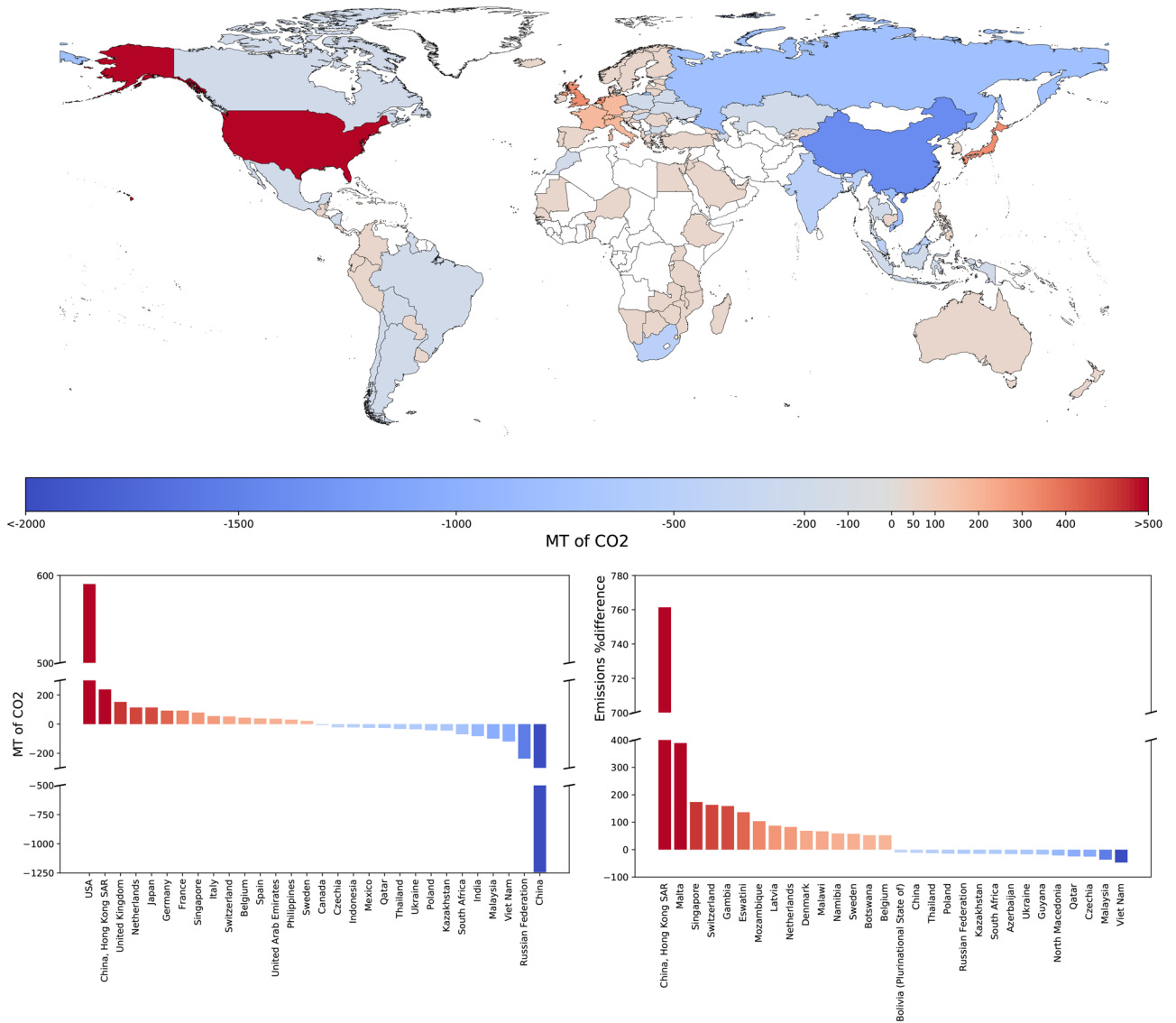


Figure 2. Top panel: geographic distribution of the differences between consumed and produced emissions, defined as $CE_i^{2020} - PE_i^{2020} \equiv \Delta_i^{2020}, \forall i$: while ‘net importers’ (or ‘consumers’) of emissions are depicted in shades of red, ‘net exporters’ (or ‘producers’) of emissions are depicted in shades of blue. Bottom-left panel: histogram of the differences between consumed and produced emissions, during the year 2020. Our analysis reveals that France, Germany, Italy, Japan, the UK and the US are among the top ten ‘net consumers’ while China, India, the Russian Federation and South Africa are among the top ten ‘net producers’—a classification that is robust across time. Bottom-right panel: histogram of the percentage differences between consumed and produced emissions, defined as $[CE_i^{2020} - PE_i^{2020}] / PE_i^{2020} \equiv \Delta_i^{2020} / PE_i^{2020}, \forall i$. The ranking changes because of the normalisation: in this case, in fact, the top ‘net consumers’ are the countries with a low level of internal production (e.g. the islands) while the top ‘net producers’ are the countries with a low level of import.

$$\delta_{CE_i^y} = \left| \frac{CE - CE_{OECD}}{CE} \right|_i^y \cdot 100 \tag{5}$$

for the G20 countries, amounts at $\approx 6\%$, throughout the whole period of time considered here (see also Fig. 14).

In order to check the robustness of the aforementioned classification over time, let us consider the sign of the temporal average $\bar{\Delta}_i \equiv \sum_{y=2000}^{2020} \Delta_i^y / 21$, allowing us to distinguish the countries that have mainly served as ‘net exporters’ (i.e. for which $\bar{\Delta}_i < 0$) from the countries that have mainly served as ‘net importers’ (i.e. for which $\bar{\Delta}_i > 0$): within G20, Argentina, Canada, China, India, Indonesia, Korea, Mexico, the Russian Federation, Saudi Arabia and South Africa belong to the first group while Australia, Brazil, France, Germany, Italy, Japan, Spain, Turkey, the UK and the US belong to the second group (see also Fig. 9).

Let us, now, study the mutual connections between the two, aforementioned groups of countries. More specifically, let us compare the behaviour of country i (be it a ‘net exporter’ or a ‘net importer’) with that of its partners, by calculating the average value of the GDP-CIs of its neighbours. To this aim, we have distinguished the nodes pointed by it (i.e. the countries it exports to) from the nodes pointing towards it (i.e. the countries it imports from). Figure 1b shows the evolution of both kinds of trajectories. Let us focus on ‘net exporters’, first: their trajectories lie below the identity line, a result indicating that their GDP-CI is steadily larger than the one of the countries they export to; for what concerns ‘net importers’, instead, the converse is true: their trajectories lie above the identity line, a result indicating that their GDP-CI is steadily smaller than the one of the countries they import from. Overall, this suggests the presence of a flux of emissions, directed from the countries for which $\overline{\Delta}_i < 0$ towards the countries for which $\overline{\Delta}_i > 0$ (see also Fig. 11).

To gain further insight into this, let us analyse the evolution of the total amount of carbon emissions embedded into the export of ‘net-exporters’. As Fig. 3 shows, both the portion of it directed towards ‘net importers’ and the one directed towards ‘net exporters’ have increased; still, the share of emissions directed towards ‘net importers’ has diminished, a result indicating that what may be called ‘exp-to-exp’ emissions (i.e. the emissions embedded into the trading relationships directed from ‘net exporters’ towards ‘net exporters’) have become increasingly relevant (see also Fig. 10).

When considering the evolution of the GDP-CIs, this result may appear paradoxical: each country has, in fact, reduced its own GDP-induced carbon intensity, the major decrease being observable for ‘net exporters’ - specifically, the Russian Federation, South Africa (whose GDP-CI, in 2020, lies slightly above 1 kg/\$), China, India and Saudi Arabia (whose GDP-CI, in 2020, lies between 1 kg/\$ and 0.6 kg/\$): as a consequence, one would expect the total amount of their trade-embedded carbon emissions to decrease as well. Its rise, only apparently contradictory, is due to an increase of the trading activity involving these countries, causing the related emissions to grow even though each actor has (individually) become more efficient.

Discussion and policy perspectives

While limiting ourselves to inspect the evolution of the GDP-CIs leads to the conclusion that each country has improved its economic efficiency, a network analysis of trade flows reveals the presence of a flux of emissions, directed from G20 countries serving as ‘net exporters’ towards G20 countries serving as ‘net importers’, whose magnitude has been rising over the past twenty-one years. In other words, our analysis reveals the presence of an unexpected, positive feedback: the rise of trading activity among countries has caused the amount of emissions to rise as well, although exchanges have (individually) become less carbon-intensive.

