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The drivers of long-run CO_2 emissions in Europe, North America and Japan since 1800

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ABSTRACT

Using an extended Kaya decomposition, we identify the drivers of long-run CO_2 emissions since 1800 for Denmark, France, Germany, Italy, the Netherlands, Portugal, Spain, Sweden, the UK, the United States, Canada and Japan. By considering biomass and carbon-free energy sources along with fossil fuels, we are able to shed light on the effects of past and present energy transitions on CO_2 emissions. We find that at low levels of income per capita, fuel switching from biomass to fossil fuels is the main contributing factor to emissions growth. As income levels increase, scale effects, especially income effects, become dominant. Technological change proves to be the main offsetting factor in the long run. Particularly in the last decades, technological change and fuel switching have become important contributors to the decrease in emissions in Europe. Our results also contrast the differentiated historical paths of CO_2 emissions taken by these countries.

1. Introduction

Our present prosperity, unprecedented by historical standards, is strongly tied to industrialization and to wide-range changes in the global patterns of energy consumption. These shifts have led to a significant rise in the level of carbon dioxide in the Earth's atmosphere, which is currently 40% above its long-term pre-industrial average. About two thirds of the historical cumulative CO_2 emissions have resulted from the combustion of fossil fuels and climate experts consider this to be the main contributing factor to the upward trend in the Earth's surface temperature since 1950 (IPCC, 2014).

CO_2 emissions are dependent both on the level of energy consumption and on the makeup of the energy mix. Emissions can thus be reduced either by lowering the level of energy consumption or by moving the composition of the energy mix to sources with a lower emission content. A decrease in energy consumption can, in turn, be brought about by means of technological progress, lower economic growth, or demographic decline. A thorough understanding of the determinants of CO_2 emissions is necessary in order to design effective climate policies. To cater to this demand from policymakers, international comparative studies that employ decomposition techniques to analyze the drivers of CO_2 emissions have been conducted (Raupach et al., 2007; Metz et al., 2007; Kojima and Bacon, 2009; Mundaca et al., 2013; Arto and Dietzenbacher, 2014; Andreoni and Galmarini, 2016). These studies find that the greatest driver of CO_2 emissions overall is economic growth, but depending on the period of analysis, the methodology applied and the level of regional aggregation, there can be disagreement on the relative importance of other factors. Although relevant, aggregated global or regional analyses mask country differences in population size, affluence and technology. Moreover, these studies cover only recent decades, which means that, with such a short time-span, they are unable to fully capture how drivers change in importance over time.

Our research investigates the drivers of CO_2 emissions in a historical and geographical diverse perspective. We use a long-run panel dataset that covers nine European countries, the United States, Canada and Japan over the period 1800–2011. Existing historical energy datasets of different lengths and coverage have been improved and extended back in time to ensure methodological consistency and the inclusion of all energy carriers. Our new dataset allows fresh insights into the earliest carbon emission pathways of these twelve countries and a comparative framework of unprecedented length. We employ a decomposition technique based on an extended Kaya identity, similar to the approach of Ma and Stern (2008), who applied it to contemporary data. Within this framework, we consider not only fossil fuels, but also biomass and carbon-free energy sources. Our findings suggest that the most important determinants of CO_2 emissions, in the long run, are income and population growth. However, at low levels of income per capita, fuel switching from biomass to fossil fuels is the dominant factor. Energy intensity growth may increase carbon emis-

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sions, especially during the early period of industrialization in the countries that relied heavily on coal, but the effect becomes negative and increases in magnitude as time advances.

Several recent studies have analyzed energy transitions using historical energy consumption datasets (Gales et al., 2007; Krausmann et al., 2008; Kuskova et al., 2008; Rubio et al., 2010; Kander et al., 2013), but only a few have investigated the long-term drivers of CO_2 emissions. Lindmark (2002) analyses the causes of CO_2 emissions in Sweden from 1870 to 1997 and concludes that technological change was an important factor contributing to the decline in emissions, markedly so during periods of slow economic growth. Tol et al. (2009) study the drivers of CO_2 emissions intensity in the United States from 1850 to 2002. They conclude that CO_2 intensity rose until 1917 due to the transition from wood to coal and declined afterwards as a result of technological and behavioral changes. Bartoletto and Rubio (2008) analyze the causes of differences in CO_2 emissions for Italy and Spain from 1861 to 2000 and find that population growth was an important determinant. Gingrich et al. (2011) investigate the differences in fossil-fuel-related CO_2 emissions in Austria and Czechoslovakia in the period 1920–2000. The higher energy and carbon intensity of the Czech Republic translated into higher CO_2 emissions in this country, even if Austria was a more developed economy during that period. Kander et al. (2013) present a simple decomposition of the aggregate increase in CO_2 emissions in eight European countries between 1870 and 2008.[1]

Our study advances this historical literature in two directions. First, by utilizing an extended Kaya identity previously employed by Ma and Stern (2008) for recent Chinese data, we shed light on how the energy mix influences CO_2 emissions by separating the contribution of fuel switching into three effects: (1) the effect of changes in the carbon intensity of the fossil fuel energy mix, (2) the effect of the transition from biomass to fossil fuels and (3) the effect of the penetration of carbon-free energy in the energy mix. By considering not only fossil fuels, but also biomass and renewable technologies, we are able to provide a more complete analysis of the various factors associated with fuel switching.

Secondly, we shed light on the impacts of historical energy transitions in an extended geographical perspective by conducting the analysis for a wider set of countries and for a much longer time period (i.e. 1800–2011) than previous studies. Our countries are representative of regions that played an important role in CO_2 emissions throughout history: Europe (Denmark, France, Germany, Italy, Portugal, Spain, Sweden, the Netherlands and the UK); North America (Canada and the United States); and Japan. A comparison with the widely used global CO_2 emissions series provided by the Carbon Dioxide Information Analysis Center (CDIAC) (Boden et al., 2013) shows that our sample of countries was responsible for more than 95% of global emissions before 1870, 82% by 1938 and more than a half at the beginning of the 1980s. By covering a range of countries that have different natural resource endowments and various developmental paths, we are able to determine the importance of each factor over time and at different stages of development. Furthermore, in this setting we are able to recognize different historical carbon dioxide emissions paths across the studied countries.

There are three reasons why a historical study of the determinants of CO_2 emission of this scope should be regarded as complementary to related research based on contemporary data. First, a long-term historical approach results in a large number of annual observations for each country, enabling more accurate insights on how CO_2 emissions progress as the energy mix changes over time, since energy transitions usually take several decades. Second, many developing countries are now industrializing and are to some extent following the energy paths of developed economies. Even if the present energy transitions of the developing countries translate into lower systemic environmental impact (Marcotullio and Schulz, 2007; Rubio and Folchi, 2012), a historical approach can still deliver important and helpful insights to contemporary policymakers when planning long-term strategies for CO_2 abatement (Grubler, 2012). Third, a long-run approach is particularly relevant in the case of CO_2, as emissions accumulate over extended periods of time in the atmosphere.

The paper is organized as follows. Section 2 explains the chosen decomposition method. Section 3 describes the construction of the database and the sources used. Section 4 presents our results and the related discussion for the observed countries, beginning with an overview of the patterns of long-run energy consumption per capita. We then show their long-term CO_2 emissions, followed by an analysis of their contributing factors, based on the extended Kaya identity. Finally, we present the results of the extended Kaya decomposition and discuss the findings. Section 5 provides some derived policy implications, together with concluding remarks.

2. Methodology

2.1. The extended Kaya decomposition identity

The Kaya identity is an extension of the IPAT identity (Ehrlich and Holdren, 1971). It expresses the emission level of CO_2 as the product of four inputs: GDP per capita, population, energy intensity per unit of GDP, and the carbon intensity of energy (emissions per unit of energy consumed), in the following way (Kaya, 1990):

$$CO_2=\frac{Y}{P}\times P\times\frac{E}{Y}\times\frac{CO_2}{E} \tag{1}$$

Eq. (1) shows how the carbon intensity of energy affects the level of CO_2 emissions but not how this level is influenced by the composition of the energy mix. In order to understand how the energy mix influences the level of CO_2 emissions, we extend the Kaya identity, following the study of Ma and Stern (2008). This allows us to decompose the carbon intensity of energy into three factors that account for three different effects: (1) the effect of changes in the carbon intensity of fossil fuel energy, (2) the effect of the transition from biomass to fossil fuels and (3) the effect of the penetration of carbon-free energy in the energy mix. The derived decomposition is formally defined as follows:

$$CO_2=\frac{Y}{P}\times P\times\frac{E}{Y}\times\frac{CO_2}{FF}\times\frac{FF}{CF}\times\frac{CF}{E}=yPIC_{ff}S_1S_2 \tag{2}$$

where:

1. CO_2 Carbon emissions from fossil fuels combustion
2. Y Gross domestic product
3. P Population
4. E Total energy consumption
5. FF Fossil fuels consumption (Coal+oil+natural gas)
6. CF Carbon-based fuel consumption (Fossil fuels+biomass, i.e. food, fodder, firewood and biofuels)
7. y GDP per capita
8. I Energy intensity of economic output
9. C_{ff} Carbon emissions intensity of fossil fuels
10. S_1 Fossil fuels as a share of carbon-based fuels
11. S_2 Carbon-based fuels as a share of total energy consumption

2.2. The Logarithmic Mean Divisia Index (LMDI) decomposition method

We now apply the method of index decomposition analysis (IDA) to our extended Kaya identity. The Logarithmic Mean Divisia Index

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[1] See also Lindmark (2004) for an overview of patterns of historical CO_2 intensity transitions among high- and low-income countries and Stern et al. (2013) for a historical literature overview on the economics of global climate change.

