Exploring carbon emissions and international inequality in a globalized world: a multiregional-multisectoral perspective

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Abstract:

The phenomenon of economic convergence has been investigated from different perspectives, aiming to analyze whether economies move towards a common growth path or tend to diverge over time, and the consequences of this for economic cohesion. However, these consequences for the evolution of CO_2 emissions in the study of global convergence of CO_2 emissions, and the implications in terms of pollution, inequality, and income-dependence have received less attention in the literature of convergence. The increasing globalization of economies and the rising fragmentation of supply chains imply many countries involved in the production chains and, in consequence, a vision is needed of worldwide emissions associated with these processes. In this paper, we use the multisectoral and multiregional perspective provided by a multiregional input-output model (MRIO), and the associated databases, to analyze the evolution of inequality in CO_2 emissions, paying attention to the roles played by regional specificities and/or productive structures. MRIO models and indicators presented, provide the basis to assess to what extent countries and/or sectors are walking towards a common path or, on the contrary, tend to be more unequal over time. Given the role that structure, final demands and international trade play in these models, we can offer a novel structural view of the *convergence* issue. Moreover, MRIO models also allow analyzing this question combining the perspectives of production and consumption,

and their relationship through international trade. Moreover, our paper attempts to shed light on the discussion about the global and regional process of generation of emissions, paying special attention to cluster analysis and to the existence of common trends by groups of countries. Empirically, the information provided by the most recent edition of the World Input-Output Database (WIOD) and environmental accounts compatible with this database, is used. In our view, the results contribute new dimensions and insights to the issue of international inequality in terms of environmental pressures and opens new debates on the relocation of environmental damage, comparative advantage, and the environmental footprint.

1. INTRODUCTION

Climate change is increasingly affecting every country worldwide, disrupting national economies and affecting lives and communities. As a consequence, taking urgent action to combat climate change and its impacts has been included as one of 17 Sustainable Development Goals by the United Nations, which also calls for international cooperation and coordinated actions in the path towards a low-carbon economy. In this context, the recent Paris Agreement (COP21 in Paris, December 2015) represented an important step forward in the international awareness of the need to take urgent action and boost national policies to combat climate change. The Paris Agreement aims to strengthen the global response to climate change and the ability of countries to deal with the negative impacts of climate change (see the United Nations Framework Convention on Climate Change, UNFCC, 2015). In order to achieve the objective of keeping the global temperature rise below 2°C by 2100, the Paris Agreement needs to be developed and incorporated in national policies, technological changes and financing, to ensure the progressive de-carbonization of economies.

In this context, the need for informative instruments and methodologies to assess the opportunities and bottlenecks of current world production becomes relevant and complex, given the fast processes of globalization and production fragmentation, and the increasing internationalization of markets and consumers.

Technological progress, population growth, and international trade have been recognized as important drivers of recent economic growth (Barro, 1991; Frankel and Romer, 1999; Grossman and Helpman, 1997; Keller, 2002). The lowering of barriers to entry into markets, and increasing internationalization has allowed emerging countries to reduce secular production and income gaps, leading to economic convergence. Globalization is also affecting the consumer side, with a convergence in lifestyles and tastes. Consumers in different countries, from different cultural origins, are developing preferences for the same products, showing increasing signs of convergence around global product identities (Kjeldgaard and Askegaard, 2006; Smith, 2009).

These changes in economic structures, however, may have a significant impact on environments. In this context, it is important to analyze whether the signs of economic convergence resulting from world globalization are leading to cleaner and less unequal environmental pressures among countries (that is, is globalization acting as a driving force for the de-carbonization of world economies) or, on the contrary, an increasing process of inequality in world emissions resulting from the delocalization of carbon-intensive industries.

The analysis international inequality in environmental emissions has received renewed attention in the literature, to identify the main driving forces, to inform the design of global policies against climate change, and to determine the criteria for the distribution of mitigation efforts worldwide (see for instance Duro et al. (2016) or Teixidó-Figueras, (2016) for a review and a comprehensive evaluation of indicators). Most of the studies focus on aggregate data by country or region, as well as on production (direct emissions), considering countries as homogenous units, without paying attention to the heterogeneity of economic sectors. This is the case of Aldy (2006), who studies whether convergence in income is sufficient for per capita CO_2 emissions convergence, by focusing on certain advanced economies. Li and Lin (2013) analyze the absolute and conditional convergence in CO_2 emissions for the period 1971-2008 and find evidence of absolute convergence and different income-emissions relationships, depending on the income level of countries. Westerlund and Basher (2008) perform an analysis of convergence in the 20th century[1], finding clear evidence of the

[1] They use an initial sample of 28 developed countries for the period 1870-2002, adding 12 developing countries during the period 1901-2002 for the complete sample.

existence of convergence at the international level. Romero-Ávila (2008) examines the stochastic and deterministic convergence of CO2 emissions in 23 countries over the period 1960–2002, finding evidence of this convergence. Other studies, such as Ozcan and Gultekin (2016) and El-Montasser et al. (2015) explicitly test the hypothesis in cross-country CO_2 emissions for OECD countries, finding mixed results.

Despite wide research on cross-country convergence of emissions, and recognition of the technological and structural composition of economies as factors driving emissions, there are very few studies that investigate the convergence process from a sectoral perspective.

Notable exceptions are Oliveira et al. (2017), who test the hypothesis of per capita convergence in direct greenhouse gas emissions, estimating dynamic multi-sectoral panel data, and the evolution of convergence GHG in 27 EU countries and the 13 largest economies around the world, finding evidence of convergence for some GHGs and for the majority of sectors. Similarly, Mulder and de Groot (2012) perform a convergence analysis, for 18 OECD countries and 50 sectors, of energy-intensity growth, finding that only after 1995 cross-country variations in energy intensity levels tend to decrease, driven by the evolution of manufacturing and services sectors.

This sectoral nature of CO_2 emissions underlies input-output studies, aiming to explore the role that technological and structural change, along with demand size and composition, have played in the evolution of direct and total emissions.

In parallel, input-output techniques have been increasingly used to analyze the role of domestic demand and international trade in driving current emissions (see Wiedmann et. al. (2007), Wiedmann (2009) for a review), acknowledging the multiregional and multi sectoral nature of economic flows, their associated environmental impacts, and bringing to the forefront the need to link the supply side and the demand side perspectives for a deeper understanding of environmental responsibilities (Lenzen et al (2012), Serrano and Dietzenbacher (2010), Duarte et al. (2018)). The increasing availability of comprehensive multiregional input-output databases has allowed better accounting to be performed of the contribution of trade flows to global CO_2 emissions trends (see Lenzen et al. 2012 and Lenzen et al. 2013; Wiedmann, 2009; Dietzenbacher et al. 2009 and Xu and Dietzenbacher, 2014, among others).

This paper builds on this literature to offer a new approach in the analysis of the evolution in CO_2 emissions, which takes into account the heterogeneity in industry structure, technology, population, and composition of production and demand of countries. More specifically, this is, to the best of our knowledge, the first paper to explicitly study some inequality measures in CO_2 emissions embodied in domestic demand, and international trade, i.e. studying the convergence or divergence of emissions to accomplish globalization trends.

Our work makes use of a multiregional input-output model (MRIO) for the global economy that serves as a basis for the formulation and evaluation of convergence in emissions[2]. This allows us to base our analysis on the structural and technological factors underlying convergence processes, taking into account the multi-regional and multi-sectoral perspective of production, and environmental impact generation.

We are also interested in the analysis of how this has been affected by the onset of the international economic crisis of 2008.

We use data from the World Input-Output Database (WIOD) (2016 Release). Regarding the environmental database, our main source is the recent database published by the Joint Research Centre of the European Commission[3], which contains data on energy use and carbon dioxide emissions by industry and country for 2000-2016, fully consistent with the Release 2016 of WIOD.

The rest of the paper is organized as follows. Section 2 presents the methodology used based on an MRIO model, from 2000 to 2014. Section 3 addresses the results obtained as they relate to the convergence process and the behaviors observed for different countries and sectors. Finally, Section 4 closes the paper with a review of our main conclusions.

2. METHODOLOGY

Our starting point is a multi-regional input-output (MRIO) model, with the basic references being Isard (1951) and Miller and Blair (2009). The use of an MRIO model allows us to study trade patterns that may condition the evolution of CO_2 emissions and the process of disparity

[2] We focus on CO2 emissions as the most representative GHG

[3] See https://ec.europa.eu/jrc/en/research-topic/economic-environmental-and-social-effects-of-globalisation

over time. Our interest is in analyzing the evolution of CO_2 emissions in a global context from the convergence perspective.