In a wider perspective, our results highlight the systemic dimension of the carbon leakage phenomenon, stressing the role played by the core countries of the international trade network of carbon exchanges²⁹. Although the aggregation level of our study does not allow us to quantify the leakage rate for our panel countries, it may nonetheless provide important insights for improving general equilibrium models like GTAP-E (e.g. for what concerns the definition of unilateral carbon policies). Results also support the need to integrate embodied carbon for designing effective policy instruments, suggesting that actions to reduce emissions solely targeting production methods in a restricted number of developed countries may be ineffective; stated otherwise, policies should explicitly account for the systemicness of the carbon leakage phenomenon as well as its national specificities—thus, refining the scenario discussed by Beck et al.²⁹, according to whom, in case of no aversion

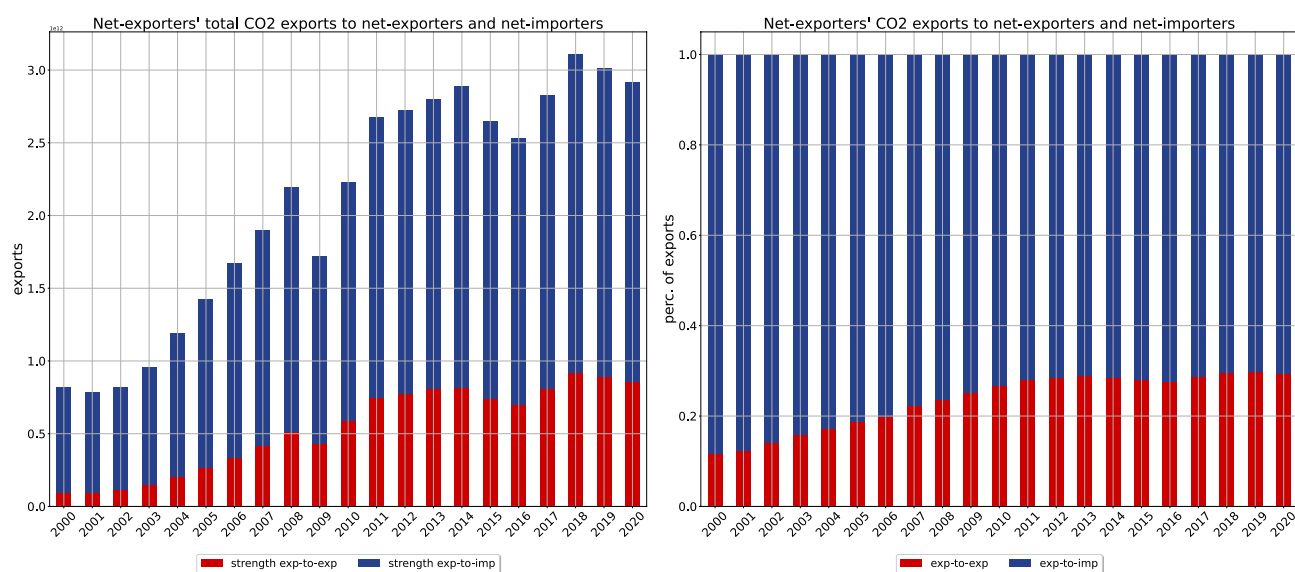


Figure 3. Partitioning the group of G20 countries into ‘net exporters’ and ‘net importers’ allows the presence of a net flux of emissions, directed from (the members of) the first set towards (those of) the second, to be revealed. Although its magnitude has, overall, risen over the past twenty-one years, the amount of emissions directed from ‘net exporters’ towards ‘net exporters’ has become increasingly relevant.

towards carbon leakage, the cost of achieving national emission targets should be minimised by adopting a uniform carbon taxation.

Our analysis of the Carbon Trade Network leads to results that are consistent with those of the econometric analysis performed by Liddle⁸, who identify a set of Asian countries for which exports/imports provide a significant contribution to lower/increase consumed emissions and conclude that a consumption-aware accounting may indeed be helpful to assess responsibility for climate change. Otherwise stated, a ‘production-based’ accounting criterion solely penalises the countries belonging to the group of ‘net exporters’: ‘net importers’, on the other hand, may take advantage of the current situation, by lowering their emissions as a consequence of practices such as that of off-shoring carbon-intensive productions, instead of adopting ‘environment-friendly’ technologies^{30,31}. In this case, the global carbon footprint would be left unchanged—if not worsened—since off-shoring is typically directed towards technologically underdeveloped, hence highly polluting, countries. As signalled by several sources, this practice seems to characterise France³², the United Kingdom³³ and the US³⁴.

Coming to comment on policy instruments, consumption-based emissions may inform taxation, as a ‘consumption-aware’ criterion would burden both the ‘net exporting’ and ‘net importing’ countries, incentivising developing countries to transition towards cleaner industrial production: a measure going in this direction is the Carbon Border Adjusting Mechanism (CBAM), recently introduced by the European Union. Still, its expected effectiveness should be carefully evaluated as European firms may experience a reduction of competitiveness and developing countries with limited access to green technologies may be overburdened; besides, the GDP-CIs tend to assume increasingly similar values: hence, the impact of the CBAM may reduce in the medium-long period³⁵.

A future direction along which the present analysis could be extended concerns the possibility of employing carbon intensity in a disaggregated fashion (as the authors of²³ explicitly acknowledge, ‘[...] the framework presented is less detailed than the EEIO framework, as it does not use a specific carbon intensity for each sector and does not include the indirect emissions.’). Here, however, an issue with data availability arises. As Caro and co-authors suggest, one may consider the *sector-specific* carbon intensities; a network approach like the one pursued here, however, would focus on the World Trade Multiplex, each layer of which corresponds to a *commodity*: an aggregation of commodities into sectors and a mapping between the corresponding carbon intensities would, thus, be required.

Data availability

The datasets used and analysed during the current study is available from the corresponding author on reasonable request.

Appendix A. Evolution of GDPs, emissions and carbon intensities over the years 2000–2020

This appendix is devoted to detailedly discuss the evolution of (1) the gross domestic product (GDP), (2) the total amount of carbon emissions, (3) the GDP-induced carbon intensity (GDP-CI) and (4) the electric energy-induced carbon intensity (EE-CI) of world countries, over the years 2000–2020. We have considered three, different geographical scales, i.e. world-wise, continent-wise, country-wise. Before proceeding, let us remind that the GDP-CI is defined as $\text{GDP-CI}_i^y = [\text{CO}_2]_i^y / \text{GDP}_i^y$, hence measuring the kilograms of carbon, per dollar of GDP, released by country *i*, during a given year *y*, and that the EE-CI is defined as $\text{EE-CI}_i^y = [\text{CO}_2]_i^y / \text{kWh}_i^y$, hence measuring the kilograms of carbon, per kilowatt hour, released by country *i*, during a given year *y*. While the GDP-CI conveys information about a country ‘economic efficiency’, the EE-CI conveys information about a country ‘environmental efficiency’.

World-wise scale. Let us start by discussing the evolution of the world GDP and total amount of CO₂ emissions. Figure 4 shows that both quantities have risen over the past twenty-one years, an evidence suggesting that economic development has led to an increase of the amount of CO₂ released into the atmosphere. Still, the impact of the two, main crises occurred within this period of time, i.e. the global, financial one (end of 2008) and the Covid-19 pandemic (beginning of 2020), has contributed to slow down the economic growth of countries that, in turn, have reduced their emissions (specifically, in 2009 and 2020).

Continent-wise scale. Let us, now, disaggregate the previous trends in a continent-wise fashion: as Fig. 5 reveals, continents are roughly split in two, i.e. the richest ones (Asia, Europe, North America) and the poorest ones (Africa, Oceania, South America). Overall, the GDP of each continent (calculated as the sum of the GDPs of the countries constituting it) has grown over the past 21 years. Interestingly, Europe had the largest GDP from 2004 to 2011, when it stopped growing and was surpassed by Asia (i.e. the continent that has grown the most throughout the whole period of time considered here); North America instead, had the second largest GDP from 2004 to 2009, when it was surpassed by Asia. Then, in 2015, the North American GDP surpassed the European GDP, thus becoming the second largest one.

When coming to consider their emissions, the three, richest continents show a quite different behaviour: while Europe and North America have undertaken a reduction pattern since 2009, Asia has kept increasing carbon emissions throughout the whole period of time considered here (although at a lower rate since 2011).

For what concerns the GDP-CI, each continent has reduced its carbon intensity (calculated as the arithmetic mean of the GDP-CIs of the countries constituting it). The Asian GDP-CI, whose value has steadily remained above 0.6 kg/\$, is the largest one. Conversely, Africa, Europe, North America, Oceania and South America have brought their GDP-CI below 0.6 kg/\$ during the triennium 2004–2006. It is worth noticing that both the Asian GDP and amount of emissions have increased (although at different rates), while this is not true for Europe and North America whose GDP has increased while their amount of emissions has decreased.

For what concerns the EE-CI, instead, Europe, North-America and Oceania have reduced it while Asia has basically kept it constant and Africa and South America have increased it. Conversely, the generation of electric

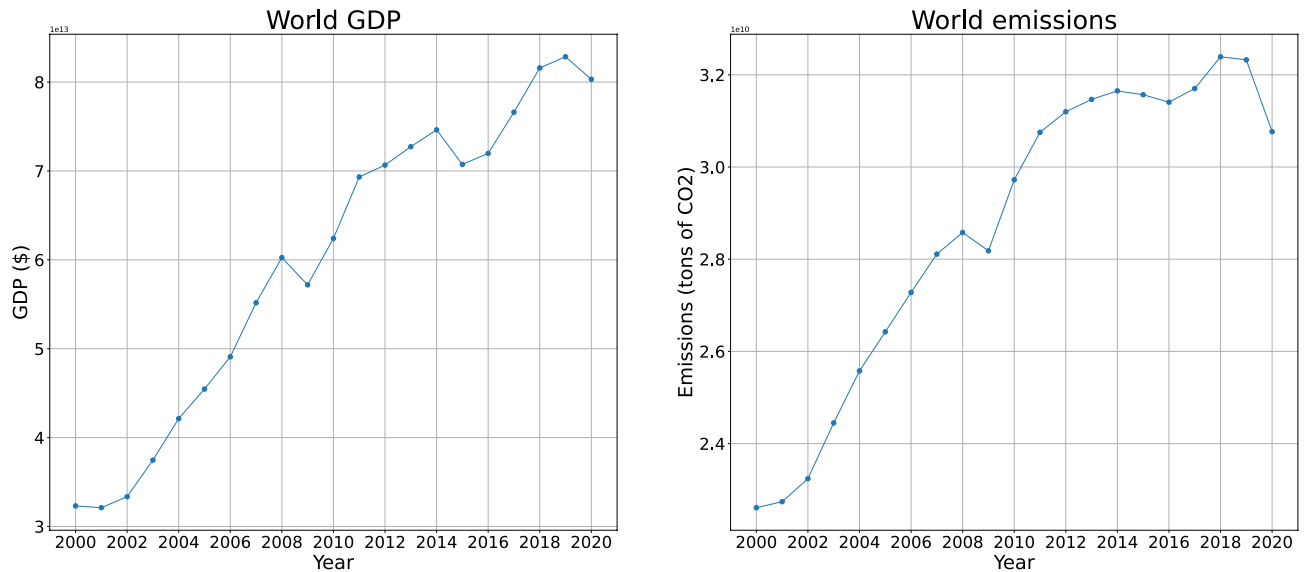


Figure 4. Both the world GDP and total amount of CO₂ emissions have risen over the past twenty-one years, suggesting that economic development has led to an increase of the overall amount of carbon released into the atmosphere; still, the impact of the two, main crises occurred within this period of time, i.e. the global, financial one (end of 2008) and the Covid-19 pandemic (beginning of 2020), is clearly visible.

energy has remained constant for Europe and North America, while any other continent has increased it—even if with differences—at a practically constant rate, over the 21 years covered by our dataset. Taken together, these results indicate that Europe and North-America have produced the same amount of electric energy in a progressively less carbon-intense way while the production of electric energy in any other continent has increased although its environmental impact has not decreased.

