Renewable and Sustainable Energy Reviews 133 (2020) 110104

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: http://www.elsevier.com/locate/rser

Drivers of CO2 emissions from electricity generation in the European Union 2000–2015

João F.D. Rodrigues [a,*], Juan Wang [b], Paul Behrens [a,c], Paul de Boer [d]

[a] Institute of Environmental Sciences CML, Leiden University, Einsteinweg 2, 2333 CC, Leiden, Netherlands
[b] Tianjin University of Finance and Economics, School of Finance, Tianjin, 300222, China
[c] Leiden University College the Hague, Anna van Buerenplein 301, 2595 DG, The Hague, Netherlands
[d] Erasmus University Rotterdam, Erasmus School of Economics, Econometric Institute, P.O.Box 1738, 3000 DR, Rotterdam, Netherlands

ARTICLE INFO

Keywords:
Electricity sector
Carbon emissions
Decomposition analysis
EU countries

ABSTRACT

Carbon emissions from electricity generation in the EU have dropped from 1198 MtCO2 in 2000 to 970 MtCO2 in 2015, after an initial increase to 1304 MtCO2 in 2007. This pattern reversal is not only explained by socio-economic drivers (an initial period of robust economic growth followed by weaker growth) but by profound shifts in the energy system. This study quantitatively evaluates the drivers of carbon emissions from EU electricity generation during two subperiods, 2000–2007 and 2007–2015. In 2000–2007 the main drivers of the decrease in carbon emissions were changes in the fossil fuel mix (replacement of coal by gas) and improvements in the efficiency of electricity use. In 2007–2015 the main drivers of the decrease in carbon emissions were the expansion of renewable electricity, improvements in the efficiency of fossil electricity production and improvements in the efficiency of electricity use. There is significant variation in the drivers of change among countries. The authors expect the continued expansion of renewables to balance economic growth in the future.

1. Introduction

The European Union has positioned itself as an international leader in the development of climate-energy policy [1]. It is a significant emitter of greenhouse gases (GHGs), comprising 10% of total global emissions on a production basis [2], and a greater proportion on a consumption basis [3]. Substantive energy climate policies have been in place for approximately 25 years [4] and a myriad of different qualitative and quantitative targets have been set. Examples of such targets include cutting GHG emissions, increasing the share of renewables, and improving energy efficiency [5,6].

Even though all economic sectors have a responsibility to achieve these targets, the electricity sector is likely to see faster decarbonisation than other energy supply and end-use sectors [7,8]. Ensuring that the energy policies are as effective as possible requires an understanding of how emissions are driven by human activities, and how historical policies have driven changes in carbon emissions from electricity generation. This paper determines the historical drivers in the evolution of carbon emissions from electricity generation in the EU and disentangle the role of fossil carriers, renewable penetration and end-use efficiency. While accounting for the economic structural changes in carbon emissions from EU electricity generation this paper will further describe how each country contributed to shaping the carbon emissions for the EU as a whole. Simply put, was there a positive effect on decarbonisation of electricity by switching from solid fossil fuels to gas? Did the increased renewable penetration rate significantly contribute to carbon emissions reduction? How did international electricity trade impact carbon emissions? Or were these factors swamped by transformations outside the energy sector (e.g., economic growth or population growth)?

To perform this analysis this paper uses IDA (index decomposition analysis), a technique that has been extensively used to investigate the driving forces of carbon emissions from electricity generation in different countries around the word, such as global [8,9], China [10–14], US [15,16], Canada [17], Korea [18], Italy [19] and Spain [20]. In most IDA studies LMDI-I is used because it has several good properties and is easy to calculate no matter how many factors are considered [21]. The present study follows common practice and uses LMDI-I as starting point. Although not considered in this study, econometrics offers alternative methods to explore this subject, as performed, among others, by Apergis [22]; Wu and Peng [23]; Mele and Randazzo [24]. Also not considered in this study, data envelopment analysis has also been combined with IDA, among others, by Du et al. [25]; Du and

---

* Corresponding author.
E-mail address: j.rodrigues@cml.leidenuniv.nl (J.F.D. Rodrigues).

https://doi.org/10.1016/j.rser.2020.110104
Received 4 February 2020; Received in revised form 13 July 2020; Accepted 14 July 2020

Lin [26]; Zha et al. [27]; Wang et al. [14].

From a methodological point of view, all of these IDA studies except Mohlin et al. [16] perform a one-stage decomposition in which an aggregate change is decomposed into changes in a certain number of factors. To account for the contribution of renewables this paper follows the approach of Mohlin et al. [16] and use a two-stage decomposition where the change in one of the factors in the first stage is, on its turn, decomposed into changes in a certain number of sub-factors, which are the contribution of different renewables to carbon emissions. Methodologically, this study differs from Mohlin et al. [16] because they assume a specific dispatch sequence for renewables while this paper obtains a decomposition that is an average of all possible dispatch sequences and is therefore independent of the order in which different types of renewable electricity are generated.

This study also differs from recent studies on the power sector of the European Union [7,28] by considering the effects of international electricity trade and transport efficiency, and by further identifying the contribution of different fossil fuel carriers, various renewables and the final-use efficiency of different end-use sectors. In particular, due to lack of information, assessing the role of electricity trade between countries requires making an assumption about reexports, a problem which is addressed by using the Leontief model [29]. For a review of different factors used in decompositions of emissions see Wang et al. [21].

Detailed mathematical calculations are reported as Supplementary Information, which together with the detailed results as well as the numerical values underlying figures can be accessed at https://doi.org/10.5281/zenodo.3939907, https://doi.org/10.5281/zenodo.3939906.

2. Methods and data

This section reports the methods and describe the data used in the study. It begins by describing the procedure of the first stage decomposition, in which all the drivers of change in carbon emissions from electricity generation are determined, except the contribution of renewables. The contribution of renewable sources to carbon emissions is performed in a second stage, described in the second subsection. The third subsection describes how the coefficients used to describe the flow of electricity from one member-state to another are obtained. The final subsection describes the data.

