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Gone with the wind:
A structural decomposition of carbon emissions

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Abstract
Understanding the driving forces underlying greenhouse gas emissions is vital for the design of climate and environmental policies aimed at promoting sustainable development and human well-being. The importance of reducing the carbon footprint has long been acknowledged and the European countries have been paving the way in this respect. In particular, we focus on Portugal where a striking reduction of carbon emissions has been observed in just a few years. We perform a structural decomposition analysis over the last two decades allowing to unveil the main drivers underlying the evolution of carbon emissions. We find that the investment on renewable energy sources, namely wind, has been key for a successful transition to a cleaner economy. The impact has been felt both on the reduction of carbon intensity as well as on the increase of energy efficiency in power generation. We also find that such benign evolution was partly counterbalanced by the increase of the contribution of final demand to carbon emissions despite being attenuated with the COVID-19 pandemic. These findings highlight the importance of the adoption of renewable energy sources to support a further mitigation of the carbon footprint in a context of economic growth.

JEL: C67, D57, Q48, Q56.
Keywords: CO_2 emissions; Structural Decomposition Analysis; Renewables; COVID-19.

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1. Introduction

The atmospheric emissions and climate change have been gaining relevance at the international and national levels over the years given the growing need to create mechanisms to mitigate the negative effects on the well-being and economic activity.

The main international convention in this field is the United Nations Framework Convention on Climate Change (UNFCCC), which aims to stabilize the concentration of greenhouse gases in the atmosphere at a level that prevents human activities to interfere negatively with the climate. The UNFCCC was agreed on 1992 and entered into force in 1994. In 1997, the Kyoto Protocol operationalized the UNFCCC and was the first international legal treaty that explicitly intended to limit greenhouse gas emissions from developed countries.

Public policy on climate change has been led by the European Union since at least the early 1990s. Europe has always been at the forefront of global efforts to reduce global emissions. Having presented in 1992 the first international proposal for a coordinated policy to reduce emissions through a tax on carbon dioxide emissions, the European Union has established itself as the moving force in the development of the international climate-change regime. This commitment has led to the full participation of the European Union as a Party to the UNFCCC, together with each of the Member States. In fact, the target established in the Kyoto Protocol for the European Union was the most ambitious among the Parties included in the Protocol. Recently, in 2021, the European Union has set a long-term climate neutrality objective. In particular, the European Climate Law sets a legally binding target of net zero greenhouse gas emissions by 2050.

In such a context of major efforts in most European countries in terms of curbing greenhouse gas emissions, one of the countries that presented a striking decrease was Portugal. Over the last fifteen years, Portugal has reduced emissions by one third, ranking sixth among all European Union countries in terms of the magnitude of the reduction. Even more remarkable, was the behavior during the second half of 2000's, presenting the largest decline within the European Union of nearly 20 per cent over just a few years. Given such impressive evolution, it is of major interest to understand the drivers that led Portugal to be one of the most successful cases in the world in reducing emissions. In fact, such development occurred along with a strong investment in renewable energy sources namely wind power generation.

To understand the relative contribution of different economic and structural changes driving carbon emissions in Portugal over the last two decades we pursue a Structural Decomposition Analysis (SDA). The SDA is based on environmental Input-Output (I-O) analysis which allows to determine the economy-wide environmental repercussions stemming from different economic sectors. In fact, the SDA enables to distinguish a range of production and final demand effects while capturing both direct and indirect effects along the whole supply chain. The SDA has been extensively used in previous work including Munksgaard *et al.* (2000)

and Rørmose and Olsen (2005) for Denmark, De Haan (2001) and Edens *et al.* (2011) for Netherlands, Seibel (2003) for Germany, Mukhopadhyay and Forssell (2005) for India, Roca and Serrano (2007) and Cansino *et al.* (2016) for Spain, Peters *et al.* (2007), Guan *et al.* (2008) and Zhang (2009) for China, Weber (2009) and Feng *et al.* (2015) for the United States, Baiocchi and Minx (2010) for the United Kingdom, Yamakawa and Peters (2011) for Norway, Cellura *et al.* (2012) for Italy, among many others.

Besides focusing on Portugal, which is in itself an interesting case study, we depart from previous literature in the following way. On top of quantifying the contributions of the several drivers to carbon emissions, we also address the uncertainty surrounding those estimates. In fact, the use of SDA does not lead to a unique decomposition and the results may vary substantially (see Dietzenbacher and Los (1998) and De Haan (2001)). However, measuring such uncertainty has been basically neglected in previous work. To address this issue, we resort to the violin plot proposed by Hintze and Nelson (1998). The violin plot displays the shape of the distribution of all estimates along with descriptive and inferential statistics which allow a more formal statistical analysis. Violin plots have been used in other fields by, for example, Chinazzi *et al.* (2013), Audrino and Knaus (2016), Blanco *et al.* (2016), Shi and Yang (2018), Newton *et al.* (2019), just to name a few.

Moreover, for policy at the national level, it is crucial to decompose total country emissions. This implies that when conducting SDA, which relies on I-O data to capture intersectoral linkages, one should distinguish between imported and domestically produced inputs to avoid overestimating the multiplier effect of a given sector (see, for example, Dietzenbacher *et al.* (2005) and Reis and Rua (2009)). However, most previous work tends to ignore such a distinction. In contrast, a few studies derive new intermediate demand matrices and final demand vectors by removing imports from the IO data assuming that each economic sector and final demand category use imports in the same proportions (see, for example, Weber *et al.* (2008)). Such an approach has been pursued empirically by, for instance, Su and Ang (2010, 2012), Su *et al.* (2010), Su *et al.* (2017), Zhen *et al.* (2019). In the case of Portugal, it is not required to make such an assumption as one can take advantage of the availability of domestic flows data.

Furthermore, as the period under study covers the year 2020, we can also investigate the role of the tremendous negative economic shock due to COVID-19 that hit the world in 2020 by assessing its contribution to the reduction in carbon emissions. Typically, economic growth induces more carbon emissions, offsetting totally or partially efficiency improvements in many developed countries while dominating in most developing countries. Hence, given the temporary nature of this type of shock it is important to assess its contribution to the recent decline in emissions as it will be reverted in the future.

The paper is organized as follows. In section 2, we lay out the methodological approach pursued namely by presenting the SDA method and the violin plots. In section 3, we describe the data and in section 4 the empirical results are discussed. Finally, section 5 concludes.