Country-wise scale. The previous trends can be further disaggregated at a country-level. For the sake of illustration, let us focus on G20 countries. Figure 6 reveals the co-existence of different tendencies, the two, far more interesting ones being those characterising China and the US. The US remains the leading country in terms of economic growth; however, while the amount of emissions released by the US has slowly started to decrease in 2008, the Chinese one has kept increasing up to 2012: then, after a stationary trend of almost five years, it has started increasing again.

For what concerns the GDP-CI, all countries have reduced their carbon intensity; still, a data-driven threshold clearly emerges, thus suggesting the presence of two, different groups. The first one is composed by China, India, the Russian Federation, Saudi Arabia and South Africa, which have kept their GDP-CI above 0.6 kg/\$—more precisely, the Russian Federation and South Africa have a GDP-CI which is above 1 kg/\$ while China, India and Saudi Arabia have a GDP-CI lying between 1 kg/\$ and 0.6 kg/\$; the second one is composed by France, Germany, Italy, Japan, Spain, United Kingdom and the US which, instead, have kept their GDP-CI below 0.6 kg/\$ throughout the whole period of time considered here. Indonesia and Turkey ‘lie in the middle’, with Indonesia having lowered its GDP-CI up to the ‘limiting’ value of 0.6 kg/\$ and Turkey having risen it during the last years of our dataset up to the same value. Interestingly, while both the Chinese GDP and amount of emissions have increased, the GDP of the US has increased while its total amount of emissions has decreased.

For what concerns the EE-CI, roughly the same groups of countries emerge: the first one is composed by Australia, China, India, Indonesia, Saudi Arabia and South Africa, whose EE-CI has been kept $\simeq 0.6$ kg/\$ for the vast majority of the temporal snapshots considered here (if not for the entire period); the second one is composed by Canada, France, Germany, Italy, Japan, Korea, Mexico, Spain, the Russian Federation, Turkey, United Kingdom and the US which, instead, have kept their EE-CI below 0.6 kg/\$.

Figure 7 illustrates the results of a more refined analysis, focusing on the temporal average of the percentage changes of the GDP, the EE-CI and the amount of emissions, computed as

$$\delta_{\text{GDP}}^t \equiv \frac{\text{GDP}_t - \text{GDP}_{t-1}}{\text{GDP}_t}, \quad t = 2001 \dots 2020 \quad (6)$$

$$\delta_{\text{EE-CI}}^t \equiv \frac{\text{EE-CI}_t - \text{EE-CI}_{t-1}}{\text{EE-CI}_t}, \quad t = 2001 \dots 2020 \quad (7)$$

$$\delta_{\text{CO}_2}^t \equiv \frac{\text{CO}_2_t - \text{CO}_2_{t-1}}{\text{CO}_2_t}, \quad t = 2001 \dots 2020 \quad (8)$$

for the countries belonging to G20. Two sets of countries, again, emerge, i.e. those for which both $\bar{\delta}_{\text{GDP}} > 0$ and $\bar{\delta}_{\text{CO}_2} > 0$ (i.e. Argentina, Australia, Brazil, China, India, Indonesia, Korea, the Russian Federation, Saudi

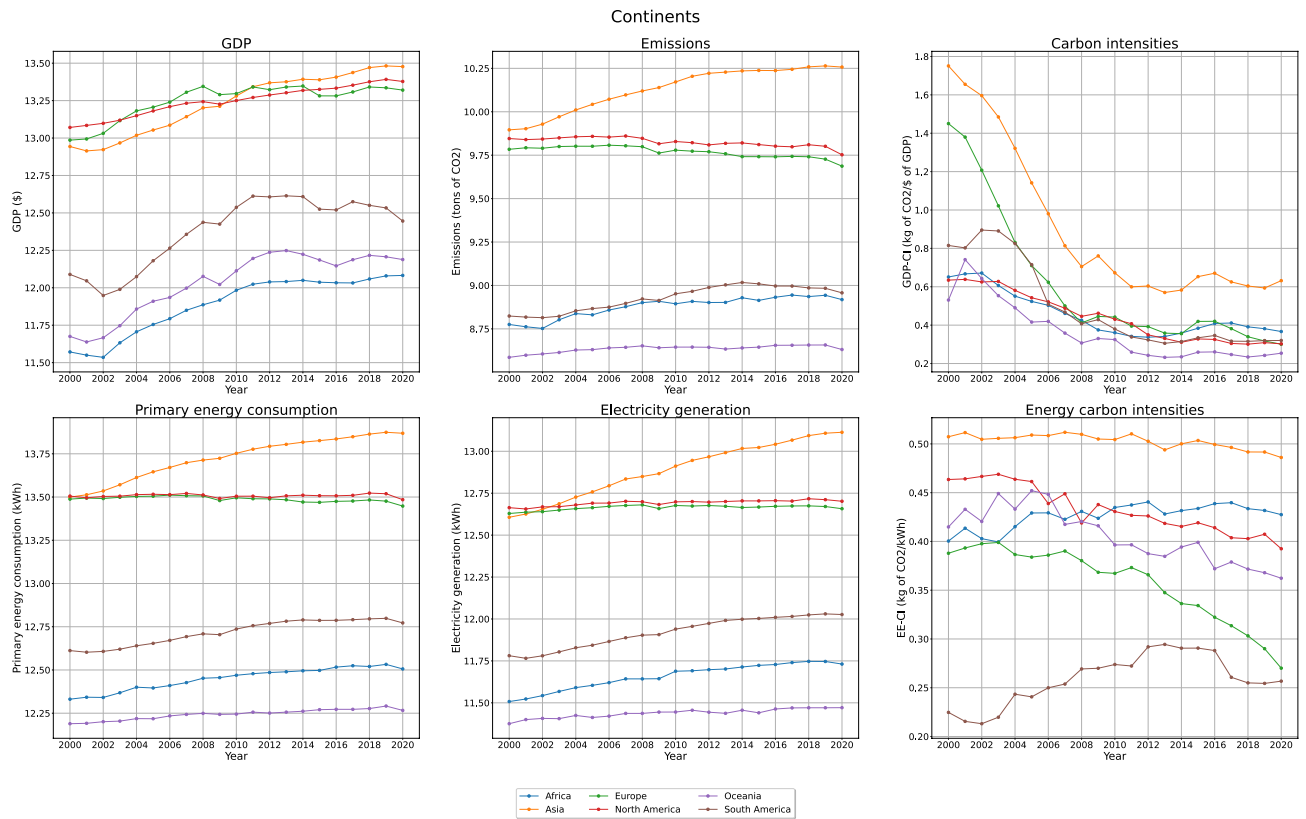


Figure 5. All continents have grown during the past twenty-one years. Still, different continents are characterised by different tendencies: Asia, Europe and North America have grown the most, the first one having ‘surpassed’ the other two in 2011. When considering their emissions, however, these three continents show a quite different behaviour: Europe and North America have undertaken a reduction pattern since 2009; Asia, instead, has kept increasing carbon emissions throughout the whole period of time considered here (although at a lower rate since 2011). For what concerns the GDP-CI, each continent has progressively reduced its carbon intensity: however, while Africa, Europe, North America, Oceania and South America have brought their GDP-CI below 0.6 kg/\$ during the years 2004–2006, Asia has kept it above 0.6 kg/\$. For what concerns the EE-CI, instead, Europe, North-America and Oceania have reduced it while Asia has basically kept it constant and Africa and South-America have increased it; conversely, the generation of electric energy has remained constant for all continents except Asia, where it has increased, at a practically constant rate, over the twenty-one years covered by our dataset.

Arabia, South Africa, Turkey—the developing ones, constituting the BRICS and MIKTA groups) and those for which $\bar{\delta}_{\text{GDP}} > 0$ but $\bar{\delta}_{\text{CO}_2} < 0$ (i.e. Canada, France, Germany, Italy, Japan, Mexico, Spain, United Kingdom and the US); notice also that for most of the countries belonging to the first (second) set, $\bar{\delta}_{\text{EE-CI}} > 0$ ($\bar{\delta}_{\text{EE-CI}} < 0$).

To gain further insight into the behaviour of G20 countries, we have divided the area of our subplots in quadrants. Figure 7c lets four groups of countries emerge: the ones with $\bar{\delta}_{\text{CO}_2} < 0$ and $\bar{\delta}_{\text{EE-CI}} < 0$, i.e. Canada, Germany, Italy, Spain, Mexico and the US; the ones with $\bar{\delta}_{\text{CO}_2} < 0$ and $\bar{\delta}_{\text{EE-CI}} > 0$, i.e. France and Japan; the ones with $\bar{\delta}_{\text{CO}_2} > 0$ and $\bar{\delta}_{\text{EE-CI}} > 0$, i.e. Argentina, Brazil and Indonesia; the ones with $\bar{\delta}_{\text{CO}_2} > 0$ and $\bar{\delta}_{\text{EE-CI}} < 0$, i.e. Australia, China, India, Korea, the Russian Federation, Saudi Arabia, South Africa and Turkey. Upon excluding the countries that have employed emissions to rise the production of electric energy—assumed to be one of the main drivers of economic development—we are left with the group of nations that have constantly played the role of ‘net exporters’ (among which the entire group of BRICS, with the only exception of Brazil).