2.1. General decomposition

The goal of this study is to perform an index decomposition analysis (IDA) that is able to differentiate emissions occurring in each of n_{reg} EU member-states due to each of n_{fos} fossil fuel carriers, in order to supply consumption in a possibly different member-state for each of n_{fin} final electricity consumption categories. The sum of all emissions in year t is thus defined as:

$$CO2^t_{EU} = \sum_{kfos}\sum_{kreg1}\sum_{kreg2}\sum_{kfin} CO2^t_{kfos,kreg1,kreg2,kfin} \tag{1}$$

In the previous expression the iterators represent the following: $kfos$ is a type of fossil fuel carrier, $kreg1$ is the member-state where electricity is generated, $kreg2$ is the member-state where electricity is consumer and $kfin$ is a category of final electricity consumption.

Naturally, the different $CO2^t_{kfos,kreg1,kreg2,kfin}$'s can be partially aggregated to obtain the emissions by fossil fuel carrier, region of emission, etc. Each $CO2^t_{kfos,kreg1,kreg2,kfin}$ is further decomposed as a product of eight factors:

$$\begin{aligned} CO2^t_{kfos,kreg1,kreg2,kfin} &= co2fos_{kfos} \times fostot^t_{kfos,kreg1} \times totren^t_{kreg1} \\ &\times traeff^t_{kreg1} \times trasha^t_{kreg1,kreg2} \times elefin^t_{kreg2,kfin} \\ &\times gvacap^t_{kreg2} \times pop^t_{kreg2} \end{aligned} \tag{2}$$

$co2fos_{kfos}$ is the emission coefficient, defined as carbon emissions per unit of fossil energy carrier combusted (tCO2/toe) and it is assumed to be carrier-specific, but otherwise identical for all regions and years, so it will not be considered as a decomposition factor.

$fostot^t_{kfos,kreg1}$ is the ratio between the volume of a particular fossil energy carrier being combusted and the electricity generated from all fossil sources (toe/toe).

$totren^t_{kreg1}$ is the ratio of fossil electricity to total electricity generated, including nuclear and renewables (toe/toe). In the results this factor is referred to as ‘share of non-fossil electricity’.

$traeff^t_{kreg1}$ is the efficiency of electricity transport, and is the ratio between total electricity generated and total electricity consumed in final uses (toe/toe). The difference between these quantities is explained by distribution losses and electricity use within the energy branch.

$trasha^t_{kreg1,kreg2}$ is the share of electricity consumed by region $kreg2$ that originates in region $kreg1$ (toe/toe).

$elefin^t_{kreg2,kfin}$ is the ratio of electricity consumed by final demand sector $kfin$ in region $kreg2$ by the GDP of region $kreg2$ (toe/Meuro).

Note that in this ratio the numerator refers to a particular sector consuming electricity while the denominator is the GDP of the whole region. Thus, this factor will capture both changes in the “pure” electricity efficiency of the sector (e.g., MWh/Meuro of gross value added (GVA) in case of an industry) and changes in composition (i.e., the share of GVA of a particular industry in national GDP). This option was taken because households are one of the sectors that consume electricity and no GVA share can conceptually be attributed to households/final consumers.

$gvacap^t_{kreg2}$ is the GDP per capita of member state $kreg2$ (Meuro/hab).

pop^t_{kreg2} is the population of member state $kreg2$ (hab).

Note that only emissions occurring within the EU to satisfy demand within the EU are being accounted for.

The decomposition of the change in EU emissions from electricity generation between years $t = 0$ and $t = 1$ was performed using the additive LMDI-I method [30]:

$$\begin{aligned} & DCO2_{EU} = CO2^1_{EU} - CO2^0_{EU} \\ & = \sum_{kfos}\sum_{kreg1}\sum_{kreg2}\sum_{kfin} DCO2_{kfos,kreg1,kreg2,kfin} \end{aligned} \tag{3}$$

where:

$$\begin{aligned} DCO2_{kfos,kreg1,kreg2,kfin} &= CO2^1_{kfos,kreg1,kreg2,kfin} - CO2^0_{kfos,kreg1,kreg2,kfin} \\ &= Dco2fos_{kfos} + Dfostot^t_{kfos,kreg1} + Dtotren^t_{kreg1} \\ &\quad + Dtraeff^t_{kreg1} + Dtrasha^t_{kreg1,kreg2} + Delefin^t_{kreg2,kfin} \\ &\quad + Dgvacap^t_{kreg2} + Dpop^t_{kreg2} \end{aligned} \tag{4}$$

Naturally, the factors (e.g., $Dfostot^t_{kfos,kreg1}$) can be aggregated to obtain EU contributions or other partial aggregates such as fuel types or countries. Each factor was calculated using the LMDI-I formula [30], e.g.:

$$\begin{aligned} Dfostot_{kfos,kreg1} = L\left(CO2^1_{kfos,kreg1,kreg2,kfin}, CO2^0_{kfos,kreg1,kreg2,kfin}\right)\backslash \\ \times \log\frac{fostot^1_{kfos,kreg1}}{fostot^0_{kfos,kreg1}} \end{aligned} \tag{5}$$

and similar expressions for the other factors, where the logarithmic mean is:

$$L(a,b) = \frac{b-a}{\log(b/a)}$$

2.2. The contribution of renewables

The factor of the ratio of fossil to total electricity generated,

$Dtotren_{kreg1}$, was further decomposed into n_{ren} factors, one for each non-fossil electricity source, following the procedure of Mohlin et al. [16]. Let FOS^t_{kreg1} be electricity generated from fossil sources, $REN^t_{kreg1,kren}$ be the electricity generated from non-fossil source *kren* and total electricity generated be defined as:

