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The Drivers of Long-run CO_2 Emissions:

A Global Perspective since 1800

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Abstract

Fossil-fuel-related carbon dioxide emissions have risen dramatically since 1800. We identify the long-run drivers of CO_2 emissions for a sample of twelve developed economies using an extended Kaya decomposition. 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 emission growth. Scale effects, especially income effects, become the most important emission drivers at higher levels of income and also dominate the overall long-run change. Technological change is the main offsetting factor. Particularly in the last decades, technological change and fuel switching have become important contributors to the decrease in emissions in Europe. Our results also individualize the different CO_2 historical paths across parts of Europe, North America and Japan.

Keywords: CO_2 emissions, Kaya decomposition, Energy transition

JEL Classifications: N70, O44, Q40, Q54, Q5

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1. Introduction

The unprecedented prosperity brought about by industrialization is strongly linked with wide-range changes in 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). This research investigates the drivers of change in fossil-fuel CO_2 emissions in a long-term and global perspective.

CO_2 emissions are dependent both on the level of energy consumption and on the makeup of the energy basket. They can be reduced through lower energy consumption, which can come about as a result of technological progress, lower economic growth, or demographic changes, or by moving the composition of the energy basket to sources with lower emission content. A thorough understanding of the historical determinants of CO_2 emissions is necessary in order to design effective climate policies. To cater to this demand from policymakers, research on the environmental effects of economic development is growing fast. International comparative studies that employ decomposition techniques to analyze the drivers of CO_2 emissions cover only the most recent decades (Raupach et al., 2007; Metz et al., 2007; Kojima and Bacon, 2009; Mundaca et al., 2013; Arto and Dietzenbacher, 2014). These studies find that the greatest driver of CO_2 emissions is economic growth, but depending on the period of analysis, the applied methodology 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, the short-time span of these studies means that they are unable to fully capture how drivers change in importance over time.

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 inclusion of all forms of energy and methodological consistency. Our revised dataset allows new 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. The emerging 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 emissions, especially during the early period of industrialization in the countries that followed the coal path, but otherwise the effect is typically negative and increases in size later on. Our findings also shed light on the historical paths in CO_2 emissions in a global context.

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 carbon dioxide 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 the 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]

This study advances the literature in two directions. First, by utilizing an extended Kaya decomposition we shed light on how the energy basket composition influenced CO_2

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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

emissions, allowing us to separate fuel switching into three effects: (1) the effect of changes in the carbon intensity of the fossil fuel energy basket, (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 basket. By considering biomass, renewable technologies and fossil fuels in one framework, we are able to provide a more complete and differentiated analysis of the various factors associated with fuel switching.

Second, we shed light on the impacts of historical energy transitions in a global perspective by conducting the analysis for a wider set of countries and for a much longer time period than previous studies (i.e. 1800-2011). Our countries are representative of all the 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 categorize the different historical carbon dioxide emissions paths across the studied countries.

There are four reasons why a historical study of CO_2 emission patterns 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. The potential bias arising from unobserved differences across countries, which might not be adequately captured in a cross-section setting, is hence alleviated. Second, a historical analysis enables more accurate insights on how CO_2 emissions progress as the energy basket changes over time, since energy transitions usually take several decades. Third, 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). Fourth, a long-run approach is particularly relevant, as emissions accumulate over extended periods of time in the atmosphere.

The paper is organized as follows. Section 2 introduces the database and decomposition method. Section 3 presents the long-run energy transition patterns for our sample. Section 4 exhibits the long-term CO_2 emissions and section 5 its determinants. Section 6 conducts the decomposition of the CO_2 emission changes and section 7 concludes.

2. Data and methodology

2.1 Data sources

Long-Run Primary Energy

We have 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 (Henriques and Sharp, 2014), France (Gales, 2013), Italy (Malanima, 2006), Germany (Gales and Warde, 2013), Portugal (Henriques, 2009), 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 (Stewart, 1978) and Japan (EDMC, 2009).

In order to improve the consistency of the various datasets, we conducted three modifications to the available data. First, we calculated the contributions of muscle power and water/wind for the countries where this information was missing. Second, we extended all series backwards until 1800, by estimating 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).

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) were calculated considering its heat content.

CO_2 emissions

CO_2 emissions are 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.[2]

The combustion of firewood also emits CO_2, but as long as biomass is sustainably burned there will be no net associated CO_2 emissions. Therefore, the Intergovernmental Panel of Climate Change (IPCC) has considered firewood combustion emissions as carbon neutral in their energy-related CO_2 emission calculations. In line with the IPCC, we do not perform the calculations of CO_2 released or captured from forests, although they were important in the past.[3]

Although CDIAC has produced historical series of CO_2 emissions from fossil fuel combustion for almost every country in the world (Boden et al., 2013), the historical statistics on which CDIAC bases these estimates (see Andres et al., 1999) are less reliable and complete than our sources.[4] As we show later, global emissions have been significantly underestimated, especially for the 19th century.

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[2] IPCC (2006).The IPCC gives a slightly higher emissions coefficient to peat (106 kg 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.

[3] For historical reconstructions taking into account forest and other land use changes see, for example, Houghton (2003), who provides regional and global estimations from 1850 to 2000, or Kander (2008).

[4] CDIAC historical reconstruction of CO_2 emissions are based on Etemad and Luciani (1991) and old editions of Mitchell (1992, 1993 and 1995).

GDP and Population

We use 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).[5] See Supplementary Material S1 in the Appendix for details on data sources and calculations.

2.2 Methodology

CO_2 emissions are a function of both the level of energy consumption and the composition of the energy basket. The Kaya identity is an extension of the IPAT identity (Ehrlich and Holdren, 1971) that allows the decomposition of CO_2 emissions in the factors that influence energy consumption (scale and technology) and carbon intensity, in the following way (Kaya, 1990):

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

The last term on the right-hand side of Eq. (1), is the carbon intensity of energy. The other terms reflect the drivers of energy consumption: GDP per capita, population and energy intensity.

In order to understand how the energy basket influences CO_2 emissions, we extend the Kaya decomposition methodology, following Ma and Stern (2008), which allows us to separate fuel switching into three effects: (1) the effect of changes in the carbon intensity of the fossil fuel energy basket, (2) the effect of the transition from biomass to fossil fuels as a driver of changes in CO_2 emissions and (3) the effect of the penetration of carbon-free energy in the energy basket. Formally, the decomposition equation is 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:

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[5] 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.

CO_2	Carbon emissions from fossil fuels combustion
FF	Fossil fuels consumption (coal + oil + natural gas)
CF	Carbon-based fossil fuel consumption (fossil fuels + biomass – i.e. food, fodder, firewood & biofuels)
E	Total energy consumption
Y	Gross domestic product
P	Population
C_{ff}	Carbon emissions coefficients from fossil fuels
S_1	Share of fossil fuels in carbon-based fuels
S_2	Share of carbon based fuels in total fuels
I	Energy intensity of economic output
y	GDP per capita

The Logarithmic Mean Divisia Index (LMDI) decomposition method can be applied to this identity. This method has the advantages of unity independency, no residual and perfect reversibility in the log form between multiplicative and additive versions (Ang and Zhang, 2000; Ang and Liu, 2001; Ang, 2004; Ang, 2005). The multiplicative form of the decomposition between time t and time 0 can be expressed as:

$$\frac{{CO_2}^T}{{CO_2}^0} = \frac{y^T}{y^0} \times \frac{P^T}{P^0} \times \frac{I^T}{I^0} \times \frac{{C_{ff}}^T}{{C_{ff}}^0} \times \frac{S_1^T}{S_1^0} \times \frac{S_2^T}{S_2^0} \tag{3}$$

Eq. (3) is a special case of the multiplicative LMDI, where the weights are set equal to unity. In this way, the total changes in emissions can be obtained from the product of the changes in the factors and Eq. (3) can be rewritten as:

$$D_{EMISS} = D_{INC} D_{POP} D_{TECH} D_{FOS} D_{BIO} D_{CARFREE} \tag{4}$$

D_{EMISS} represents the total change in CO_2 emissions; D_{INC} and D_{POP} are the effects of changes in income per capita and population, respectively; D_{TECH} is the technological effect derived from changes in the ratio between energy and economic growth (energy intensity); D_{FOS} represents the inter-fossil fuel substitution effect due to changes in the emissions coefficients of the fossil fuel basket; D_{BIO} is the biomass substitution effect derived from the transition from food, fodder and firewood to fossil fuels; $D_{CARFREE}$ is the penetration of carbon-free fuels such as nuclear, hydro, solar, geo, aeolian, wind and water power in the energy basket. To facilitate comparison between time-periods, the multiplicative form of this decomposition can be expressed additively in annual growth rates by applying logarithms to Eq. (4), a procedure that is followed in section 6.

While the multiplicative version of the LMDI expresses changes in relative terms, the additive version expresses changes in absolute terms. In order to enrich our study, we apply an additive chaining decomposition analysis to our time series, as shown in Eq. (5).

$$CO_2{}^T - CO_2{}^0 = \Delta INC + \Delta POP + \Delta TECH + \Delta FOS + \Delta BIO + \Delta CARFREE \qquad (5)$$

Where for each driver x_k,

$$\Delta x_k = \frac{CO_2{}^T - CO_2{}^0}{\ln CO_2{}^T - \ln CO_2{}^0} \ln\left(\frac{x_k^T}{x_k^0}\right). \qquad (6)$$

3. Energy transitions

3.1 Energy per capita

In the long term, all the countries under observation exhibit increasing trends in per capita energy use – a well-established feature of industrialization. However, there is significant heterogeneity in the points of departure, magnitude and pace of this shift, as illustrated by Figure 1. Globally we can distinguish three main epochs of energy pathways that have long-term relevance: 1800-1938 (differentiated energy paths); 1950-1973 (extreme growth) and 1973-2011 (stagnation).

The first phase is characterized by different points of departure and energy per capita growth. We can distinguish three regional groups of resource use. The first group comprises the UK, Canada and the United States, which around 1850 were leading the rest of the world with levels of consumption of 70 to 120 GJ per capita. The UK, thanks to its abundant high-quality domestic coal reserves was at the forefront of industrialization. On the other hand, 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 three country group followed a long-term high energy path with no equivalent in the rest of the world. Until the present day the levels of energy consumption in Canada and in the United States remain unchallenged.

In 1850, energy consumption in the remaining countries varied between 8 GJ per capita in densely populated Japan to 35 GJ per capita in cold and wood-rich Sweden. The second group in our analysis, constituted by 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. Japan, Portugal, Italy and Spain had an atypical transition, following a path of very low energy consumption per capita until World War II, reaching levels of between 20 and 30 GJ per capita in the 1930s. They constitute a third group, the energy consumption laggards, displaying energy use levels that Grubler (2004) considers representative of the per capita consumption of pre-industrial societies.

The second phase (1950-1973) saw most countries increasing their levels of per capita energy consumption at a very fast rate, almost doubling pre-World War II levels. Italy and Japan narrowed significantly the gap with the leaders. The UK was losing its resource-intensive character during this period, so here the upswing was much less pronounced. While the differences in energy per capita between the UK and the two New World countries widened during this period, the gap with the other European countries narrowed markedly.