In that follows we present the main features of the methodological approach adopted.

Equation 1 represent the equilibrium equation in a multiregional model context, with m countries and n sectors, where **x** ((m×n)×1) denotes the total output, **A**((m×n)×(m×n))is the matrix of multiregional technical coefficients. The representative element a_{ij}^{rs} shows the intermediate input i of a country r necessary to produce a unit of output j in country s, and **f** ((m×n)×1) is the of final demand of countries, where if each representative element f_i^{rs} is the final demand of good i produced in country r and consumed in country s. with $\mathbf{f} = \left(\mathbf{f_i^r}\right)$ with $\mathbf{f_i^r} = \sum_{s=1}^{m} f_i^{rs} = f_i^{rr} + \sum_{s \neq r} f_i^{rs}$ This equation can be also represented in terms of the well-known Leontief inverse **L** ((m×n)×(m×n)) defined for the whole economy.

$$\mathbf{x = Ax+f} \Leftrightarrow \mathbf{x = (I\text{-}A)^{-1}f = Lf} \tag{1}$$

Moreover, let's consider the vector of emissions directly generated by the countries and sectors **e** ((m×n)×1). We can define the following direct emission coefficients $\mathbf{c = e}^{'} \left(\hat{\mathbf{x}}\right)^{\mathbf{-1}}$ showing the direct emissions per unit of production (emission intensity).

Pre-multiplying equation 1 by the diagonalized vector of direct emissions intensities and allocating final demands to the different productive countries and sectors, we obtain the following matrix

$$\boldsymbol{\Omega} = \hat{\mathbf{c}}\ \mathbf{L}\hat{\mathbf{f}} \tag{2}$$

where each element $\boldsymbol{\Omega}_{ij}^{rs}$ depicts the CO_2 emissions generated in sector i of region r to meet the final demand of sector j in region s.

The reading by columns and rows of the matrix above gives us significant information on the origins and destination of emissions through the global production chains.

Thus, the sums of the elements by rows reproduce the *direct emissions* (production-based emissions) by sectors and countries, that is to say, $\mathbf{w^{emi}} = \boldsymbol{\Omega}\ \mathbf{i} = \hat{\mathbf{c}}\mathbf{L}\hat{\mathbf{f}}\mathbf{i} = \mathbf{e}$ being **i** a unitary vector of appropriate dimension. In consequence, the different elements of each row in $\boldsymbol{\Omega}$

show how the direct emissions of a country and sector are incorporated in its sales to other sectors and countries though the global production chain.

The reading by columns shows the *embodied emissions*, that is, $\boldsymbol{\omega}^{emi} = \mathbf{i'\Omega}$ depicts, for each sector and country, the emissions generated across the world and crystalized in the final demand of each country and sector. That is to say, this is the description of the world emissions from a "consumption-based approach". Obviously, the total amount of world emissions under both approaches is the same, that is to say $\mathbf{i'w^{emi}} = \boldsymbol{\omega}^{\mathbf{emi}}\mathbf{i} = \mathbf{i'\Omega\ i} = \mathbf{i'e}$

Moreover, as we are studying a global scenario, we can distinguish between the emissions generated in each country and ending in the final demand consumed in the own country, and the emissions generated and embodied in the goods and services traded with other countries and consumed in a foreign country. That is to say, we can distinguish two parts in $\mathbf{L} = \left(L_{ij}^{rs}\right) = \mathbf{L^d} + \mathbf{L^m}$ with $\mathbf{L^d} = \left(L_{ij}^{rs}\right)$ if r=s and 0 if r≠s, $\mathbf{L}^m = \left(L_{ij}^{rs}\right)$ if r≠s and 0 if if r=s. Similarly, the final demand **f**, can be divided into $\mathbf{f} = \mathbf{f^d} + \mathbf{f^z}$, with $\mathbf{f}^d = \left(f_i^{rr}\right)$ being the interior consumption and $\mathbf{f}^z = \sum_{s \neq r}^{m} f_i^{rs}$ the foreign demand for final consumption.

In consequence, we can extend equation 2 as follows:

$$\boldsymbol{\Omega} = \hat{\mathbf{c}}\,\mathbf{L}\hat{\mathbf{f}} = \hat{\mathbf{c}}\,\mathbf{L^d}\hat{\mathbf{f}}^{\mathbf{d}} + (\hat{\mathbf{c}}\,\mathbf{L^m}\hat{\mathbf{f}}^{\mathbf{d}} + \hat{\mathbf{c}}\mathbf{L}\hat{\mathbf{f}}^{\mathbf{z}}) = \boldsymbol{\Omega}^{\mathbf{domestic}} + \boldsymbol{\Omega}^{\mathbf{trade}} \tag{3}$$

Note that other different breakdowns can be considered, depending on the definition of domestic production, both in the case of intermediate inputs and finals demands. In our case, we consider as domestic production the goods and services produced in the country and that are finally consumed in the country (for simplicity we also include as domestic a small spillover effect as $\mathbf{L^d > (I - A^d)^{-1}}$).

Looking at (3), the evolution of matrix $\boldsymbol{\Omega}^{\mathbf{domestic}}$ will be marked by the evolution of domestic emissions associated with the internal production and consumption of own products in each country (intermediate and final demand); while the evolution of the second, $\boldsymbol{\Omega}^{\mathbf{trade}}$,will be strongly linked to the evolution of international trade of emissions, including the emissions of a country embodied in products traded as intermediate inputs or final products, with other countries. Again, the reading by columns (and rows) of these matrices gives us information on the distribution of the process of emissions generation (and distribution) across countries.

The decomposition of flows described above, based on the MRIO structure, allows us a more complete view of the (complex) process of convergence in emissions, and, as far as possible, an analysis of the contribution, by both generation and distribution, of the different variables (domestic demand and trade) and sectors, and the cross-country relationships.

In other words, these flows by country, sector, and year, can be highly informative for the evaluation of convergence in world emissions. In this regard, although it is not common in the literature, the MRIO models and indicators presented, also provide the basis to evaluating to what extent countries and/or sectors are walking towards a common path or, on the contrary, tend to be more unequal over time. Given the role that structure, final demands and international trade play in these models, we can offer a novel structural view of the *convergence* issue. Moreover, MRIO models also allow analyzing this question combining the perspectives of production and consumption, and their relationship through international trade.

The evolution of global world regions has attracted attention in the literature in recent decades. On the basis of the seminal works of Sala-i-Martin (1992, 1994, 1996) in the economic literature, numerous papers have emerged that focus on studying the inequality in emissions using the well-known the sigma or beta convergence indexes (see for instance Brock and Taylor, 2010; Ordás Criado et al., 2011). Economic convergence has traditionally been evaluated on the basis of *sigma* convergence, making use of a range of dispersion measures (see for instance Sala-i-Martin, 1994; Lein et al. 2007; Dietzenbacher et al. 2009, Fagerberg et al. 2014). In our case, in order to analyze the level of inter-country imbalance between 2000 and 2014, we study the standard deviation of the log emissions as an indicator of inequality. On the basis of the indicators presented in the previous equations, we can define the following dispersion indexes for the direct (production-based approach) and the embodied (consumption-based) emissions as follows:

$$\sigma^{e}{}_{t} = \left[\frac{\sum_{r} (\log(\sum_{i,j,s} \Omega^{rs}_{ij,t}) - u^{e}{}_{t})^{2}}{m} \right]^{\frac{1}{2}}$$

$$\sigma^{\omega}{}_{t} = \left[\frac{\sum_{s} (\log(\sum_{i,j,s} \Omega^{rs}_{ij,t}) - u^{\omega}{}_{t})^{2}}{m} \right]^{\frac{1}{2}} \qquad (4)$$

where σ_t^e and σ_t^ω are, respectively, the dispersion measures of country direct and embodied emissions in a specific year *t*; u_t^e and u_t^ω are the corresponding average of the logarithms of the emissions data analyzed. Note that we can estimate these dispersion indexes at different aggregation levels (country, sector-country, country or regional blocks) and for different components in $\mathbf{\Omega}$, being of interest the above presented $\mathbf{\Omega^{domestic}}$ and $\mathbf{\Omega^{trade}}$. Additionally, we perform *beta*-convergence analysis, in this case looking at the relationship between direct or embodied emissions and their associated growth rate. The hypothesis of *beta* convergence relates emissions growth over a period with the initial emissions levels. If *beta* convergence exists, a direct association with negative slope would be expected.