2. Methodological approach

2.1. The Input-Output model

Let us assume that there are N sectors in the economy and consider the equilibrium between total supply and total demand for each good

$$x_i + m_i = \sum_{j=1}^{N} z_{ij} + y_i \tag{1}$$

where x_i corresponds to domestic output of product i $(i = 1, ..., N)$, m_i denotes the imports of product i, z_{ij} denotes the output of sector i used as intermediate consumption by branch of activity j $(j = 1, ..., N)$, and y_i is final demand of product i. Note that, the intermediate consumption includes both domestic output and imports, that is, $z_{ij} = z_{ij}^d + z_{ij}^m$, and the same applies to final demand, $y_i = y_i^d + y_i^m$. Since

$$m_i = \sum_{j=1}^{N} z_{ij}^m + y_i^m \tag{2}$$

substituting (2) into (1) we obtain

$$x_i = \sum_{j=1}^{N} z_{ij}^d + y_i^d \tag{3}$$

that is, the domestic ouput of each product can be used as intermediate consumption in the production of other products or to satisfy final demand. Defining $a_{ij}^d = \frac{z_{ij}^d}{x_j}$, that is, the domestic output of product i used to produce a unit of product j, one obtains for the N products in matrix terms

$$X = A^d X + Y^d \tag{4}$$

where

$$X = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_N \end{bmatrix} \quad A^d = \begin{bmatrix} a_{11}^d & a_{12}^d & \cdots & a_{1N}^d \\ a_{21}^d & a_{22}^d & \cdots & a_{2N}^d \\ \vdots & \vdots & & \vdots \\ a_{N1}^d & a_{N2}^d & \cdots & a_{NN}^d \end{bmatrix} \quad Y^d = \begin{bmatrix} y_1^d \\ y_2^d \\ \vdots \\ y_N^d \end{bmatrix} \tag{5}$$

Solving (4) for X one obtains

$$X = \left(I - A^d\right)^{-1} Y^d \tag{6}$$

where I is an identity matrix $N \times N$ and $L^d = \left(I - A^d\right)^{-1}$ is the domestic Leontief inverse matrix. The element (i, j) of the domestic Leontief matrix allows to assess the increase in domestic output of product i if there is an unitary increase of final demand of the domestic output of product j. Note that, to quantify the intersectoral linkages within a country, it is crucial to distinguish between imported and domestically produced inputs in order to avoid overestimating the multiplier effect of a given sector (see Dietzenbacher *et al.* (2005) and Reis and Rua (2009)). Despite that, most of previous work on the decomposition analysis of carbon emissions has basically disregarded this issue or drawn on some simplifying assumption to cope with the lack of data (see Su and Ang (2013) for further discussion). Since, in general, the available data regarding the direct requirements matrix A does not distinguish between domestically produced and imported products, it has been suggested, for example, by Weber *et al.* (2008) to derive the domestic production technology matrix by assuming that each economic sector and final demand category use imports in the same proportions. In the case of Portugal, we do not need to follow such common practice as domestic flows data are available.

2.2. The environmental extension of the I-O model

The above economic I-O analysis framework has been extended to the environmental I-O analysis (see, for example, Miller and Blair (2009) for an overview). The environmental extension relates the standard I-O model with matrices of physical energy use and emissions. In this way, it is possible to analyze the link between carbon emissions, intersectoral linkages and final demand. The basic environmental extension of the I-O model is obtained through a pre-multiplication of model (6) by a vector of emission intensity coefficients, that is, total emissions e can be written as[1]

$$e = KL^dY^d \tag{7}$$

where K is a $(1 \times N)$ vector of emission coefficients (emissions per unit of output in each sector). To better understand emission coefficients it is key to assess both emissions per unit of energy consumption (energy mix) and energy efficiency. In fact, it has been common practice in the literature to take on board these two effects separately (see, for example, Freitas and Kaneko (2011), Feng *et al.* (2015), Cansino *et al.* (2015, 2016)) Hence, one can further decompose the emission coefficients into emission intensity and energy efficiency so that

$$e = CEL^dY^d \tag{8}$$

where C is $(1 \times N)$ vector of emission intensities (emissions per unit of energy use) and E is a diagonal $(N \times N)$ matrix, with the diagonal entries corresponding to the energy efficiency (energy use per unit of output) in each sector.

1. Note that e corresponds to production-based emissions and does not include household direct emissions such as heating and driving.

Furthermore, regarding final domestic demand, we further decompose it into three components namely demand structure, per capita demand and population (see also Brizga *et al.* (2014) and Feng *et al.* (2015)). Hence, total emissions are now given by

$$e = CEL^d Y_s^d y_c^d p \tag{9}$$

where Y_s^d is a $(N \times 1)$ vector of per capita demand composition (*i.e.* sectoral demand shares), y_c^d is a scalar of per capita demand and p is a scalar of population. Therefore, according to (9) country emissions are determined by six factors namely the carbon intensity, energy intensity, production technology, demand composition, demand level and population. This model can be used to perform a decomposition analysis of total emissions and assess the contributions of the different factors to changes in emissions over time.

2.3. A Structural Decomposition Analysis

The SDA has been widely used to compute the contribution of the different factors to the developments in emissions or energy use (see, for example, Hoekstra and der Berg (2002) and Su and Ang (2012) for a survey).[2] The SDA is preferred over other decomposition approaches as it captures both direct and indirect effects along the entire supply chain across upstream and downstream industries, that is, it captures the interdependency of different economic sectors (Hoekstra and der Berg (2003), Miller and Blair (2009)). Moreover, it allows to distinguish a range of production and final demand effects (Hoekstra and der Berg (2003) and Feng *et al.* (2012)). Therefore, the SDA method allows for a more in-depth analysis by taking on board the intersectoral production linkages within an economy and enables the evaluation of the impact on emissions due to changes in the production structure and final demand. Despite the SDA is more data intensive than other approaches as it requires detailed information on economic activities (such as the I-O tables) and emissions, the growing data availability is supporting its increased usage.