(LMDI) decomposition method given by Ang (2005) is the currently preferred form of IDA. For a discussion of its several advantages over competing methods we refer to Ang and Zhang (2000), Ang and Liu (2001), Ang (2004, 2005) and Ma and Stern (2008).

In its multiplicative form, the general formula of the decomposition is:

$$D_{tot}=\frac{V_t}{V_0}=D_{x_1}D_{x_1}\ldots D_{x_n} \tag{3}$$

where V is an energy aggregate of interest composed of n factors x_1, x_2, ... x_n. In the period 0 to T the aggregate changes from V_0 to V_T. The goal is to derive the contributions of each factor to the change in the aggregate. When not considering sub-categories within each factor, each D_{x_k} is given simply by:

$$D_{x_k}=\frac{x_k^T}{x_k^0} \tag{4}$$

The ratio between CO_2 emissions in year T and year 0 can then be expressed as a product of the ratios of the factors in the extended Kaya decomposition, as follows:

$$\frac{CO_2^T}{CO_2^0}=\frac{y^T}{y^0}\times\frac{P^T}{P^0}\times\frac{I^T}{I^0}\times\frac{C_{ff}^T}{C_{ff}^0}\times\frac{S_1^T}{S_1^0}\times\frac{S_2^T}{S_2^0} \tag{5}$$

We rewrite Eq. (3) using the following notation:

$$D_{EMISS}=D_{INC}D_{POP}D_{TECH}D_{FOS}D_{BIO}D_{CARFREE} \tag{6}$$

D_{EMISS} is the total change in CO_2 emissions, expressed as a ratio; D_{INC} and D_{POP} are the changes in income per capita and population, respectively; D_{TECH} is the change in the ratio between energy consumption and economic growth (energy intensity) and for this reason is a proxy for technology improvements; D_{FOS} represents the changes in the emissions coefficient of fossil fuels due to inter-fossil fuel substitution in the energy mix; D_{BIO} represents the changes in the share of fossil fuels relative to carbon-based fuels and measures the biomass substitution effect, i.e. the transition from food, fodder and firewood to fossil fuels; $D_{CARFREE}$ gives the change in the share of carbon-based fuels relative to total energy consumption and measures the impact of penetration of carbon-free fuels such as nuclear, hydro, solar, geo, aeolian, wind and water power in the energy mix.

Since we will be studying several distinct time periods of unequal lengths we need, for comparison purposes, to transform Eq. (6) to obtain the average annual growth rate for each period. We do this by applying logarithms to each side of the equation to obtain a summation and then dividing each parcel by the number of years in the period. We thus obtain Eq. (7):

$$\frac{\ln\,(D_{EMISS})}{T}=\frac{\ln\,(D_{INC})}{T}+\frac{\ln\,(D_{POP})}{T}+\frac{\ln(D_{TECH})}{T}+\frac{\ln\,(D_{FOS})}{T}+\frac{\ln\,(D_{BIO})}{T}+\frac{\ln\,(D_{CARFREE})}{T} \tag{7}$$

In order to enrich our study, we also apply an additive chaining decomposition analysis to our time series, as shown in Eq. (8).

$$CO_2^T-CO_2^0=\Delta INC+\Delta POP+\Delta TECH+\Delta FOS+\Delta BIO+\Delta CARFREE \tag{8}$$

While the multiplicative version of the LMDI expresses change in relative terms, the additive version expresses change in absolute terms. In Eq. (8), the numerical value for each one of the six drivers of change in the level of CO_2 emissions is calculated in the following way:

$$\Delta x_k=\frac{CO_2^T-CO_2^0}{\ln CO_2^T-\ln CO_2^0}\ln\left(\frac{x_k^T}{x_k^0}\right) \tag{9}$$

3. Data

3.1. Long-Run Primary Energy

We compiled and partially reconstructed an international long-run energy database, which includes traditional energy carriers such as wind, water, firewood, peat and muscle power (i.e. feed for draft animals and food for humans) alongside modern forms of energy such as coal, oil, natural gas and primary electricity. Our historical energy dataset includes Denmark[2] (Henriques and Sharp, 2016), France (Gales, 2013), Italy (Malanima, 2006), Germany (Gales and Warde, 2013), Portugal (Henriques, 2009; Henriques, 2011), Spain (Rubio, 2005), Sweden (Kander, 2002), the Netherlands (Gales et al., 2007), the UK (Warde, 2007), the United States (Schurr and Netschert, 1960; EIA, 2010), Canada (Steward, 1978) and Japan (EDMC, 2009).

In order to improve the consistency and comparability of the various datasets, we conducted three modifications to the available data. First, we calculated the contributions of muscle power and water and wind for the countries where this information was missing. Second, we extended all series backwards in time until 1800, by including new series of coal consumption for early periods. Third, for the period post 1960, we made use of international databases, such as the FAO database for food consumption and the IEA primary energy data (FAO, 2014; IEA, 2013), which are characterized by an international recognized common methodology. It was not possible to reconstruct early consumption of traditional energy carriers for Canada (1800–1870), Japan (1800–1879), Italy (1800–1860) and Portugal and Spain (1800-1850s). We have backcast their traditional energy consumption assuming a time invariant per capita consumption, a procedure that has been frequently used in the literature (Smil, 2010; Kander et al., 2013). Non-energy uses of coal, oil and natural gas were excluded from the totals, and primary electricity (nuclear, hydro, aeolian, geo, solar) was calculated considering its heat content.

3.2. CO_2 emissions

CO_2 emissions were calculated from the historical energy consumption datasets, and refer to fossil fuel combustion from coal, oil and natural gas. Under the coal grouping we include peat, a fossil fuel with limited importance nowadays, but which was relevant in the 19th century energy systems of the Netherlands and Denmark, and to a lesser extent Germany. We use the emission factors of 94.6 kg CO_2/GJ for coal and peat, 73.1 kg CO_2/GJ for oil and 56.1 kg CO_2/GJ for natural gas.[3]

The combustion of firewood also releases CO_2, but if forest is sustainably regrowth in the process, the associated emissions will be subsequently removed from the atmosphere. The Intergovernmental Panel on Climate Change (IPCC) does not include biomass combustion emissions in their energy-related CO_2 emissions, accounting for the CO_2 released and captured from the forests in their Agriculture, Forests and Other Land Use Sector. Our study does not attempt to calculate emissions and removals from the forest sector,[4] although they were probably important in the past.[5] The inclusion of biomass energy is still

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[2] Henriques and Sharp (2016) cover only the period 1800–1913. The remaining sources are new and are detailed in the Appendix, Supplementary Information (S1).

[3] IPCC (2006). The IPCC gives a slightly higher emissions coefficient to peat (106kg CO_2/GJ). We use the same coefficient as coal (94.6) due to some uncertainty in the proportions of peat relative to coal in some of the series.

[4] And therefore assumes the carbon neutrality of biomass as most of the decomposition studies which focus on CO_2 emissions from fuel combustion.

[5] Country-based studies that reconstruct forest net emissions are rare, probably due to lack of reliable forestry data. Kander (2008) has shown that in Sweden CO_2 emissions from the forest sector surpassed CO_2 emissions from fossil fuels during the nineteenth century but that from the early 20th century on Swedish forests have acted as sink of emissions, making the overall long-run effect of forests neutral by 2000. Birdsey et al. (2006) show that United States forest emissions peaked in 1900, becoming a carbon sink

justified on the grounds of the fact that the transition from biomass to modern energy sources remains an important unresearched driver of changes in historical fossil-fuel energy related emissions.

3.3. GDP and Population

We used population and GDP series from various sources such as Maddison (2010) and the newly available international updates on GDP pre-1820 (Bolt and van Zanden, 2013).[6] An extended summary of the sources and calculations used to construct our databases is provided as Supplementary material S1 in the Appendix.

4. Results and discussion

This section is organized as follows: We start by briefly characterizing the chosen countries in terms of their long-run energy consumption per capita in Section 4.1. We then follow, in Section 4.2, with the evolution of CO_2 emissions, which is the object of our decomposition. In Section 4.3 we discuss how the factors that influence CO_2 emissions have evolved over time: Scale factors (population and GDP), technology (energy intensity) and the CO_2 intensity of the energy mix. Finally, in Section 4.4 we present the results of the extended Kaya decomposition and the drivers of change in CO_2 emissions.