As can be seen, the multi-sectoral nature of the MRIO information allows us a more detailed study of the economic sectors involved in the process of *sigma* convergence around the world. In this regard, we can compare the results obtained at the more aggregated country level and those appearing when sectoral disaggregation is used. We study the convergence through the global value chains (i.e., in the emissions generated in the world and embodied in the final demand of countries) and analyze the evolution of convergence in its different components (domestic and trade), which is the main contribution of the study and a novel approach to convergence and inequality issues.

While the traditional measures of convergence are based on direct emissions, the study of convergence in global value chains directs us to the driver role of final demand patterns (consumption and investment patterns) as sources of income convergence or divergence.

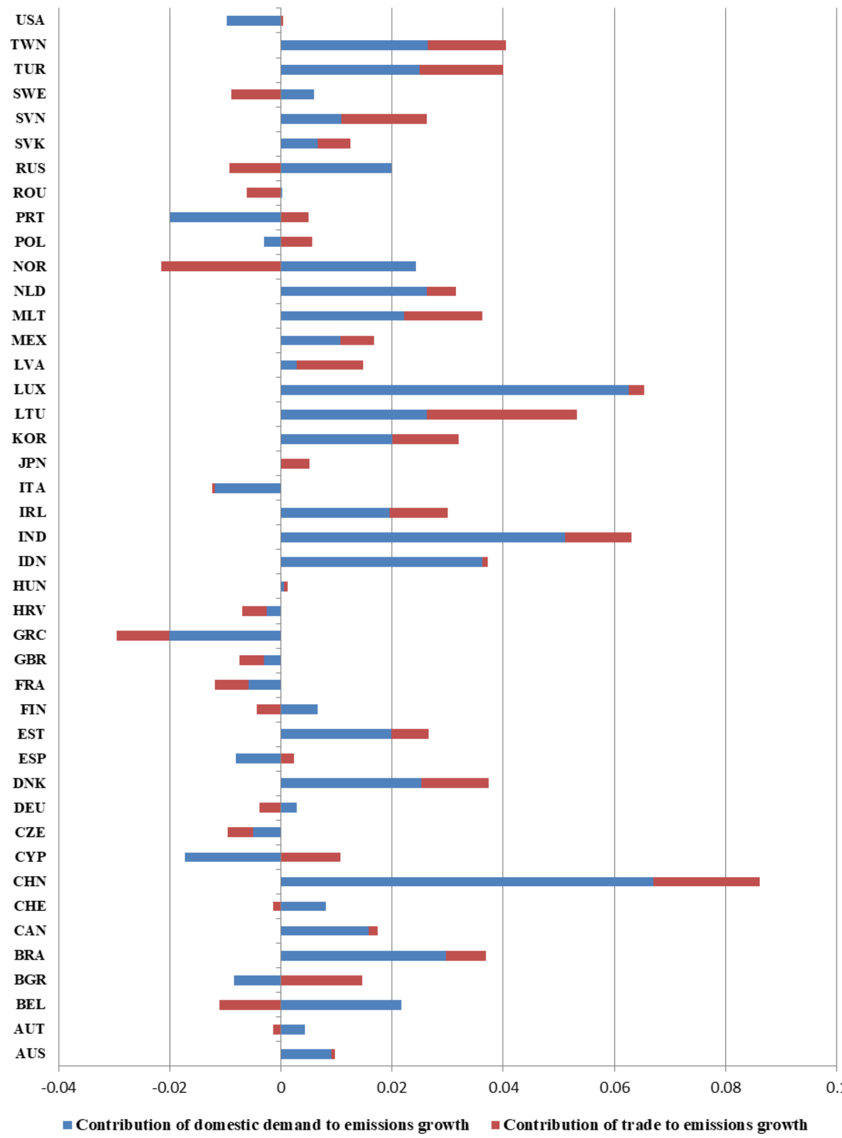
Empirically, we make use of the World Input-Output Database WIOD (see Timmer, M. P., Dietzenbacher, E., Los, B., Stehrer, R. and de Vries, G. J. (2015)), which covers 28 EU Member States and 15 other major countries in the world for the period 2000-2014, our period of analysis. The WIOD database has a breakdown of 56 industries in the Release of 2016 for each country, covering all economic sectors: agriculture, mining, construction, utilities, manufacturing, and services. As it was mentioned above, we make use of the new emissions data published recently by the Joint Research Centre of the European Commission (WIOD Environmental Accounts 2019), which are completely consistent with the WIOD Release 2016. Therefore, this database provides information for 44 countries (including the Rest of the World) and 56 industries by country.

3. RESULTS

3.1. *Trends in CO_2 emissions and main components*

In order to better understand the trends observed in CO_2 emissions and the role of domestic and foreign demand, Figure 1 illustrates the contribution of domestic and trade components to emission growth for the 43 countries included in the WIOD database.

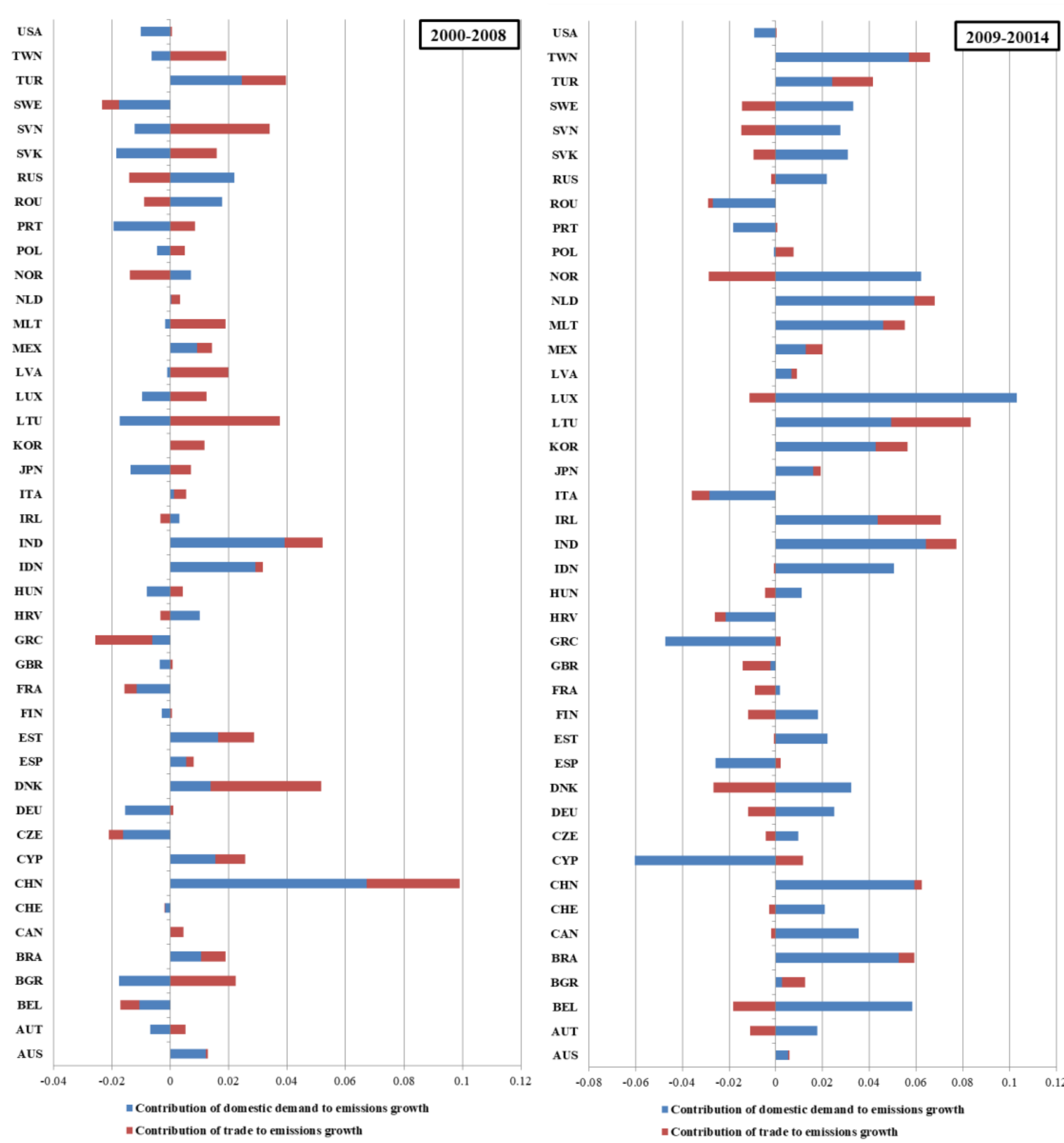
Figure 1. Contributions of domestic demand and trade to average emissions growth, by country, 2000-2014