Taken together, our results suggest that (1) the countries for which both $\bar{\delta}_{\text{GDP}} > 0$ and $\bar{\delta}_{\text{CO}_2} > 0$ export towards the countries for which $\bar{\delta}_{\text{GDP}} > 0$ but $\bar{\delta}_{\text{CO}_2} < 0$; (2) (only) the countries belonging to the second set have grown in a progressively less carbon-intense way. Appendix B. Evolution of the carbon trade network over the years 2000–2020

This appendix is devoted to discuss the evolution of the global network properties of the CTN over the twenty-one years covered by our dataset. Let us start by defining the link density, reading

$$d = \frac{L}{N(N-1)} \quad (9)$$

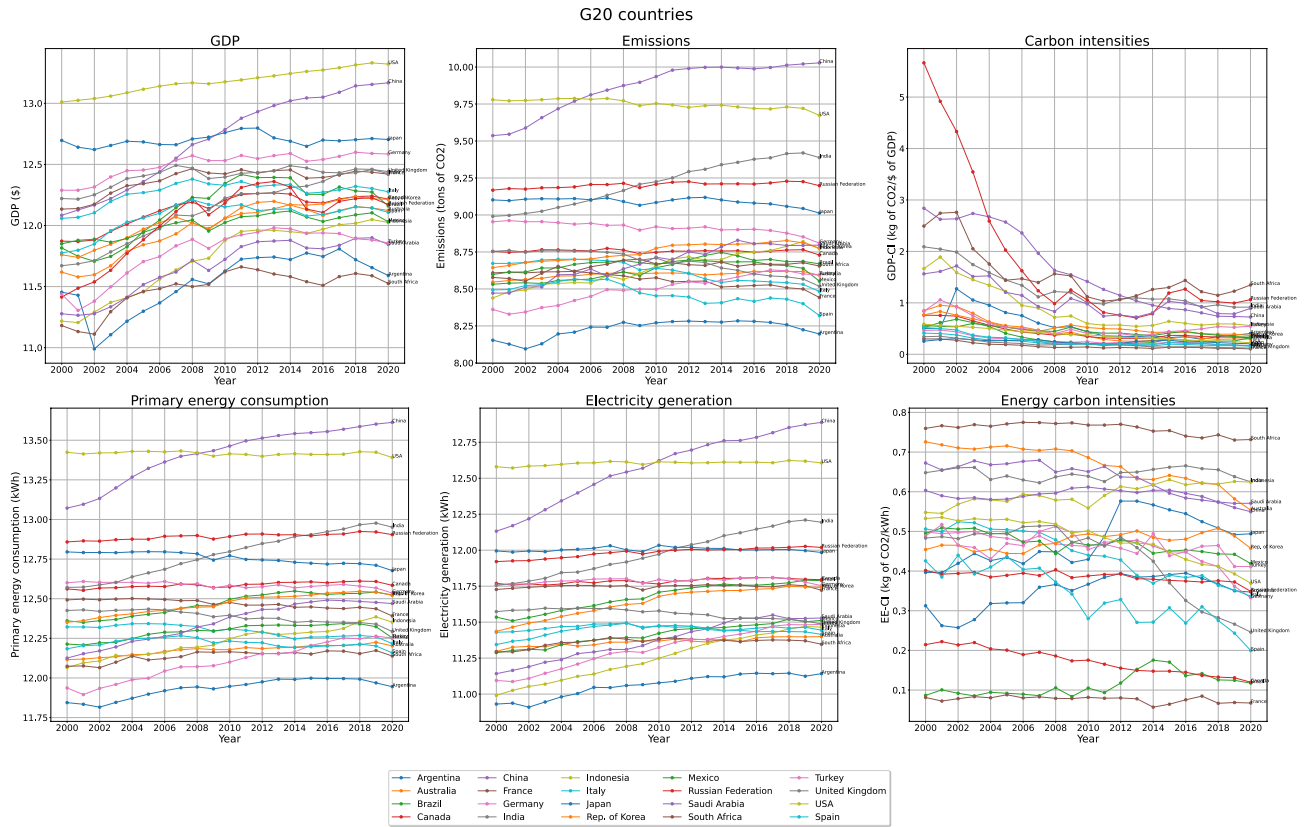


Figure 6. All countries have grown during the past 21 years. Still, different countries are characterised by different tendencies. The two, far more interesting ones are those characterising China and the US. For what concerns the economic growth, the US remains the leading country; however, while the US emissions have (slowly) started to decrease in 2008, the Chinese ones have kept increasing up to 2012: then, after a stationary trend of almost five years, they have started increasing again. For what concerns the GDP-CI, all countries have reduced their carbon intensity: however, the Russian Federation and South Africa have kept it above 1 kg/\$ while China, India and Saudi Arabia have kept it between 1 kg/\$ and 0.6 kg/\$; on the other hand, France, Germany, Italy, Japan, Spain, United Kingdom and the US have kept their GDP-CI below 0.6 kg/\$ throughout the whole period of time considered here. For what concerns the EE-CI, roughly the same groups of countries emerge.

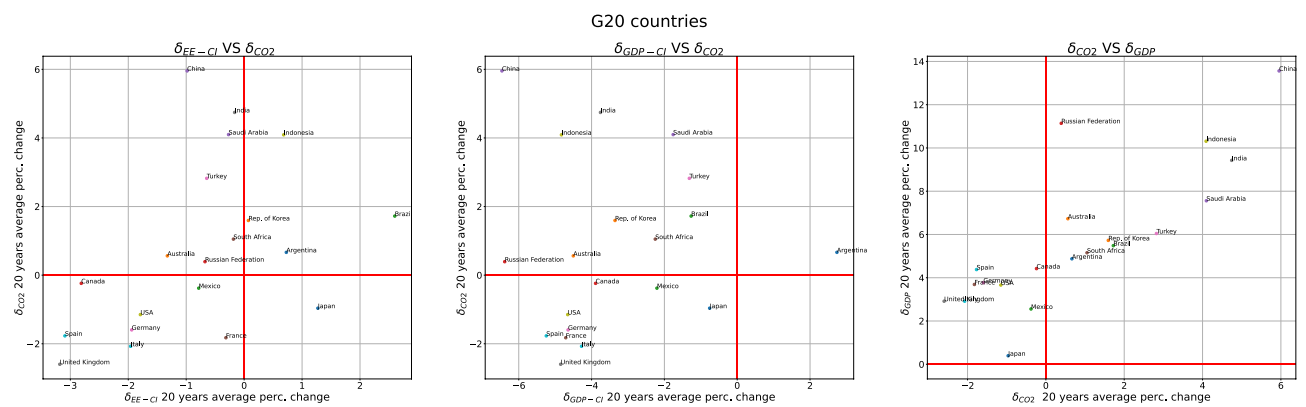


Figure 7. Temporal average of the percentual changes of the GDP, the EE-CI and the amount of emissions, for the countries belonging to G20. As our analysis reveals, two sets of countries emerge, i.e. those for which both $\delta_{GDP} > 0$ and $\delta_{CO2} > 0$ (i.e. Argentina, Australia, Brazil, China, India, Indonesia, Korea, the Russian Federation, Saudi Arabia, South Africa, Turkey) and those for which $\delta_{GDP} > 0$ but $\delta_{CO2} < 0$ (i.e. Canada, France, Germany, Italy, Japan, Mexico, Spain, United Kingdom and the US). As our analysis suggests, the countries belonging to the first set export towards the countries belonging to the second set. Moreover, the analysis of the sign of δ_{EE-CI} reveals that (only) the countries belonging to the second set have grown in a progressively less carbon-intensive way.

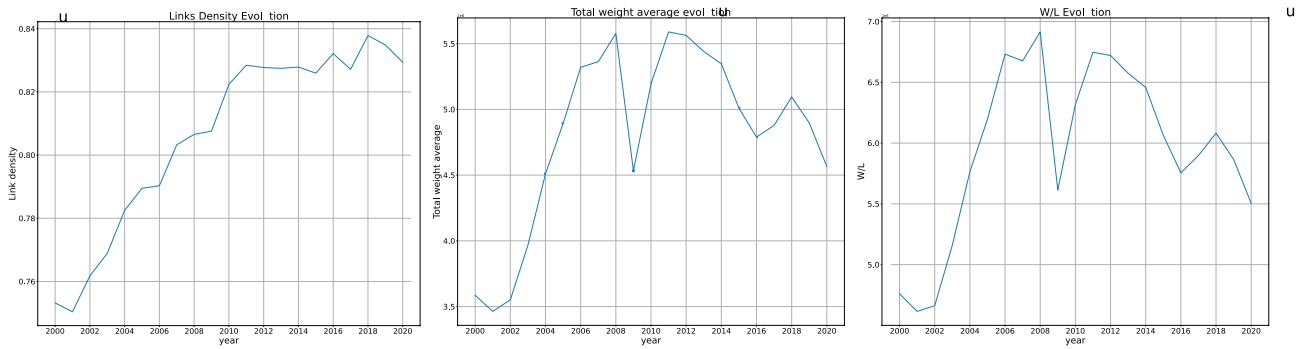


Figure 8. Left panel: evolution of the CTN link density, that has risen up to the value of ≈ 0.83 . Middle panel: evolution of the CTN average weight, that has increased from 2002 to 2008. Since the network volume is constant, its rise points out that the worldwide amount of emissions embedded into trade exchanges has risen as well; from 2008 on, however, an overall decreasing trend can be appreciated, affected by the two, main crises occurred during this period. Right panel: evolution of the weight-per-link, confirming that, since 2008, individual exchanges have become less carbon-intensive.