4.1. Energy pathways

In the long run, all the countries under observation exhibit, as illustrated by Fig. 1, a trend of increasing per capita energy use – a well-established feature of industrialization. In spite of their different starting points and trajectories, it's possible to identify three distinct time periods with long-term relevance for energy pathways: from 1800 until the break of World War II (WWII) they mostly follow differentiated energy paths; then comes a period of extreme growth in the 1950s and 1960s; and finally the oil crisis of the early 1970s inaugurates a period of stagnation that still persists nowadays.

The first period, from 1800 until the end of the 1930s, is characterized by different starting points and different energy per capita growth between countries. Nevertheless, we can still distinguish three main groups in terms of resource usage. The first group comprises the UK, Canada and the United States, which around 1850 were leading the rest of the world in levels of consumption, using between 70 and 120 GJ per capita. The UK, thanks to its abundant high-quality domestic coal reserves was then at the forefront of industrialization. In turn, both the United States and Canada possessed a vast array of natural resources: land, forests, coal and oil reserves and hydro-power. For the better part of two centuries, this group of countries followed a long-term high energy path with no equivalent in the rest of the world. The levels of per capita energy consumption in Canada and the United States remain unmatched even today.

In the other countries energy consumption varied, in 1850, between 8 GJ per capita in densely populated Japan and 35 GJ per capita in cold and wood-rich Sweden. These remaining countries can be further divided in two groups: Germany, France, Denmark, Sweden and the Netherlands would soon diverge from Southern Europe and Japan, attaining 60 GJ to 100 GJ per capita in the late 1930s, in contrast to Japan, Portugal, Italy and Spain, who got stuck in a path of very low energy consumption per capita, reaching levels of only between 20 and 30 GJ per capita by the same date. This last group, the energy consumption laggards, displayed at the time energy use levels that Grubler (2004) considers representative of the per capita consumption of pre-industrial societies.

The decades of 1950 and 1960 saw most countries increasing their levels of per capita energy consumption at a very fast rate, almost doubling pre-WWII levels. The economy of the UK started to lose its resource-intensive character around this time and so had a much less pronounced upswing than the laggards. This allowed Italy and Japan to somehow catch up with the more advanced countries in Europe. On the other hand, the difference in the level of energy per capita usage between the US and Canada and the remaining countries widened considerably during the same period, creating two distinct packs – the New World and the rest.

The oil crisis brought about a clear trend reversal for most countries. After 1973, the available energy per person in countries with consumption levels above 150 GJ per capita started to stabilize. However, latecomers Portugal and Spain and, to a lower extent, Italy and Japan, only plateaued in the late 2000s. By 2011, the average European consumed about 130 GJ per year, roughly the same as a Japanese citizen, but only half of a North-American.

4.2. CO_2 emissions

Fig. 2 demonstrates a dramatic rise in CO_2 emissions, from 0.04 Gt in 1800 to 9–10 Gt in the 2000s. The greatest contributor in 1800 was the UK, generating 87% of the total CO_2 emissions, followed by France (5%), the Netherlands (4%) and Germany (2%). In per capita terms, the emissions in the Netherlands and Denmark are only noticeable due to the widespread use of peat, which substituted for firewood in household use in these deforested countries. The dominance of the UK, which in 1800 accounted for only about 8% of the population of the studied countries, is notable.

In 1870, CO_2 emissions for the selected countries amounted to 0.5 Gt. The UK still remained the largest producer, accounting for about half of the total. By this date, the United States (21%), Germany (16%) and France (10%), had also become significant contributors. Between 1870 and 1938, a seven-fold rise occurred, bringing the total to 3.4 Gt. In 1938, CO_2 emissions from the United States reached nearly half of total emissions (48%), more than Germany (18%), the UK (15%), France (6%) and Japan (5%) combined. After WWII, the amount of CO_2 produced by the United States increased even further, reaching 59% of the total by 1950.

Most countries also increased their carbon emissions, which led to a doubling of the total CO_2 output by 1973, relative to 1950. From 1973 onwards the trend of sharp rising emissions stalled, with an additional increase of only 3.5% until 2011. In Europe, emissions decreased by 20% during the same period. The contribution of the United States remained well above 50% of the total CO_2 emissions in our sample in 2011, followed by Japan (13%), Germany (8%), Canada (5%) and the UK (5%).

In terms of all-time cumulative CO_2 emissions, the United States is by far the largest contributor, being responsible for 53% of the cumulative total in our sample. Despite the early global dominance of the UK in terms of CO_2 emissions over the course of the 19th century, its long-term contribution to global carbon emissions is confined to just 12%, on par with Germany but above Japan (8%). Considering all the covered European countries, CO_2 emissions attributable to Europe represent about one-third of the cumulative total.

Fig. 3 compares our series with the alternative historical fossil-fuel CO_2 emissions series provided by the Carbon Analysis Information Center (CDIAC) (Boden et al., 2013) for the same group of countries and for the world. The figure shows that in 1800, our series value is 46% above what is reported by the CDIAC. The difference gets smaller as time increases, hovering around 20% in 1860, 10% in 1910 and becoming negligible after 1960. This discrepancy stems from two

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(*footnote continued*)
only in the 1980s. In other countries, forests were more sustainable: Gingrich et al. (2007) have shown that Austrian forest have been acting as a carbon sink since the late 1870s. For regional and global estimations from 1850 to 2000 that take into account forest and other land use changes see, for example, Houghton (2003).

[6] With the exception of Canada, Denmark and France, for which 1820 estimations from Maddison (2010) were backcast to 1800, under the assumption of a stable GDP per capita.

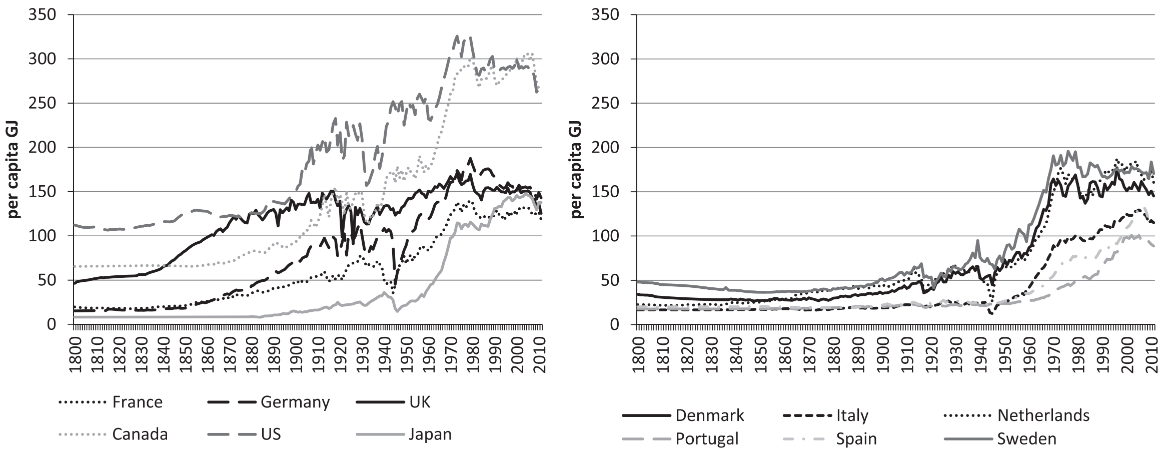

Fig. 1. Energy per capita, 1800–2011 (GJ).
Sources: See Section 3 and Supplementary Material (S1).

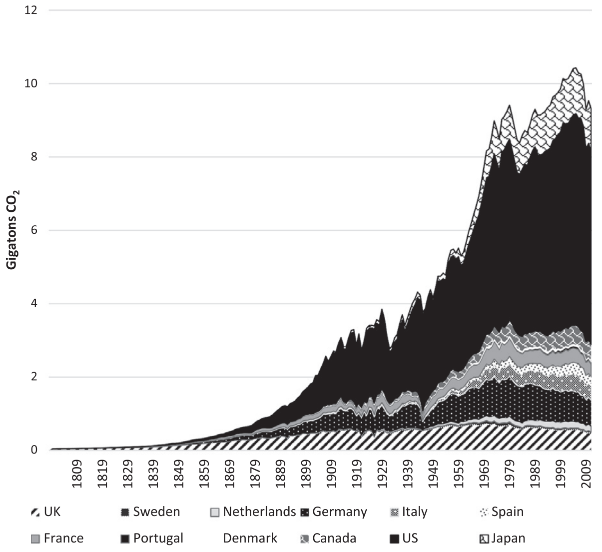

Fig. 2. Total CO_2 emissions (Gigatons).
Source: See Section 3 and Supplementary Material (S1).