$$TOT^t_{kreg1} = FOS^t_{kreg1} + \sum_{kren} REN^t_{kreg1,kren} \tag{6}$$

The ratio of fossil to total electricity generated, $totren^t_{kreg1}$, can now be expressed as a product of n_{ren} terms:

$$\begin{aligned} totren^t_{kreg1} &= \frac{FOS^t_{kreg1}}{TOT^t_{kreg1}} = totren^t_{kreg1,1} \times totren^t_{kreg1,2} \times \cdots \times totren^t_{kreg1,n_{ren}} \\ &= \frac{FOS^t_{kreg1}}{FOS^t_{kreg1} + REN^t_{kreg1,1}} \times \frac{FOS^t_{kreg1} + REN^t_{kreg1,1}}{FOS^t_{kreg1} + REN^t_{kreg1,1} + REN^t_{kreg1,2}} \\ &\quad \times \cdots \times \frac{TOT^t_{kreg1} - REN^t_{kreg1,n_{ren}}}{TOT^t_{kreg1}} \end{aligned} \tag{7}$$

In words, the right hand side of the previous expression (Eq. (7)) is a product of terms, where in each consecutive term another element of the list of non-fossil sources is added.

Mohlin et al. [16] use the above procedure to estimate the impact of renewables on emissions from fossil sources. However, the ordering of the non-fossil sources considered will have an impact on its estimated contribution so this paper calculates the contribution of each non-fossil source following each possible permutation and afterwards calculate the arithmetic average. That is:

$$Dtotren_{kreg1,kren} = \frac{1}{n_{perm}} \sum Dtotren^{kperm}_{kreg1,kren}$$

where n_{perm} is the number of permutations and

$$\begin{aligned} Dtotren^{kperm}_{kreg1,kren} = L\left(CO2^1_{kfos,kreg1,kreg2,kfin}, CO2^0_{kfos,kreg1,kreg2,kfin}\right) \\ \times \log\left(\frac{totren^1_{kreg1,kren}}{totren^0_{kreg1,kren}}\right) \end{aligned}$$

where *kperm* indicates that the non-fossil factor *kren* appeared in a particular position in the sequence of non-fossil factors. Supplementary Information A illustrates the pertinent procedure for five renewables. This is done analogously to the comparable structural decomposition analysis (SDA) with five factors given in De Boer and Rodrigues [31].

2.3. Electricity trade

The electricity trade statistics report the electricity that flows between each pair of countries A and B, but do not specify whether an international trade flow is reexported (e.g., if this flow is then transferred by B to another country C). This study assumes that the electricity sold by a country either for domestic final use or for exports is a mix of the domestically produced electricity and imported electricity. This assumption is a middle ground between assuming all exports to be produced domestically or being reexports, and means that in practice the conventional Leontief model [29] is used to calculate the electricity produced in region A to be consumed in region B.

The value $trasha^t_{i,j}$ is the (i,j) element of matrix $\mathbf{R}\mathrm{diag}(\mathbf{v})^{-1}$ where $\mathbf{v}$ is the vector of domestic electricity production, diag denotes diagonal matrix, and $\mathbf{R}$ is obtained as:

$$\mathbf{R} = \mathrm{diag}(\mathbf{b})(\mathbf{I} - \mathbf{A})^{-1}\mathrm{diag}(\mathbf{y}) \tag{8}$$

In turn $\mathbf{I}$ is an identity matrix, $\mathbf{A} = \mathbf{Z}\mathrm{diag}(\mathbf{x})^{-1}$, $\mathbf{b}' = \mathbf{v}'\mathrm{diag}(\mathbf{x})^{-1}$, $\mathbf{Z}$ is the matrix of international trade in electricity, $\mathbf{v}'$ is the row vector of domestic generation of electricity (vectors are in column format by default and prime (') denotes transpose), $\mathbf{y}$ is the column vector of final use of electricity and $\mathbf{x}$ is the column vector of total electricity output. Quantities $\mathbf{Z}$, $\mathbf{v}$, $\mathbf{y}$ and $\mathbf{x}$ are constrained by the following accounting identities: $\mathbf{Zi} + \mathbf{y} + \mathbf{exp} = \mathbf{x}$ and $\mathbf{i}'\mathbf{Z} + \mathbf{v}' + \mathbf{imp}' = \mathbf{x}'$, where $\mathbf{i}$ is a column vector of ones, and **exp** and **imp** are, respectively, the vectors of exports and imports of electricity to/from outside the EU.

The input data for the calculation of the electricity trade share are $\mathbf{Z}$, $\mathbf{y}$, **exp** and **imp** in each year, with all other quantities being endogenously determined. Supplementary Information B provides a derivation of Eq. (8).

2.4. Data

The primary data source for this study was the Eurostat database (https://ec.europa.eu/eurostat/data/database), from where all data was extracted, except for the emission factors, which were obtained from Table AI.1 of Annex 1 of [32]. The specific Eurostat tables used were the energy balances (nrg_110a) for fossil fuel use and all electricity data except trade, which were obtained from tables nrg_125a and nrg_135a. GDP was obtained from nama_10_a64 and population from pop.

The time frame of the study was set to 2000–2015 as that was the widest range for which a harmonized data set was available for all countries. The set of countries examined is the EU28 except Malta, Cyprus and Luxembourg (which together constitute 0.5% of the EU's population or electricity consumption), hence $n_{reg} = 25$. The set of fossil fuel sources considered is: 'anthracite', 'other bituminous coal', 'sub bituminous coal', 'lignite', 'peat', 'oil' and 'gas' ($n_{fos} = 7$). For the purpose of presentation, in the figures reported in the main text 'other bituminous coal' is referred to simply as 'bituminous coal' and 'sub-bituminous coal' and 'peat' are combined in a category of 'other coal'. The set of non-fossil electricity sources considered is: 'nuclear', 'hydro', 'wind', 'solar' and 'other renewables' ($n_{ren} = 5$). Finally, the set of final electricity use sectors is: 'iron steel', 'chemical', 'non ferrous metals', 'non metalic minerals', 'transport equipment', 'machinery', 'mining', 'food', 'paper, 'wood', 'construction', 'textile', 'non specified industry', 'rail', 'other transport', 'residential', 'services', 'agriculture', 'other sector' ($n_{fin} = 19$). In the plots presented in the main text all sectors not explicitly mentioned are aggregated in the 'other' category.