Source: Own elaboration

As can be seen, China, India and Luxembourg stand out as the countries with the highest rates of emissions growth, and are also main contributors to current global CO_2 emissions. Both show a high contribution of their domestic demand to emissions growth. Economic expansion in these economies is reflected in vigorous domestic production and in increasing trade with the rest of the world, thus contributing to the expansion of CO_2 emissions. Trade has been the main contributor to global emissions for most of the countries, and we can see that Central and Eastern Europe and Asian countries are the ones with higher rates of emissions growth associated with the dynamism of their trade. This is the case, for instance, of Denmark, and Estonia. The lowest growth rates in CO_2 emissions over the period can be found for the US and the Mediterranean Europe countries. Nevertheless, when we look at the two sub-periods, before and after the 2008 economic crisis, we can appreciate different characteristics regarding CO_2 emissions and the contributions of domestic demand and trade.

Figure 2. Contributions of domestic demand and trade to average emissions growth, before and after the crisis



Source: Own elaboration

As can be seen in Figure 2, in the period 2000 to 2008 (the expansive period), international trade between countries caused a large increase in air emissions, leading to an increase in global pollution, especially in the case of some Central European countries such as Denmark, Lithuania, and Luxembourg. In addition, some Asian countries, such as Japan, and some Eastern European countries had negative emissions growth rates associated with domestic demand. When we focus on the second graph, the onset of the international crisis affected the generation of emissions, with certain clear features. First, the growth rate of CO_2 associated with exports is reduced, but the decrease of domestic demand is much greater. After the crisis, some major EU countries, such as Greece, Italy, and Spain, are those that show the most negative contributions of domestic demand to emissions growth, while the emissions associated with exports are maintained.

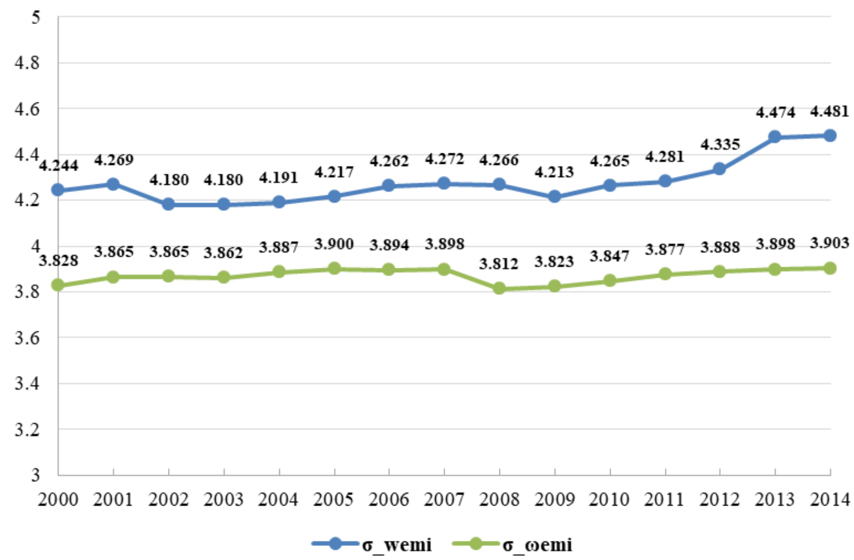
The questions are, in consequence, whether these differential behaviours resulted in an increasing convergence or divergence between countries, in terms of carbon emissions, which have been the contributing factors, and how can we evaluate the results from an integrated global perspective.

3.2. *Environmental inequality analysis*

As it mentioned above, there are many indicators of inequality that have been used in the literature. In this work, we make use of the measure of *sigma*-convergence process on the basis of the estimations described in (6) during the period 2000-2014, and taking two types of variables as measures of emissions: first, the "Direct emissions", that is, the total emissions generated in each country and sector, both internally and traded with other countries. That is, *sigma*-convergence on the components of $\mathbf{e}$. Second, we compute the process of *sigma*-convergence on "Embodied emissions", that is, the convergence in the total emissions generated and incorporated in the final products of each sector and country. Thus, in this first analysis, our sample has, for each year, 1,462 observations (43 countries, with 34 sectors for each[4]).

[4] The sectors have been grouped according to the International Standard Industrial Classification in the World Input-Output database, Release 2013.

Figure 3. Evolution of inequality in total emissions (total direct and embodied), 2000-2014



Source: Own elaboration

Figure 3 shows in the blue line the environmental inequality calculated as a measure of dispersion in the direct emissions (“$\mathbf{w}^{emi}$ = total direct magnitude”) and in the green line, calculated over the total global emissions and embodied in the final products. We can see a period of stability in the convergence index until 2008, followed by a period of a marked divergence in emissions[5].

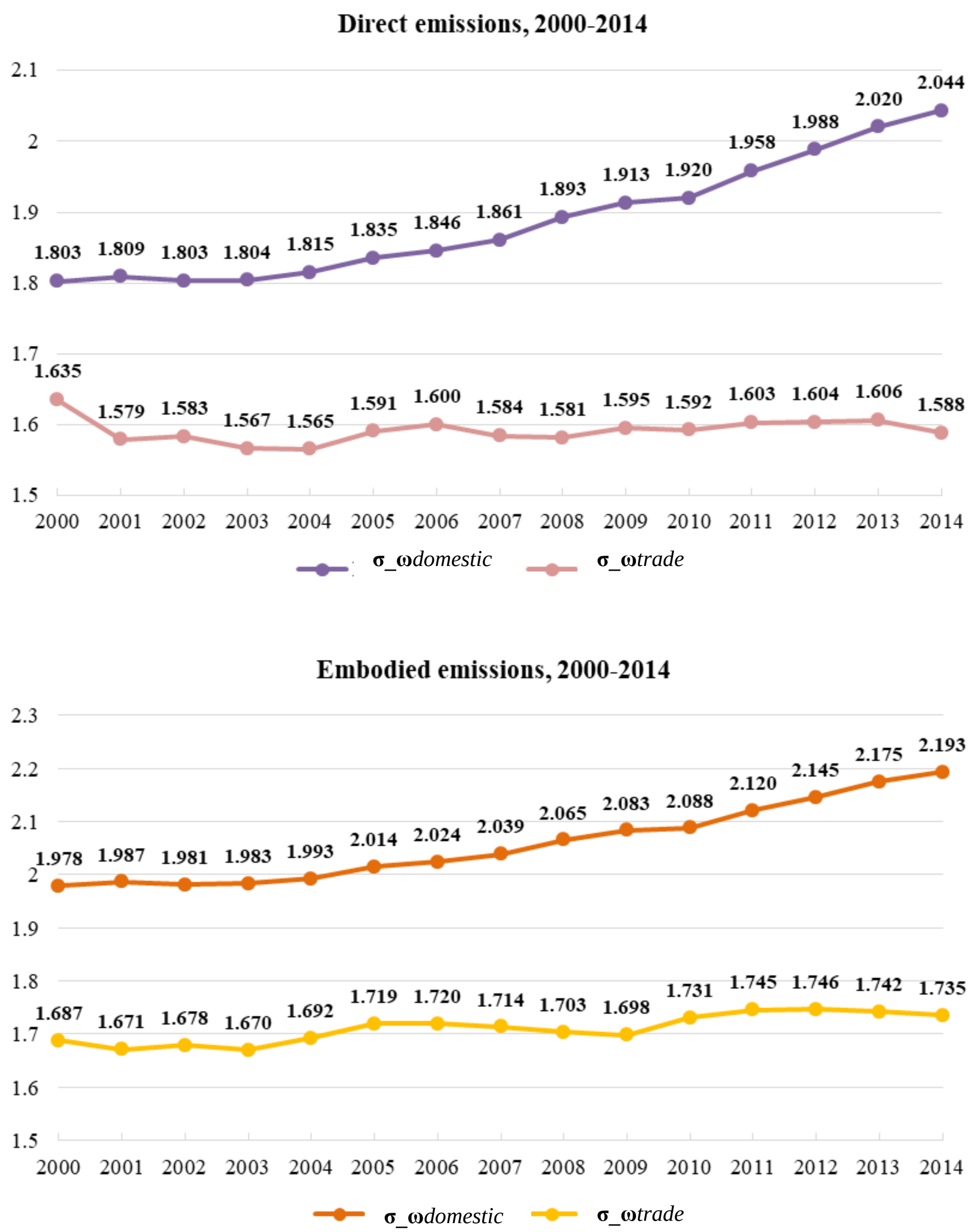
While the evolution of traditional *sigma*-convergence reflects a period of rapprochement or distancing of countries in the direct emissions generated in production, the evolution of the “embodied magnitudes” indicates an approach or distancing of countries to a similar composition in their final products, that is, certain similarity of countries in technologically-integrated productivity.