The oil crisis brought with it a clear trend reversal for most countries. After 1973 the available energy per person started to stabilize in countries with consumption levels above 150 GJ per capita. By contrast, 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 a North-American.

3.2 The energy basket

Figure 2 characterizes how the global energy system moved away from traditional energy sources to the fossil-fuel-based system of today.[6]

In pre-industrial societies, energy was obtained almost exclusively from biomass. Arable land provided the food for humans, pastures the feed for animal power and forests the wood for heating and industrial needs. Water and wind were the two only

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

non-biomass sources of energy, albeit of marginal importance. By 1800, 14% of total energy consumption resulted from coal burning, mainly in the UK. By 1876, coal accounted for 50% of the energy basket, not only due to the UK, where the Industrial Revolution was well underway, but also Germany, the Netherlands and France, who made an early transition to coal. Overall, coal continued to expand its share of the total energy system until the 1930s, when other sources of energy, such as oil, later natural gas, and to a smaller extent hydro-power, began to increase in importance. The epoch of 1950-1973 was characterized by a universal expansion of modern energy sources, with a clear preponderance of 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, like Portugal, Spain, Italy and Japan, than in the countries with abundant coal reserves, like Germany and the UK.

The 1973 oil crisis marked a shift in the energy structures of developed countries. International oil prices quadrupled almost overnight, challenging the prospect of continuous economic growth based on cheap oil. This forced countries to diversify their energy mix, increasing the share of coal, natural gas and nuclear power in order to reduce external dependence on oil. Since the late 1990s, pressing environmental concerns became central and European electricity systems have since been shifting to low carbon forms of energy in response to climate change concerns. As a consequence, natural gas and renewable sources such as wind and solar energy have seen a spurt of investment. Nowadays, countries rely on a diversified and heterogeneous portfolio of energy carriers. Shifting a national 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 difficulty in drastically reverting past decisions and the tension between conflicting goals, the energy mix for electricity generation is quite different across countries.

4. Global CO_2 emissions

The long-run CO_2 emissions series for the covered countries are presented in Figure 3, showing a dramatic rise from 0.04 Gt in 1800 to 9-10 Gt in the 2000s. The year 1800 is dominated by the UK which contributed with 87% of global CO_2 emissions, followed by France (5%), the Netherlands (4%) and Germany (2%). Since the values measure total, and not per capita, emissions, large countries naturally have a greater weight. In per capita terms, the emissions in the Netherlands and Denmark are noticeable due to the inclusion of peat. Nonetheless, the dominance of the UK, which in 1800 accounted for only about 8% of the population of the studied countries, is notable.

In 1870, global CO_2 emissions amounted to 0.5 Gt. The UK remained the largest producer, accounting for about half of total global emissions. Other countries became significant contributors to global CO_2 emissions: the United States (21%), Germany (16%) and France (10%). A seven-fold rise to 3.4 Gt occurred from 1870 to 1938. In 1938, CO_2 emissions from the United States reached nearly half of global emissions (48%), clearly above Germany (18%), the UK (15%), France (6%) and Japan (5%). After World War II the impact caused by the United States increased further, reaching 59% of global CO_2 emissions by 1950.

Most countries increased further their carbon emissions, leading to a doubling of the global CO_2 output in 1973 relative to 1950. The trend of sharp rising emissions stalled from 1973 onwards, 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%).

The United States is by far the largest contributor in terms of all-time cumulative CO_2 emissions, responsible for 53% 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 limited to 12%, on par with Germany and above Japan (8%). Considering all the covered European countries, cumulative CO_2 emissions attributable to Europe represent about one-third of the total.

Figure 4 reports three different benchmarks that compare our sample with the series provided by CDIAC. In 1800, CO_2 emissions in our 12 countries account for 138% of the global emissions reported by CDIAC and 146% of the sub-sample of CDIAC consisting of the same twelve countries covered here. We interpret this discrepancy as supportive of the assertion that our database records historical emissions with greater accuracy. Finally, we report on the share of adjusted world CO_2 emissions (i.e. our sample extended by the remaining countries from the CDIAC sample) chargeable to the countries in our sample. They produced more than 90% of the world CO_2 emissions until 1870, about three quarters by the mid-20th century and more than half by 1973. These coefficients support the view that, from a long-term perspective, our sample covers all major emitters.

5. Contributing factors

This section presents the main factors used in our decomposition. We show, for the countries under observation, the long-term trends in GDP per capita and population, energy intensity and CO_2 intensity of the energy basket.

5.1 GDP per capita and population

Our set of countries exhibits various development paths, as seen in Table 1. In the early 19th century, with the exception of the UK and the Netherlands, per capita incomes were rather similar across regions. Japan, followed by Sweden and Canada, were the most backward countries and yet their incomes varied between 55% and 74% of our sample 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, there was already much more divergence in per capita incomes, with Japan and Portugal falling to just one third and 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. In 1950, Japan, Portugal and Spain were the most backward countries. Incomes per capita increased much more rapidly in the post-war period, with the less developed countries growing faster than the more developed ones. By the end of the period we consider, income divergence across countries was smaller than in 1800. Today 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 (27.3m population), Japan (25.5m) and Germany (24.5m), followed by Italy (18.3m). Population sizes in the UK and Spain were within close range of our average of 11m. All remaining countries had a population size of less than half the average. By 1870 the largest population increase in Europe had occurred in fast developing UK.

Nonetheless, the fastest growing countries were by far the United States and Canada, new world countries that received a massive influx of migrants. Between 1870 and 2011, the population in our sample more than tripled, from 239 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 between 1870 and 2011 by a factor of 9 and 8, respectively. The Netherlands almost quintupled its population, while in Japan the increase was by a factor of 4.

5.2 Energy intensity

The most widespread view on the long-run evolution of energy intensity is the one associated with the concept of two stages of development. In the first stage, energy intensity grows as a result of the structural effects related to 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 one less energy-intensive based on services (Percebois, 1989).

Analyzing long-run energy transitions in Spain, Italy, the Netherlands and Sweden, Gales et al. (2007) question the universality of this model. 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 explain 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 throughout history but also on the effects of technological change in the broader sense, for example indirect improvements in labour productivity.

Figure 5 presents the long-run energy intensities for our twelve countries. While there is a long-run general decline in the energy intensities of individual countries, as suggested by early works (Gales et al., 2007; Grubler, 2004), there are some disparities in the historical paths and levels of energy intensity. We can distinguish three major types 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) which 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 strong substitution of modern energy carriers for less efficient ones and the declining importance of the household sector (Kander et al., 2013). A second energy intensity type, consisting of the UK and Germany, exhibits a clear inverted U-shaped pattern. In these countries, the effect of coal-based economic growth based on energy-intensive industries clearly offsets the effect 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, declining thereafter. A third group of countries starts from much lower energy intensities (12-27 MJ/USD) and exhibits more modest long-term declines. Still, the tendency towards a decline is not linear and phases of growth or stagnation also occur. France and Japan have phases of growth in their energy intensities during the coal period of industrialization based on coal, while the Netherlands, Denmark and Italy have a period of growth in the late 1960s at a time of low oil prices.

These three main differentiated paths of long-run energy intensity have today converged substantially. Differences in energy intensities between the European countries and Japan practically disappeared after the oil crisis (5-7 MJ/USD in 2008), which can be interpreted as a result of the convergence of economic structures, consumption patterns and technology. 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 to the use of bigger, less energy efficient cars and large houses, coupled with low electricity prices, resulted in higher levels of household consumption per capita.

Due to their size, the UK and Germany are able to exert a strong influence on global energy intensity, 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, from a global perspective, 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. 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 become 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, 2011).

5.3 CO_2 intensity

Differences between the levels of energy and the levels of CO_2 emissions in the various countries are due to differing energy mixes. Most studies focus only on the analysis of the CO_2 emissions per GJ of fossil fuels and find a historical decline in the intensity of emissions due to 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).

Figure 6 shows the emission intensities we calculated with all energy carriers included. It can be observed that all countries increased their carbon intensity as a result of the transition towards fossil fuels and that their emissions peaked at a certain point in time. Countries that attained a large share of coal in their energy basket early on peaked at 75-90 kg CO_2/GJ. In these countries, emission intensities started to decline either in the inter-war period (the United States, Canada and France) or after World War II, as a result of switching to oil or natural gas. The rise and peak in CO_2 emissions 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 pattern (Italy, Spain, Portugal and Sweden), the shift occurred later in time and at lower levels than their predecessors, at around 55-65 kg CO_2/GJ.

After reaching the peak, the decarbonization trend becomes substantially different across countries, which can be attributed to different energy policies and natural resource endowments. The shift is very swift in Sweden and in France, which by 2011 reached 31 and 46 kg CO_2/GJ, respectively, thanks to a growing share of primary electricity, especially nuclear, in their energy basket. The trend is practically flat for Italy, Spain and Portugal over the last decade of the 20th century, with a drop after 2007. As a result of steeper decreasing tendencies in countries with high emissions, and late peaks as well as flatter decarbonization trends in latecomers, carbon intensities across countries are much more homogeneous nowadays than in the late 19th century, with the notable exception of Sweden.

6. Drivers of change in CO_2 emissions

Employing our time series, we conduct a multiplicative decomposition for each country and report the results by sub-period.

The drivers of CO_2 emissions for the period from 1800 to 1870 are shown in Table 2. Global emissions grew 3.6% a year, caused mostly by 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. For the remaining countries, fuel switching effects dominated, which is primarily attributable to the transition from biomass to fossil fuels. The technological factor had a small impact on global CO_2 emissions (0.3% a year), with four countries exhibiting positive trends and five countries showing negative trends.

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 an early transition to coal. They surpassed scale effects in Sweden, Spain, Italy, Portugal and Japan, the lowest emitters and less developed countries. Technology was the most important offsetting factor, but its role in reducing emissions was small compared to the positive biomass effects. The influence of inter-fossil fuel substitution and carbon-free energy penetration was almost negligible, although the effects of carbon-free energy should be interpreted with care, mainly due to the larger efficiency of hydropower relative to thermal sources[7]. Leapfrogging to hydro-power, as Sweden, Italy, Canada and Japan did, precluded coal usage and therefore contributed to lower emissions. Nevertheless, we should be aware that the fuel switching effect represents changes in the emission content of the primary energy sources only, and that the effect of the higher efficiency of hydro-power vis-a-vis thermo-power is incorporated in the technology factor.

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 catch-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 global 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 emission growth. For countries with a large share of biomass, the impact of fuel switching from coal to oil was also significant, but was offset by the biomass to fossil-fuels transition (e.g. Portugal, Spain, Italy and Japan). Interestingly, the country with a higher positive impact from biomass transition, Portugal (+2.4%/year), also exhibits a strong negative impact (-2.7%/year) from energy intensity 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 (e.g. Italy).

Decomposition results for the period 1973-1990 are presented in Table 5. After the oil crisis of 1973-1974, 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 slower economic and population growth, the technology effect drastically rose

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[7] Hydro-power efficiency is considered to be 100%, while thermo-electricity efficiencies were in the 4-6% range before World War I and 12-16% in the 1930s, depending on the countries considered (Henriques, 2009; Schurr and Netschert (1960)).

in importance. Energy intensity falls of about 2.0-2.7% a year occurred in most of the countries, with the exception of latecomers Portugal (-0.2%) and Spain (-1.3%). Combined technological and fuel switching factors offset scale effects and contributed to the decline of emissions in five of the countries (the UK, Germany, Denmark, Sweden and France). The most important fuel switching effect was the expansion of carbon-free technologies, especially 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 biomass effects reversed in some countries, especially in Sweden.[8] Fuel switching had an important role in reducing CO_2 emissions in Sweden, Canada and France. In 1990, 50% and 70%, respectively, of Swedish and French electricity came from nuclear power.