By differencing equation (9), the change in emissions over a given period of time can be written as

$$\begin{aligned} \Delta e &= \Delta CEL^d Y_s^d y_c^d p + C\Delta EL^d Y_s^d y_c^d p + CE\Delta L^d Y_s^d y_c^d p + \\ &\quad + CEL^d \Delta Y_s^d y_c^d p + CEL^d Y_s^d \Delta y_c^d p + CEL^d Y_s^d y_c^d \Delta p \end{aligned} \tag{10}$$

2. Another frequently used method is the Index Decomposition Analysis (IDA) (see, for example, Hoekstra and der Berg (2003) for a discussion). The Index Decomposition Analysis, which is based on index theory, is a simpler and less data demanding decomposition method than SDA. Naturally, such lower data requirements implies a less detailed decomposition of the economic production structure. As stressed by Su and Ang (2012), the IDA is often adopted when the focus is on understanding the drivers of emissions or energy use in a specific sector whereas SDA is used to extend the I-O analysis to study changes in emissions or energy use in the whole economy, taking on board the intersectoral linkages.

where Δ is the difference operator. In this way, the change in emissions is determined by six additive terms, where each term represents the contribution of each factor to the total change in emissions, assuming all the other factors constant. That is,

$$\Delta e = \Delta e_C + \Delta e_E + \Delta e_L + \Delta e_Y + \Delta e_y + \Delta e_p \tag{11}$$

where

$$\Delta e_C = \Delta C E L^d Y_s^d y_c^d p \tag{12}$$
$$\Delta e_E = C \Delta E L^d Y_s^d y_c^d p \tag{13}$$
$$\Delta e_L = C E \Delta L^d Y_s^d y_c^d p \tag{14}$$
$$\Delta e_Y = C E L^d \Delta Y_s^d y_c^d p \tag{15}$$
$$\Delta e_y = C E L^d Y_s^d \Delta y_c^d p \tag{16}$$
$$\Delta e_p = C E L^d Y_s^d y_c^d \Delta p \tag{17}$$

However, in the decomposition given by (10), it is possible to evaluate the different factors at the start or the end-point of the time period. For instance, if one uses the value of the factors at the initial period to weight the changes of each factor, we have a Laspeyres weighting scheme. If one uses end of period values, then we get a Paasche weighting type. However, the total change is underestimated in the former case and overestimated in the latter. That is, decompositions where the Laspeyres or the Paasche indices are applied lead to a residual. To cope with this issue some ad-hoc attempts have been pursued in the literature. For example, Lin and Polenske (1995) and Rose and Casler (1996) mix Lapeyres and Paasche indices to eliminate the residuals while Wier (1998) and Jakobsen (2000) consider the mean of two decomposition forms, one based on the Lapeyres and one based on the Paasche index, but are left with a residual term.

A more thorough and systematic approach to this problem has been laid out by Dietzenbacher and Los (1998), De Haan (2001) and Seibel (2003). The structural decomposition of changes in emissions between two periods (*i.e.* the initial period 0 and the end period 1) using the additive identity splitting method can be as derived as follows

$$
\begin{aligned}
\Delta e &= e_1 - e_0 \\
&= C_1 E_1 L_1^d Y_{s,1}^d y_{c,1}^d p_1 - C_0 E_0 L_0^d Y_{s,0}^d y_{c,0}^d p_0 \\
&= \Delta C E_1 L_1^d Y_{s,1}^d y_{c,1}^d p_1 + C_0 E_1 L_1^d Y_{s,1}^d y_{c,1}^d p_1 - C_0 E_0 L_0^d Y_{s,0}^d y_{c,0}^d p_0 \\
&= \Delta C E_1 L_1^d Y_{s,1}^d y_{c,1}^d p_1 + C_0 \Delta E L_1^d Y_{s,1}^d y_{c,1}^d p_1 + C_0 E_0 L_1^d Y_{s,1}^d y_{c,1}^d p_1 + \\
&\quad - C_0 E_0 L_0^d Y_{s,0}^d y_{c,0}^d p_0 \\
&= \Delta C E_1 L_1^d Y_{s,1}^d y_{c,1}^d p_1 + C_0 \Delta E L_1^d Y_{s,1}^d y_{c,1}^d p_1 + C_0 E_0 \Delta L^d Y_{s,1}^d y_{c,1}^d p_1 + \\
&\quad + C_0 E_0 L_0^d Y_{s,1}^d y_{c,1}^d p_1 - C_0 E_0 L_0^d Y_{s,0}^d y_{c,0}^d p_0 \\
&= \Delta C E_1 L_1^d Y_{s,1}^d y_{c,1}^d p_1 + C_0 \Delta E L_1^d Y_{s,1}^d y_{c,1}^d p_1 + C_0 E_0 \Delta L^d Y_{s,1}^d y_{c,1}^d p_1 + \\
&\quad + C_0 E_0 L_0^d \Delta Y_s^d y_{c,1}^d p_1 + C_0 E_0 L_0^d Y_{s,0}^d y_{c,1}^d p_1 - C_0 E_0 L_0^d Y_{s,0}^d y_{c,0}^d p_0 \\
&= \Delta C E_1 L_1^d Y_{s,1}^d y_{c,1}^d p_1 + C_0 \Delta E L_1^d Y_{s,1}^d y_{c,1}^d p_1 + C_0 E_0 \Delta L^d Y_{s,1}^d y_{c,1}^d p_1 + \\
&\quad + C_0 E_0 L_0^d \Delta Y_s^d y_{c,1}^d p_1 + C_0 E_0 L_0^d Y_{s,0}^d \Delta y_c^d p_1 + C_0 E_0 L_0^d Y_{s,0}^d y_{c,0}^d p_1 + \\
&\quad - C_0 E_0 L_0^d Y_{s,0}^d y_{c,0}^d p_0 \\
&= \Delta C E_1 L_1^d Y_{s,1}^d y_{c,1}^d p_1 + C_0 \Delta E L_1^d Y_{s,1}^d y_{c,1}^d p_1 + C_0 E_0 \Delta L^d Y_{s,1}^d y_{c,1}^d p_1 + \\
&\quad + C_0 E_0 L_0^d \Delta Y_s^d y_{c,1}^d p_1 + C_0 E_0 L_0^d Y_{s,0}^d \Delta y_c^d p_1 + C_0 E_0 L_0^d Y_{s,0}^d y_{c,0}^d \Delta p
\end{aligned} \tag{18}
$$

As shown, this decomposition form is complete, meaning that it has no residual. However, this decomposition is not unique. By changing the order of the variables, one ends up with a different form and there is no *rationale* for any specific ordering. In fact, for n factors there are $n!$ possible different decomposition forms which follow a similar structure as presented in equation (18), each including n separate terms with only one difference term, Δ, in each of them.[3] In particular, with six factors, as in our case, there are 720 possible decompositions. To cope with this non-uniqueness issue, Dietzenbacher and Los (1998) have suggested to take the average of all decompositions.[4]

Furthermore, it has been documented that different decomposition forms can lead to quite different results regarding the contributions of the factors (see Dietzenbacher and Los (1998) and De Haan (2001)). Besides reinforcing the danger of drawing conclusions on choosing arbitrarily just one of the $n!$ decompositions, it highlights the importance of assessing the uncertainty surrounding the estimate

3. One should note that, as mentioned by Dietzenbacher and Los (1998) and De Haan (2001), those $n!$ decomposition forms do not exhaust all possibilities. In fact, equations with more than one Δ in each term could be derived too. However, this leads to a set of decomposition forms with a different structure where the economic interpretation of those terms is not straightforward.