Our results show a continuous process of inequality in direct CO_2 emissions from the early 2000s, which increases from 2008 and onwards. Moreover, values of *sigma* are lower for the embodied emissions, and it is possible to identify two trends. A period of convergence and stability until 2007, and an increasing estrangement in embodied emissions from then on. In order to go deeper into the behaviour of the different structural components regarding the

[5]The analysis with EORA database is available upon request.

trend observed in convergence, we analyse the same indicator in the "trade" and "domestic" components of direct and embodied emissions. Equations (3), (4) and (5) show the significance of these components.

Figure 4. Evolution of inequality in the different components of direct and embodied emissions, 2000-2014



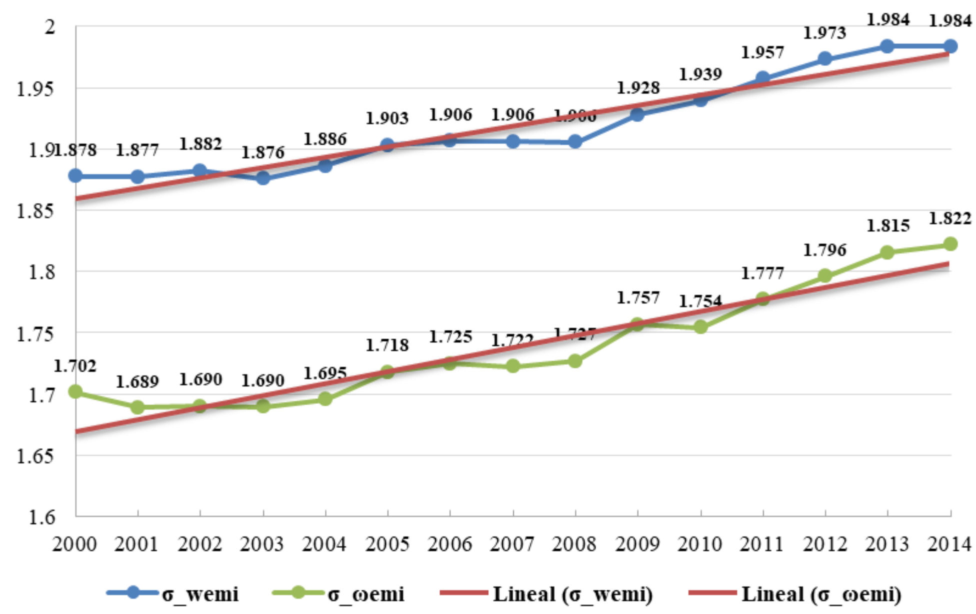
Source: Own elaboration

As can be seen, both in direct and embodied emissions, the main contributor to the rising disparity in emissions is the domestic component. The 2008 economic crisis also seems to inaugurate a period of rising inequity in the emissions associated with trade, also contributing to increasing inequality in world emissions.

Once the hypothesis of convergence has been studied at the most disaggregated level, we perform a similar analysis aggregating the data by country that is, eliminating the sectoral variability within countries. For this reason, we have only 43 observations per year, corresponding to the 43 countries of the study (not including the Rest of the World). As a general result, the values confirm the trends obtained at the disaggregated level.

As in the previous case, the magnitudes present a clear rising gap throughout the period, but more marked in the second half.

Figure 5. Evolution of inequality in total emissions (total direct and total embodied), 2000-2014. Aggregated data by country



Source: Own elaboration

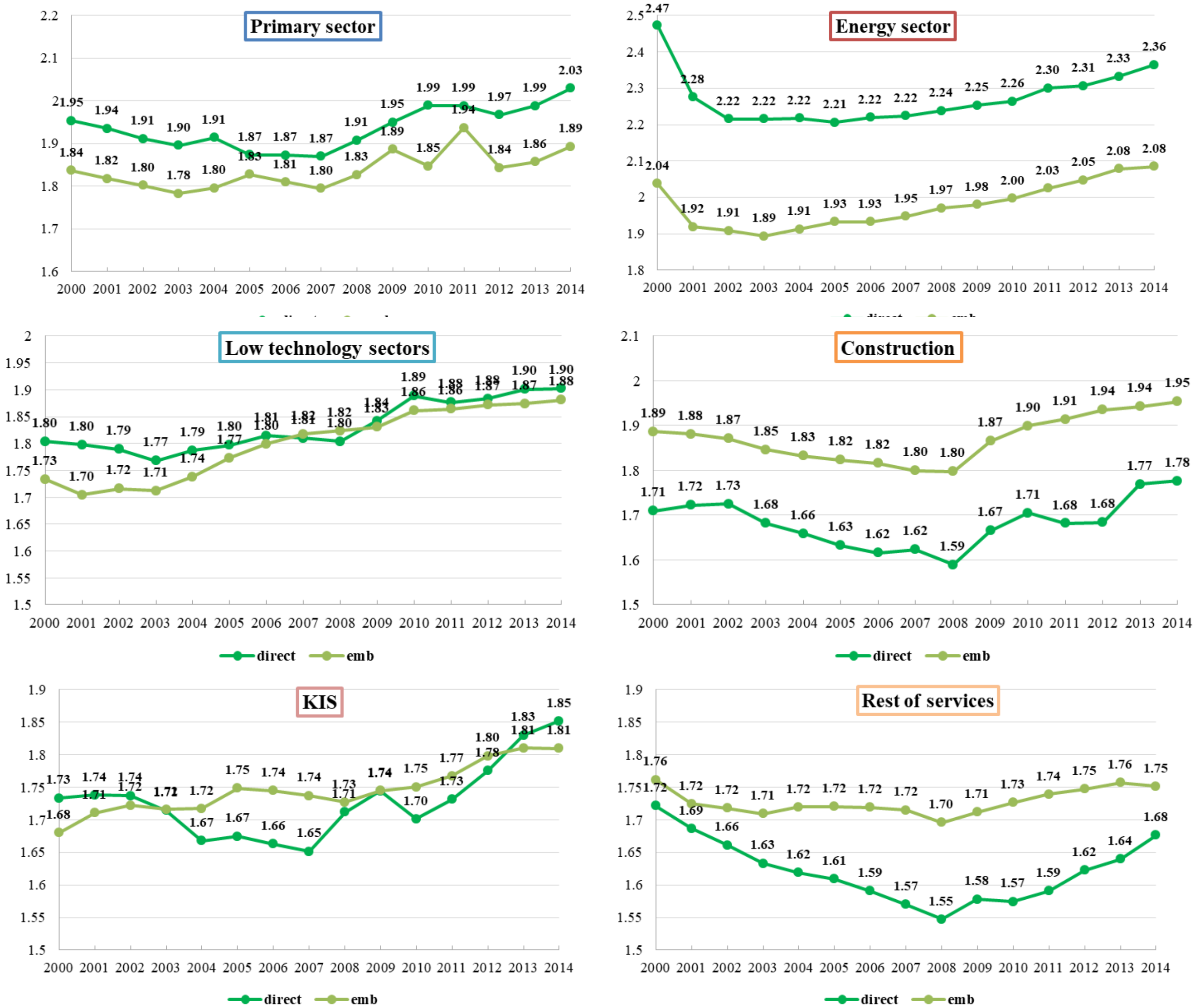
These results show that countries tended to diverge over the period in the production of emissions and embodied emissions. As can be seen, the trend lines of both variables present an increasing evolution of the indicator, that is, an increase of the divergence in generated and embodied emissions. However, comparing these results with those obtained at the most disaggregated level, the stability period observed in embodied emissions is not so clearly appreciable when data are aggregated by country, nor is the significant role played by the domestic component in explaining the rising inequality in emissions from the economic crisis. This suggests the importance of structural components and sectoral specialization in countries, in explaining emissions trends.