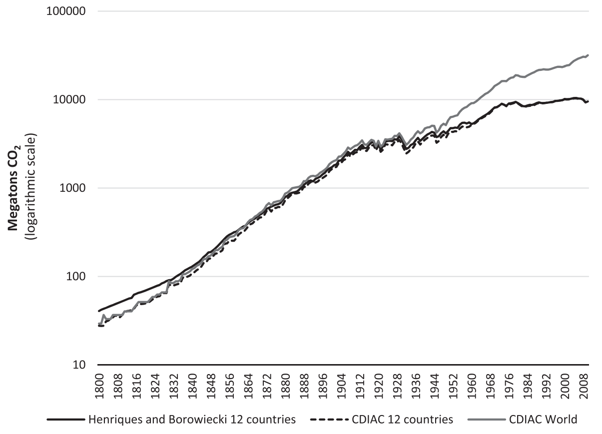

Fig. 3. Comparison with CDIAC database.
Sources: Boden et al. (2013) and own calculations.

sources: First, we use a different source for the UK's coal emissions, which has a significant impact on the overall value for earlier periods.[7] Second, the historical statistics on which CDIAC bases earlier estimates (see Andres et al., 1999) are less exhaustive than our sources,[8] and for this reason they underreport emissions for a variety of countries.

Fig. 3 also shows that, until the advent of WWII, the twelve countries considered accounted for almost all of the world CO_2 emissions. This adds a global dimension to our study if we consider only the period from 1800 until the middle of the 20th century. Afterwards, the progressive industrialization of countries such as China, India and Brazil gradually dilutes this global perspective.

4.3. Factors influencing the level of CO_2 emissions

4.3.1. Scale factors: GDP per capita and population

Per capita incomes were rather similar across regions in the early 19th century, with the exceptions of the UK and the Netherlands, as shown in Table 1. The most underdeveloped countries were Japan, Sweden and Canada and yet their incomes still varied between 55% and 74% of the sample's average. During the first wave of industrialization, per capita income grew at a fast pace in the UK, the US, Canada, Germany and France but slowly in Southern Europe and Japan. By 1870, the divergence in per capita incomes had grown wide, with Japan and Portugal falling behind to just one third and one half of the average, respectively. In addition to its already backward position in 1870, Portugal was the country which grew at the lowest rate until World War I, in sharp contrast to Canada, Sweden and the US. After World War I, the United States took over the leadership from the UK. By 1950, the rear of the pack was composed of Japan, Portugal and Spain. Incomes per capita increased much more rapidly in the post-war period, with the less developed countries growing faster than the more developed ones. Right now, income divergence across countries is smaller than at any time since 1800 and all these countries are considered post-industrialized societies.

There is also considerable variety in country size and especially in their population growth rates. Using contemporary borders, the most populous countries in 1800 were France (population 27.3 m), Japan (25.5 m) and Germany (24.5 m), followed by Italy (18.3 m). Population sizes in the UK and Spain were within close range of the average value of 11 m for our sample. All remaining countries had a population size

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[7] Our coal consumption series is from Warde (2007), which in turn is based on official series from the Department of Energy & Climate Change (2013). CDIAC reconstruction

(*footnote continued*)
of CO_2 emissions are exclusively based on Etemad and Luciani (1991) and old editions of Mitchell (1992, 1993 andand, 1995). The UK series is 20–30% above CDIAC series before 1860. Other available coal series for the UK (see Fouquet, 2014) also differ significantly from CDIAC series.

[8] CDIAC sources do not include coal and peat consumption for early periods of time for several countries. See Appendix, Supplementary Material 1 for a description of our sources.

Table 1
GDP per capita and Population.
Source: Our calculations from Maddison (2010), Bolt and van Zanden (2013) and sources listed in Supplementary Material (S1).

	GDP per capita (thousands 1990 PPP USD)						Population (in millions)			
	1800	1870	1913	1950	1973	2011	1800	1870	1950	2011
Denmark	1.27	2	3.91	6.94	13.95	23.53	0.9	1.9	4.3	5.6
France	1.17	1.96	3.63	5.27	13.12	22.99	27.3	36.9	41.8	62.2
Germany	0.99	1.77	3.54	3.88	11.97	21.25	24.5	40.8	68.4	82.1
Italy	1.36	1.59	2.67	3.64	10.74	19.3	18.3	27.4	46.8	58.8
Netherlands	1.79	2.65	3.94	6	13.08	23.91	2.1	3.6	10.1	17
Portugal	1.02	1	1.21	2	6.56	14.02	3.1	4.3	8.4	10.7
Spain	0.92	1.22	2.05	2.2	7.66	18.28	11	16.1	28	42.1
Sweden	0.86	1.35	2.87	6.74	13.49	25.33	2.3	4.2	7	9.2
UK	1.84	4.19	5.94	7.35	12.19	23.2	10.8	25	48.6	59.5
Canada	0.9	1.69	4.45	7.29	13.84	25.23	0.4	3.8	14	34.2
US	1.3	2.44	5.3	9.56	16.69	30.7	5.3	40.2	152.3	312
Japan	0.64	0.74	1.39	1.92	11.43	21.94	25.5	34.4	83.8	127
Total	1.1	2	3.8	5.7	13.2	25.1	132	239	514	820
Simple average	1.2	1.9	3.4	5.2	12.1	22.5	11	20	43	68

of less than half the average. By 1870 the largest population increase in Europe had occurred in the fast developing UK. Nonetheless, the fastest growing countries were by far the United States and Canada, new world countries that were receiving a massive influx of migrants. Between 1870 and 2011, population more than tripled in our selected countries, from 239 m to 820 m. The increase over this period was by a factor of 2–3 in most countries, with the exception of Canada, the United States, the Netherlands and Japan. The population in Canada and the United States grew by a factor of 9 and 8, respectively, between 1870 and 2011. The Netherlands almost quintupled its population, while Japan saw a fourfold increase.

4.3.2. Energy intensity

The long-run evolution of the energy intensity of a country is usually associated with two stages of development. In the first stage, energy intensity grows as a result of the transformation from an agricultural to an industrial society. Economic growth in this phase is mainly dependent on the intensification of energy use (Percebois, 1989; Martin, 1988; Reddy and Goldemberg, 1990). In the second stage there is a decline in energy intensity, due to improvements in the efficiency of the energy chain, the substitution of energy carriers and the transition from an industrial society to a less energy-intensive one based on services (Percebois, 1989).

Gales et al. (2007) questioned the universality of this model, however, based on an analysis of long-run energy transitions in Spain, Italy, the Netherlands and Sweden. If traditional energy carriers are considered along with fossil fuels, they show that these four countries exhibit a long-run declining trend in their energy intensities. The authors see this as a consequence of continuous technical change surpassing the effects of structural change, i.e. industrialization. Their argument hinges strongly on the benefits derived from the transition to more efficient modern energy carriers and on the continuous improvements in the efficiency of energy converters, but also on the effects of technological change in the broader sense, for example indirect improvements in labour productivity.

Fig. 4 presents the long-run energy intensities of our twelve countries. While there is a long-run general decline in the energy intensities of individual countries, as suggested by earlier works (Gales et al., 2007; Grubler, 2004), there are some disparities in their historical paths and levels of energy intensity. We can distinguish between three major patterns of energy intensity paths. The first one, exhibited by the United States, Canada and Sweden, is characterized by high initial levels of energy intensity (56–87 MJ/USD). These are largely attributable to high levels of consumption of traditional energy carriers, arising from a combination of vast endowments of forest, adverse climatic conditions and low population densities. These countries experience a strong decline in energy intensity over the 19th century, as a result of the substitution of modern energy carriers

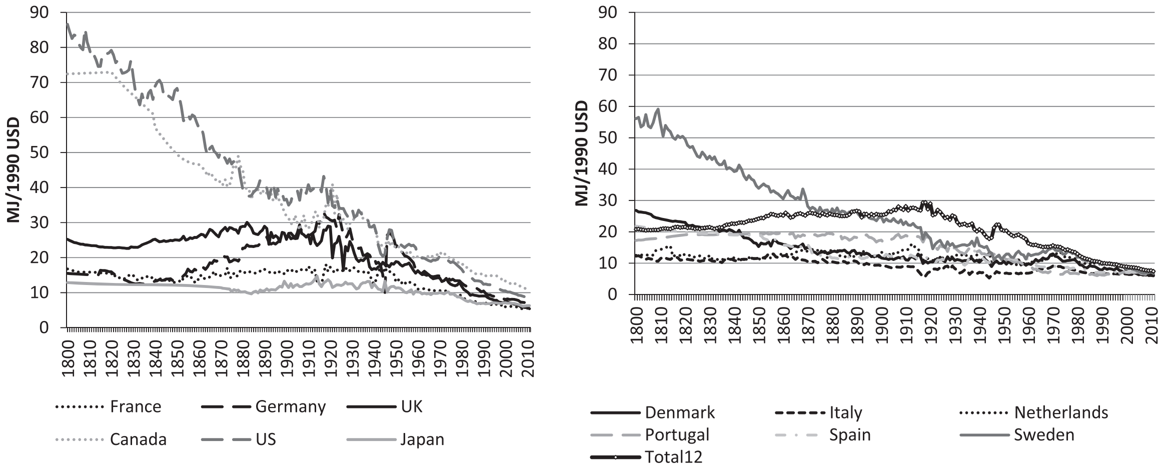

Fig. 4. Energy intensity (MJ/1990 USD).
Source: See Section 3 and Supplementary Material (S1).