4. From a computational point of view, it is not required to compute all the $n!$ decomposition forms. De Haan (2001) and Seibel (2003) show that there are only 2^{n-1} different coefficients attached to each factor change. For instance, with $n = 6$, we only have $2^{6-1} = 32$ different coefficients, as each of these coefficients appear repeated a specific number of times in the $n!$ decompositions.

for the contribution of each factor. In this respect, Dietzenbacher and Los (1998) suggest reporting the corresponding standard deviations or at least the range of the estimates (minimum and maximum). Despite the importance of assessing the uncertainty, such analysis is rarely found in the literature. A few exceptions include De Haan (2001) who illustrates the variability of the estimates by ploting all the possible contributions for all years and for all factors in a single graph, Rørmose and Olsen (2005) report the standard deviation for one year only while Baiocchi and Minx (2010) display the range along the average for each year.

The assessment of the uncertainy is key for the interpretation of the results. Taking on board the variability of the estimates in the analysis is essential for evaluating the robustness of the findings. It is therefore crucial to depict the distribution of the different estimates to infer about the statistical significance of the results. Herein, we propose the use of the so-called violin plots for SDA.

Although the standard deviation can be informative, such statistic is clearly not enough to unveil more complex data structures. Alternatively, one can consider a Box-and-whisker plot where some summary statistics are displayed such as the median and interquartile ranges. The box plots are simple to create and to read, so naturally, they are of widespread use in many contexts. However, box plots can be misleading since they do not fully capture the distribution of the data. To overcome this caveat, one can resort to violin plots (see Hintze and Nelson (1998)). Besides including all the statistics present in a box plot, violin plots show the probability density of the data at different values, usually smoothed by a kernel density estimator. In practice, the violin plot has literally a box plot inside the violin whereas the violin shape comes from the density plot of the data which is displayed sideways on both sides of the box plot, mirroring each other. Hence, violin plots display the shape of the distribution along with descriptive and inferential statistics enabling a more detailed and rich statistical analysis.

3. Data

The data used in this paper is provided by Statistics Portugal and allows to cover the period from 2000 up to 2020. In particular, we make use of the so-called symmetric I-O matrices, which convey information on the intermediate consumption and final use by sector in the economic territory, distinguishing if the supply comes from imports or domestic production. Hence, these data, which correspond to a breakdown of the standard supply and use tables of annual national accounts, include both the imports and domestic output matrices. Given that the level of disaggregation of the symmetric matrices released has changed throughout the period considered and there have been changes in the product nomenclature of the national accounts, these matrices were aggregated considering the highest possible detail by product to ensure comparability over time, resulting in 49 products/branches of activity. Since this information is only available in nominal terms, we had to compute deflators, with the same disaggregation level, to have matrices at constant prices of a reference year, as standard in related literature. All deflators have been obtained from the annual national accounts, considering for each year the deflators implicit in comparable national accounts data at both current and previous year prices. In this way, the cumulative price change has been obtained for each year allowing to compute estimates at constant prices of 2016, which is the current reference year of national accounts. One should note that the symmetric input-output matrices are not released with the same frequency of annual national accounts and tend to be published only every five years. In the case of Portugal, the symmetric I-O matrices are available for the years 1999, 2005, 2008, 2013, 2015, 2017 and 2020. Hence, we compute the domestic Leontief inverse matrix, L^d, for each of those years and for the remaining years we obtain the corresponding matrix by linear interpolation at the elementary level (i, j) of adjacent years.[5]

We resort to the physical energy flow accounts to collect data on sectoral energy consumption and consider the same sectoral disaggregation. Concerning the greenhouse gas emissions by branch of activity, the data is taken from the air emissions accounts and measured in metric tons of CO_2 equivalent (tCO_2e).

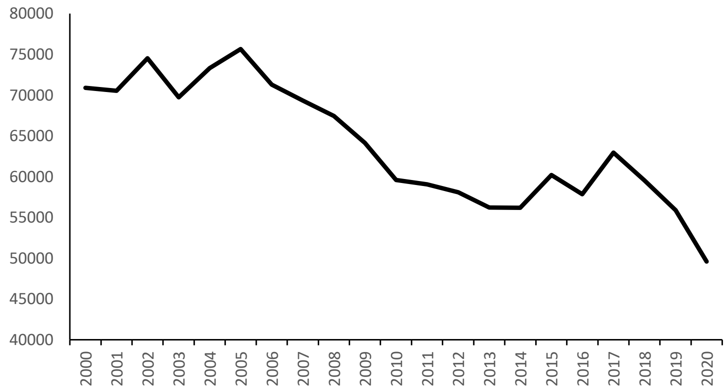


Figure 1: Total carbon emissions (in 1000 tCO_2e)

The evolution of total production-based greenhouse gas emissions over the last two decades is depicted in Figure 1.[6] As mentioned earlier, there has been a pronounced decline in total emissions in the second half of the 2000's and in the last few years, particularly in 2020. Over the whole period, emissions felt by around 30 per cent.

5. Given the overall stability of L^d over time in the case of Portugal, the main findings are robust to such a procedure.

6. As noted previously, herein the focus is on production-based emissions and therefore it does not include household direct emissions. One should note that production-based emissions account for around 85 per cent of total Portuguese emissions and its evolution is very similar to the one observed for the economy-wide emissions.

4. Results

In this section, we present the decomposition results obtained for the Portuguese case over the last two decades. Firstly, in subsection 4.1 we discuss the overall results for the period 2000-2020 as a whole and then address the contribution of each factor over time. Afterwards, to shed further light on these developments we conduct an analysis both at the sectoral level and for each final demand component in subsections 4.2 and 4.3, respectively.[7]

4.1. Decomposition of carbon emissions evolution

In Figure 2, we present the contributions of the six factors considered, namely emission intensity, energy efficiency, production structure, final demand structure, per capita final demand level and population, (Δe_C, Δe_E, Δe_L, Δe_Y, Δe_y, Δe_p, respectively) to the change in total emissions over the period 2000-2020 as a whole.