Thus, in order to have a clearer insight into the role that specific sectors or groups of sectors can play in the evolution of a country's emissions, and in convergence, in what follows we show the evolution of the inequality indicators by sectoral blocks, grouped according to their technological levels.

The final analysis refers to convergence in the generation of pollution by sectoral groups. The economic sectors have been aggregated into 8 sectoral blocks, according to their technological level namely: primary sector, energy sector, high and medium-high technology industrial sectors, medium-low technology industrial sectors, low technology industrial sectors, construction sector, knowledge-intensive services and the rest of services[6]. Our interest here is to see if this divergence process over time is due to the extreme behavior of some sectors in particular, or is mainly due to a trend observed in most of them. In figure 6, we show the evolution of inequality for the sectoral groups, having now 43 observations for each sectoral block and year, corresponding to the 43 countries of the sample.

[6] The sectors have been grouped in these blocks according to their technology intensity definition (following the OECD Directorate for Science, Technology and Industry, 2011, and Knowledge intensive services (KIS) classification. In this way, the sectors are grouped as follows: primary (crop and animal production, forestry and fishing), energy (mining, electricity, gas, water collection and sewage), HTS&MHT (manufacture of chemicals, pharmaceutical products, computer, electronic and optical products, electrical equipment, motor vehicles and other transport equipment), MLT (manufacture of coke and petroleum, rubber and plastic products and non-metallic mineral products), LT (manufacture of food, beverages, tobacco, textiles, wood and paper products), Construction, KIS (water and air transport, publishing activities, telecommunications, information services, financial service activities and insurance, reinsurance and pension funding) and RS (wholesale and retail trade, land transport, warehousing, support and real estate activities). Tourism is not classified independently, which is strange given its importance and impact on the Spanish economy, for instance, on specific areas like Venice, areas around airports, islands with high contamination, etc.

Figure 6. Evolution of inequality in total direct and embodied emissions, by block sector, 2000-2014



Source: Own elaboration

Figure 6 shows the evolution of inequality (*sigma*) on direct emissions generated by each block, as well as inequality (*sigma*) in emissions generated by total production and incorporated into the final products of each block (embodied emissions). Significant differences can be observed, breaking the smooth trend toward increasing divergence observed in the previous results.

On the one hand, when we take into account direct values (dark green lines), the high and medium-high-technology industrial sectors are the most divergent over the period. Thus, countries present the greatest differences in the emissions generated by the most technology-intensive sectors. Medium-low technology sectors exhibit the clearest tendency towards convergence over the whole period, showing that they are the sectors where the generated emissions have been distributed globally. The Rest of Services and construction show the most marked change in the trend, due to the 2008 economic crisis, with a clear tendency towards convergence in the expansive period pre-crisis and a marked movement towards divergence afterward.

On the other hand, when we look at the embodied values (light green lines), we obtain a different picture. When we observe the embodied values, we can appreciate that for the majority of blocks, their values are smaller than in the case of direct magnitudes, and moreover they present a clear divergence process since the beginning of the analyzed period. The behaviour of high and medium-high-technology industrial sectors is clearer than others, suggesting that products consumed by world citizens have more different technology-intensity content, no matter the country where this is generated. In other words, it seems that world trade has not allowed technological diffusion between countries, but has contributed to a progressive specialization of countries, which causes significant divergence in the generation and incorporation of emissions in production.

The results above tell us that the general trend in CO_2 emissions is toward an increasing inequality in CO_2 emissions of countries, also implying a certain specialization of countries in production, and with global values strongly driven by the evolution of the domestic demand of countries.

At this point, several questions arise. First, the existence of *sigma* divergence implies more inequality in world emissions: to what extent do initial conditions of countries affect this inequality (which implies an analysis of the so-called *beta* convergence in emissions)? Second, different clusters can be identified, and to what extent do these clusters refer to geographical areas and/or to different economic conditions? Finally, we go further into the link between per capita income growth and per capita emissions, to test how convergence in per capita income, technology, and population affects convergence in emissions.

3.3. *Beta convergence analysis*

The problem we now face is whether the observed *sigma* divergence in emissions is mainly due to the smaller growth rate of emissions in less polluting countries, or to the increasing rate of the most polluting countries. As has been stated, the hypothesis of *beta* convergence relates emissions growth over a period with the initial emissions levels. A direct association with negative slope should be expected in presence of beta-convergence.

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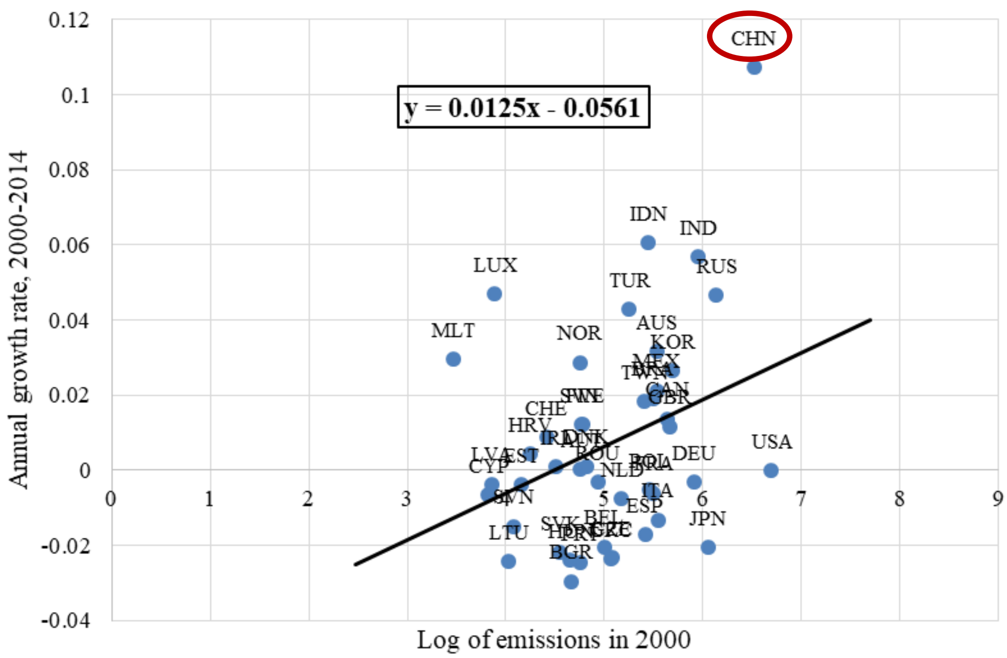
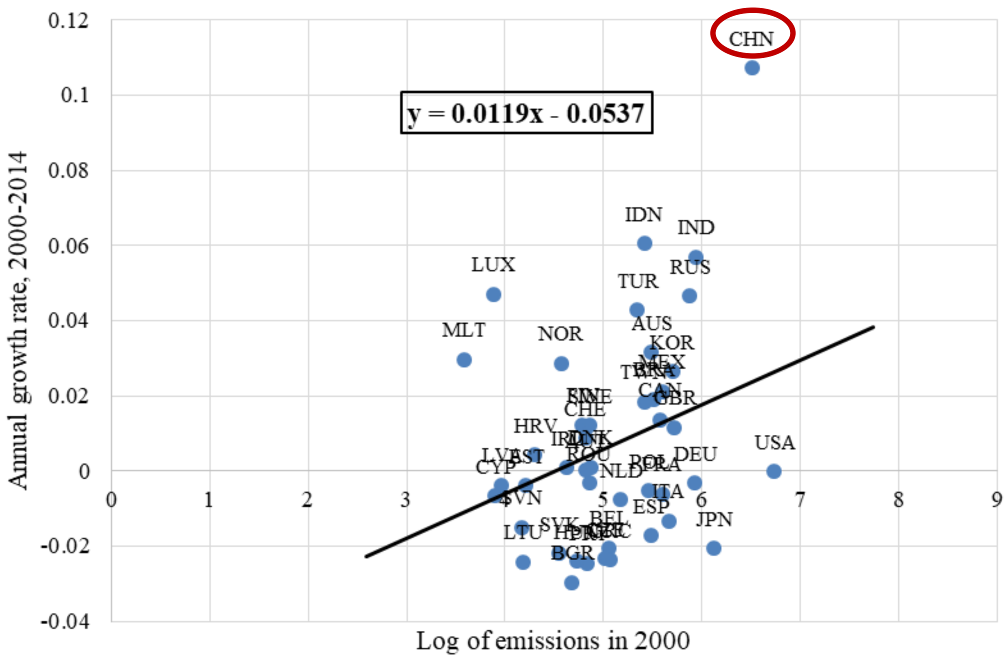
Figure 7. *Beta* convergence in direct emissions, 2000-2014



Source: Own elaboration

As can be seen in Figure 7, the analysed countries present a clear *beta* divergence in emissions, which is fully compatible with the results on *sigma*. The graph shows that the countries with the highest level of emissions at the beginning of the analyzed period are the ones that increased their pollution levels the most during the analyzed period, and in the same way, those countries with the lowest levels of pollution are those ones that increased their emissions the least. Therefore, *beta* divergence is telling us that *sigma* divergence is associated with a significant increase in the pollution rate of those countries that had levels of pollution above the average at the beginning of the analyzed period. The case of China stands out in the sample; it presents the highest annual emissions growth rate over the period, related not only to its initial pollution levels but also with the consistently high level of economic growth experienced over the period. In addition, we can observe that the *beta* divergence is caused by the behavior of the most industrialized countries, that have been those that increased their pollution levels the most.