In the last period, 1990-2011, we can observe the evolution of each factor during the time the Kyoto targets were in effect. The Kyoto Protocol 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). In spite of the Kyoto agreement, emissions still increased at a fast rate (0.9%/year) in the period from 1990 to 2005. From that point on CO_2 emissions started to decline, a trend accentuated by the onset of the global recession at the end of that decade. Table 6 shows that most of our studied European countries managed to curb their fossil-fuel CO_2 emissions to the agreed levels by 2011, 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.[9]

The slump in the last years of the 2000 decade was still not enough to reverse the trend from the 1973-1990 period. Changes in the yearly growth rate of total emissions (+0.1%) were of the same magnitude as in the previous period, with an intensification

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[8] 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.

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

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 period 1973-1990. 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. Fuel switching occurred mainly as a result of climate mitigation policies, with inter-fossil fuel substitution emerging as the most important 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 establishment 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. Globally, 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, nuclear power ground to a halt due to safety concerns.[10]

In order to understand the magnitude of change in CO_2 emissions, we also apply an additive decomposition to our time series. The cumulative historical drivers of global emissions are summarized in Figure 7[11]. Until early 20th century, the transition from biomass to fossil fuels was the main driver of changes in fossil 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 World War II, 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. Effects associated with increased carbon free energy usage were small by

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[10] Sweden decided to decommission existing nuclear plants and instituted a freeze on new plants. This decision was reversed in 2010. In Italy, nuclear power was discontinued in 1990. Germany is currently planning to phase out nuclear power by 2022.

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

comparison. From 1800 to 2011, cumulative changes in emissions since 1800 totaled 9.3 Gt. Income is the most important long-run effect (13.8 Gt) followed by population (5.4 Gt) and biomass (1.2 Gt). Cumulative offsetting forces are split between technological change (-9.1 Gt), fossil fuel switching (-1.3 Gt) and carbon free penetration (-0.6Gt).

Figure 8 shows the historical cumulative changes in emissions by country. Income 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 coal path, 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.

7. Conclusions

This article explores the drivers behind long-run CO_2 emissions across countries, by decomposing changes in carbon emissions into energy intensity, population, income and changes in the energy mix. By building on nine European countries, the United States, Canada and Japan, which were responsible for more than three quarters of worldwide CO_2 emissions until 1950 and more than half until the 1980s, we are able to shed light on the drivers of carbon emissions in a global context. Furthermore, by incorporating into our calculations traditional energy carriers and modern renewable energy technologies along with fossil fuels, we provide a more detailed account of the drivers of historical change in CO_2 emissions.

Our findings indicate that, in the long run, scale effects, especially income growth, are the most important drivers of changes in CO_2 emissions and that energy intensity is the main offsetting factor. During the early periods of industrialization, changes in energy intensity may lead to an increase in carbon emissions, especially for countries that followed the coal path, but the effect is typically negative and strengthens significantly at later stages of development. We show that changes in the energy mix (fuel switching) are non-negligible factors as well. At low levels of income per capita, the transition from biomass towards fossil fuels contributes greatly to a rise in CO_2 emissions. At high levels of income per capita, substitution of natural gas for coal and oil, and the expansion of carbon-free sources are also important forces, which, along with declining energy intensities, contribute to a reduction in emissions in some early-industrializers.

Energy baskets have evolved in a somewhat similar fashion in most countries: from biomass through coal to oil, then natural gas and carbon-free energy sources. However, the relative importance of each of the transition stages and their precise timing are strongly dependent on historical endowments and, at later stages of development, on public policy. Partly due to their poor coal endowments, latecomers avoided the high energy and CO_2 intensities of the pioneers and reached equivalent levels of development with much less environmental impact. At the same time, countries with low historical energy and CO_2 intensities and without the nuclear power option have smaller reduction potential at later phases of development. Policymakers need to be aware of this trade-off when they decide on future emission targets and mitigation policies.

Our study suggests that, at early 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 to find ways to build energy systems that simultaneously foster technological change and ensure environmental sustainability.

Mankind's activity has been contributing to the rise in CO_2 concentration on the Earth's atmosphere for more than two centuries. However, energy policy has only recently started to address the long-term environmental impact of CO_2 emissions. In this regard, our results indicate that the combined contribution of changes in energy intensity and fuel switching to the decline in CO_2 emissions was weaker in the more recent period 1990-2011 than in 1973-1990. Nevertheless, Europe fared better in this regard than non-European countries, possibly thanks to stronger political commitment.[12] This supports the view that in order to limit further emissions, a much more comprehensive global energy policy is needed.

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[12] The United States did not ratify the Kyoto Protocol, and Canada and Japan have withdrawn from the second period of commitment.

References

Andres, R.J., D.J. Fielding, G. Marland, T.A. Boden, and N. Kumar (1999), Carbon dioxide emissions from fossil-fuel use, 1751-1950. *Tellus*, 51B, 759-765.

Ang, B.W. and F.Q. Zhang (2000), A survey of index decomposition analysis in energy and environmental studies, *Energy*, 25, 1149-1176.

Ang, B.W. and F.L. Liu (2001), A new energy decomposition method: Perfect in decomposition and consistent in aggregation, *Energy*, 26, 537-547.

Ang, B.W. (2004), Decomposition analysis for policymaking in energy: Which is the preferred method? , *Energy Policy*, 32, 1131-1139.

Ang, B.W. (2005), The LMDI approach to decomposition analysis: A pratical guide, *Energy Policy*, 33, 867-871.

Arto, I.E. and Dietzenbacher, E. (2014), Drivers of the growth in global greenhouse gas emissions, *Environmental Science and Technology*, 48 (10), 5388-5394.

Bartoletto, S. and M.d.M. Rubio (2008), Energy Transition and CO_2 Emissions in Southern Europe: Italy and Spain (1861–2000), *Global Environment*, 2, 47–81.

Boden, T.A., Andres, R.J. and G. Marland (2013), *Global, regional and National Fossil* CO_2 *emissions 1751-2010*. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A. doi 10.3334/CDIAC/00001_V2013

Bolt, J. and J.L. van Zanden (2013), The first update of the Maddison Project re-estimating growth before 1820, *Maddison Project Working Paper*, WP-4.

EDMC - Energy Data and Modelling Center (2009), *EDMC Handbook of Energy & Economic Statistics in Japan*, Tokyo: The Energy Conservation Center

Ehrlich, P.R. and J.P. Holdren (1971), Impact of population growth, *Science*, 171 (3977), 1212-1217.

EIA - United States Energy Information Administration (2010), *Annual Energy Review 2009*.

Etemad, B. and J. Luciani (1991), *World energy production 1800-1985*, Genève: Librairie Droz.

FAO - Food and Agricultural Organization of the United Nations (2014) , FAOSTAT, *Food Balance Sheets*, http://faostat3.fao.org/faostat-gateway/go/to/download/FB/FB/E, last accessed February 2014.

Gales, B., A. Kander, P. Malanima and M. Rubio (2007), North versus South: Energy transition and energy intensity in Europe over 200 years, *European Review of Economic History*, 11(2), 219-253.

Gales, B. (2013), Energy series for France in A. Kander, P. Malanima and P. Warde (2013), *Power to the People. Energy in Europe over the Last Five Centuries*. Princeton: Princeton University Press, www.energyhistory.org, last accessed February 2014.

Gales, B. and P. Warde (2013), Energy series for Germany in A. Kander, P. Malanima and P. Warde (2013) *Power to the People. Energy in Europe over the Last Five Centuries*. Princeton: Princeton University Press, www.energyhistory.org, last accessed February 2014.

Gingrich, S., P. Kuskova and J.K. Steinberger (2011), Long-term changes in CO_2 emissions in Austria and Czechoslovakia — Identifying the drivers of environmental pressures, *Energy Policy*, 39, 535-43.

Grubler, A. and N. Nakicenovic (1996), Decabornizing the global energy system, *Technological Forecasting and Social Change*, 53 (1), 97-110.

Grubler, A. (2004), Transitions in energy use, *Encyclopedia of Energy*, 6, 163-77.

Grubler, A. (2012), Energy transitions research: Insights and cautionary tales, *Energy Policy*, 50, 8-16.

Henriques, S.T. (2009), *Energy Consumption in Portugal 1856-2006*. Naples: Consiglio Nazionalle delle Ricerche.

Henriques, S.T. And A. Kander (2010), The modest environmental relief from a transition to the service economy, *Ecological Economics*, 70 (2), 271-282.

Henriques, S.T. (2011), *Energy Transitions, Economic Growth and Structural Change: Portugal in a Long-run Comparative Perspective*, Lund: Lund University.

Henriques, S.T. and P. Sharp (2014), The Danish Agricultural Revolution in an energy perspective: a case of development with few domestic energy sources, *Working Paper European Historical Society (EHES*), 56.

Houghton, R.A. (2003), Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850-2000, *Tellus*, 55B: 378-390.

IEA – International Energy Agency (2013), Energy Balances of OECD countries, http://data.iea.org.

IPCC – The Intergovernmental Panel of Climate Change (2006), 2006 IPCC Guidelines for National Greenhouse Gas Inventories, prepared by the National Greehouse Gas Inventories Programme, Eggleston, H.S., L. Buendia, K. M., T. Ngara and K. Tanale (eds), IGES: Japan.

IPCC, 2014: Summary for Policymakers, In: Climate Change 2014, Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

Kander, A. (2002), *Economic growth, energy consumption and* CO_2 *emissions in Sweden 1800-2000*,Lund: Lund University.

Kander, A. (2008), Is it simply getting worst? Agriculture and Swedish greenhouse gas emissions over 200 years, *Economic History Review*, 61(4), 773-797.

Kander, A., P. Malanima and P. Warde (2013), *Power to the People. Energy in Europe over the Last Five Centuries*. Princeton: Princeton University Press.

Kaya, Y. (1990), Impact of carbon dioxide emission control on GNP growth: interpretation of proposed scenarios, paper presented at the IPCC Energy and Industry Subgroup, Response Strategies Working Group, Paris, France in: Albretch, J., Francois, D. and Schoors, K. (2002), A Shapley decomposition of carbon emissions without residuals, *Energy Policy*, 30 (9), 727-736.

Kojima, M. and R.Bacon (2009), Changes in CO_2 emissions from energy use: a multi-country decomposition analysis, *Extractive Industries for Development Series 11*, the World Bank.

Krausmann, F., H. Schandl and R.P. Sieferle (2008), Socio-ecological regime transitions in Austria and the United Kingdom, *Ecological Economics*, 65(1), 187–201.

Kuskova, P., S. Gingrich and F. Krausmann (2008), Long term changes in social metabolism and land use in Czechoslovakia, 1830–2000: An energy transition under changing political regimes, *Ecological Economics*, 68(1-2), 394–407.