Most data elements in the analysis were extracted directly from the energy balance or other table without additional processing except the trade data, which required additional processing. Eurostat provides electricity trade tables that report the electricity exported and imported by each member-state with a set of partners that includes both other member-states and partners outside the EU. The sum across trade with all partners yields a total of imports or exports for the corresponding table that is in agreement with the imports and exports reported in the national energy balances. However, particular inter-country trade values are not consistent between the import and the export electricity trade tables. Whenever such a disagreement was found it was assumed that the true trade value was the highest reported. To keep totals unchanged a corresponding trade value with the outside of the EU had to be reduced. At the end of this procedure some trade values with the outside of the EU had become negative and were exogenously set to zero. This harmonized set of international electricity trade and the sum of final electricity use were the source data used in the reallocation of electricity reexports reported in Supplementary Information B.

3. Results

3.1. Background

Fossil fuelled electricity generation from three different types of coal, gas and oil, along with their associated carbon emissions are shown in Fig. 1a. EU fossil electricity generation increased from 2000 to 2007 but decreased below the 2000 level by 2015 (144, 170, and 137 Mtoe for each year respectively). Carbon emissions from electricity generation decreased between 2000 and 2015 (from 1198 to 970 MtCO2eq).

Between 2000 and 2006, emissions increased at an annual average growth rate of 1.4%/yr (to 1304 MtCO2eq). Afterwards, emissions declined at an annual average rate of 3.2%/yr until 2015, neglecting slight increases in some years. The largest contributor of emissions was bituminous coal (35%–40% of the total), followed by lignite (26–31%), then natural gas (19–29%). The share of emissions from oil decreased from 10% to 4% and other coal 4%–2% between 2000 and 2015.

Non-fossil electricity generation including wind, solar, nuclear, hydro and others increased from 2000 to 2015 (from 114 to 138 Mtoe in 2015, see Fig. 1b). Non-fossil surpassed fossil electricity in 2014 and 2015. The major source of non-fossil generation was nuclear power despite a slight decline from 2000 to 2015. Hydropower was another main source, fluctuating around 30 Mtoe. Generation from wind power and solar power were relatively small before 2007, increasing rapidly thereafter.

The contribution of international electricity trade to carbon emissions is examined in Fig. 1c. It is shown that the share of electricity traded within the EU, relative to total electricity produced and consumed within the EU, remained in the range of 7–8% from 2000 to 2010 and rose to 10% by 2015. This is a proportionally important increase but the overall scale is still small. International trade contributes to lower emissions if imported electricity is less carbon-intensive than when domestically produced. Fig. 1c also shows the ratio of EU-wide actual carbon intensity to the carbon intensity in a counterfactual scenario where imported electricity would have been produced domestically. A value lower than one means that importing electricity has the effect of reducing emissions. This ratio rose from 0.65 in 2000 to 0.99 in 2009 and decreased thereafter to 0.90 in 2015. In the whole period under study the ratio was always below 1 meaning that electricity transmission between countries has consistently lowered carbon emissions across the international network.

Ultimately, electricity is generated to satisfy consumer demand and economic growth. As shown in Fig. 1d GDP grew steadily from 2000 to 2008, from 9.9×10^{12} to 11.7×10^{12} euro, having dropped and rebounded thereafter, reaching 12.2×10^{12} euro in 2015. Electricity consumption increased from 217 Mtoe in 2000 to 245 Mtoe in 2008 and fluctuated around 235 Mtoe during the period 2009–2015. As for the consumption patterns of different end-use sectors, the residential sector and service sector each accounted for almost 30% of total electricity in 2015. The next largest electricity consumer was chemical sector, which consumed ~7% of total electricity in 2015. The shares of electricity consumption in the remaining sectors were all below 5% in 2015.

3.2. *Drivers of EU emissions*

From 2000 to 2007 carbon emissions increased by 8.9% (relative to the 2000 total). This was mainly driven by strong economic growth (accounting for 18.0%), as shown in Fig. 2a. The decreasing share of non-fossil sources in electricity generation also contributed to increase emissions by 4.1%, mainly from decreasing shares of nuclear and hydropower (see Fig. 2c). Shifts in the mix of fossil fuels contributed to a decrease of 8.2% of emissions (see Fig. 2b for more details) and changes in efficiency of final electricity use contributed to a decrease of 6.6% (see Fig. 2d for more details). All other factors had a contribution of less than 3% in absolute terms.

Emissions decreased from 2007 until 2015 by 25.7% (relative to the total 2007), see Fig. 2a, driven mostly by changes in the mix of non-fossil sources (13.2%), the mix of fossil fuels (8.4%) and efficiency of final electricity use (7.4%). The changing mix of non-fossil sources was explained mostly by increasing renewable capacity on the grid, especially wind (7.5%) but also a significant contribution from solar too (3.8%), as shown in Fig. 2c.