Figure 8. *Beta* convergence in embodied emissions, 2000-2014



Source: Own elaboration

Figure 8 shows a similar picture for the relationship to embodied (global) emissions. Again, we can confirm the existence of *beta* divergence and see that the positive relationship between the emissions growth rate and the initial pollution levels is due to the rapid growth of the most polluting countries, such as India, Indonesia, Turkey, and, notably, China[7].

In order to go deeper into the behaviour of countries and the existence of common trends by group of countries, these results are complemented with a cluster analysis and the subsequent convergence analysis in the following section.

<u>3.4. *Cluster analysis*</u>

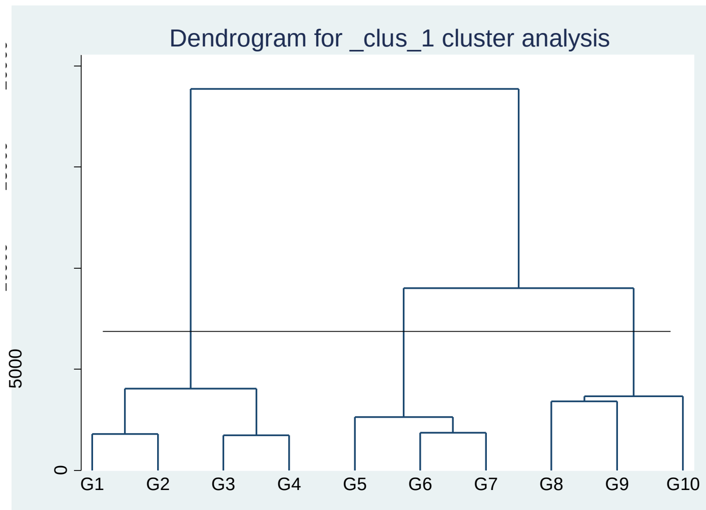
The trends observed for the full sample of countries can be analysed by cluster analysis, to identify common and differential behaviours among countries following some geographical

[7] Given the exceptional impact of China, the analysis has also been developed for the full sample, omitting China, and confirming a positive and significant relationship between growth rate in emissions and emissions in 2000.

and/or economic criteria. We have developed a cluster analysis applying the Ward criterion, that uses the variance as a dissimilarity metric (see Ward, 1963). The study has been carried out in Stata for a total sample of 645 observations, corresponding to the 43 countries in the sample and to 15 years. In addition, this study has been carried out for total emissions data, so that we can know the clusters by size (larger, more polluting economies).

Applying Ward's method, the following dendogram is obtained, showing three groups across the countries and the years of the analyzed period:

Figure 9. Dendogram for cluster analysis, total emissions data, 2000-2014



Source: Own elaboration from the Ward clustering method in Stata

These groups correspond to the countries (from most to least CO_2 emitters):

- Cluster 1: Australia, Brazil, China, Germany, France, UK, Indonesia, India, Italy, Japan, Korea, Mexico, Poland, Russia, Turkey, Taiwan, USA.
- Cluster 2: Austria, Belgium, Bulgaria, Switzerland, Czech Republic, Denmark, Spain, Finland, Greece, Hungary, Ireland, Netherlands, Portugal, Romania, Slovakia, Sweden.
- Cluster 3: Cyprus, Estonia, Croatia, Lithuania, Luxembourg, Latvia, Malta, Norway, Slovenia.

When we look at the three groups of countries, we can see that the first group includes the leading countries in economic growth and therefore in emissions. In the second group, most of the countries of Central and Mediterranean Europe, and in the third cluster, we mainly find the Eastern European countries, with the exception of Norway.

Table 1. Convergence in emissions by clusters, total emissions, 2000-2014

	Cluster 1	Cluster 2	Cluster 3
α	0.867128	0.526696	0.905428
β	0.00703412	0.00121914	-0.00891384
p-value	4.61e-09 ***	0.0301 **	2.61e-09 ***

Source: Own elaboration

When we focus on the results of this table, we can see that the time trend coefficient of cluster 1 and cluster 2 is positive, indicating divergence in emissions (not being so significant in the second case), while in cluster 3 the coefficient is positive, which means that Eastern European countries show convergence in the generation of emissions. Thus, although the countries belonging to cluster 1 and 2 are generating the global divergence, there are also differences among them. However, those countries with lower levels of emissions are the ones with the greatest similarities and, therefore, the greater convergence among them.

Finally, we have checked the consistency of our results with other international databases. More specifically we have compared these results with those obtained using the EORA database for the same period (we have used the reduced version with 190 countries and 26 productive sectors per country). Because of the differences between WIOD and EORA databases, and the different country and sector aggregations, the values of *sigma* are bigger than in the case of WIOD. However, its trend/evolution, which is what really informs us about convergence, follows the same path in both cases (direct and embodied) with a convergence period until 2008 followed by a divergence process until 2014. More detailed results are available upon request.

5. CONCLUSIONS

The phenomenon of economic convergence has been analyzed from several perspectives, taking into account the effects of population, economic growth, and the stage of development, and providing diverse results. The objectives in the literature have been to study whether economies move toward a common growth path, or tend to diverge over time, and to determine the consequences of this on economic cohesion. However, the analysis of global convergence of CO_2 emissions and the implications in terms of pollution and the income-dependence of emissions has received little attention in the literature of convergence.

The main objective of this paper is to study the evolution of inequality in the emissions generated and embodied around the world. We make use of traditional measures of economic convergence as inequity indicators, and we extend them to a multi-regional input-output framework to check whether the phenomenon of convergence or divergence is due to a specific region, a country, or a particular productive structure.

Our results show a general process of growth in emissions accompanied by a continuous process of divergence worldwide. Regarding the evolution of world emissions, the temporal reduction in emissions observed in some economies was only due to the contraction of the economies during the first years of the economic crisis, and not to an improvement in the production conditions (technological improvement that reduces unit emissions). These general and global results, however, can be better qualified when sectoral and regional characteristics of countries are taken into account. First, the analysis by industry-blocks reveals that countries are specialized in specific economic structures, conditioning the evolution of emissions. Direct emissions and embodied emissions present a greater divergence in those sectors that are more technology-intensive. So, it seems that the general trend in emissions is towards an increasing inequality in the CO_2 emissions of countries, which also implies a certain specialization of countries in production, with global values strongly driven by the growth in domestic demand of countries.

The study of *beta* convergence offers other interesting insights. Our results show that the observed *sigma* divergence is the result of a clear process of *beta* divergence, marked by the fact that the largest polluters at the beginning of the period have continued to increase emissions over the period, and at the highest rate. This suggests the existence of different country behaviours related to productive and developmental characteristics. To approach the role of country features, a cluster analysis has been carried out, finding significant regional clusters. On the one hand, developed countries such as China, the US, Central and Mediterranean European countries, presented a divergence process in emissions, showing that there are significant differences between them. On the other hand, Eastern European countries exhibited a clear process of convergence in emissions. In the Appendix, all the results have been checked at the per capita level, confirming the previous findings.

Finally, our findings contribute new dimensions to the issue of international inequality in terms of environmental pressures, and open new debates on the relocation of environmental damage, comparative advantage, and environmental footprints.