Lindmark, M. (2002), An EKC-pattern in historical perspective: carbon dioxide emissions, technology, fuel prices and growth in Sweden 1870–1997, *Ecological Economics*, 42, 333–47.

Lindmark, M. (2004), Patterns of historical CO_2 intensity transitions among high and low-income countries, *Explorations in Economic History*, 41, 426–47.

Ma, C. and D.I. Stern (2008), Biomass and China´s carbon emissions: A missing piece of carbon decomposition, *Energy Policy*, 36(7), 2517-26.

Maddison, A. (2010), *Statistics on World Population, GDP and per capita GDP, 1-2008 AD*, www.ggdc.net/maddison, last accessed February 2014.

Malanima, P. (2006), *Energy consumption in Italy in the 19th and 20th Centuries. A statistical outline*. Naples: Consiglio Nazionale delle Ricerche.

Marcotullio, P.J. and N.B. Schulz (2007), Comparison of Energy Transitions in the United States and Developing and Industrializing Economies. *World Development*, 35(10): 1650–83.

Martin, J.M. (1988). L'intensité énergetique de l'activite économique dans les pays industrialisés. Les evolutions de très longue periode livrent-elles desenseignements utiles? *Economies et Sociétés* 4, 9–27.

Metz, B., Davidson, O., Bosh, P., Dave, R. and Meyer, L. (eds.) (2007), Climate Change 2007: Mitigation of Climate Chage. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental

Mitchell, B.R. (1992), *International Historical Statistics: Europe 1750-1988*, New York: Stockton Press.

Mitchell, B.R. (1993), *International Historical Statistics: the Americas: 1750-1988*, New York:Stockton Press.

Mitchell, B.R. (1995), *International Historical Statistics: Africa, Asia and Oceania, 1750-1988,* New York: Stockton Press.

Mulder, P. and Groot, H.L.F. (2011), Energy intensity across sectors and countries: empirical evidence (1980-2005), *CPB Discussion Paper 171*.

Mundaca T., L., A. Markandya and J.Nørgaard (2013). Walking away from a low-carbon economy? Recent and historical trends using a regional decomposition analysis, *Energy Policy*, 61, pp. 1471-1480.

Percebois, J. (1989), *Economie de l´énergie*, Paris: Economica.

Raupach, M.R., G. Marland, P. Ciais, C. Le Quéré, J.G. Canadell, G. Klepper, C.B. Field (2007) Global and regional drivers of accelerating CO2 emissions, *Proceedings of the National Academy of Sciences* 104(24): 10288-10293

Reddy, A.K.N. and J.Goldemberg (1990), Energy for the developing world, *Scientific American*, 263, 63-72.

Rubio, M.d.M. (2005), Economía, Energía y CO_2: España 1850-2000, *Cuadernos Económicos de ICE 70*, vol. 2, 55-71.

Rubio, M.d.M., C. Yánez, M. Folchi and A. Carreras (2010), Energy as an indicator of modernization in Latin America, *Economic History Review*, 63 (3), pp.769-804.

Rubio, M. and M. Folchi (2012), Will small consumers be faster in transition? Evidence from the early shift from coal to oil in Latin America, *Energy Policy,* 50, 50-61.

Schurr, S.H. and C. Netschert (1960), *Energy in the American economy 1850-1975: an economic study of its history and prospects*, Baltimore: The Johns Hopkins Press.

Smil, V. (2010)*, Energy transitions: history, requirements, prospects*, Santa Barbara, Colorado, Oxford: Praeger.

Stern, D.I., F. Jotzo and L. Dobes (2013), The economics of global climate change: A historical literature review, *CCEP Working Paper,* 1307.Crawford School of Public Policy, the Australian National University.

Steward, F.R. (1978), Energy consumption in Canada since confederation, *Energy Policy*, 6 (3), pp. 239-245.

Tol, R.S.J., S.W. Pacala and R.H. Socolow (2009), Understanding long-term energy use and carbon dioxide emissions in the USA, *Journal of Policy Modeling*, 31, 425–4

Warde, P. (2007), *Energy Consumption in England & Wales 1560-2000*, Naples: Consiglio Nazionale delle Richerche.

Warr, B., R. Ayres, N. Eisenmenger, F. Kraussman, H. Schandl (2010), Energy use and economic development: a comparative analysis of useful work supply in Austria, Japan, the United Kingdom and the US during 100 years of economic growth, *Ecological Economics*, 69, 1904-1917.

Tables and Figures

Table 1. GDP per capita and Population

	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

Source: Our calculations from Maddison (2010), Bolt and van Zanden (2013) and sources listed in Supplementary Material (S1).

Table 2. Drivers of CO_2 emissions, yearly growth rates (%), 1800-1870

	1800					Scale		FSW		
	tCO_2 pc	EMISS	Scale	TECH	FSW	INC	POP	FOS	BIO	CARFREE
UK	4	2.8	2.4	0.1	0.4	1.2	1.2	0.0	0.3	0.0
Netherlands	0.8	2.4	1.3	0.1	0.9	0.6	0.8	0.0	0.8	0.2
Denmark	0.7	2.1	1.7	-0.8	1.3	0.6	1.0	0.0	1.3	0.0
France	0.1	4.7	1.2	-0.2	3.7	0.7	0.4	0.0	3.7	0.0
Germany	0.03	6.5	1.6	0.3	4.6	0.8	0.7	0.0	4.6	0.0
Portugal	0.01									
Sweden	0.01	5.8	1.5	-1.0	5.3	0.6	0.8	0.0	5.3	0.0
Spain	0.003									
Italy	*0.002**									
Europe	0.46	3.3	1.5	0.1	1.7	0.8	0.7	0.0	1.7	0.0
US	0.06	8.4	3.8	-0.8	5.3	0.9	2.9	0.0	5.3	0.0
Canada	*0.04**									
Japan	*0.01**									
Global	0.36	3.6	1.7	0.3	1.7	0.8	0.9	0.0	1.6	0.0

Note: Emissions for Italy, Canada and Japan are estimated.

Table 3. Drivers of CO_2 emissions, yearly growth rates (%), 1870-1938

	1870					Scale		FSW		
	tCO2 pc	EMISS	Scale	TECH	FSW	INC	POP	FOS	BIO	CARFREE
UK	11.8	1.0	1.7	-0.7	0.0	0.8	0.9	0.0	0.0	0.0
Netherlands	2.2	2.5	2.3	-0.2	0.4	1.0	1.3	-0.1	0.4	0.1
Germany	2.0	3.0	2.3	0.1	0.6	1.5	0.8	0.0	0.6	0.0
Denmark	1.5	2.7	2.6	-0.5	0.6	1.6	1.0	-0.1	0.6	0.1
France	1.4	2.1	1.4	0.0	0.6	1.2	0.2	0.0	0.7	0.0
Sweden	0.3	4.5	2.5	-0.9	2.9	1.9	0.6	-0.1	2.9	0.0
Spain	0.2	3.2	1.2	-0.2	2.2	0.6	0.7	0.0	2.2	0.0
Italy	0.1	3.9	1.8	-0.6	2.7	1.1	0.7	0.0	2.8	-0.1
Portugal	0.1	3.1	1.6	-0.5	2.0	0.8	0.8	-0.1	2.1	0.0
Europe	2.8	1.9	1.8	-0.3	0.4	1.2	0.7	0.0	0.4	0.0
US	2.6	4.0	3.1	-0.8	1.8	1.4	1.7	-0.2	2.0	0.0
Canada	0.6	5.4	3.1	-0.6	2.9	1.5	1.6	-0.1	3.1	-0.1
Japan	0.03	7.5	2.8	0.2	4.4	1.8	1.1	-0.1	4.5	-0.1
Global	2.3	2.8	2.3	-0.3	0.8	1.3	1.0	-0.1	0.9	0.0

Table 4. Drivers of CO2 emissions, yearly growth rates (%), 1950-1973

	1950					Scale		FSW		
	tCO2 pc	EMISS	Scale	TECH	FSW	INC	POP	FOS	BIO	CARFREE
UK	14	0.8	2.7	-1.3	-0.7	2.2	0.5	-0.6	0.0	-0.1
Germany	7.7	3.1	5.5	-2.0	-0.5	4.9	0.6	-0.6	0.2	0.0
Denmark	5.6	3.8	3.7	0.3	-0.3	3.0	0.7	-0.7	0.4	0.0
Netherlands	5.1	4.6	4.6	1.1	-1.1	3.4	1.2	-1.4	0.3	0.0
France	4.9	3.7	4.9	-0.9	-0.3	4.0	1.0	-0.7	0.5	0.0
Sweden	4.5	4.3	3.7	0.7	0.0	3.0	0.6	-0.6	0.9	-0.3
Spain	1.4	5.6	6.4	-1.4	0.6	5.4	1.0	-0.8	1.5	-0.1
Italy	1.0	8.5	5.3	1.3	1.9	4.7	0.6	-0.7	2.4	0.2
Portugal	0.6	5.1	5.4	-2.7	2.4	5.2	0.2	-0.5	3.1	-0.3
Europe	6.1	3.0	4.6	-1.2	-0.5	3.9	0.7	-0.7	0.3	0.0
US	17.2	2.5	3.9	-1.1	-0.2	2.4	1.4	-0.4	0.2	0.0
Canada	11.5	3.6	4.9	-0.5	-0.8	2.8	2.1	-0.8	0.2	-0.1
Japan	1.3	9.2	8.9	-0.5	0.9	7.8	1.1	-0.8	1.4	0.2
Global	8.7	3.1	4.7	-1.3	-0.3	3.6	1.0	-0.5	0.2	0.0