In both periods the changes in the fossil fuel mix contributed to decreasing emissions (8.2 and 8.4% in each period respectively). In the

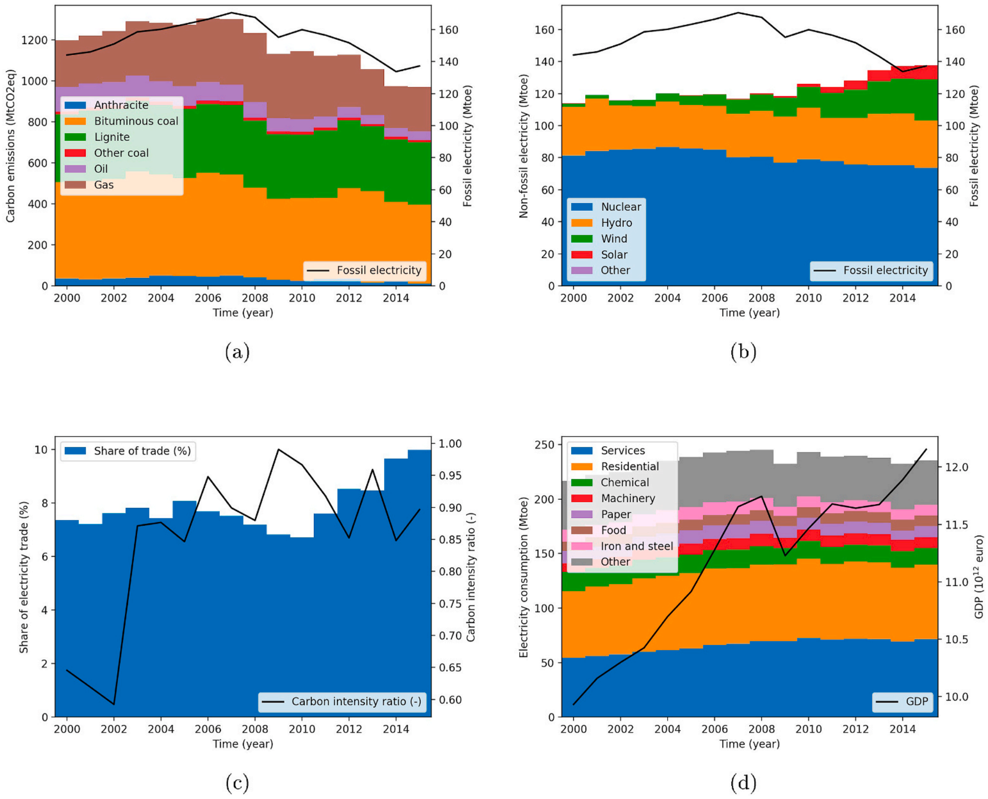
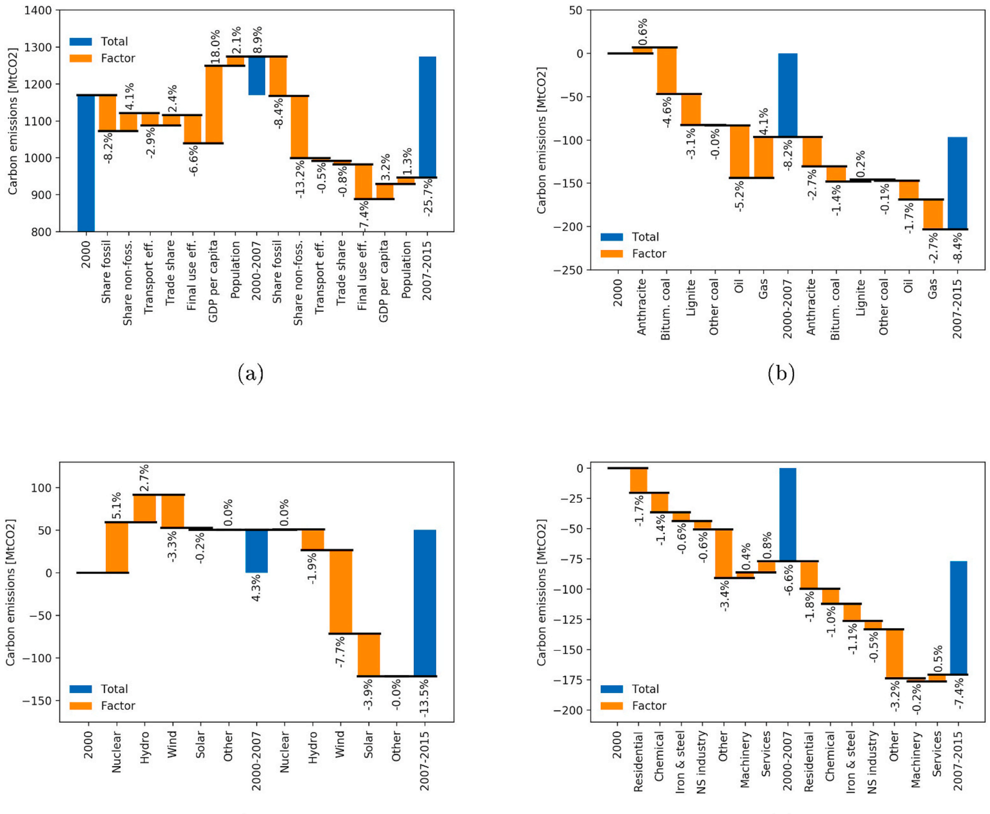


Fig. 1. Background patterns of the electricity system. a) The carbon emissions of electricity from fossil fuels (left axis) and the fossil electricity generation in the EU (right axis). b) The electricity generation from non-fossil sources. c) Share of electricity trade in total electricity consumption and carbon intensity ratio. d) Electricity consumption of end-use sectors and GDP growth.



(a) (b)

(c) (d)

Fig. 2. The results of index decomposition of carbon emissions from electricity generation in the EU25. a) Decomposition by factor type. Transport eff. = transport efficiency (see Section 2 for details). b) The decomposition results of fossil fuel carriers. c) The decomposition results of non-fossil electricity types. d) The decomposition results of final use of electricity efficiency. NS = non-specified.

earlier period natural gas substituted for coal and oil, in the latter period there was a decrease across all fuel types (see Fig. 2b), implying that there was a general improvement in efficiency (electricity output per fossil fuel consumed). The efficiency of final electricity use improved in both periods at roughly the same rate (6.5 and 7.3%). The residential, chemical and iron & steel sectors witnessed the largest efficiency gains, but gains were registered across all sectors except services (and machinery in the earlier period), as shown in Fig. 2d. Transport efficiency, electricity trade and population growth all had a relatively minor contribution in both periods (Fig. 2a).