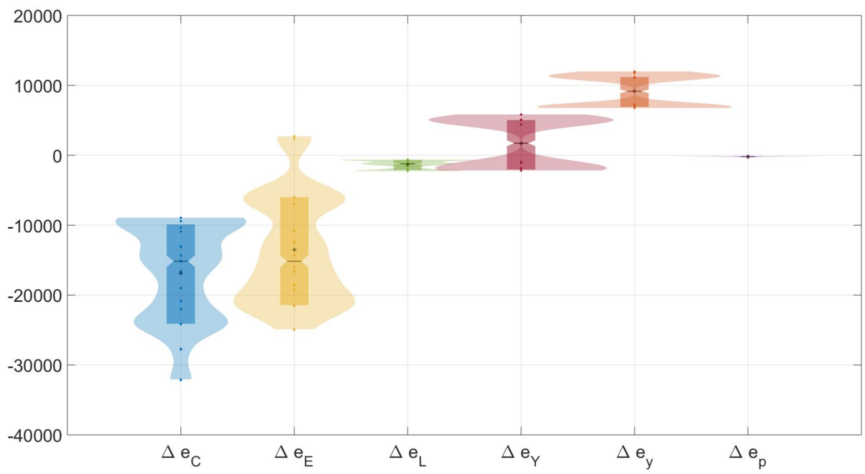


Figure 2: Decomposition of total carbon emissions change over the period 2000-2020 (in 1000 tCO_2e)

Note: Δe_C, Δe_E, Δe_L, Δe_Y, Δe_y, Δe_p denote the contributions of emission intensity, energy efficiency, production structure, final demand structure, per capita final demand level and population, respectively

In particular, a violin plot is displayed for each factor. In each violin plot, the dots along the vertical axis correspond to the estimates obtained with all possible

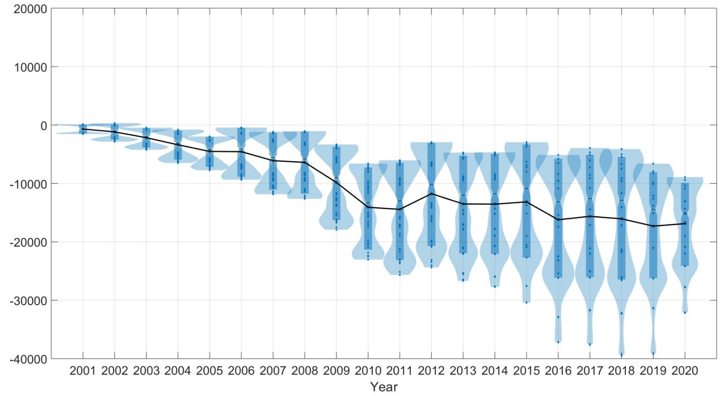
7. To save space and ease of reading, only the key results are presented but, as usual, all the results at the sectoral level and by final demand component are available from the authors upon request.

decompositions whereas the asterisk denotes the corresponding average as usually reported in related literature. The kernel density estimate, which is mirrored and flipped over, depicts the shape of the distribution of those estimates and is displayed for the range between the 2.5th and 97.5th percentiles to highlight the location of the mass of the distribution accounting for 95 per cent. Concerning the box inside the violin, it provides the interquartile range defined as usual by the 75th and 25th percentiles whereas the median is denoted by a dash along with a 95 per cent confidence interval delimited by inferior and superior notches (see McGill *et al.* (1978)).

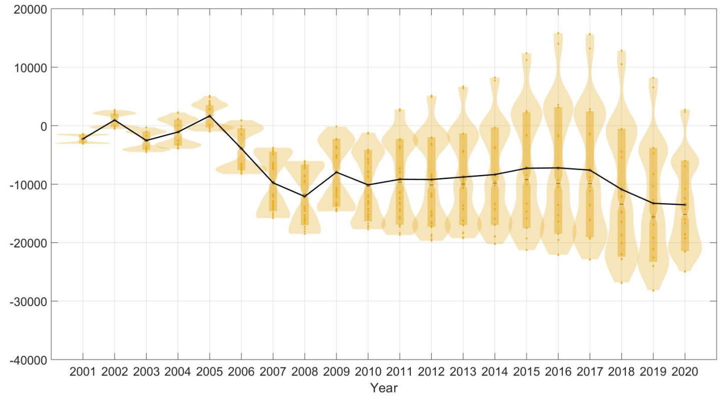
From the analysis of Figure 2, it becomes clear that the main contributors to the reduction of carbon emissions over the last twenty years are the changes in emission intensity and energy efficiency. In fact, these two factors would have led, *ceteris paribus*, to a decline of more than 40 per cent in carbon emissions. Note that the estimate of the contribution based on the average of all decompositions, represented by the asterisk, is more negative for emission intensity than for energy efficiency but the median estimates, as displayed by the dash, are similar. This reflects the difference in the shape of the distribution of the estimates of those two factors as highlighted by the violin plot. In the case of emission intensity, the distribution of the estimates is negatively skewed whereas in the case of energy efficiency the distribution is positively skewed. In the latter case, given the long right tail of the distribution, a null contribution cannot be rejected with a 95 per cent confidence level. However, based on the evidence for the median, one clearly rejects a null contribution for energy efficiency.

Regarding the remaining factors, the production structure presents a statistically significant negative contribution to the change in emissions, albeit relatively small. In contrast, the final demand structure and per capita final demand level contributed to increase carbon emissions with the latter factor being much more important than the former. In particular, per capita final demand contributed to increase carbon emissions by 13 per cent whereas one cannot reject a null contribution for the demand structure factor. Finally, the population factor presents a negligible contribution.

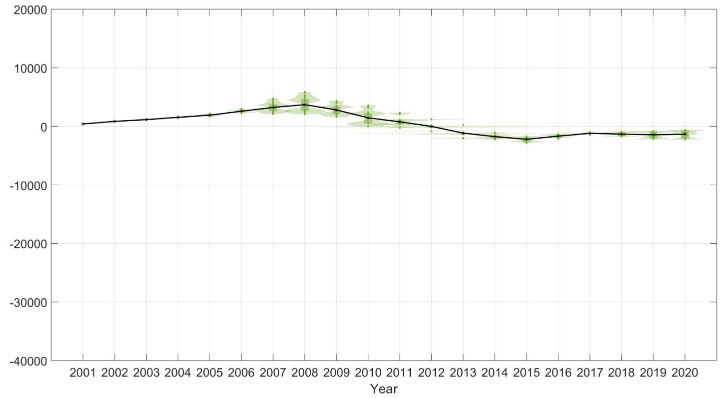
To better understand what lies behind such overall behavior in the last two decades, we start by assessing the evolution of the contribution of each factor over time. In Figure 3, we present the cumulated contribution of each factor to the change in emissions during the period under study. Along with the violin plot for each year, a solid line is displayed corresponding to the average as usually reported in related literature. To ease the visual comparison across factors, we kept fixed the axis range and the color scheme used for each factor in the previous figure.