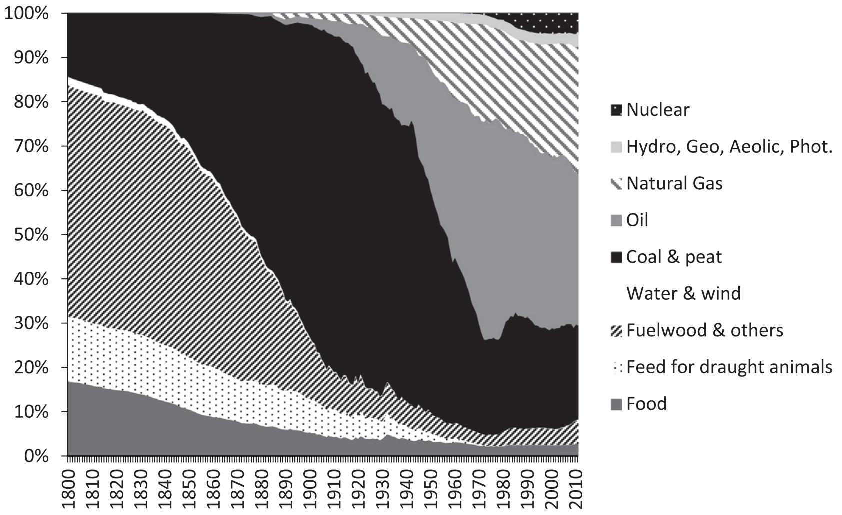

Fig. 5. Energy consumption by source, Europe, North America and Japan (%).
Sources: See Section 3 and Supplementary Material (S1 and S2). Note: Water & wind corresponds to direct uses. Hydro, Geo, Aeolian and Photovoltaic corresponds to renewable energy used for electricity production.

for less efficient ones and the declining importance of the household sector (Kander et al., 2013). Another energy intensity pattern is the inverted U-shaped curve clearly exhibited by the UK and Germany. In these countries, the effect of coal-based economic growth based on energy-intensive industries clearly offsets the effects of technological change in the early periods of industrialization. Their energy intensity increases sharply, from less than 20 MJ/USD in pre-industrial times, to 30 MJ/USD around 1913 and declines thereafter. The remaining countries have a much lower value of energy intensity as a starting point (12–27 MJ/USD) and exhibit a modest long-term decline. Still, this decline is not monotonous and later periods of growth or stagnation do occur. France and Japan have phases of growth in their energy intensities during the period of industrialization based on coal, while the Netherlands, Denmark and Italy have a period of growth in the late 1960s due to the low oil prices that existed at the time.

Today, these three main differentiated paths of long-run energy intensity have mostly converged. Differences in energy intensities between the European countries and Japan were essentially gone after the oil crisis of the 1970s (5–7 MJ/USD in 2008). This can be ascribed to the convergence of economic structures, consumption patterns and technology between these countries. However, energy intensities are still higher in the United States and Canada than in Europe (9–12 MJ/USD in 2008). The persistence of this gap is probably due not only to a more intensive industrial structure, but also to much higher levels of personal energy consumption per capita as a result of past technological choices. For example, historically low oil prices led over time to the use of bigger, less energy efficient cars, which coupled with large houses and low electricity prices, have resulted in higher levels of household consumption per capita than in the rest of the world.

Due to their size, the UK and Germany exert a strong influence on the total energy intensity of the twelve countries, which therefore also exhibits the same inverted U-shaped pattern, increasing from 20 MJ/USD in 1800 to 29 MJ in 1918, then dropping to 14–15 MJ/USD in the 1970s and then further to 7–8 MJ/USD in the late 2000s. This favours the interpretation that energy had a crucial role in stimulating growth during the first phase of industrialization.

The drop in energy intensity over the twentieth century has stimulated research about its causes. Warr et al. (2010) show that improvements in the conversion efficiency of primary to useful energy explain the 1900–1970 energy intensity declines in the UK, the United States, Japan and Austria. After 1970, improvements in conversion efficiency reach a plateau (Warr et al., 2010) and the main factors explaining the sharp energy intensity reductions in western countries are other technological changes within the industrial sector, linked to the rising importance of information and communications technology as a driver of economic growth (Henriques and Kander, 2010; Mulder and Groot, 2012).

4.3.3. CO_2 intensity and the effect of the energy mix

Due to different goals and constraints, each country adopts a distinct energy mix, which leads to striking differences in the levels of CO_2 intensity between them. Fig. 4 shows the transition from traditional energy sources to the fossil-fuel-based energy system of today.[9]

In pre-industrial societies, energy was obtained almost exclusively from biomass. Arable land was used to grow food for humans, pastures provided the feed for animals and forests supplied the wood necessary for heating and industrial needs. Water and wind were the two only non-biomass sources of energy, but were only of secondary importance. In 1800, only 14% of the total energy consumed by these twelve countries resulted from the burning of coal, most of it done by the UK. By 1876, coal already accounted for about 50% of the total energy consumed in these countries, not only due to the influence of the UK, where the Industrial Revolution was well underway, but also to Germany, the Netherlands and France, countries that made an early transition to coal. Overall, coal continued to expand its share of the total energy system until the 1930s, at which time other sources of energy, such as oil, natural gas, and to a smaller extent hydro-power, began to increase in importance. The 1950s and 1960s were characterized by a universal expansion of modern energy sources, particularly oil, which surpassed coal as a major energy carrier in the early 1960s. The transition from coal to oil was faster in North America and in the countries that missed out on the first wave of industrialization, such as Portugal, Spain, Italy and Japan, than in the countries with abundant coal reserves, like Germany and the UK (Fig 5).

The oil crisis of 1973 marked a shift in the energy structures of developed countries. International oil prices quadrupled almost overnight, challenging the prospect of a continued economic growth based on cheap oil. It forced countries to diversify their energy mix, increasing the share of coal, natural gas and nuclear power in order to reduce the external dependence on oil. Beginning in the late 1990s, environmental and climate change concerns have become pivotal

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[9] Some trends in the process of transition have been common across countries, others divergent. The reader interested in disaggregated trends is referred to the Supplementary Material (S2).

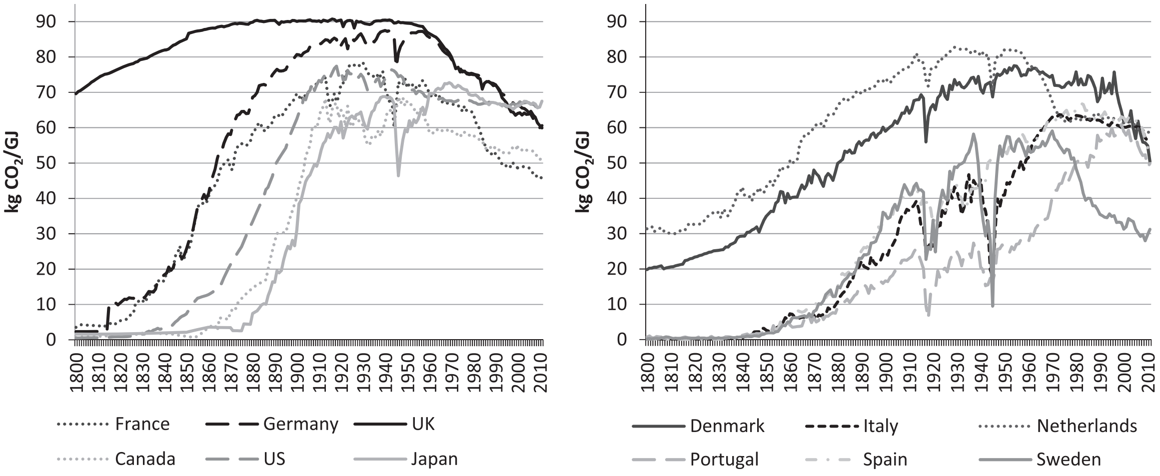

Fig. 6. CO_2 intensity of all forms of energy (kg CO_2/GJ).
Sources: See Section 3 and Supplementary Material (S1).

regarding policy issues. Since then, European electricity systems have been shifting to forms of energy with lower carbon emissions: natural gas and renewable sources such as wind and solar energy have seen a spurt of investment. Presently, every country relies on a diversified and heterogeneous portfolio of energy carriers. Choosing the right energy mix is far from easy, as environmental goals usually conflict with economic, health, safety and security of supply considerations. As a result of the tension between conflicting goals and the difficulty associated with reverting past decisions, the energy mix utilized for electricity generation is quite different across countries.