Table 5. Drivers of CO$_2$ emissions, yearly growth rates (%), 1973-1990

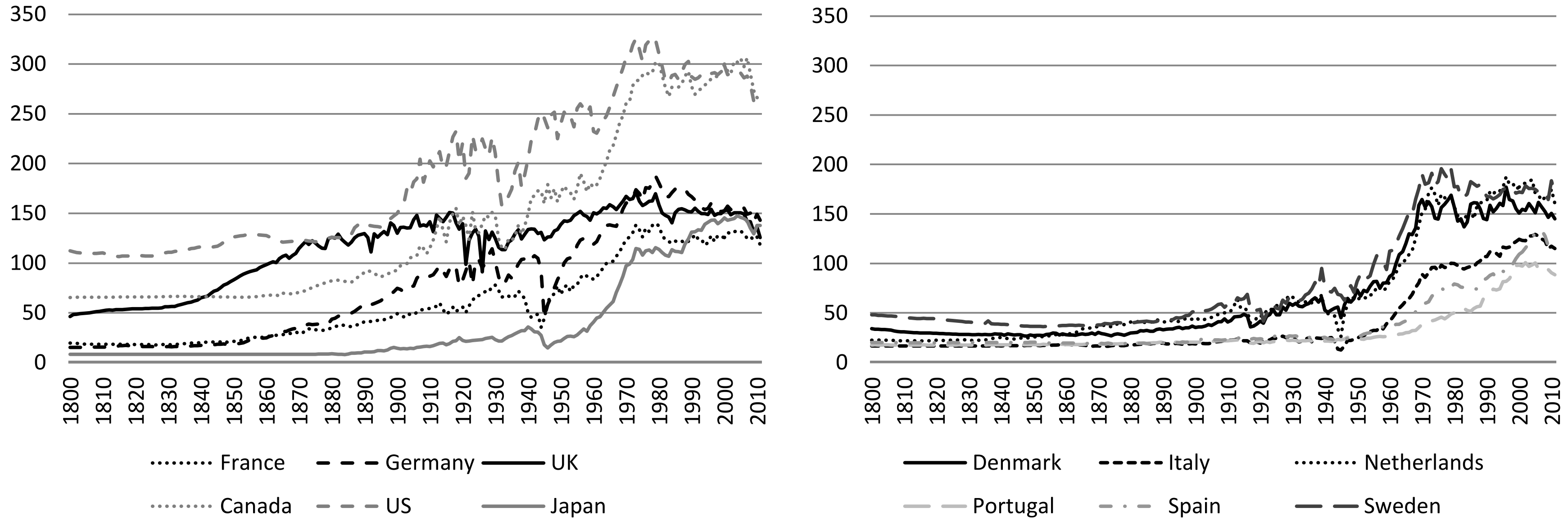
	1973					Scale		FSW		
	tCO2 pc	EMISS	Scale	TECH	FSW	INC	POP	FOS	BIO	CARFREE
UK	14	-1.0	2	-2.6	-0.2	1.9	0.1	-0.2	0.0	-0.1
Germany	13	-0.6	1.7	-1.9	-0.4	1.7	0.0	-0.1	-0.1	-0.2
Denmark	11	-0.6	1.8	-2.2	-0.3	1.6	0.1	0.3	-0.3	-0.2
Netherlands	11	0.1	2.3	-2.1	0.0	1.6	0.6	0.2	-0.1	-0.1
Sweden	10	-3.0	1.9	-2.3	-2.6	1.6	0.3	0.2	-1.1	-1.6
France	9	-1.5	2.4	-2.6	-1.4	1.9	0.5	-0.2	-0.2	-0.9
Italy	6	0.9	2.8	-1.8	-0.1	2.4	0.4	-0.2	0.1	-0.1
Spain	4	2.1	3.4	-1.3	0.0	2.7	0.7	0.1	0.1	-0.2
Portugal	2	4.8	3.6	-0.2	1.4	3.0	0.6	0.2	1.1	0.1
Europe	10	-0.4	2.3	-2.2	-0.5	2.0	0.3	-0.1	-0.1	-0.3
US	18	0.2	2.9	-2.7	-0.1	1.9	1.0	0.2	-0.1	-0.2
Canada	16	0.7	3.1	-1.9	-0.4	1.8	1.2	0.0	0.0	-0.4
Japan	8	1.1	3.7	-2.1	-0.4	2.9	0.8	-0.1	0.0	-0.3
Global	13	0.1	2.8	-2.4	-0.3	2.1	0.6	0.1	-0.1	-0.2

Table 6. Drivers of CO_2 emissions, yearly growth rates (%), 1990-2011

						Scale		FSW				
	1990 tCO2 pc	EMISS	Scale	TECH	FSW	INC	POP	FOS	BIO	CARFREE	Change (%) 90-11	Kyoto Target (%)
UK	12	-1.5	1.9	-2.5	-0.4	1.6	0.3	-0.5	-0.2	-0.1	-26	-13
Germany	12	-1.4	1.5	-2.1	-0.8	1.4	0.2	-0.3	-0.5	-0.1	-26	-21
Netherlands	10	0.2	2.2	-1.6	-0.4	1.6	0.6	-0.1	-0.2	-0.1	3	-6
Denmark	10	-1.1	1.5	-1.1	-1.5	1.2	0.4	-0.4	-0.8	-0.3	-20	-21
Italy	7	-0.1	0.9	-0.5	-0.5	0.8	0.1	-0.2	-0.2	-0.1	-2	-6.5
France	6	-0.4	1.6	-1.3	-0.6	1.1	0.4	-0.2	-0.2	-0.3	-8	0
Sweden	6	-0.2	2	-1.6	-0.6	1.7	0.3	-0.1	-0.9	0.4	-4	4
Spain	5	1.1	2.3	-0.6	-0.6	2.0	0.3	-0.4	0.0	-0.1	26	15
Portugal	4	1.1	1.6	0.1	-0.6	1.2	0.4	-0.4	0.1	-0.2	27	27
Europe	9	-0.7	1.6	-1.6	-0.8	1.3	0.3	-0.3	-0.3	-0.1		
US	17	0.4	2.4	-1.8	-0.2	1.3	1.1	-0.1	-0.1	-0.1	9	(-7)*
Canada	15	0.4	2.4	-1.6	-0.3	1.4	1	-0.2	-0.1	0.0	14	-6
Japan	9	0.4	0.9	-0.5	0.0	0.7	0.1	-0.1	0.0	0.1	9	-6
Global	12	0.1	1.9	-1.4	-0.3	1.3	0.6	-0.2	-0.1	-0.1		

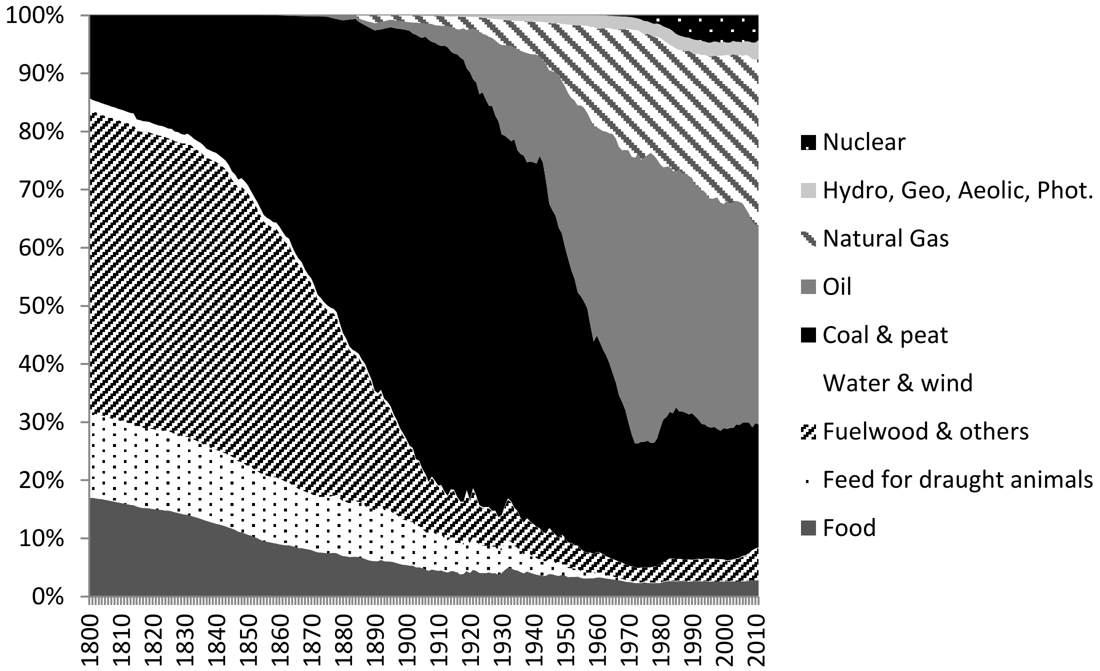
*The United States did not ratify the Kyoto protocol

Figure 1. Energy per capita, 1800-2011 (GJ)



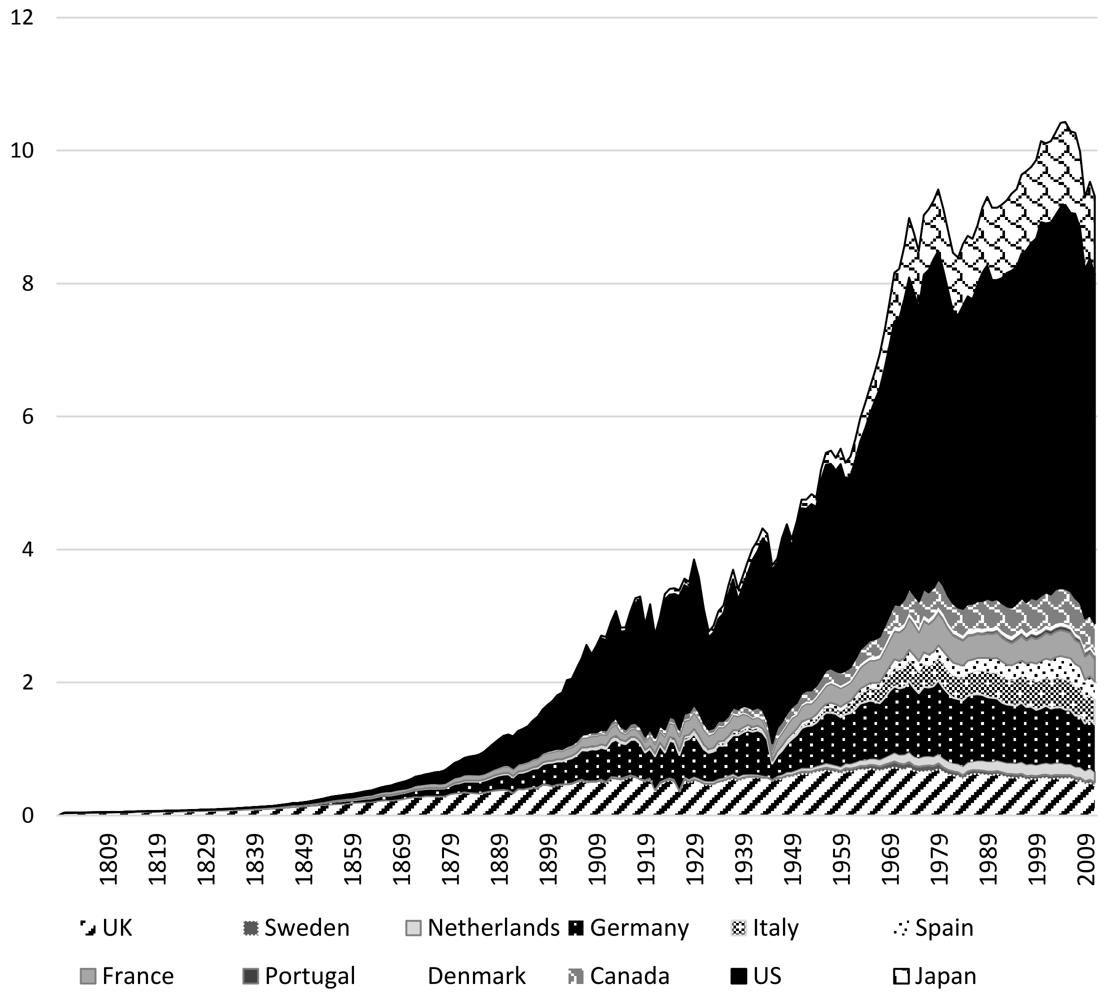
Source: See text and Supplementary Material (S1).