(a) Emission intensity

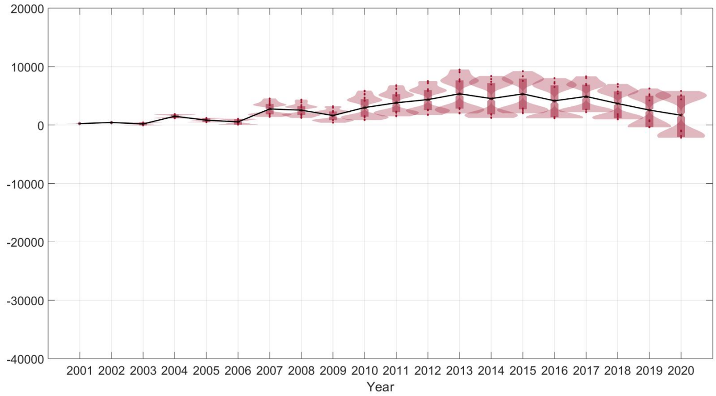


(b) Energy efficiency

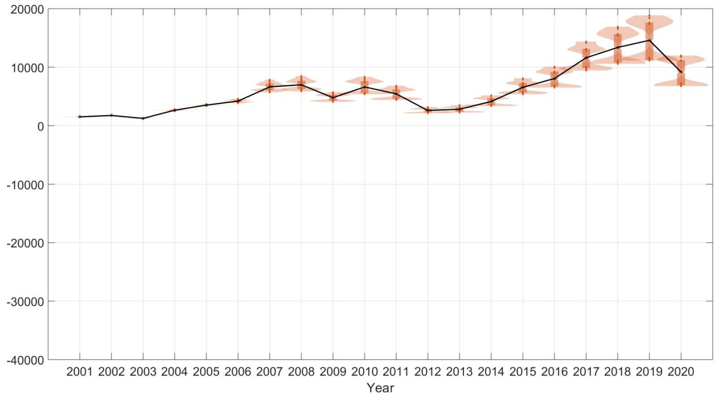


(c) Production structure

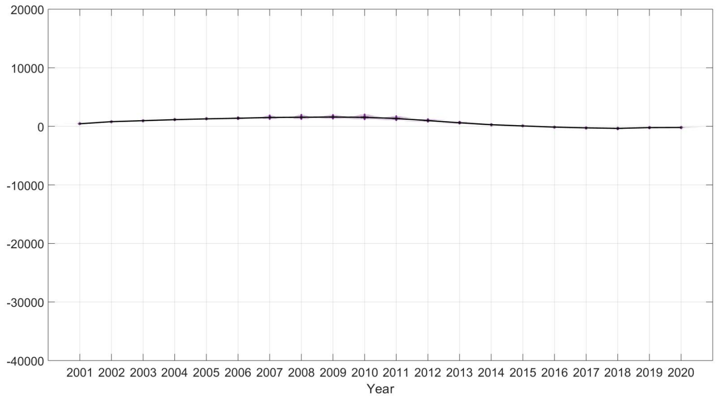
Figure 3: Cumulated contribution of each factor to total carbon emissions change (in 1000 tCO_2e)



(d) Final demand structure



(e) Per capita final demand level



(f) Population

Figure 3: Cumulated contribution of each factor to total carbon emissions change (in 1000 tCO_2e) (continued)

From the analysis of Figure 3, one can conclude that the contributions of the different drivers have varied over the years. Concerning the emission intensity, one can see that there was a decline in the contribution to carbon emissions throughout the 2000's which was particularly pronounced in the second half of that decade. Afterwards, it remained relatively stable with a slight decrease in the last few years. Interestingly, the contribution of energy efficiency presented broadly a similar behavior. In particular, it declined sharply in the second half of the 2000's, remaining relatively unchanged until recently when it decreased again. In fact, the evolution of these factors is to a large extent related, as discussed more thoroughly in the next subsection, reflecting the role of renewable energy sources, namely wind, in power generation.

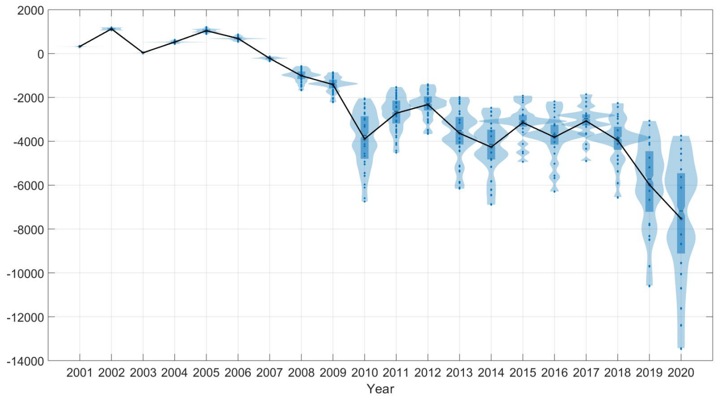
Besides these two factors which are indisputably the main drivers of carbon emission changes in Portugal, it is also worth mentioning the evolution of the contribution of final demand level. As expected, its behavior reflects the business cycle. It presents an underlying upward trend interrupted by decreases at recessionary periods, namely the Great Recession in 2009, the sovereign debt crisis that hit Portugal in 2011 and more recently the sharp decline in economic activity due to COVID-19 in 2020. In particular, the fall of final demand in 2020 due to the Coronavirus disease pandemic led to a reduction of almost 8 per cent in carbon emissions. This means that, over the last two decades, final demand would have contributed to increase carbon emissions by more than 20 per cent in the absence of the COVID-19 shock.

To a lesser extent, the contribution of demand structure also presents some variation over time namely by increasing slowly until mid-2010's and decreasing slightly afterwards. The contribution of the remaining factors, production structure and population, have been relatively unchanged.

4.2. Insights at the sectoral level

To gain further understanding on the remarkable evolution of the contributions of emission and energy intensities throughout time it is key to perform a sectoral analysis. In this respect, we find that, among the nearly fifty sectors considered, the electricity sector is, to a large extent, responsible for the behavior of such factors. In particular, it accounts for about two thirds of the overall contribution of those factors to carbon emissions change. In Figure 4 we present the cumulated contribution of each of those factors in the electricity sector to total carbon emissions change.