Most studies concerning CO_2 emissions focus only on fossil fuels and find a historical decline in the intensity of emissions. This is the result of a transition from carbon-intensive coal to less carbon-intensive oil and natural gas. This shift is usually referred to as decarbonization (Grubler and Nakicenovic, 1996).

Fig. 6 shows our calculations of CO_2 emissions intensities when all energy carriers are included. It can be observed that all countries increase their carbon intensities as a result of the transition towards fossil fuels until they eventually peak. Countries that reached a large share of coal in their energy mix early on peak at 75–90 kg CO_2/GJ. In the United States, Canada and France, emission intensities start to decline in the inter-war period, while in the Netherlands this happens after WWII, as a result of a switch to oil and natural gas. The rise and peak in CO_2 intensity is less marked in the UK, which was already dependent on coal by the early 19th century. In countries that skipped the early coal-intensive path (Italy, Spain, Portugal and Sweden), the shift occurs later in time and at lower levels of CO_2 intensity than their predecessors, at around 55–65 kg CO_2/GJ.

In the second half of the 20th century, the decarbonization trend then becomes very diverse across countries, which can be attributed to different energy policies and natural resource endowments. The shift away from fossil fuels was very swift in Sweden and in France, thanks to a growing share of primary electricity, especially nuclear, in their energy mix, while the trend has remained practically flat for Italy and Spain. As a result of steeper decreases in countries that had reached high emission levels early on, and late peaks as well as a flatter decarbonization trend in latecomers, carbon intensities are much more homogeneous nowadays across countries than in the late 19th century, with the notable exception of Sweden.

4.4. *The drivers of change in CO_2 emissions: application of the extended Kaya decomposition*

We conducted a multiplicative extended Kaya decomposition for each country, considering five distinct periods. 1800–1870 covers the time period where old traditional energy sources dominated the landscape. Then comes the age of coal, from 1870 to 1938, where the first divergences in the types of energy transitions and economic growth paths start to manifest themselves. We can refer to 1950–1973 as the age of oil, a period characterized by fast economic growth.[10] In 1973–1990 alternatives to oil start to be considered, in the aftermath of the 1973 oil crisis. Finally, the period after 1990 is characterized by an increased environmental awareness and concerted global climate policies.

The drivers of change in CO_2 emissions for the period 1800–1870 are shown in Table 2. Global emissions grew 3.6% per year, due mostly to fuel switching effects (1.7%) and scale effects (1.7%). However, there are some strong differences across the nine countries for which this decomposition is available. In the UK, the Netherlands and Denmark, where CO_2 emissions per capita were the largest at the beginning of the period, scale effects were greater than the effects associated with fuel switching. In the remaining countries, fuel switching effects dominated, which was primarily attributable to the transition from biomass to fossil fuels. Technological factors had a small impact on total CO_2 emissions (0.3% a year), with four countries exhibiting a positive trend and five countries showing a negative trend.

In the period from 1870 to 1938 scale effects dominated the changes in global CO_2 emissions, as shown in Table 3. The effects of fuel switching associated with the transition from biomass were also important, with the exception of the UK, which had already had an early transition to coal, but they only surpassed scale effects in Sweden, Spain, Italy, Portugal and Japan, the less developed countries and hence lowest emitters. Technology was the most important offsetting factor in this period, but its role in reducing emissions was small compared to the positive effect of the transition from biomass to fossil fuel. The influence of inter-fossil fuel substitution and carbon-free energy penetration was almost negligible.

The drivers of change in CO_2 emissions for the period 1950–1973 are presented in Table 4. This period is associated with large emissions growth in the catching-up countries, represented by Southern Europe and Japan, and low growth in the United States and the UK, the leaders. Scale effects, mostly income effects, explain the bulk of changes in the total and individual country emissions. Fuel switching and shifts in energy intensity contributed to a slight decrease in emissions. However, this was not enough to offset scale effects. For large emitters, the fuel switching effects related to the transition from coal to oil (and to natural gas, in the case of the United States and the Netherlands) had an important role in reducing emissions growth. For the countries

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[10] We do not perform a decomposition over the period 1938–1950 due to the impact of WWII.

Table 2
Decomposition of CO_2 emissions in average annual growth rates 1800–1870 (%)[a].

	1800		Scale			Fuel Switching		
	tCO_2 pc	EMISS	INC	POP	TECH	FOS	BIO	CARFREE
UK	4	2.8	1.2	1.2	0.1	0	0.3	0
Netherlands	0.8	2.4	0.6	0.8	0.1	0	0.8	0.2
Denmark	0.7	2.1	0.6	1	−0.8	0	1.3	0
France	0.1	4.7	0.7	0.4	−0.2	0	3.7	0
Germany	0.03	6.5	0.8	0.7	0.3	0	4.6	0
Portugal	0.01							
Sweden	0.01	5.8	0.6	0.8	−1	0	5.3	0
Spain	0.003							
Italy[b]	*0.002*							
Europe	0.46	3.3	0.8	0.7	0.1	0	1.7	0
US	0.06	8.4	0.9	2.9	−0.8	0	5.3	0
Canada[b]	*0.04*							
Japan[b]	*0.01*							
Global	0.36	3.6	0.8	0.9	0.3	0	1.6	0

[a] *EMISS* represents the change in CO_2 emissions; *Scale* are the effects of changes in income per capita (INC) and population (POP); *TECH* is the technological effect derived from changes in energy intensity; fuel switching effects consist of the sum of the inter-fossil fuel substitution effect (*FOS*), the biomass substitution effect (*BIO*); and the penetration of carbon-free fuels in the energy basket (*CARFREE*). The values were obtained using the transformation described in Eq. (5).

[b] denotes countries for which emissions are estimated, see Supplementary Material.

Table 3
Decomposition of CO_2 emissions in average annual growth rates 1870–1938 (%).

	1870		Scale			Fuel Switching		
	tCO2 pc	EMISS	INC	POP	TECH	FOS	BIO	CARFREE
UK	11.8	1	0.8	0.9	−0.7	0	0	0
Netherlands	2.2	2.5	1	1.3	−0.2	−0.1	0.4	0.1
Germany	2	3	1.5	0.8	0.1	0	0.6	0
Denmark	1.5	2.7	1.6	1	−0.5	−0.1	0.6	0.1
France	1.4	2.1	1.2	0.2	0	0	0.7	0
Sweden	0.3	4.5	1.9	0.6	−0.9	−0.1	2.9	0
Spain	0.2	3.2	0.6	0.7	−0.2	0	2.2	0
Italy	0.1	3.9	1.1	0.7	−0.6	0	2.8	−0.1
Portugal	0.1	3.1	0.8	0.8	−0.5	−0.1	2.1	0
Europe	2.8	1.9	1.2	0.7	−0.3	0	0.4	0
US	2.6	4	1.4	1.7	−0.8	−0.2	2	0
Canada	0.6	5.4	1.5	1.6	−0.6	−0.1	3.1	−0.1
Japan	0.03	7.5	1.8	1.1	0.2	−0.1	4.5	−0.1
Global	2.3	2.8	1.3	1	−0.3	−0.1	0.9	0

Table 4
Decomposition of CO_2 emissions in average annual growth rates 1950–1973 (%).

	1950		Scale			Fuel Switching		
	tCO2 pc	EMISS	INC	POP	TECH	FOS	BIO	CARFREE
UK	14	0.8	2.2	0.5	−1.3	−0.6	0	−0.1
Germany	7.7	3.1	4.9	0.6	−2	−0.6	0.2	0
Denmark	5.6	3.8	3	0.7	0.3	−0.7	0.4	0
Netherlands	5.1	4.6	3.4	1.2	1.1	−1.4	0.3	0
France	4.9	3.7	4	1	−0.9	−0.7	0.5	0
Sweden	4.5	4.3	3	0.6	0.7	−0.6	0.9	−0.3
Spain	1.4	5.6	5.4	1	−1.4	−0.8	1.5	−0.1
Italy	1	8.5	4.7	0.6	1.3	−0.7	2.4	0.2
Portugal	0.6	5.1	5.2	0.2	−2.7	−0.5	3.1	−0.3
Europe	6.1	3	3.9	0.7	−1.2	−0.7	0.3	0
US	17.2	2.5	2.4	1.4	−1.1	−0.4	0.2	0
Canada	11.5	3.6	2.8	2.1	−0.5	−0.8	0.2	−0.1
Japan	1.3	9.2	7.8	1.1	−0.5	−0.8	1.4	0.2
Global	8.7	3.1	3.6	1	−1.3	−0.5	0.2	0

Table 5
Decomposition of CO_2 emissions in average annual growth rates 1973–1990 (%).