To understand better the evolution of carbon emissions from 2007 to 2015 Fig. 3 shows the per capita decomposition by country (using 2007 population) with the data underlying the figure being reported as Supplementary Information (as is the case for all figures). In most countries the per capita carbon emissions declined (all except Latvia and Lithuania), with an average (± std. dev.) across countries of −0.70 (±0.74) MtCO2/cap. The best performer was Finland, with a change of −2.86 MtCO2/cap, and the worse was Latvia, with an increase of 0.29 MtCO2/cap. The most significant factor for emission decreases was the shift in the share of non-fossil electricity of −0.33 (±0.36) MtCO2/cap (best performer Finland with −1.03 MtCO2/cap and worst performer Lithuania with 0.76 MtCO2/cap). This was followed by the shift in the share of fossil fuels of −0.22 (±0.22) MtCO2/cap (best performer Finland with −0.97 MtCO2/cap and worst performer Portugal with 0.05 MtCO2/cap) and a shift in the efficiency of final electricity use of −0.16 (±0.29) MtCO2/cap (best performer Ireland with −0.91 MtCO2/cap and worst performer Greece with 0.73 MtCO2/cap). Other factors had smaller averages in absolute value.

Trade share and GDP per capita, although not significant on average, exhibited extreme contributions to the emissions for some countries (mean and standard deviations respectively of −0.08 (±0.33) MtCO2/cap and 0.07 (±0.34) MtCO2/cap). In the case of GDP per capita the extreme cases were Greece (−0.99 MtCO2/cap) and Poland (0.85 MtCO2/cap). The GDP patterns are explained by the financial crisis (in Greece) and sound economic growth (in Poland). In the case of trade share the most extreme cases were those of Estonia (−1.34 MtCO2/cap) and Austria (0.29 MtCO2/cap). These are explained by big shifts in the sourcing of electricity in both countries.

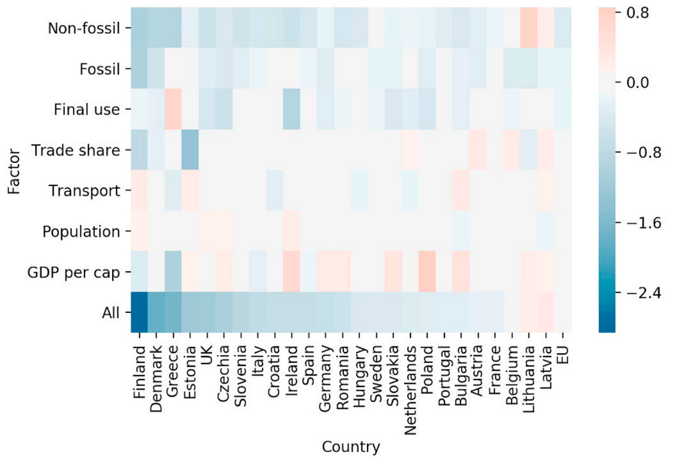


Fig. 3. The decomposition results of per capita carbon emissions (tCO2/cap) at country level from 2007 to 2015.

4. Discussion

The main findings of this study were that after an initial period in which there was an increase of 8.9% in emissions (2000–2007), in the second period under examination (2007–2015) there was a decrease of 25.7%, explained primarily by shifts in the share of non-fossil fuel sources (13.2%) followed by shifts in the use of fossil fuel sources (8.4%) and final electricity use efficiency (7.4%). In order to gain some insight into general trends and what might happen post-2015 it is investigated whether any acceleration in factor contributions can be observed.

There is significant year-on-year variation for all main drivers, as shown in Figure SI.1a, reported in Supplementary Information (as are the other figures mentioned in this section). The growth of GDP per capita, except in 2007–2009 and 2011–2013 has contributed to increase carbon emissions. In the period after 2007 non-fossil electricity contributed to decrease emissions in all years except 2010–2011 and 2014–2015. This is explained by hydro, which experiences substantial year-on-year variation, as does nuclear, to a lesser extent (see Figure SI.1c for details). This underlines the need to disaggregate renewable energy types in decomposition studies. Solar and particularly wind witnessed a steady increase. After 2007 shifts in fossil fuel carriers have mostly contributed to decrease emissions except in 2011–2012, explained mostly by an increase in other bituminous coal (see Figure SI.1b). After 2007 changes in the efficiency of final electricity use have always contributed to decrease emissions except in 2009–2010. Although there are significant year-on-year variations, in the most recent years (after 2009) services have been synchronized with the residential sector and generally contribute to reduce emissions (see Figure SI.1d).

The cost of renewable electricity has been decreasing steadily [33], making it currently competitive with fossil electricity. With the current system, fossil electricity is still necessary for balancing the grid due to renewable variability. However, as the interconnection of European grids deepens [34]), the complementarity of spatially remote renewable production may allow for a further expansion of overall renewable production. As such it is expected that the contribution of renewable expansion to reduce the carbon emissions from electricity consumption will continue, compensating the effect of growth in GDP per capita. The role of fossil fuel shifts will probably diminish but the role of shifts in the efficiency of final electricity use will persist, if current patterns persist into the future.

It is also interesting to examine whether there has been a convergence in the patterns of carbon emissions from electricity consumption across countries. Figure SI2 (reported in Supplementary Information) shows that although the median variation in carbon emissions per capita has shifted from positive to negative around 2007 (with significant year-on-year variation) the spread has remained roughly constant across the whole period (again, with significant year-on-year variation). This means that in some years at least some countries experienced emission reduction prior to 2007 while others experienced emission increases after 2007.