Figure 2. Energy transition (%)



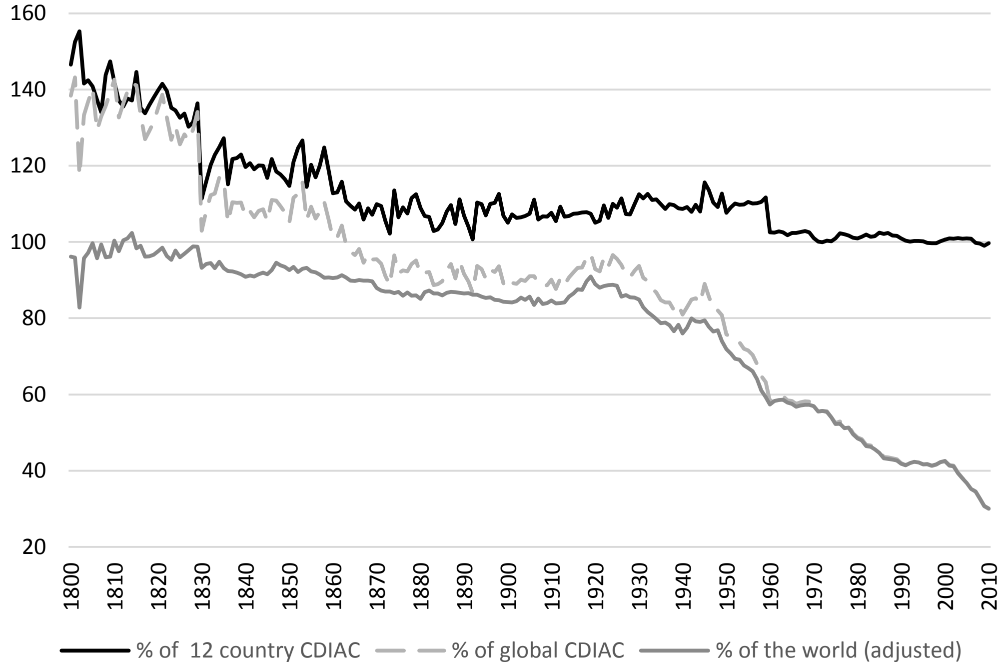
Source: See text and Supplementary Material (S1). Note: Water & wind corresponds to direct uses. Hydro, Geo, Aeolian and Photovoltaic corresponds to renewable energy used for electricity production.

Figure 3. Total CO_2 emissions (Gt)



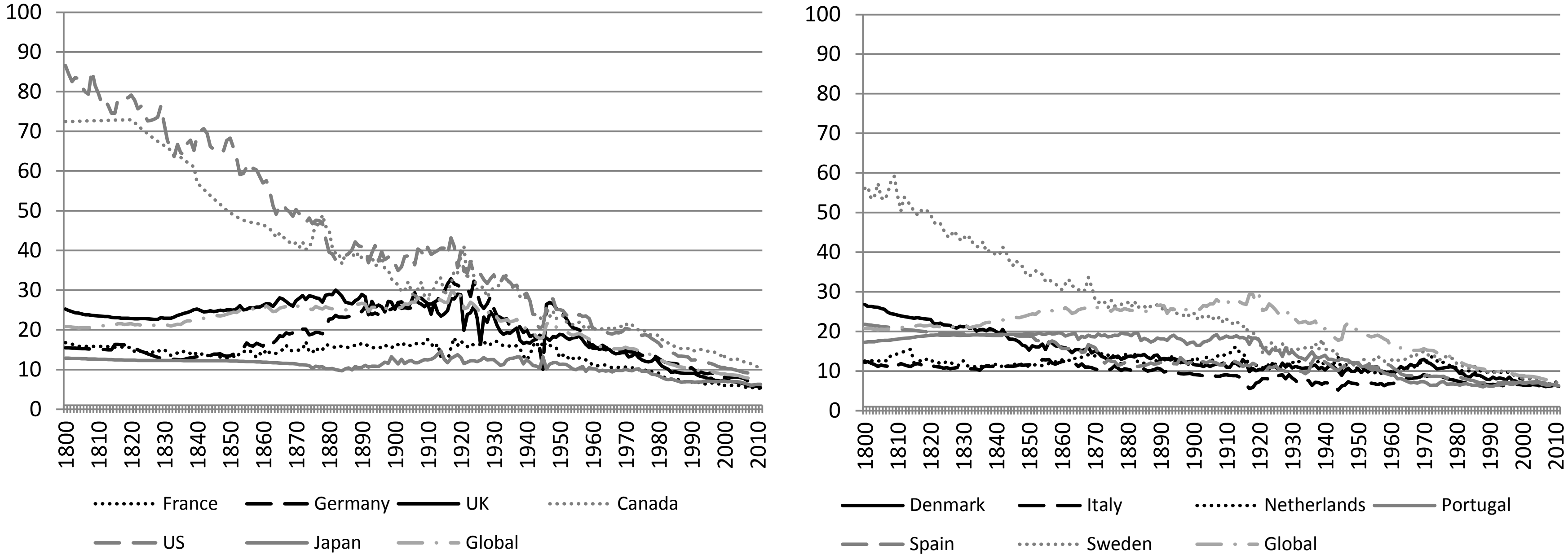
Source: See text and Supplementary Material (S1).

Figure 4. Comparison with CDIAC indicators (%)



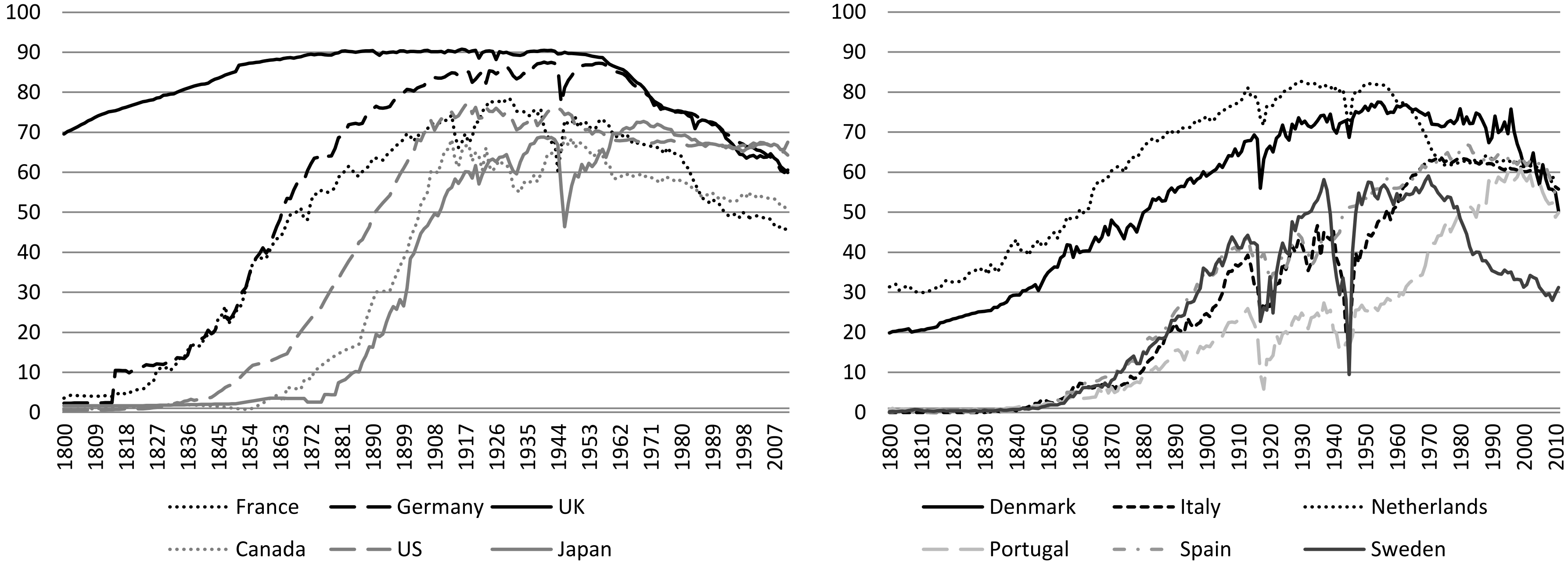
Source: Own calculations from Boden et al. (2013) and sources listed in Supplementary Material (S1).

Figure 5. Total energy intensity (MJ/1990 USD)



Source: See text and Supplementary Material (S1).

Figure 6. CO_2 intensity of all forms of energy (kg CO_2/GJ)



Sources: See text and Supplementary Material (S1).

Figure 7. Cumulative time-series decomposition of the changes in CO_2 emissions, 1800-2011, Gt