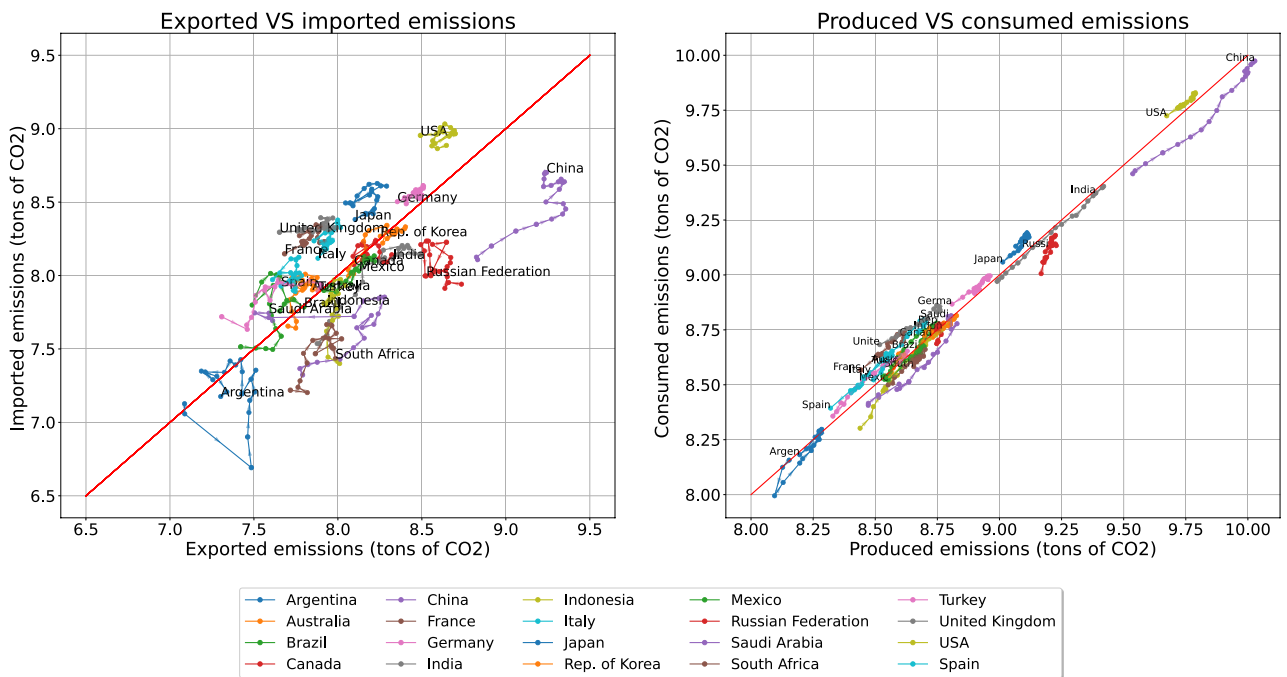


Figure 9. Left panel: scattering a country out-strength versus its in-strength reveals its behaviour over the twenty-one years considered here. Argentina, Canada, China, India, Indonesia, Korea, Mexico, the Russian Federation, Saudi Arabia and South Africa are countries whose amount of exported emissions has exceeded the amount of imported emissions; on the other hand, Australia, Brazil, France, Germany, Italy, Japan, Spain, Turkey, the UK and the US are countries whose amount of imported emissions has exceeded the amount of exported emissions. Right panel: the trajectory of G20 countries in the plane defined by scattering the amount of consumed emissions versus the amount of produced emissions. Names of countries indicate the last year covered by our dataset, i.e. 2020.

where $N = 111$ and $L = \sum_{i=1}^N \sum_{j(\neq i)=1}^N a_{ij}$ where the generic entry a_{ij} is 1 if $c_{ij} > 0$ and zero otherwise. As shown in Fig. 8, the CTN link density has risen up to ≈ 0.83 . The weighted counterpart of the link density is the average weight, reading

$$\bar{W} = \frac{W}{N(N - 1)} \tag{10}$$

where $W = \sum_{i=1}^N \sum_{j(\neq i)=1}^N c_{ij}$. As shown in Fig. 8, the CTN average weight has increased from 2002 to 2008: since the network volume is constant, this means that the total weight, i.e. the worldwide amount of emissions embedded into trade exchanges has risen; since 2008, however, an overall decreasing trend ('affected' by the two,

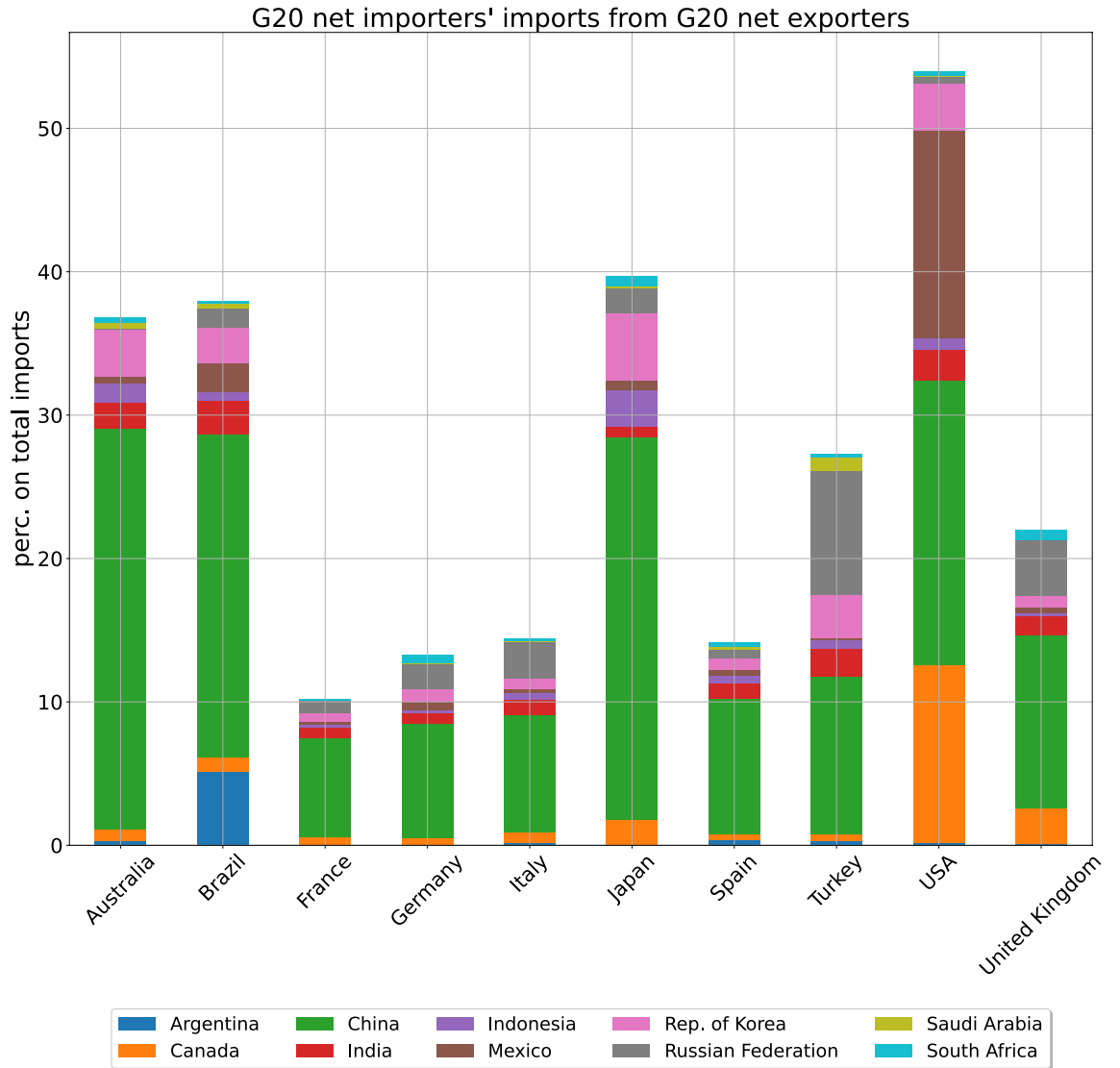


Figure 10. Composition of the import basket of each ‘net consumer’, belonging to G20, partitioned according to the share of emissions coming from each ‘net producer’, belonging to G20 as well. The role played by ‘net exporters’ of emissions is, in some cases, substantial as it amounts at (more than) the 50% of the total import of the US, $\approx 40\%$ of the total import of Australia, Brazil and Japan, $\approx 30\%$ of the total import of Turkey, $\approx 20\%$ of the total import of the United Kingdom.

main crises occurred during this period) can be appreciated. Plotting the evolution of the ratio W/L confirms that individual exchanges have become less carbon-intensive.