There were several data limitations in this study that should be mentioned. Yearly energy balances were used and thus assumed that every final demand sector is consuming a homogeneous bundle of electricity generated from various sources. Furthermore, the sequence in which non-renewable electricity sources were brought to the grid is not known, and for computational purposes homogeneity had to be assumed. Finally, information about the electricity that is imported by a country to be reexported is not available, and therefore assumed that all electricity consumed within a country or exported is a homogeneous mix of the electricity which is imported and produced within the country. Because the mix of electricity generation varies in time (e.g., hydro is more abundant in winter, solar more so during the day) and the demand of different sectors also varies in time (e.g., electricity for commercial use peaks during the day while residential peaks outside work hours) the allocations reported in this study should be interpreted with caution. If data of electricity generation and consumption is available at a finer-grained scale and reexports are reported separately the results may differ.

Note that economic growth may impact energy efficiency through technology innovation. However, in the IDA framework drivers are decomposed based on the (modified) Kaya identity and are thus strictly independent. Therefore, in our work we consider the effects of economic growth and energy efficiency on CO2 emissions separately.

5. Conclusions and policy implications

Evidence was found for a structural change in the electricity system around the time of the global financial crisis (around 2007). Economic growth (GDP per capita) was the main contributor to the increase in electricity emissions before and after the global financial crisis but its effect was smaller during period of 2007–2015 (3.2% compared to 18.0% in 2000–2007). Shifts in the share of non-fossil sources contributed to increase emissions before 2007 (due to the contraction in nuclear and hydro) but became the dominant factor explaining the decrease in emissions in 2007–2015 (mainly due to the expansion of wind and solar). The effect of shifts in fossil fuel and the efficiency of final use of electricity showed a similar trend before and after the global financial crisis, contributing to a decrease in emissions. The remaining factors: efficiency of electricity transport, international trade in electricity and population change had an overall small effect.

When examining the improvements in the period 2007–2015 at the country level it was found there is relatively little variation in the per capita improvements concerning the effect of non-fossil electricity and fossil fuel sources, but more variation concerning improvements in the efficiency of final electricity use, as well as in the roles of international trade and economic growth, which are important for specific countries.

This work has a bearing on policy discussions surrounding the speed of energy transitions [35,36]. This work shows that the expansion of renewable energy and improvements in energy efficiency can drive reductions in electricity emissions over short periods. This dynamic in the electricity system is important for policy makers to keep in mind when considering the energy system more broadly as we can expect further electrification in mobility (for environmental and health reasons), heating (including a move away from natural gas for environmental and energy security reasons) and industry (for environmental reasons). Whether this can continue in the long term is a question of reducing renewable energy costs set against the difficulty of further electrification in the energy system. Although transmission has played a small role in the reduction of carbon emissions until now, policy makers should be cognisant of its critical role in enabling further renewable electricity expansion across Europe. That is, electricity trading between EU countries should be encouraged from countries with low carbon intensity to countries with high carbon intensity.

Credit author statement

Joao F. D. Rodrigues: conceptualization, methodology, software, resources, data curation, writing – original draft, writing – review and editing; Juan Wang: validation, investigation, resources, data curation, writing – review and editing; Paul Behrens: conceptualization, investigation, writing – original draft, writing – review and editing; Paul de Boer: methodology, formal analysis, writing – review and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

Any errors this study may contain are the sole responsibility of the authors.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2020.110104.

References

[1] Scott J, Rajamani L. EU climate change unilateralism. Eur J Int Law 2012;23: 469–94. https://doi.org/10.1093/ejil/chs020.

[2] Olivier JGJ, Muntean M, Peters JAHW. Trends in global CO2 emissions: 2015 report. Hague, Netherlands: PBL Netherlands Environmental Assessment Agency and European Commission's Joint Research Centre (JRC); 2015. p. 1–78. Technical Report, https://www.pbl.nl/sites/default/files/cms/publicaties/pbl-2015-trends-in-global-co2-emisions_2015-report_01803.pdf.

[3] Peters GP, Davis SJ, Andrew R. A synthesis of carbon in international trade. Biogeosciences 2012;9:3247–76. https://doi.org/10.5194/bg-9-3247-2012.

[4] EEC. Council Directive 93/76/EEC of 13 September 1993 to limit carbon dioxide emissions by improving energy efficiency (SAVE). In: Official journal of the European communities (L): 28-30. Brussels, Belgium: European Economic Community; 1993. http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:31993L0076&from=EN.

[5] European Commission. Communication from the commission to the council, the European parliament, the European economic and social committee and the committee of the regions - limiting global climate change to 2 degrees celsius - the way ahead for 2020 and beyond. Brussels, Belgium: Commission of the European Communities; 2007. Technical Report, https://ec.europa.eu/europeaid/sites/devco/files/communication-climatechange-com20072-20070110_en.pdf.

[6] European Commission. Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions - a policy framework for climate and energy in the period from 2020 to 2030. Technical Report. Brussels, Belgium: Commission of the European Communities; 2014. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A52014DC0015.

[7] Karmellos M, Kopidou D, Diakoulaki D. A decomposition analysis of the driving factors of CO2 (carbon dioxide) emissions from the power sector in the European Union countries. Energy 2016;94:680–92. https://doi.org/10.1016/j.energy.2015.10.145.

[8] Goh T, Ang BW, Su B, Wang H. Drivers of stagnating global carbon intensity of electricity and the way forward. Energy Pol 2018;113:149–56. https://doi.org/10.1016/j.enpol.2017.10.058.

[9] Ang BW, Su B. Carbon emission intensity in electricity production: a global analysis. Energy Pol 2016;94:56–63. https://doi.org/10.1016/j.enpol.2016.03.038.