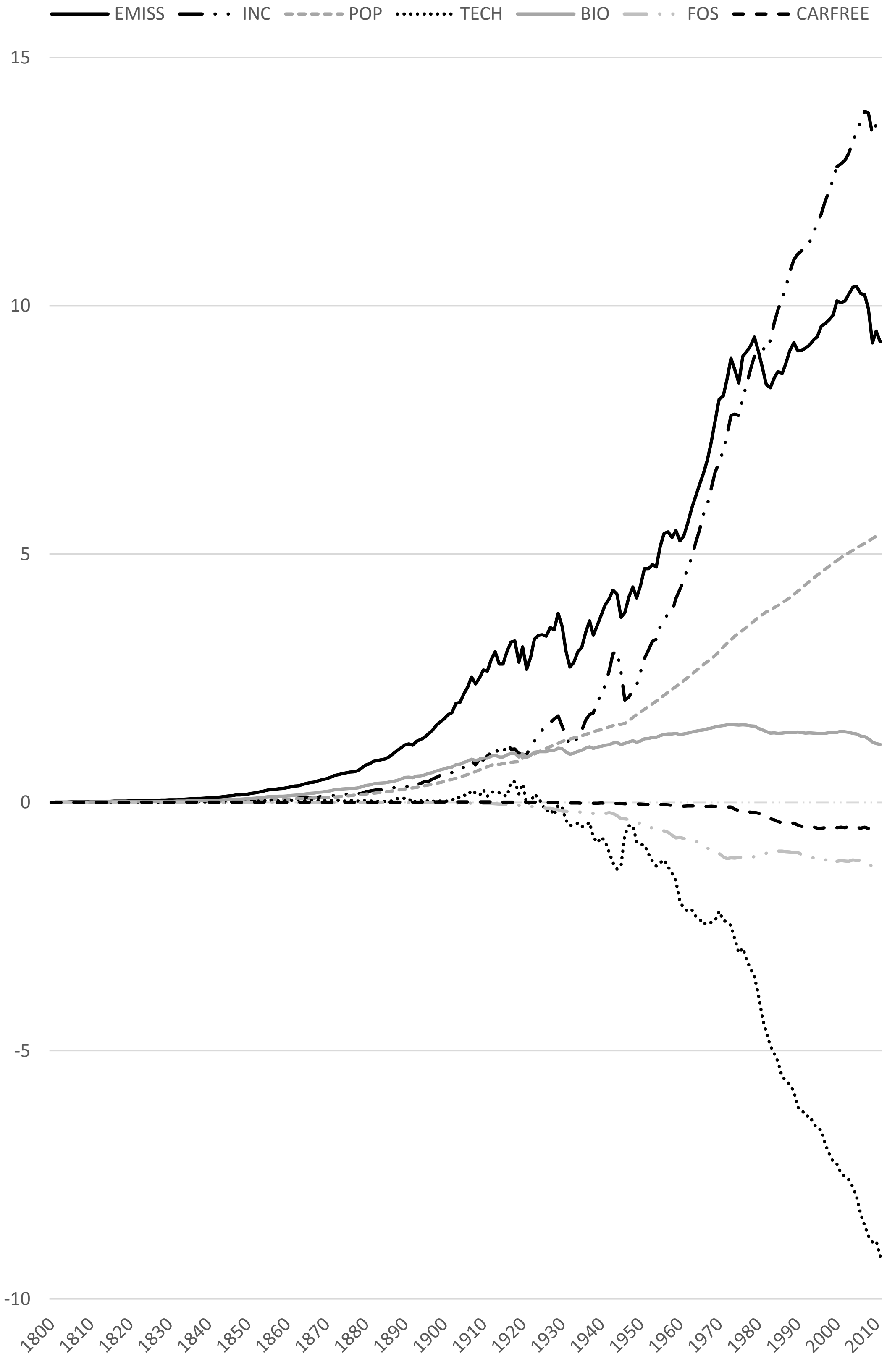
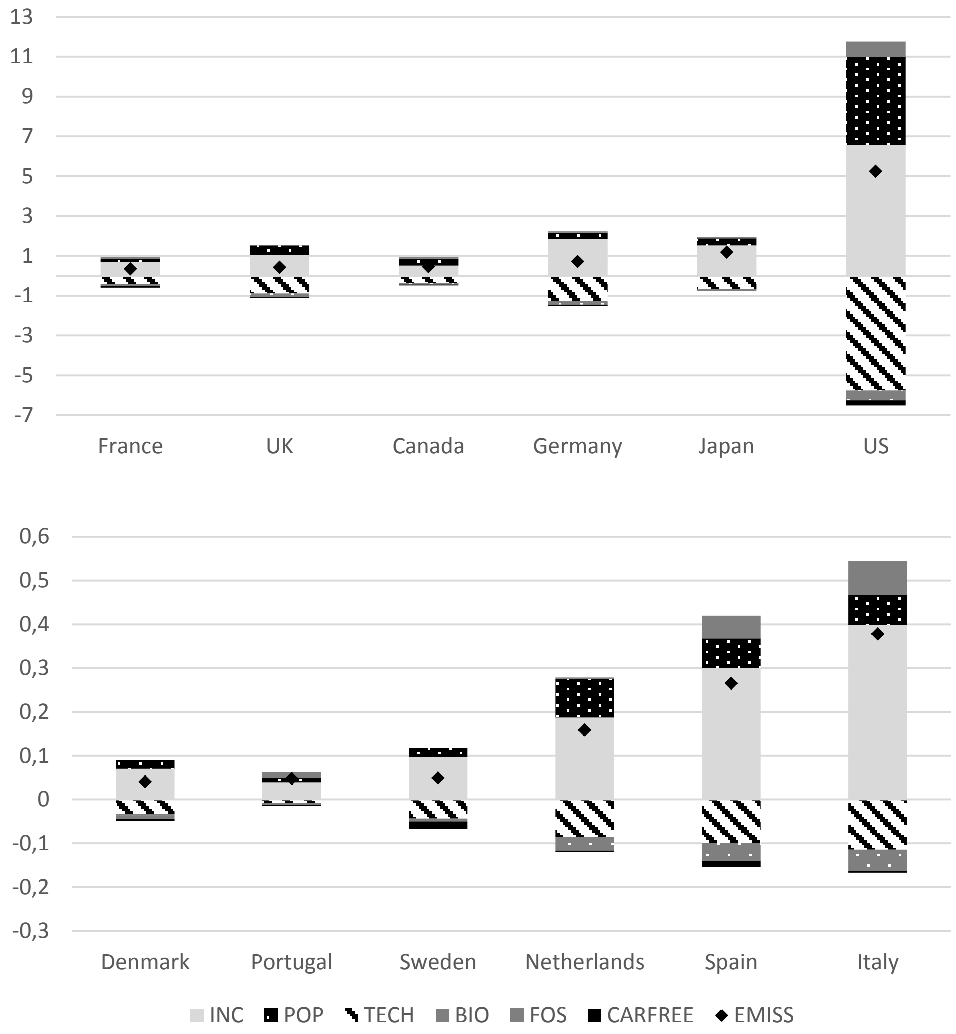


Figure 8. Long-run time-series decomposition by country, Gt



Online Supplementary Material

S1. Detailed data sources

This section presents the detailed sources for the primary energy data included in the paper. The energy carriers included in the series are: coal & peat; oil, natural gas, primary electricity, muscle energy (feed for working animals and food for humans), firewood and direct uses of water and wind, solar and geothermal heat. The reader interested in the methodological details is referred to our article and the works of Kander (2002), Kander et al. (2013), Henriques (2011), Malanima (2006) and Warde (2007).

Canada

Primary energy : 1800-1870 **-** Coal consumption in the period 1827-1870 was calculated using data from Mitchell (2007c), Urquarth and Buckley (1965), HCPP (1866); Taylor (1848); GB, *Tables of Revenue* (several years); and GB, *Annual Statement of Trade and Navigation…* (several years). Missing coal consumption data in 1800-1826 were extrapolated to mirror US consumption during the same period. For traditional energy carriers (food, firewood, wind and water), we assume a constant per capita consumption equal to 1871. Feed consumption for working animals was calculated for the period 1851-1870 from Mitchell (2007c). Before that we assume a constant per capita consumption equal to 1851. 1871-1959 **-** The main source is Stewart (1978). The following adjustments and additions were made: based on statistics on Canadian vessels by Mitchell (2007c), windpower from sailing ships was recalculated using the method proposed by Lindmark (2007) – this method assumes a power of 0.6 KW per vessel/ton and 3650 hours working time a year; international coal trade for the period 1871-1880 is missing form Stewart's original figures, so the sources listed for the period 1800-1870 were used to calculate coal consumption in this period; food consumption was backcasted from post-1961 data, assuming a constant per capita consumption equal to 1961; feed for horses and working oxen was calculated from Mitchell (2007c) and Statistics Canada (2014) assuming a feed requirement equal to the US. 1960-2011 **-** Data on fossil fuels, primary electricity and firewood are from IEA (2013); food consumption is from FAO (2014). **Population and GDP:** Data for 1820-2008 are from Maddison (2010), extended to 2011 using IEA (2013) trends. GDP per capita for the years 1800-1819 was assumed to have the same value as in 1820.

Denmark

Primary energy: 1800-1959 **-** Henriques and Sharp (2014). 1960-2011 **-** Feed is from Henriques and Sharp (2014); Food consumption is from FAO (2014); Remaining energy sources are from IEA (2013). **Population and GDP:** Data for 1820-2008 are from Maddison (2010), extended to 2011 using EUROSTAT (2014) and IEA (2013) trends. Population data for the period 1800-1819 are from Statistics Denmark (2014). GDP per capita for the years 1800-1819 was assumed to have the same value as in 1820.

France

Primary energy: 1800-1959 **-** The main source is Gales (2013). Our additions: Wind energy from sailing ships was calculated from the tonnage of sailing ships (1838-1949) in Mitchell (2007b), using Lindmark's method (2007). We calculated primary energy from water using water-power estimates derived from the information in Carreras (1983) for 1845 and in Huber (1932) for 1861-1926. These were converted to primary energy equivalents assuming a usage of 3000 hours per year and an efficiency of 70% in 1845 and 85% in 1906[13]. 1960-2011 **-** Food consumption is from FAO (2014). Feed consumption is from Gales (2013). Remaining energy sources are from IEA (2013). **Population and GDP:** Until 2008, population is from Gales (2013) extended to 2011 using the trends from Eurostat (2014).GDP for 1820-2008 is from Maddison (2010), extended to 2011 using IEA (2013) trends. GDP per capita for the years 1800-1819 was assumed to have the same value as in 1820.

Germany

Primary energy: 1800-1959 **-** Gales and Warde (2013). 1960-2011 **–** Food consumption is from FAO (2014); feed consumption is from Gales and Warde (2013) and the remaining energy sources are from IEA (2013). **Population and GDP:** Population until 2008 is from Gales and Warde (2013) extended to 2011 using EUROSTAT (2014) trends. GDP is from Maddison (2010) and Pfister (2011), compiled in Bolt and van Zanden (2013), extended to 2011 using IEA (2013) trends.

Italy

Primary energy: 1800-1860 **-** Coal consumption for 1831-1860 was backcasted from the 1861 value in Malanima (2006) using an index of coal imports from Britain to the Italian states from 1831-1860. We assume a constant per capita consumption of coal for the period 1800-1830, equal to 1831.For traditional energy carriers, we assume a constant per capita consumption equal to 1861. 1861-1959 **-** Malanima (2006). 1960-2011 **-** Feed is from Malanima (2006). Food is from FAO (2014). **Population and GDP:** GDP is from Malanima (2011) and Bafigi (2011), compiled in Bolt and van Zanden (2013), extended to 2011 using IEA (2013) trends. Population is from Malanima (2006), extended to 2011 using Eurostat (2014) trends.

Japan

Primary energy: 1800-1880 – Coal consumption in 1820 is assumed to be equivalent to the coal production indicated in Totman (2014). Coal consumption between 1859 and 1879 is from Sugiyama (2012). We assume a constant per capita consumption of coal for the period 1800-1819, equal to 1820. For traditional energy carriers we assume a constant per capita consumption equal to 1880. Oil consumption for 1874-1880 is taken from MIC (2008). 1880-1959 **-** Firewood, fossil fuels and primary electricity are from EDMC (2009). Food consumption is taken from Mosk (1978) and MIC (2008). Feed for working animals was calculated from cattle and horse numbers in Mitchell (2007a). These numbers were reduced by 15% and 20% to exclude young animals. We assumed that all cattle (cows and oxen) worked until 1923. After 1923, working cattle was assumed to increase at the same rate as horses. We considered the following feed intake: 23 MJ per year for cattle and 28 MJ per year for horses. We calculated primary energy from water using water-power estimates derived from the information in Minami (1977) and Minami (1982) for 1880-1930. Industrial water-power was converted to primary energy equivalents assuming 3000 useful hours per year and an efficiency of 70% in 1880 and 85% in 1930. Water-use in rice-mills was calculated considering the quantity of grinded rice. 1960-2011 **-** Food is from FAO (2014). Feed is calculated from Mitchell (2007a). Remaining energy sources are from IEA (2013). **Population and GDP:** We use 1800-1819 data

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[13] Primary Energy from Water/Wind = Power x Hours x 1/efficiency

from Bassino et al. (2011), compiled in Bolt and van Zanden (2013). For the period 1820-2008 we use Maddison (2010), extended until 2011 using IEA (2013) trends.

Netherlands

Primary energy: 1800-1959 **-** Peat and firewood data were obtained directly from Ben Gales (unpublished). Remaining energy sources are from Gales et al. (2007). 1960-2011 **-** Feed is from Gales et al. (2007). Food is from FAO (2014). The remaining energy sources are from IEA (2013). **Population and GDP**: Population and GDP are from Gales et al. (2007), extended to 2011 using Eurostat (2014) and IEA (2013) trends.