Acknowledgements

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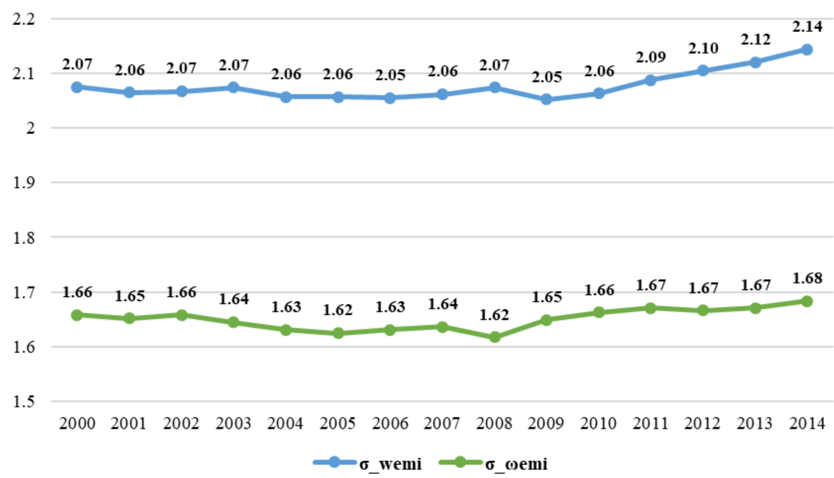
Appendix: Per capita emissions analysis

All the previous analysis has been calculated on the basis of the total emissions generated and embodied in country production, confirming the roles of domestic growth, international trade, and sector specialization in the trends observed in global emissions and convergence measures. In order to better capture the relationship between the level of development and the growth in emissions, as well as the consequences of convergence trends, we replicate the analysis above but now referring to the *sigma* and *beta* convergence among countries in per capita emissions.

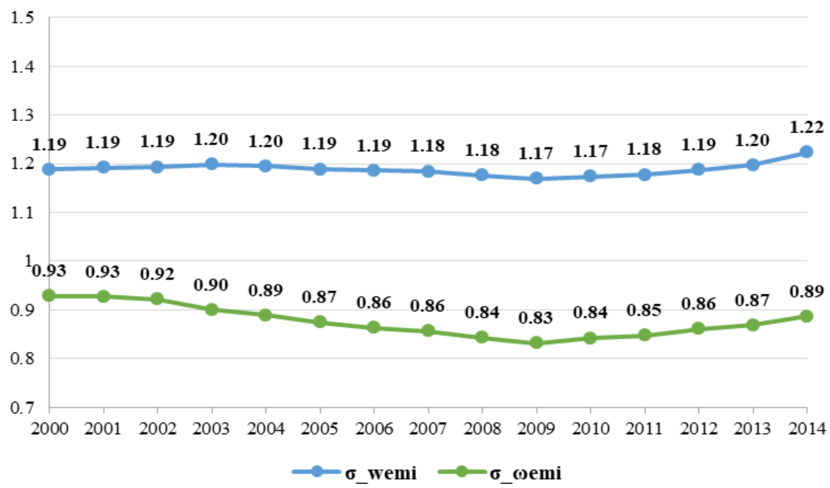
Figure A.1. Evolution of inequality in per capita emissions (total direct and embodied), 2000-2014



Source: Own elaboration

Figure A.1 shows the same analysis as Figure 3. In this case, the evolution of convergence in direct and embodied per capita emissions is similar to the earlier figure. Two main magnitudes present a certain period of stability in the convergence index, followed by some instability in the last years of the analyzed period. On the one hand, we can appreciate that the per capita emissions generated directly by each country (blue line) show certain divergence at the end of the period. On the other hand, the green line, corresponding to the embodied emissions, tells us that from the beginning to the end of the period, the countries have not tended to incorporate the same amount of emissions in their final products, and they have differed in terms of the composition of their products.

Figure A.2. Evolution of inequality in per capita emissions (total direct and total embodied), 2000-2014. Aggregated data by country

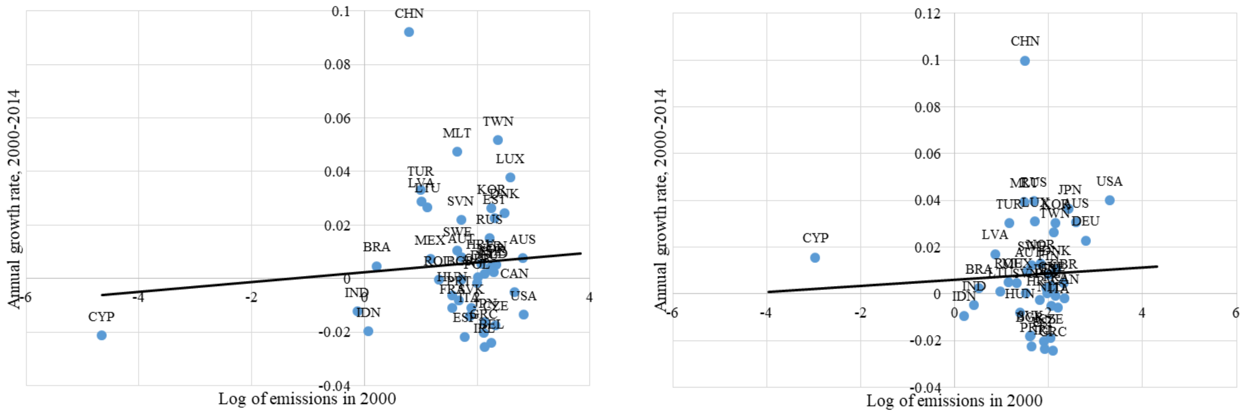


Source: Own elaboration

This graph shows the same analysis as Figure 5. In this case, we have aggregated the information by country, but the evolution is somewhat different from before. It is true that the effects of population soften the results obtained previously, although the two magnitudes show the same trend, with a slight convergence process until 2009, followed by a certain divergence until the end of the analyzed period. Again, in this case, the values are smaller when we compact the information by country and eliminate the sectoral variability.

Once the tendency of the countries to present divergence towards the end of the period is verified, it is necessary to know if this divergence is due to the fact that the most developed countries move away, or that the developing countries are lagging behind in terms of emissions. This study is carried out through the *beta* convergence analysis shown in the following figures.

Figure A.3. ***Beta*** **convergence in direct and embodied per capita emissions, 2000-2014**



Source: Own elaboration

Figure A.3 shows the evolution of *beta* convergence in direct and embodied per capita emissions, respectively. As the logic shows, if there is *sigma* divergence, there must be *beta* divergence, but not necessarily the contrary. As shown in the two graphs above, the countries present *beta* divergence in per capita emissions, because those that issued a large amount of emissions at the beginning of the period, are those that present a higher rate of growth of per capita emissions throughout the analyzed period. The case of China stands out as an outlier, since it is the country that generates the largest amount of emissions globally, and the one that generates the most emissions in the elaboration of its final products.

A cluster analysis is carried out to check if there is a common tendency in groups of countries. When we carry out this study for per capita emissions data to determine the clusters by pollution intensity, the countries are grouped as follows[8]:

- Cluster 1: Australia, Bulgaria, Brazil, Canada, China, Indonesia, India, Korea, Latvia, Mexico, Poland, Russia, Slovakia, Turkey, Taiwan.
- Cluster 2: Austria, Switzerland, Czech Republic, Denmark, Spain, Estonia, Greece, Croatia, Hungary, Ireland, Lithuania, Luxembourg, Malta, Portugal, Slovenia and Romania.
- Cluster 3: Belgium, Germany, Finland, France, United Kingdom, Italy, Japan, Netherlands, Norway, Sweden and USA.

[8] Cyprus has been eliminated from the analysis because it does not belong to any cluster.

When we look at the three groups of countries, we can see that the classification has changed in terms of total emissions. In the first group are countries with higher pollution intensity, while in the last group there are countries with the lowest emissions intensity. Thus, in the same way as before, a convergence analysis is carried out within each of the clusters formed after applying the cluster methodology. Table A.1 shows a summary of the results.

Table A.1 Convergence in emissions by clusters, per capita emissions, 2000-2014

	Cluster 1	Cluster 2	Cluster 3
α	0.930718	0.373607	0.327609
β	-0.00745014	0.00736691	0.000480688
p-value	3.75e-06 ***	2.28e-06 ***	0.3321

Source: Own elaboration

When we observe the results, the time trend coefficient presents a negative sign for cluster 1, indicating the existence of convergence, while that same coefficient for clusters 2 and 3 is positive (being not significant in the latter case), which in itself indicates the presence of a divergence process.