Different accounting criteria impact on different sets of countries: in fact, a context where attributions are production-based disfavors those whose amount of exported emissions is larger than the amount of imported emissions. This consideration suggests us to (try to) classify each country either as a ‘net producer’ or as a ‘net consumer’ of emissions. To this aim, let us consider that the amount of consumed emissions can be re-written as

$$\text{Consumed Emissions}_i^y = \text{Produced Emissions}_i^y + [t^{in}]_i^y - [t^{out}]_i^y \tag{11}$$

i.e. as the amount of produced emissions, plus those due to import and minus those due to export—to be attributed to other countries as a consequence of the trading activity ‘stimulated’ by them. From the equation above, it follows that

$$\text{Consumed Emissions}_i^y - \text{Produced Emissions}_i^y = [t^{in}]_i^y - [t^{out}]_i^y \tag{12}$$

a relationship establishing that the difference between the total amount of consumed emissions and the total amount of produced emissions by country i matches the difference between its total import and its total export. If

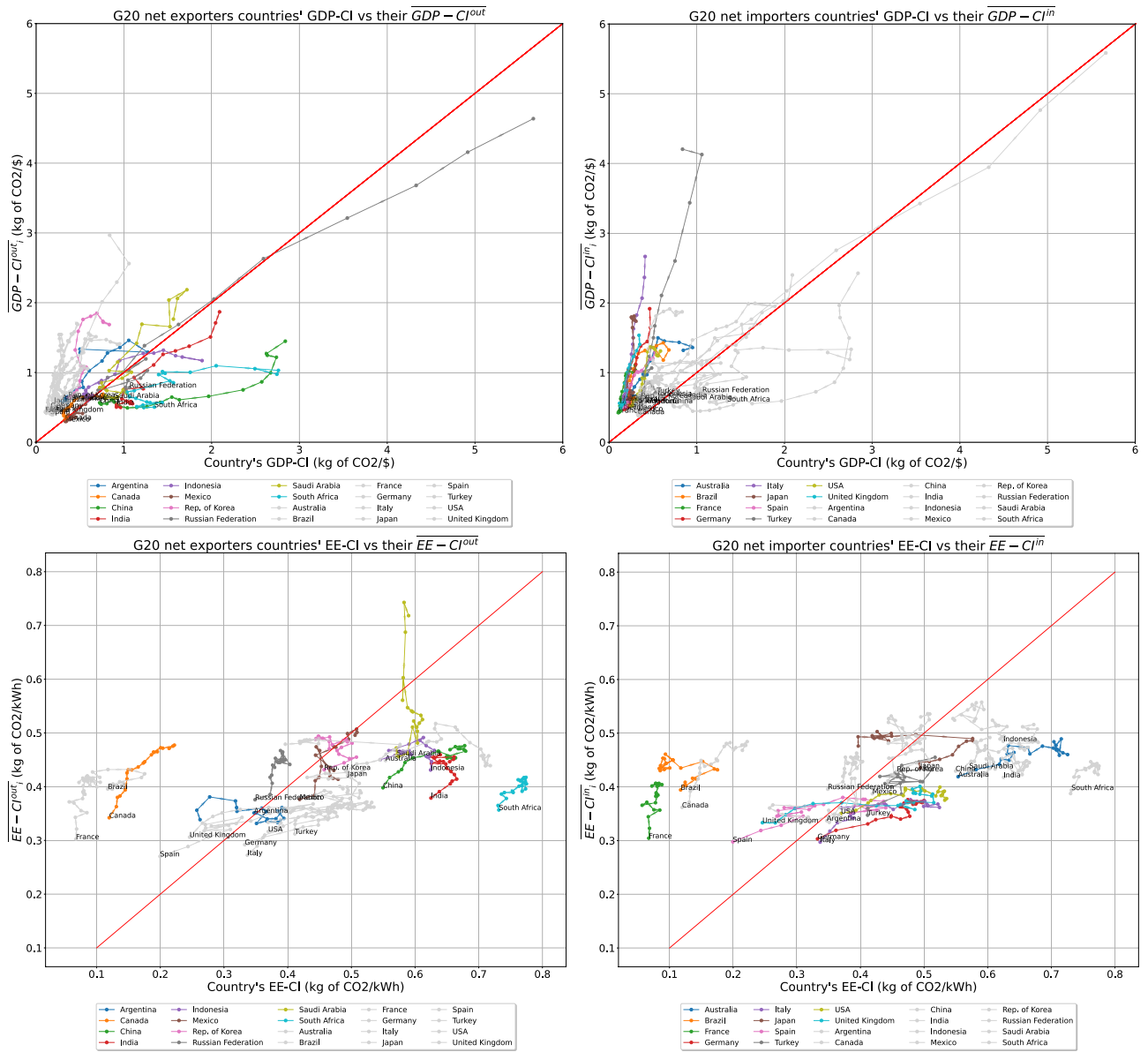


Figure 11. Top panels: scattering the weighted mean of the GDP-CIs of each country ‘exporting partners’ versus its own GDP-CI reveals that many ‘net exporters’ are less economically efficient than the countries they export to (left panel); analogously, scattering the weighted mean of the GDP-CIs of each country ‘importing partners’ versus its own GDP-CI reveals that many ‘net importers’ are more economically efficient than the countries they import from (right panel). Bottom panels: scattering the weighted mean of the EE-CIs of each country ‘exporting partners’ versus its own EE-CI reveals that many ‘net exporters’ have an EE-CI that is steadily larger than the one of the neighbours they export to (left panel); analogously, scattering the weighted mean of the EE-CIs of each country ‘importing partners’ versus its own EE-CI reveals that many ‘net importers’ still have an EE-CI which is larger than the EE-CI of the neighbours they import from (right panel); their trajectories, however, have evolved towards the left, an outcome suggesting that their EE-CI has decreased, over the past twenty-one years, at a higher rate than that of their partners.

$$\text{Consumed Emissions}_i^y - \text{Produced Emissions}_i^y = [t^{in}]_i^y - [t^{out}]_i^y \geq 0 \tag{13}$$

then, country i is a ‘net importer’, or ‘net consumer’, of emissions; if, on the other hand,

$$\text{Consumed Emissions}_i^y - \text{Produced Emissions}_i^y = [t^{in}]_i^y - [t^{out}]_i^y \leq 0 \tag{14}$$

then, country i is a ‘net exporter’, or ‘net producer’, of emissions. Let us, now, spot the trading behaviour of each country, by scattering its out-strength versus its in-strength: as Fig. 9 shows, China, India, Indonesia, Mexico, the Russian Federation and South Africa are countries whose amount of exported emissions has steadily exceeded the amount of imported emissions; on the other hand, Brazil, France, Germany, Italy, Japan, Spain, Turkey, the

Carbon Intensities with different GDPs

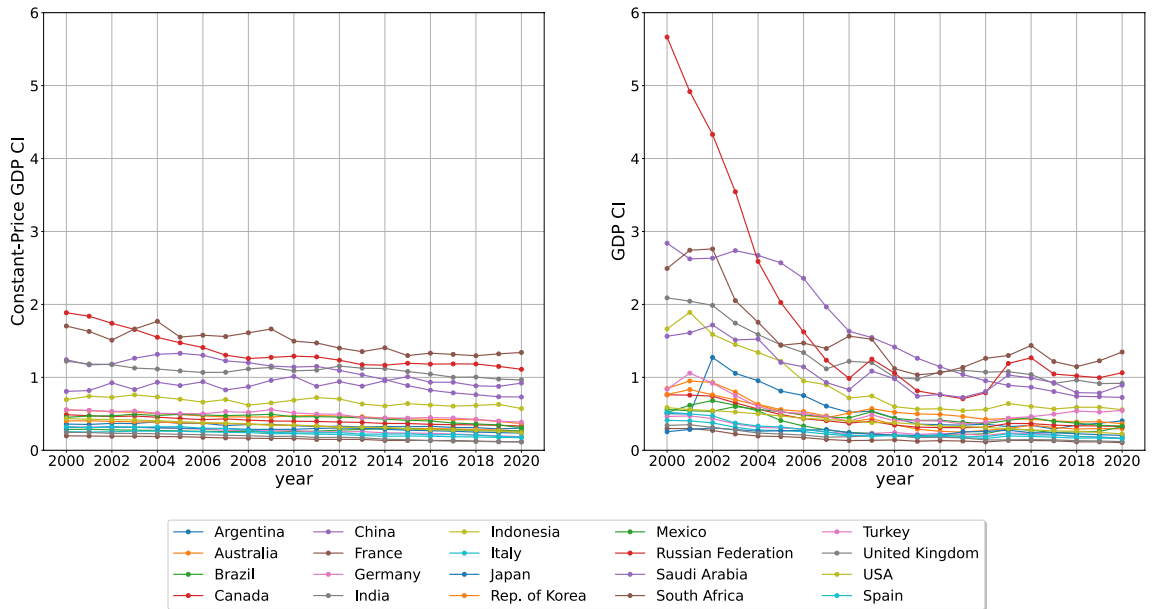


Figure 12. GDP-CI values, calculated by employing the 2015 constant-price GDP (left panel) and the nominal GDP (right panel): as we approach 2020, the two sets of values become closer, a result implying that the overall picture provided by Fig. 1 does not change (see also Fig. 13). The average of the relative errors $\delta_{GDP-CI} = |(GDP-CI_n - GDP-CI_{cp})/GDP-CI_n| \cdot 100$ decreases from $\lesssim 40\%$ in 2000 to $\simeq 8\%$ in 2020.