[10] Zhang M, Liu X, Wang WW, Zhou M. Decomposition analysis of CO2 emissions from electricity generation in China. Energy Pol 2013;52:159–65. https://doi.org/10.1016/j.enpol.2012.10.013.

[11] Liu N, Ma Z, Kang J. A regional analysis of carbon intensities of electricity generation in China. Energy Econ 2017;67:268–77. https://doi.org/10.1016/j.eneco.2017.08.018.

[12] Yang L, Lin B. Carbon dioxide-emission in China's power industry: evidence and policy implications. Renew Sustain Energy Rev 2016;60:258–67. https://doi.org/10.1016/j.rser.2016.01.058.

[13] Peng X, Tao XM. Decomposition of carbon intensity in electricity production: technological innovation and structural adjustment in China's power sector. J Clean Prod 2018;172:805–18. https://doi.org/10.1016/j.jclepro.2017.10.236.

[14] Wang JF, He ST, Qiu Y, Liu N, Li YJ, Dong ZF. Investigating driving forces of aggregate carbon intensity of electricity generation in China. Energy Pol 2018;113: 249–57. https://doi.org/10.1016/j.enpol.2017.11.009.

[15] Feng KS, Davis SJ, Sun LX, Hubacek K. Drivers of the US CO2 emissions 1997-2013. Nat Commun 2015;6:7714. https://doi.org/10.1038/ncomms8714.

[16] Mohlin K, Camuzeaux JR, Muller A, Schneider M, Wagner G. Factoring in the forgotten role of renewables in CO2, emission trends using decomposition analysis. Energy Pol 2018;116:290–6. https://doi.org/10.1016/j.enpol.2018.02.006.

[17] Steenhof PA, Weber CJ. An assessment of factors impacting Canada's electricity sector GHG emissions. Energy Pol 2011;39:4089–96. https://doi.org/10.1016/j.enpol.2011.03.056.

[18] Kim S, Kim SK. Decomposition analysis of the greenhouse gas emissions in Korea's electricity generation sector. Carbon Manag 2016;7:1–12. https://doi.org/10.1080/17583004.2016.1224440.

[19] Andreoni V, Galmarini S. Decoupling economic growth from carbon dioxide emissions: a decomposition analysis of Italian energy consumption. Energy 2012; 44:682–91. https://doi.org/10.1016/j.energy.2012.05.024.

[20] Cansino JM, Sanchez-Braza A, Rodriguez-Arevalo ML. Driving forces of Spain's CO2 emissions: a LMDI decomposition approach. Renew Sustain Energy Rev 2015; 48:749–59. https://doi.org/10.1016/j.rser.2015.04.011.

[21] Wang H, Ang BW, Su B. Assessing drivers of economy-wide energy use and emissions: IDA versus SDA. Energy Pol 2017;107.

[22] Apergis N. Environmental kuznets curves: new evidence on both panel and country-level co2 emissions. Energy Econ 2016;54:263–71.

[23] Wu Q, Peng C. Scenario analysis of carbon emissions of China's electric power industry up to 2030. Energies 2016;9:988.

[24] Mele M, Randazzo L. A causal investigation on the determinants of CO2 in China. Int J Sustain Dev World Ecol 2019;26:665–71.

[25] Du K, Xie C, Ouyang X. A comparison of carbon dioxide (CO2) emission trends among provinces in China. Renew Sustain Energy Rev 2017;73.

[26] Du K, Lin B. Understanding the rapid growth of China's energy consumption: a comprehensive decomposition framework. Energy 2015;90:570–7.

[27] Zha D, Yang G, Wang Q. Investigating the driving factors of regional co2 emissions in China using the IDA-PDA-MMI method. Energy Econ 2019;84:104521. https://doi.org/10.1016/j.eneco.2019.104521.

[28] Gonzalez PF, Landajo M, Presno M. Tracking European Union CO2 emissions through LMDI (logarithmic-mean divisia index) decomposition. the activity revaluation approach. Energy 2014;73:741–50. https://doi.org/10.1016/j.energy.2014.06.078.

[29] Miller RE, Blair PD. Input-output analysis: foundations and extensions. second ed. Cambridge, UK: Cambridge University Press; 2009.

[30] Ang BW. LMDI decomposition approach: a guide for implementation. Energy Pol 2015;86:233–8. https://doi.org/10.1016/j.enpol.2015.07.007.

[31] De Boer P, Rodrigues JFD. Decomposition analysis: when to use which method? Econ Syst Res 2019;32:1–28. https://doi.org/10.1080/09535314.2019.1652571. 0.

[32] Koffi B, Cerutti AK, Duerr M, Iancu A, Kona A, Janssens-Maenhout G. Covenant of mayors for climate and energy: default emission factors for local emission inventories - version 2017. Luxembourg: Publications Office of the European Union; 2017. Technical Report EUR 28718 EN.

[33] IRENA. Renewable power generation costs in 2018. Abu Dhabi, United Arab Emirates: International Renewable Energy Agency; 2019. Technical Report, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/May/IRENA_Renewable-Power-Generations-Costs-in-2018.pdf.

[34] European Union. Towards a sustainable and integrated Europe. In: Report of the commission expert group on electricity interconnection targets. Brussels, Belgium: European Union; 2017. Technical Report, https://ec.europa.eu/energy/sites/ener/files/documents/report_of_the_commission_expert_group_on_electricity_interconnection_targets.pdfΩ.

[35] Smil V. Examining energy transitions: a dozen insights based on performance. Energy Res. Soc. Sci. 2016;22:194–7. https://doi.org/10.1016/j.erss.2016.08.017.

[36] Sovacool BK, Geels FW. Further reflections on the temporality of energy transitions: a response to critics. Energy Res. Soc. Sci. 2016;22:232–7. https://doi.org/10.1016/j.erss.2016.08.013.