	1973		Scale			Fuel Switching		
	tCO2 pc	EMISS	INC	POP	TECH	FOS	BIO	CARFREE
UK	14	−1	1.9	0.1	−2.6	−0.2	0	−0.1
Germany	13	−0.6	1.7	0	−1.9	−0.1	−0.1	−0.2
Denmark	11	−0.6	1.6	0.1	−2.2	0.3	−0.3	−0.2
Netherlands	11	0.1	1.6	0.6	−2.1	0.2	−0.1	−0.1
Sweden	10	−3	1.6	0.3	−2.3	0.2	−1.1	−1.6
France	9	−1.5	1.9	0.5	−2.6	−0.2	−0.2	−0.9
Italy	6	0.9	2.4	0.4	−1.8	−0.2	0.1	−0.1
Spain	4	2.1	2.7	0.7	−1.3	0.1	0.1	−0.2
Portugal	2	4.8	3	0.6	−0.2	0.2	1.1	0.1
Europe	10	−0.4	2	0.3	−2.2	−0.1	−0.1	−0.3
US	18	0.2	1.9	1	−2.7	0.2	−0.1	−0.2
Canada	16	0.7	1.8	1.2	−1.9	0	0	−0.4
Japan	8	1.1	2.9	0.8	−2.1	−0.1	0	−0.3
Global	13	0.1	2.1	0.6	−2.4	0.1	−0.1	−0.2

with a large share of biomass, like Portugal, Spain, Italy and Japan, the impact of fuel switching from coal to oil was also significant, but was offset by the transition from biomass to fossil fuels. Interestingly, the country with a higher positive impact from biomass transition, Portugal (+3.1%/year), also exhibits a strong negative impact (−2.7%/year) from technology changes, showing that the evolution of energy intensity may be strongly connected with the replacement of traditional energy carriers with more efficient, modern ones. However, a significant replacement of traditional energy carriers by fossil fuels does not necessarily imply a decline in energy intensity if, for example, structural changes towards heavy industries occur, like in the case of Italy.

Decomposition results for the period 1973–1990 are presented in Table 5. After the oil crisis of 1973, emissions decreased slightly in Europe (−0.4%/year) and its growth slowed down in the United States (0.2%), Canada (0.7%) and Japan (1.1%). During this period of modest economic and population growth, the technology effect rose drastically in importance. Most countries observed sharp energy intensity drops of about 2.0–2.7% a year, whereas latecomers Portugal (−0.2%) and Spain (−1.3%) saw milder decreases. Combined technological and fuel switching factors offset scale effects and contributed to declining emissions in five countries (the UK, Germany, Denmark, Sweden and France). The most important fuel switching effect was the expansion of carbon-free technologies, especially nuclear power. It had an important role in reducing CO_2 emissions in France and Sweden. By 1990, 50% and 70%, respectively, of Swedish and French electricity was coming from nuclear power.

Inter-fossil fuel substitution had a very small and mixed impact, as shifts to coal in power generation also occurred in many countries, for energy security reasons. The effects from biomass went into reverse in some countries, especially in Sweden.[11]

In the period from 1990 to 2011 emissions still increased at a fast rate of 0.9%/year until 2005, in spite of the Kyoto agreement of 1997,[12] ushered in by growing concerns about the adverse effects of climate change. From that point on, CO_2 emissions started to decline, a trend

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[11] Kander (2002) explains that this reversal was due to a larger utilization of spent pulping liquor (a waste product) in the pulp and paper industry (representing half of the biomass) and a refinement of firewood into pellets which is a denser product and easier to handle.

[12] The Kyoto Protocol, signed in 1997 and coming into effect in 2005, committed a group of industrialized countries to cut down CO_2 emissions by 5% in 2008–2012, relative to 1990 baseline levels, with a target of −6% for Canada and Japan, −7% for the United States and −8% for the European Union as a whole. The European Union further established a burden sharing agreement that allocated different reduction targets to its members, with stronger target reductions for high emitting countries (e.g. the UK and Germany) and lower requirements for convergent, low emitting ones (e.g. Spain and Portugal).

Table 6
Decomposition of CO_2 emissions in average annual growth rates 1990–2011 (%).

	1990		Scale			Fuel Switching			Change (%)	Kyoto Target
	tCO2 pc	EMISS	INC	POP	TECH	FOS	BIO	CARFREE	90-11	(%)
UK	12	−1.5	1.6	0.3	−2.5	−0.5	−0.2	−0.1	−26	−13
Germany	12	−1.4	1.4	0.2	−2.1	−0.3	−0.5	−0.1	−26	−21
Netherlands	10	0.2	1.6	0.6	−1.6	−0.1	−0.2	−0.1	3	−6
Denmark	10	−1.1	1.2	0.4	−1.1	−0.4	−0.8	−0.3	−20	−21
Italy	7	−0.1	0.8	0.1	−0.5	−0.2	−0.2	−0.1	−2	−6.5
France	6	−0.4	1.1	0.4	−1.3	−0.2	−0.2	−0.3	−8	0
Sweden	6	−0.2	1.7	0.3	−1.6	−0.1	−0.9	0.4	−4	4
Spain	5	1.1	2	0.3	−0.6	−0.4	0	−0.1	26	15
Portugal	4	1.1	1.2	0.4	0.1	−0.4	0.1	−0.2	27	27
Europe	9	−0.7	1.3	0.3	−1.6	−0.3	−0.3	−0.1		
US	17	0.4	1.3	1.1	−1.8	−0.1	−0.1	−0.1	9	(−7)[a]
Canada	15	0.4	1.4	1	−1.6	−0.2	−0.1	0	14	−6
Japan	9	0.4	0.7	0.1	−0.5	−0.1	0	0.1	9	−6
Global	12	0.1	1.3	0.6	−1.4	−0.2	−0.1	−0.1		

[a] The Kyoto protocol was signed only in 1997 by all countries covered, except the United States.

accentuated by the onset of the global recession at the end of the first decade of the 21st century. Table 6 shows that by 2011 most of our studied European countries had managed to curb their fossil-fuel CO_2 emissions to the agreed levels, with the exception of Spain, Italy and the Netherlands. The United States, which did not ratify the agreement, Canada and Japan were significantly off target, however.[13]

The slump in the last years of the 2000 decade was still not enough to reverse the trend from the 1973–1990 period. At +0.1%, the average yearly growth rate of total emissions in 1990–2011 was of the same magnitude as in 1973–1990, with an intensification of the decline in Europe, a slower growth rate in Japan and in Canada and a higher growth rate in the United States. As a result of lower population and income per capita growth, scale effects decreased in importance compared to the previous time period. Energy intensity and fuel switching continued to play a role in curbing emissions, although their combined effect was smaller than in the previous period. These two drivers more than offset scale effects in the UK, Italy, France, Germany, Denmark and Sweden. Relative to the previous period, fuel switching increased its role in reducing emissions in all countries, except in Sweden, France and Canada. This occurred mainly as a result of climate mitigation policies, with inter-fossil fuel substitution emerging as the most important policy initiative. This period saw increased adoption of natural gas in the electricity, manufacturing and household sectors. The transition from fossil fuels to modern forms of biomass got a significant push from the institution of carbon taxes in the early 1990s, which sought to promote renewable energy sources. This was an important factor in Denmark, Sweden, Germany and the Netherlands. In total, the role of carbon-free energy in reducing emissions was more limited than in the preceding period. While the share of electricity from renewable sources such as wind-power increased in many countries, the expansion of nuclear power ground to a halt due to safety concerns.[14]

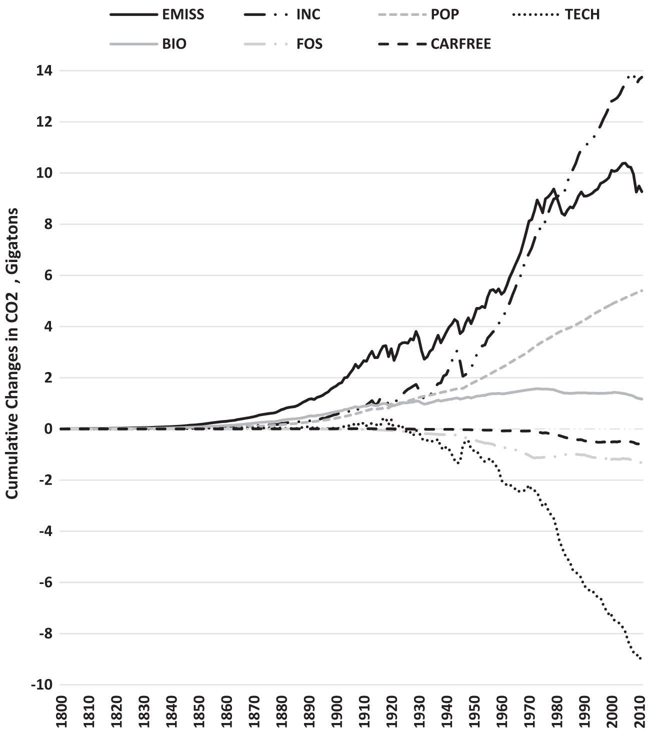

Fig. 7. Cumulative changes in Total CO_2 emissions by driving factor, 1800–2011, $GtCO_2$.
Sources: Own calculations. See Supplementary Material (S3) for full decomposition.