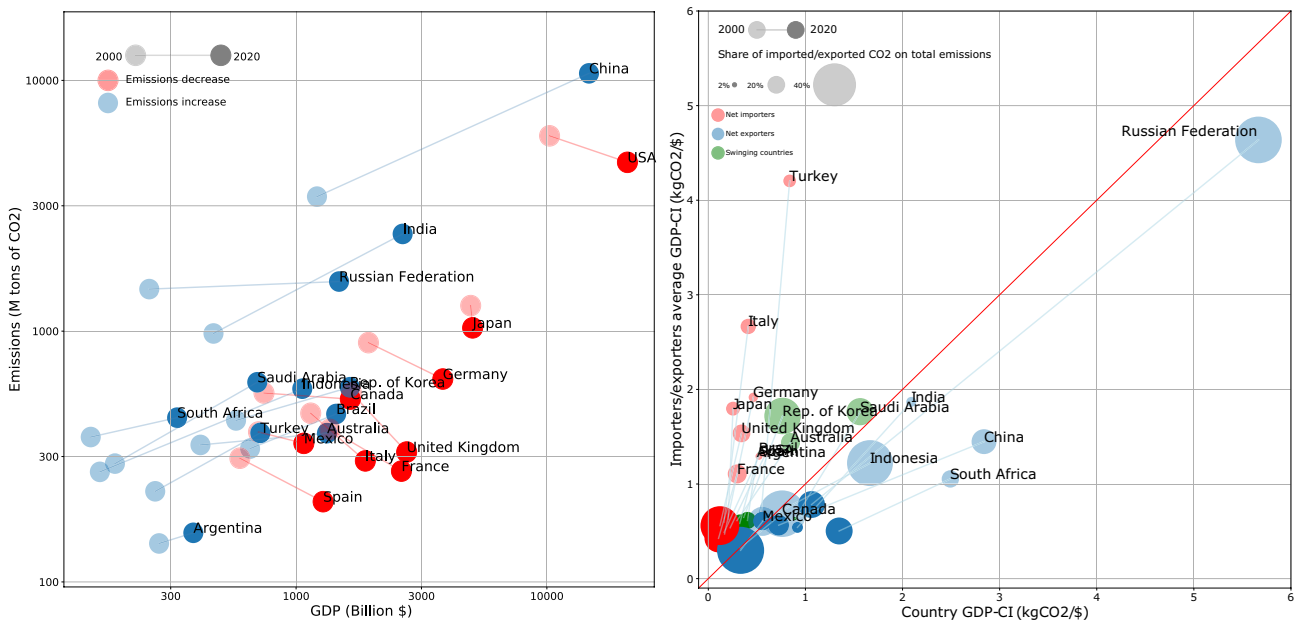


Figure 13. Employing the nominal GDP-CI does not change the overall picture provided by Fig. 1 as (1) the two tendencies characterising G20 countries can still be identified; (2) one can still conclude that countries whose export exceeds the import, export towards ‘cleaner’ countries; equivalently, countries whose import exceeds the export, import from ‘less clean’ countries. The size of ‘net exporter’ i is proportional to $[t^{out}]_i^y / PE_i^y$; the size of ‘net importer’ i is proportional to $[t^{in}]_i^y / PE_i^y$. Numbers are plotted on a doubly logarithmic scale. Names of countries indicate the last year covered by our dataset, i.e. 2020.

UK and the US are countries whose amount of imported emissions has steadily exceeded the amount of exported emissions. The other G20 countries are ‘swinging states’ whose role changes during the years: specifically, Argentina, Canada, Korea and Saudi Arabia have mainly served as ‘net exporters’ while Australia has mainly served as ‘net importer’. Notice that the set of ‘net exporters’ roughly matches the group of nations whose GDP-CI is $\simeq 0.6$ kg/\$.

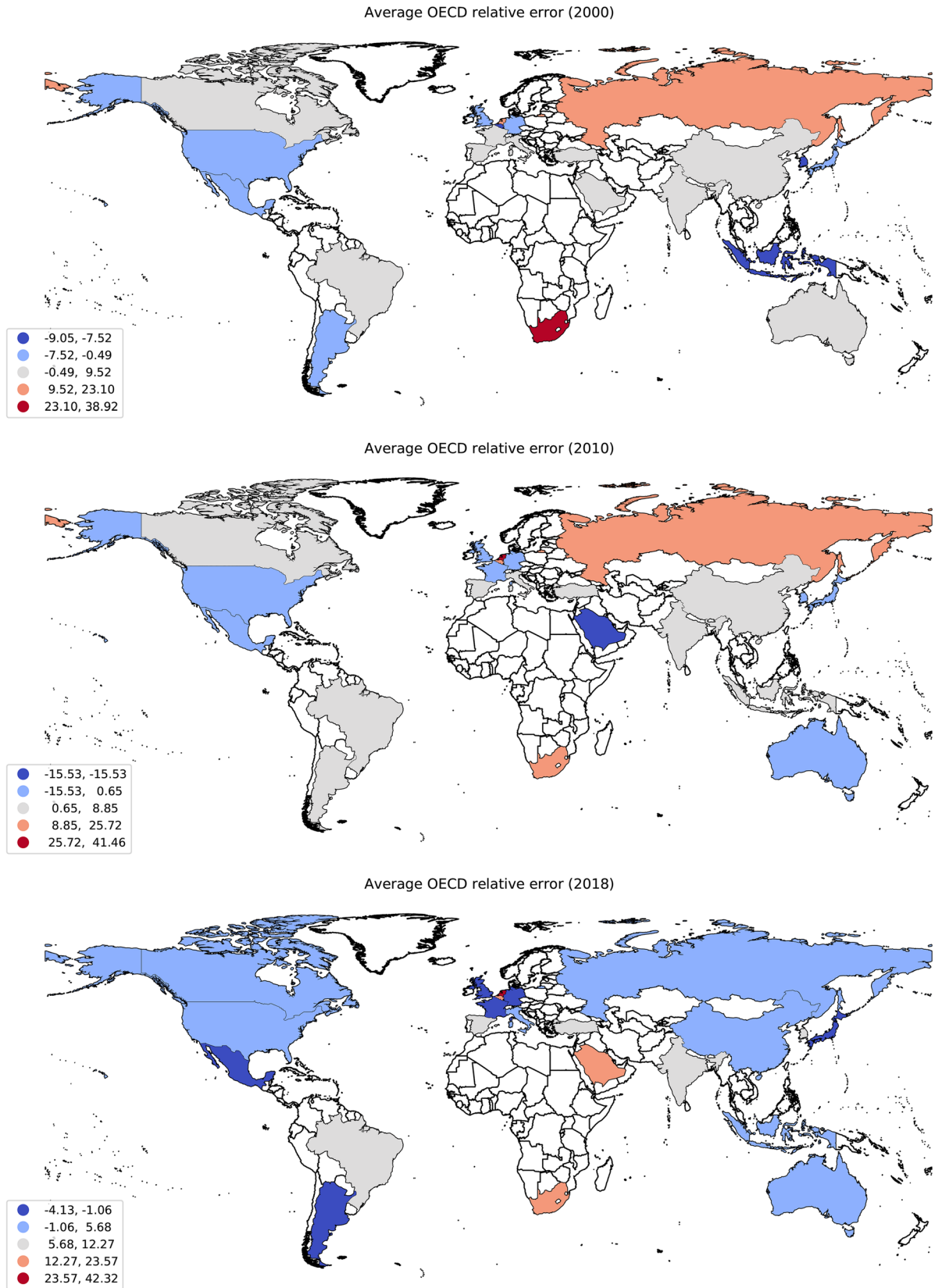


Figure 14. Our estimates of the consumed emissions do not differ much from the estimates provided by OECD: computing such discrepancies as the relative errors $\delta_{CE_i^y} = |(CE - CE_{OECD})/CE_i^y| \cdot 100, \forall i, y$ reveals that their average steadily amounts at $\simeq 6\%$. Source: authors' elaboration with Python 3.8 (<https://www.python.org/downloads/release/python-380/>) and Geopandas 0.10.2 (<https://geopandas.org/en/stable/index.html>).

Partitioning the group of G20 countries into the two, aforementioned sets and studying the evolution of the weight of the connections directed from ‘net exporters’ towards ‘net importers’ leads to Fig. 3: as it reveals, the total amount of carbon emissions embedded into the export of the first group of countries has, overall, increased. While this is true in absolute terms, the share of emissions directed towards the group of ‘net importers’ has diminished, a result indicating that the role played by the emissions embedded into the trading relationships directed from ‘net exporters’ towards ‘net importers’ has become increasingly relevant. For the sake of completeness, we have partitioned the import of each ‘net consumer’ according to the share of emissions due to each ‘net producer’: as Fig. 10 reveals, the role played by the ‘net exporters’ of emissions is, in some cases, substantial, amounting at (more than) the 50% of the total import of the US, \simeq 40% of the total import of Australia, Brazil and Japan, \simeq 30% of the total import of Turkey, \simeq 20% of the total import of the United Kingdom.

As we have pointed out in the main text, observing a decrease of the carbon intensities does not necessarily lead to a conclusive answer about the ‘cleanness’ of an agent production (be it a continent or a country) as it may adopt strategies such as delocalisation: the likelihood of such a possibility can be explicitly inspected upon analysing the behaviour of a country neighbours. The results obtained so far suggest us to check the identity of the countries importing from the ‘net exporters’ of emissions: should the former ones have smaller GDP-CI and EE-CI, one may indeed suspect them to take advantage of the current regulation about emissions accounting. To this aim, let us consider network properties capturing the behaviour of a node neighbours: in particular, we can define the weighted average nearest neighbours GDP-CI as

$$\overline{\text{GDP-CI}}_i^{\text{out}} = \frac{\sum_{j=1}^N w_{ij} \cdot \text{GDP-CI}_j}{\sum_{j=1}^N w_{ij}} = \frac{\sum_{j=1}^N w_{ij} \cdot \text{GDP-CI}_j}{s_i^{\text{out}}}, \quad \forall i, \quad (15)$$

$$\overline{\text{GDP-CI}}_i^{\text{in}} = \frac{\sum_{j=1}^N w_{ji} \cdot \text{GDP-CI}_j}{\sum_{j=1}^N w_{ji}} = \frac{\sum_{j=1}^N w_{ji} \cdot \text{GDP-CI}_j}{s_i^{\text{in}}}, \quad \forall i, \quad (16)$$

i.e. distinguishing the weighted mean of the GDP-CIs of the nodes pointed by node i from the weighted mean of the GDP-CIs of the nodes pointing towards node i . Analogously, we can define the weighted average nearest neighbours EE-CI as

$$\overline{\text{EE-CI}}_i^{\text{out}} = \frac{\sum_{j=1}^N w_{ij} \cdot \text{EE-CI}_j}{\sum_{j=1}^N w_{ij}} = \frac{\sum_{j=1}^N w_{ij} \cdot \text{EE-CI}_j}{s_i^{\text{out}}}, \quad \forall i, \quad (17)$$

$$\overline{\text{EE-CI}}_i^{\text{in}} = \frac{\sum_{j=1}^N w_{ji} \cdot \text{EE-CI}_j}{\sum_{j=1}^N w_{ji}} = \frac{\sum_{j=1}^N w_{ji} \cdot \text{EE-CI}_j}{s_i^{\text{in}}}, \quad \forall i; \quad (18)$$

as evident from our definitions, $s_i^{\text{out}} = \sum_{j=1}^N w_{ij}$ is nothing but the purely trade-induced out-strength of node i while $s_i^{\text{in}} = \sum_{j=1}^N w_{ji}$ is nothing but the purely trade-induced in-strength of node i .