Focusing on the contribution of emission intensity in the electricity sector, one can see that it was slightly positive until 2005 and then decreased markedly until 2010. Afterwards, it remained at similar levels decreasing significantly in the last few years.

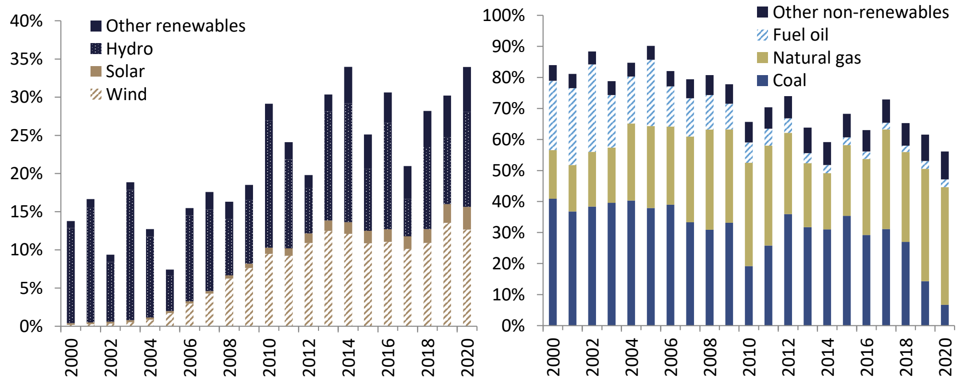


(a) Emission intensity

(b) Energy efficiency

Figure 4: Cumulated contribution of the electricity sector to total carbon emissions change (in 1000 tCO_2e)

The marked decline in the second half of 2000s was due to the fast increase of renewable energy sources in power generation, namely wind energy. In Figure 5, one can see that the relative importance of renewable energy sources in power generation increased from less than 10 per cent up in 2005 to near 30 per cent in 2010. Behind this evolution there was a notable increase in the role played by wind energy. The roots of such developments trace back to 2001 when the Portuguese government launched a new energy policy instrument, the E4 Programme (Energy Efficiency and Endogenous Energies), consistent with the EU Directive on renewable electricity (2001/77/CE). The E4 Programme entailed a set of measures promoting energy efficiency and the use of renewable energy (endogenous) sources for power generation, allowing to upgrade the competitiveness of the Portuguese economy while preserving the environment by reducing greenhouse gas emissions. The resulting legislation and incentive schemes stimulated the interest of private investors.[8] Such stimulus led to a major investment on wind farms. For instance, in 2008, it was inaugurated in Portugal the Europe's largest onshore wind farm. Portugal ranked among the top ten countries in the world with higher installed wind power capacity throughout the second half of 2000's and early 2010's. In 2012, wind accounted for half of the renewable energy sources and Portugal ranked second among the European countries in terms of the relative importance of wind in electricity generation, only surpassed by Denmark. At the end of 2012, the legal framework changed, and the incentives weakened which led to a retraction of new investment. This putted a halt to the striking trend observed in the second half of the 2000's.



(a) Renewables (b) Non-renewables

Figure 5: Energy sources for power generation, percentage

More recently, the contribution of emission intensity in the electricity sector felt again. This reflects the abrupt decline of the role played by coal, which is highly pollutant, in power generation in the last couple of years (see Figure 5). In 2018, Portugal committed to close all of the country's coal producing facilities by 2030. However, it was pursued a progressive reduction of electricity generation based on coal much stronger than initially expected, leading to an anticipation of the closure of the coal-fired power plants of nearly ten years. In fact, the country's largest coal-fired power station, in Sines, was closed in January 2021 whereas the last remaining coal-fired power plant, the Pego power plant, was shut down in November 2021.

Regarding the contribution of energy intensity in the electricity sector to total carbon emissions, it was observed a sharp decline in the second half of 2000's remaining relatively unchanged afterwards. This decrease also reflects the

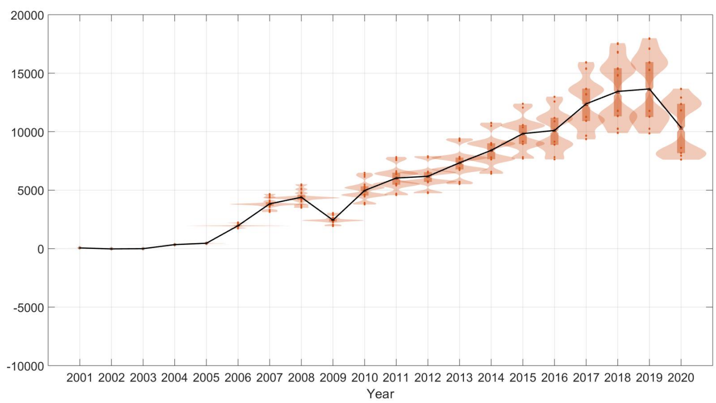
8. The legislation included the Decree-Law 312/2001 defining the conditions regulating the awarding and management of grid interconnection points for independent power producers and the Decree-Law 339-C/2001 establishing a range of favorable feed-in tariffs for electricity generation based on renewable energy sources. There was also a broadening of the scope of financial incentives for energy efficiency and use of endogenous energies in the framework of the PRIME Programme aimed at the modernization of the economy.

above discussed developments in renewable energy sources. In particular, the sharp increase in the weight of renewable energy sources in the second half of 2000's, led to an increase of energy efficiency in the electricity sector as renewables are much more efficient than non-renewables (see, for example, Pietzcker *et al.* (2021)). Hence, the increased role of wind on electricity generation led to the reduction of carbon emissions through two channels. Not only wind is a clean energy source as it is more efficient than coal or natural gas.

4.3. Decomposing final demand

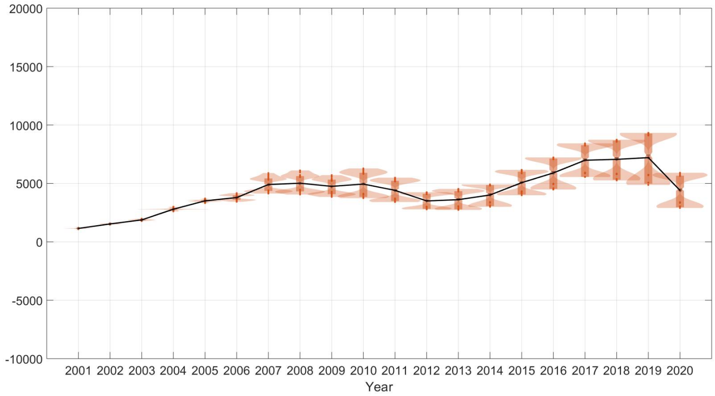
As discussed above, emission and energy intensities are the main drivers behind the observed reduction in carbon emissions. In the opposite direction, one should highlight the contribution of final demand level. To unveil which final demand components lie behind the increase of the contribution of final demand level, we assess the contribution corresponding to its main components, namely, private consumption, public consumption, investment, and exports (see Figure 6).