In order to understand the magnitude of change in CO_2 emissions, we also applied an additive decomposition to our time series[15] using Eq. (8). The cumulative historical drivers of CO_2 emissions for the twelve countries are summarized in Fig. 7. Until the early 20th century, the transition from biomass to fossil fuels was the main driver of changes in CO_2 emissions. At this time, cumulative changes in emissions were less than 3 Gt and average world income was below 3500 USD per capita. Income surpassed the biomass effect in the early 1910s and population did the same by the mid-1920s. Energy intensity effects increased until 1918, decreasing thereafter. From around WWII, technological change contributed to a clear decrease in CO_2 emissions, surpassing the cumulative positive effects of population by 1980. The transition from coal to oil and to natural gas also contributed to a reduction in emissions, offsetting the cumulative biomass effects by 2010. The effects associated with increased carbon-free energy usage were small by comparison. From 1800–2011, cumulative changes in emissions totaled 9.3 Gt. Income is the most important long-run effect (13.8 Gt) followed by population (5.4 Gt) and biomass effects (1.2 Gt). The offsetting forces are technological change (−9.1 Gt), fossil fuel switching (−1.3 Gt) and carbon free penetration (−0.6Gt). Fig. 8 shows the historical cumulative changes in emissions by country. Income

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[13] The Kyoto targets include emissions from land use and forest sectors. Here, we only report CO_2 emissions related to fossil-fuel combustion.

[14] Sweden decided to phase out nuclear power in 1980, although this decision was revoked by the parliament in 2010. Nevertheless, more recent decisions were made for reducing nuclear power capacity by 2020. In Italy, nuclear power was discontinued in 1990. Germany is currently planning to phase out nuclear power by 2022.

[15] The additive annual decomposition is presented in the online Supplementary Material (S3).

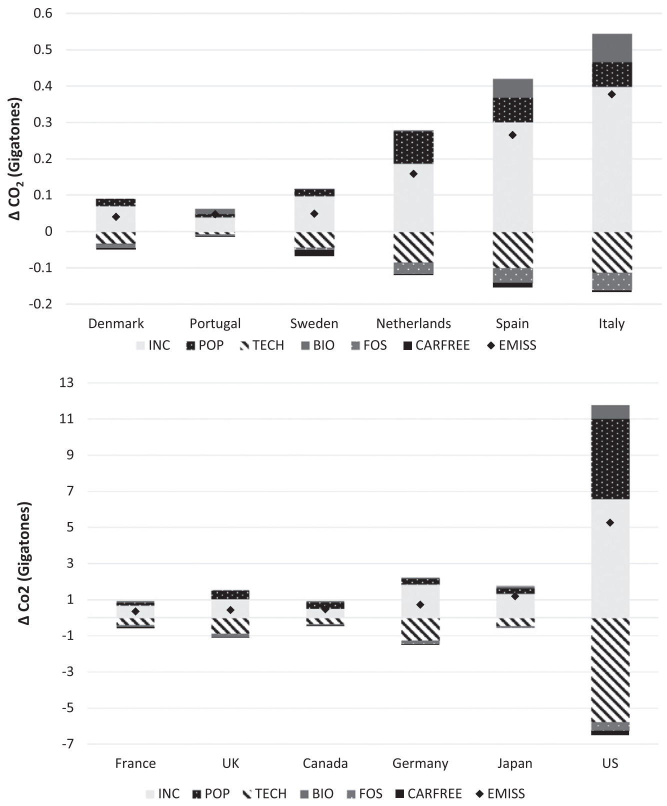

Fig. 8. Changes in CO_2 emissions by country and driving factor, $GtCO_2$, 1800–2011. Source: Own Calculations. Note: Chaining decomposition, using time series data.

appears every time as the most important driver and technology as the most relevant offsetting force, but with some degree of regional variation. Technology effects are higher for countries that followed the early coal-intensive path of development, like the UK and Germany, than for latecomers Portugal, Spain and Italy. Portugal and Italy have positive fuel switching effects as a result of a slow historical transition towards a fossil fuel system, while Denmark, Sweden and the UK exhibit strong negative effects.

The existing literature agrees in general with our results. It also identifies economic growth as the most important driver of CO_2 emissions. In addition, Tol (2009) also found for the US, as we did for many countries, an important effect of the biomass transition to coal on growing CO_2 emissions at low levels of income and an increasing importance of technological change as an offsetting factor thereafter. Technical change is also identified as the main offsetting driver in Kander et al. (2013). Andreoni and Galmarini (2016) analyzed the drivers of CO2 emissions in the period 1995–2007 for 33 countries and also found that the improvement in energy efficiency has been the main element contributing to the reduction of overall CO_2 emissions. It's hard to gauge if these corroborations contribute to increase the validity of our work, since these studies exhibit shorter time frames, cover different countries or use different methodologies.

5. Conclusions and policy implications

This article explores the drivers behind long-run fossil-fuel CO_2 emissions since 1800 in the United States, Canada, Japan and nine European countries, by decomposing the annual changes in carbon emissions into a product of changes in energy intensity, population, income and energy mix. Besides fossil fuels, we also incorporate traditional energy carriers and modern renewable energy technologies in our calculations, this way providing a more detailed account of the drivers of historical changes in CO_2 emissions than in previous studies.

Our findings indicate that, in the long run, scale effects, especially income growth, are the most important drivers of CO_2 emissions and that energy intensity is the main offsetting factor. During the early periods of industrialization, changes in energy intensity can lead to an increase in carbon emissions. This happened in the UK and Germany, countries that followed the early coal-intensive path, but on the whole this effect is negative and strengthens significantly at later stages of development. Modifications of the energy mix (fuel switching) also play an important role in driving changes in emissions. At low levels of income per capita, the transition from biomass towards fossil fuels contributes greatly to a rise in CO_2 emissions, but at high levels of income per capita, the substitution of natural gas for coal and oil, along with the expansion of carbon-free sources was a significant factor in reducing emissions in the early-industrializing countries.

Understanding how changes in energy intensity, income, population and the composition of the energy mix interplay to drive CO_2 emissions should inform environmental policy making. In particular, developing countries that are currently seeking to improve living standards while at the same time dealing with growing populations, can derive important insights from this research for steering their own CO_2 paths in an environmentally responsible way.

Since technological progress (change in energy intensity) was found to be the main driver in reducing CO_2 emissions, we contend that mitigation efforts should be concentrated first and foremost on technology transfers from developed to developing countries, in order to replicate improvements in those parts of the world that still exhibit an above-average energy intensity. These improvements should come at moderate cost since these more efficient technologies are already developed and readily available. For BRIC countries in particular, Cowan et al. (2014) suggest increasing investment in electricity infrastructure to improve delivery efficiency, resulting simultaneously in higher levels of electricity production and lower levels of CO_2 emissions. This has further implications for the negotiations of international environmental agreements. Comprehensive international regulatory frameworks dealing with the institution of carbon taxes or the setting of emissions targets are notoriously difficult to negotiate and implement, while efficiency improvements can be readily replicated. The implementation of agreements based on technology transfers might thus prove to be a better option (Aldy et al., 2010).

For developed countries, however, Ang and Su (2016) contend that further efficiency gains from improvements in technology are already hard to come by and that these countries would be better advised to concentrate their efforts on the optimization of their energy mixes instead. The European Union has been moderately successful with this strategy, reflected in its climate policy, seeing significant reductions due to fuel switching in countries such as Sweden[16] and Denmark in the period 1990–2011.

The composition of the energy mix has evolved in a somewhat similar fashion in most countries: from biomass through coal to oil, and then to natural gas and carbon-free energy sources. However, the impact of each transition and their precise timing are strongly dependent on historical endowments and, at later stages of development, on public policy. Never before has there been such a wide array of available sources of energy, so an additional lever of control for policymakers comes from the selection of the energy mix, in the context of the country's local endowments and historical path of development. Mostly due to their poor coal endowments, the latecomers in our study did not follow the high energy and CO_2 intensities path of the pioneers but were still able to reach equivalent levels of development with much less environmental impact. At the same time, countries with low historical energy and CO_2 intensities and without nuclear power in their energy system, show smaller reduction potential at later phases of development. These lessons are of special interest for developing countries not yet locked in carbon-intensive paths of development.

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[16] Sweden became a member of the EU in 1995.

They should bear in mind that energy development paths are hard to reverse.

Our study also suggests that there exists an interplay between changes in energy intensity and changes in the energy mix. In earlier stages of development, reductions in energy intensity were closely related to the transition from biomass towards more efficient but polluting energy carriers. A challenge to policymakers in developing countries is thus to find ways to build energy systems that simultaneously foster technological change and ensure environmental sustainability.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.enpol.2016.11.005.

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