The top-left panel of Fig. 11 shows the evolution of the set of values $\{\overline{\text{GDP-CI}}_i^{\text{out}}\}$, scattered versus the set of values $\{\text{GDP-CI}_i\}$, for the ‘net exporters’: as it can be appreciated, most of their GDP-CIs are steadily larger than the GDP-CI of the neighbours they export to. The top-right panel of Fig. 11 shows the evolution of the set of values $\{\overline{\text{GDP-CI}}_i^{\text{in}}\}$, scattered versus the set of values $\{\text{GDP-CI}_i\}$, for the ‘net importers’: in this case, most of their GDP-CIs are steadily smaller than the GDP-CI of the neighbours they import from.

The bottom panels of Fig. 11 show the evolution of the set of values $\{\overline{\text{EE-CI}}_i^{\text{out}}\}$, scattered versus the set of values $\{\text{EE-CI}_i\}$ and the evolution of the set of values $\{\overline{\text{EE-CI}}_i^{\text{in}}\}$, scattered versus the set of values $\{\text{EE-CI}_i\}$ for the same sets of countries as above. Many of the trajectories of ‘net exporters’ lie below the identity line; although many of the trajectories of ‘net importers’ lie below the identity line as well, it should be noticed that they evolve in a horizontal fashion, moving from right to left, an outcome suggesting that their EE-CI has decreased over the past twenty-one years while that of their partners is not. Overall, this leads us to conclude that countries whose export exceeds the import, export towards ‘cleaner’ countries; equivalently, countries whose import exceeds the export, import from ‘less clean’ countries.

Appendix C. Consistency checks. This appendix is devoted to illustrate the results of a number of consistency checks.

First, let us show that employing the 2015 constant-price GDP, instead of the nominal GDP, does not change the overall picture following by our results. As Fig. 12 shows, the effect of the inflation is larger for the first years of our dataset; as we approach 2020, however, the values of the GDP-CI calculated by employing the 2015 constant-price GDP become closer to the values of the GDP-CI calculated by employing the nominal GDP. This, in turn, leads to Fig. 1, closely resembling Fig. 13. More quantitatively, the average of the relative errors $\delta_{\text{GDP-CI}} = |(\text{GDP-CI}_n - \text{GDP-CI}_{\text{cp}})/\text{GDP-CI}_n| \cdot 100$, for the G20 countries, decreases from \lesssim 40% in 2000 to \simeq 8% in 2020.

Second, let us show that the values of consumed emissions derived by us, and computed by using the nominal GDP, do not differ much from those computed by OECD (as the sum of the amount of carbon that is emitted for domestic production and the amount of carbon that is emitted abroad and embodied into imports). The results are depicted in Fig. 14, showing the set of relative errors $\delta_{CE_i^y} = |(CE - CE_{OECD})/CE_i^y| \cdot 100$, whose average, for the G20 countries, steadily amounts at $\simeq 6\%$.

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References

1. Canadell, J. G. *et al.* Contributions to accelerating atmospheric CO₂ growth from economic activity, carbon intensity and efficiency of natural sinks. *Proc. Natl. Acad. Sci.* **104**, 18866 (2007).
2. UN, 2006. IPCC Guidelines for National Greenhouse Gas Inventories (2006).
3. UN, 2019. Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (2019).
4. Peters, G. & Hertwich, E. CO₂ embodied in international trade with implications for global climate policy. *Environ. Sci. Technol.* **42**, 1401 (2008).
5. Hertwich, E. & Peters, G. Carbon footprint of nations: A global, trade-linked analysis. *Environ. Sci. Technol.* **43**, 6414 (2009).
6. Davis, S. J. & Caldeira, K. Consumption-based accounting of CO₂ emissions. *Proc. Natl. Acad. Sci.* **107**, 5687 (2010).
7. Davis, S. J., Peters, G. P. & Caldeira, K. The supply chain of CO₂ emissions. *Proc. Natl. Acad. Sci.* **108**, 18554 (2011).
8. Liddle, B. Consumption-based accounting and the trade-carbon emissions nexus in Asia: A heterogeneous, common factor panel analysis. *Sustainability* **10**, 1456. <https://doi.org/10.3390/su10103627> (2018).
9. Khan, Z., Ali, M., Jinyu, L., Shahbaz, M. & Siqun, Y. Consumption-based carbon emissions and trade nexus: Evidence from nine oil exporting countries. *Energy Econ.* **89**, 104806 (2020).
10. Franzen, A. & Mader, S. Consumption-based versus production-based accounting of CO₂ emissions: Is there evidence for carbon leakage?. *Environ. Sci. Policy* **84**, 34 (2018).
11. Baumert, N., Kander, A., Jiborn, M., Kulionis, V. & Nielsen, T. D. Global outsourcing of carbon emissions 1995–2009: A reassessment. *Environ. Sci. Policy* **92**, 228 (2019).
12. Grubb, M. *et al.* Carbon leakage, consumption, and trade. *Annu. Rev. Environ. Resour.* **47**, 753 (2022).
13. Zhang, Q. & Fang, K. Comment on “consumption-based versus production-based accounting of CO₂ emissions: Is there evidence for carbon leakage?”. *Environ. Sci. Policy* **101**, 94 (2019).
14. Fernández-Amador, O., Francois, J. F., Oberdabernig, D. A., & Tomberger, P. Carbon dioxide emissions and economic growth: An assessment based on production and consumption emission inventories. *Ecol. Econ.* **135**, 269 (2017).
15. Böhringer, C., Rosendahl, K. E. & Storøsten, H. B. Robust policies to mitigate carbon leakage. *J. Public Econ.* **149**, 35 (2017).
16. Misch, F. & Wingender, M. P. *Revisiting carbon leakage* (International Monetary Fund, 2021).
17. Sun, X., Gao, X., Jia, X. & Liu, X. Indirect energy flow between industrial sectors in China: A complex network approach. *Energy* **94**, 195 (2016).
18. Wu, X., Guo, J., Li, C., Chen, G. & Ji, X. Carbon emissions embodied in the global supply chain: Intermediate and final trade imbalances. *Sci. Total Env.* **707**, 134670 (2019).
19. Chen, B. *et al.* Global energy flows embodied in international trade: A combination of environmentally extended inputoutput analysis and complex network analysis. *Appl. Energy* **2018**, 210 (2018).
20. Zhu, Y., Shi, Y., Wu, J., Wu, L. & Xiong, W. Exploring the characteristics of CO₂ emissions embodied in international trade and the fair share of responsibility. *Ecol. Econ.* **146**, 574 (2018).
21. Kang, C. *et al.* Carbon emission flow in networks. *Sci. Rep.* **2**, 479 (2012).
22. Zhuang, M. *et al.* Emissions of non-CO₂ greenhouse gases from livestock in China during 2000–2015: Magnitude, trends and spatiotemporal patterns. *J. Environ. Manage.* **242**, 40 (2019).
23. Caro, D., Bastianoni, S., Borghesi, S. & Maria, F. On the feasibility of a consumer-based allocation method in national GHG inventories. *Ecol. Ind.* **36**, 640 (2014).
24. Albert, R. & Barabási, A.-L. Statistical mechanics of complex networks. *Rev. Mod. Phys.* **74**, 47 (2002).
25. Boccaletti, S., Latora, V., Moreno, Y., Chavez, M. & Hwang, D.-U. Complex networks: Structure and dynamics. *Phys. Rep.* **424**, 175 (2006).
26. Squartini, T., Caldarelli, G., Cimini, G., Gabrielli, A. & Garlaschelli, D. Reconstruction methods for networks: The case of economic and financial systems. *Phys. Rep.* **757**, 1 (2018).
27. Cimini, G., Mastrandrea, R. & Squartini, T. *Reconstructing Networks* (Cambridge University Press, 2021).
28. Caro, D., Pulselli, F., Borghesi, S. & Bastianoni, S. Mapping the international flows of GHG emissions within a more feasible consumption-based framework. *J. Clean. Prod.* **147**, 142 (2017).
29. Beck, U. R., Kruse-Andersen, P. K. & Stewart, L. B. Carbon leakage in a small open economy: The importance of international climate policies. *Energy Econ.* **117**, 106447 (2023).
30. Michel, B. Does offshoring contribute to reducing domestic air emissions? evidence from Belgian manufacturing. *Ecol. Econ.* **95**, 73 (2013).
31. Levinson, A. Offshoring pollution: Is the united states increasingly importing polluting goods. *Rev. Environ. Econ. Policy* **4**, 63 (2010).
32. Dussaux, D., Vona, F. & Dechezlepretre, A. What drives emission reductions? Carbon offshoring vs. environmental policy impacts in French manufacturing companies, ETH Zurich Research Collection for scientific publications and research data (2020).
33. Panigrahi, S. Offshoring climate change to carbon havens: Carbon leakages pt. I. *Econ. Rev.* **2022**, 896 (2022).
34. Dai, R., Duan, R., Liang, H. & Ng, L. Outsourcing climate change. In *European Corporate Governance Institute—Finance Working Paper No. 723/2021* (2021).
35. Sun, X., Mi, Z., Cheng, L., Coffman, D. & Liu, Y. The carbon border adjustment mechanism is inefficient in addressing carbon leakage and results in unfair welfare losses. *Fundam. Res.* <https://doi.org/10.1016/j.fmre.2023.02.026> (2023).

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Author contributions

Study conception and design: AF, RM, TS. Data collection: AF, GG. Analysis and interpretation of results: AF, GG, CK, RM, TS. Draft manuscript preparation: AF, RM, TS. Manuscript revision: AF, GG, CK, RM, TS.

Competing interests

The authors declare no competing interests.

Additional information

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