The demand components that have been pushing carbon emissions upwards over the last two decades are exports and to a lesser extent private consumption. The contribution due to exports present a noteworthy increasing trend since 2005 only interrupted in 2009 with the Great Recession and in 2020 with the COVID-19 global shock. In fact, exports have been gaining momentum over the years in the Portuguese economy, from weighting around 25 per cent of GDP, in real terms, in 2005 to more than 43 per cent in 2019 reflecting an accumulated real growth during that period of nearly 90 per cent.

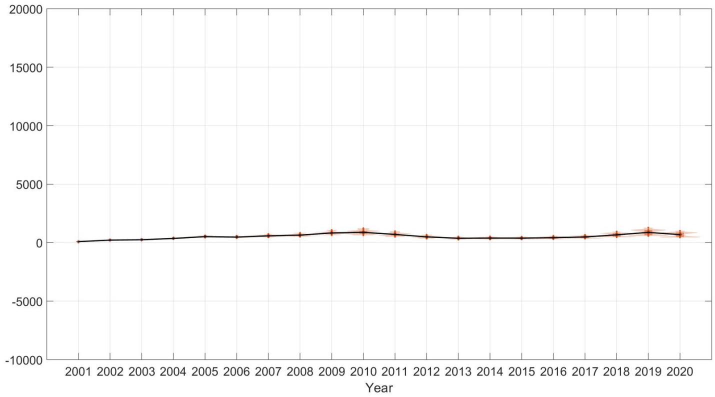


(a) Exports

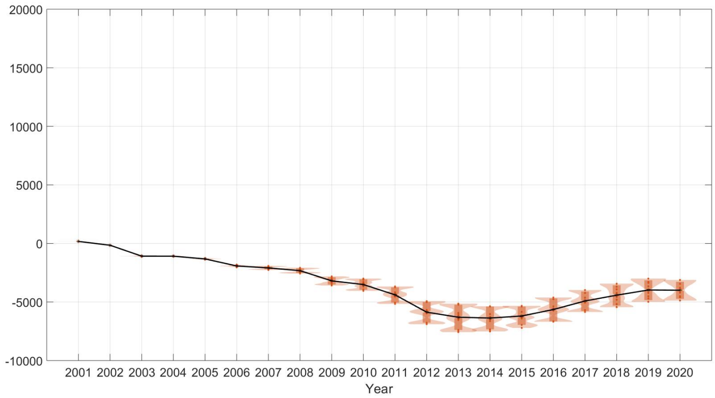
Figure 6: Decomposition of the contribution of final demand level to carbon emissions change by demand component (in 1000 tCO_2e)



(b) Private consumption



(c) Public consumption



(d) Investment

Figure 6: Decomposition of the contribution of final demand level to carbon emissions change by demand component (in 1000 tCO_2e) (continued)

Regarding private consumption, its contribution increased sharply until 2007, period in which it grew by more than 10 per cent in real terms. Afterwards, it remained around that level although influenced by the business cycle with a more pronounced fall in 2020 with the pandemics. Public consumption presented a positive but very small contribution throughout the whole period.

In contrast, investment has contributed negatively to carbon emissions change. In particular, it was observed a marked drop between late 2000's and early 2010's during the Great Recession and the sovereign debt crisis. In fact, between 2008 and 2013, total investment contracted almost 40 per cent. Investment in the construction sector was the hardest hit and ended up attaining a cumulated decrease of nearly 60 per cent in 2014 since its peak in the early 2000's. Afterwards, investment recovered slowly, in particular in the construction sector where it is still well below the peak levels observed in the past.

5. Conclusions

To limit global warming and promote a sustainable development it is key to curb greenhouse gas emissions. In particular, the European Union has been paving the way towards decarbonization and is committed to reach net zero emissions in 2050. In fact, the European Union is aiming to be the world's first net zero continent, and is hence strengthening energy policies and regulations, being the first region to put the net zero target into law. To support the transition to a low-emission and climate-resilient future, raising the ambitions in terms of energy efficiency and renewable energy sources is absolutely essential.

Within the European Union, Portugal recorded a striking decrease of around 30 per cent over the last two decades in terms of greenhouse gas emissions. To understand the drivers behind this evolution, we performed a structural decomposition of carbon emissions which allows to distinguish the role played by several factors namely emission intensity, energy efficiency, production structure, final demand structure, per capita final demand level and population. Departing from previous literature, we addressed explicitly the uncertainty surrounding the estimates of the contributions of the different drivers. We have shown that such uncertainty can be comprehensively characterized through a violin plot. Furthermore, we distinguished between imported and domestically produced inputs when assessing intersectoral linkages by resorting to domestic flows data for Portugal. Such data, which is typically not available for many countries, allows a more proper estimation of carbon emissions decomposition.

We found that the main contributors to the reduction of carbon emissions over the whole period are the changes in emission intensity and energy efficiency. These two factors would have led, *ceteris paribus*, to a decline of more than 40 per cent in carbon emissions. In particular, both of these two factors contributed to a sharp decline in carbon emissions in the second half of the 2000's. Such developments reflect the steep increase of renewable energy sources in power generation, namely wind. In fact, not only wind is a clean energy source as it is more efficient than non-renewables energy sources, such as coal or natural gas. Stimulated by energy policies and legal framework, the importance of renewable energy sources in power generation increased from less than 10 per cent up in 2005 to near 30 per cent in 2010, improving only slightly afterwards due to a less benign context.

The decline of emission intensity and the improvement of energy efficiency were only partially offsetted by final demand evolution. In fact, economic growth tends to increase carbon emissions, offsetting totally or partially other factors that contribute to reduce carbon emissions. In this respect, one should note that the COVID-19 pandemic significantly reduced human activities in 2020, leading to a temporary fall in carbon emissions. As economic activity recovers from the pandemic, emissions are expected to rise unless further steps are taken to shift the economy towards carbon neutrality.

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