Portugal

Primary energy: 1800-1856 **-** Coal consumption was calculated using data in Madureira (1997); GB -*Tables of Revenue*, and Guedes (2000). For traditional energy carriers, we assume a constant per capita consumption equal to 1856. 1856-1959 **-** Henriques (2009). 1960-2011 **-** Feed is from Henriques (2009); Food is from FAO (2009). Firewood and primary electricity is from Henriques (2009). Remaining energy sources are from IEA (2013). **Population and GDP:** For the period 1856-2006 population data are from Henriques (2009), extended to 1800 with the data in Leite (2005) and to 2011 with Eurostat (2014) trends. For the period 1800-1850 GDP data come from Reis et al. (2011), compiled in Bolt and van Zanden (2013). For the period 1850-1990, GDP comes from Henriques (2009), who draws from Lains (2003) GDP historical reconstructions. From 1990-2008 we use Maddison (2010), extended to 2011 using IEA (2013) trends.

Spain

Primary energy: 1800-1849 **-** Coal consumption comes from Coll and Sudrià (1987) and Carreras and Tafunell (2005). Water-power for 1840 is found in Nadal (2003). Series were backcasted until 1800 assuming the same per capita consumption as in 1850 for feed, food and firewood and wind; and as in 1840 for water. 1850-1959 - The main source is Rubio (2005). Firewood is from Gales et al. (2007). Based on statistics on Spanish vessels by Mitchell (2007b), windpower from sailing ships was recalculated using Lindmark's (2007) method. 1960-2011 **-** Food consumption comes from FAO (2014). Feed comes from Rubio (2005). Coal consumption between 1960 and 1990 is from Rubio (2005), extended until 2011 with IEA (2013). Firewood from 1963 to 1990 was estimated by Henriques (2011) with information from Odyssee (2011), extended until 2011 with IEA (2013). Remaining energy sources are from IEA (2013). **Population and GDP:** Alvarez-Nogal and Prados (2013), compiled in Bolt and van Zanden (2013) for 1800-1849 and Maddison (2010) for the later period. Data are extended until 2011 using EUROSTAT (2014) and IEA (2013) trends.

Sweden

Primary energy: 1800-1959 **-** The main source is Kander (2002). Our additions to the original data: water-power was calculated based on text information in Kander (2002) for the period 1830-1896 and industrial water-power statistics for the years 1900, 1913 and 1917 (BISOS, 1902; SOS, 1915; SOS; 1919). Wind-power from sailing ships (1820-1934) is calculated using information in Mitchell (2007b) and applying Lindmark´s method (2007). Water and Wind series were backcasted from 1830 and 1820 to 1800 assuming a constant per capita consumption. 1960-2011**:** Food consumption is from FAO (2014). Feed is from Kander (2002).

Remaining energy sources are from IEA (2014). **Population and GDP**: Data for the period 1800-1949 is from Schön and Krantz (2012) and for 1950-2010 is from TED the Conference Board, compiled in Bolt and van Zanden (2013). Population data was extended to 2011 using Eurostat (2014) trends. GDP data was extended to 2011 using IEA (2013) trends.

United States

Primary energy: 1800-2011 **-** Firewood consumption figures are taken from the following sources: 1800-1849 are from EIA (2010); 1850-1948 are from Schurr (1960); 1949-1959 are from EIA (2010) and 1960-2011 are from IEA (2013). Coal consumption is reconstructed from the following sources: from 1800 to 1849 we used coal production from Carter et al. (2006) and international trade from Schumpeter (1960), HCPP (1866) and Taylor (1848). From 1850 to 1949 we used Schurr and Netschert (1960) data and from 1960 to 2011 we used the data from IEA (2013). For Oil, Natural Gas and Primary electricity we used 1850-1948 data from Schurr and Netschert (1960), 1949-1959 data from AEI (2009) and 1960-2011 data from IEA (2013). We calculated primary energy from water using water-power estimates derived from the information in Schurr and Netshert (1960) for 1840 and 1860 and from Daugherty (1933) for the period 1869 to 1929. These were converted into primary energy equivalents assuming 3000 useful hours per year and an efficiency of 70% in 1840 and 85% in 1929. Power of farm windmills in Hurst & Church (1933) was converted into primary wind energy assuming a use of 1000 hours a year and an efficiency of 10-15%. Based on statistics on the tonnage of American vessels for the period 1800-1970 (Carter et al., 2006), we have followed Lindmark's (2007) method to calculate wind energy from vessels. We calculated feed from working animals using Hurst & Church (1933), and Daugherty (1933) for the 1850 to 1930 period and Carter et al. (2006) for the later period. Animal feed intake was modeled using the feed requirements suggested for England & Wales in Kander and Warde (2011). We calculated food consumption from the food balances (1909-2011) in Carter et al. (2006) and FAO (2014). Due to missing information, we backcasted food (1800-1908), feed (1800-1849) and water (1800-1840) assuming a per capita consumption equal to the first available year. **Population and GDP:** Population is from Maddison (2010). GDP per capita 1800-2010 from Sutch (2006), compiled in Bolt and van Zanden (2013). Data is extended to 2011 using IEA (2013) trends.

United Kingdom

Primary energy: 1800-1959 **-** The main source are figure from Warde (2007) for England and Wales. We converted them into UK equivalents using the population method provided by the author. Exception is made for coal as the series that Warde uses is for Great Britain. 1960-2011 **-** Feed is from Warde (2007). Food consumption is from FAO (2014). Coal consumption series is from Warde (2007), which in turn is a long-run series from the Department of Energy & Climate Change (2013). It is used until 2008 to avoid a break in the series. Remaining energy sources are from IEA (2014). **Population and GDP:** GDP and population data are from Warde (2007), converted into UK equivalents. All data is extended until 2011 using Eurostat (2014) and IEA (2013) trends.

References for Data Sources

Álvarez-Nogal, C. and L. Prados de la Escosura (2011). "The Rise and Fall of Spain (1270-1850)," CEPR Discussion Papers 8369, C.E.P.R. Discussion Papers.

Bassino, J.P., S. Broadberry, K. Fukao, B. Gupta and M. Takashima (2011). "Japan and the Great Divergence, 730-1870", working paper.

Baffigi, A. (2011), Italian National Accounts, 1861-2011, Banca d'Italia Economic History Working Papers 18.

BISOS – Bidrag till Sveriges Officiela Statistik (1902), D) Fabriker och Handtverk, Kommerskollegi I underdåniga berättelse for år 1900, Stockholm: Ivar Haegaströms Bogtryckeri.

Bolt, J. and J.L. van Zanden (2013), The First Update of the Maddison Project Re-estimating Growth before 1820, *Maddison Project Working Paper*, WP-4.

Carreras, A. (1983), El aprovechamiento de la energía hidráulica en Cataluña. 1840-1920: un ensayo de interpretacion, *Revista de Histórica Económica*,**1** (2), 31-63.

Carreras, A. and Tafunnel, X. (2005), *Estadisticas Históricas de España: siglos XIX-XX*, volume 1.

Coll, S. And C. Sudrià (1987), *El carbón en España, 1770-1961, una história económica*, Madrid: Turner.

Carter, S. B., A.L. Olmstead, R., Sutch, G. Wright, S.S. Gartner and M. R. Hains (2006), The Historical Statistics of the United States, vol.4, Part D: Economic Sectors, Millennial Edition, New York: Cambridge University Press.

Daugherty, C.R. (1933), Horsepower equipment in the United States, *The American Economic Review*, 23 (3), 428-440.

Department of Energy & Climate Change (2013), Coal Statistics, Historical Coal Data: Coal Production, Availability and Consumption, https://www.gov.uk/government/statistical-data-sets/historical-coal-data-coal-production-availability-and-consumption-1853-to-2011.

EDMC - Energy Data and Modelling Center (2009), *EDMC Handbook of Energy & Economic Statistics in Japan*, Tokyo: The Energy Conservation Center.

EIA - United States Energy Information Administration (2010), *Annual Energy Review 2009*.

Eurostat (2014), Statistics Database: Total Population http://epp.eurostat.ec.europa.eu/portal/page/portal/eurostat/home/.

FAO - Food and Agricultural Organization of the United Nations (2014) , FAOSTAT, *Food Balance Sheets*, http://faostat3.fao.org/faostat-gateway/go/to/download/FB/FB/E, last accessed February 2014.

Gales, B., A. Kander, P. Malanima and M. Rubio (2007), North versus South: Energy transition and energy intensity in Europe over 200 years, *European Review of Economic History*, 11(2), 219-253.

Gales, B. (2013), Original energy series: France in A. Kander, P. Malanima and P. Warde (2013), *Power to the People. Energy in Europe over the Last Five Centuries*. Princeton: Princeton University Press, www.energyhistory.org.

Gales , B. and P. Warde (2013), Original energy series : Germany in A. Kander, P. Malanima and P. Warde (2013) *Power to the People. Energy in Europe over the Last Five Centuries*, Princeton: Princeton University Press, www.energyhistory.org.

GB – Great Britain, *Annual Statement of the Trade of the United Kingdom with Foreign Countries and British Possessions*, London, several years.

GB –Great Britain, *Tables of Revenue, Population, Commerce of the United Kingdom and its dependences*, London, several years.

Guedes, J.M. (2000), *Minas e Mineiros em S. Pedro da Cova*, Lisboa:*Universidade Nova de Lisboa*.

HCPP – House of Commons Parliamentary Papers (1866), Reports received from her Majesty´s secretaries of embassy and legation respecting coal with an Appendix, presented to both Houses of Parliament by Command of Her Majesty.

Henriques, S. T. (2009), *Energy consumption in Portugal 1856-2006*, Naples: Consiglio Nazionale delle Ricerche.

Henriques, S. T. (2011), *Energy Transitions, Economic Growth and Structural Change: Portugal in a Long-run Comparative Perspective*, Lund: Lund University.

Henriques, S.T. and P. Sharp (2014), The Danish Agricultural Revolution in an energy perspective: a case of development with few domestic energy sources, *working paper European Historical Society (EHES)*, 56.

Huber, M. (1932), M., La statistique des forces motrices, *Journal de la société statistique de Paris*, tome 73 (1932), 397-422.

Hunter, L. C. (1979), *Waterpower in the Century of The Steam Engine (A History of Industrial Power in the United States 1780-1830),* University Press of Virginia.

Hurst, W.M. and L.M. Church (1933), Power and Machinery in Agriculture, *United States Department of Agriculture, Miscellaneous Publication*, 157.

IEA – International Energy Agency (2013), *Energy Balances of OECD Countries*, http://data.iea.org.

Kander, A. (2002), Economic growth, energy consumption and CO_2 emissions in Sweden 1800-2000, Lund: Lund University.

Kander, A. and P. Warde (2011). 'Energy availability from livestock and agricultural productivity in Europe, 1815–1913: a new comparison'. *Economic History Review* 64:1, pp. 1-29.

Kander, A., P. Malanima and P. Warde (2013), *Power to the People. Energy in Europe over the Last Five Centuries*. Princeton: Princeton University Press.

Lains, P. (2003), *Os progressos do atraso: uma nova história económica de Portugal 1842-1992*, Lisboa: Imprensa das Ciências Sociais.

Leite, J.C. (2005), População e crescimento económico, in: P. Lains and A.F.d. Silva (2005), *História Económica de Portugal 1700-2000: o século XIX, vol.II,* Lisboa: Imprensa das Ciências Socias.

Lindmark, M. (2007), *Estimating Norwegian Energy Consumption 1830-2000,* paper presented at the 26th Nordic History Congress, Reykjavik, 8-12 August 2007.

Maddison, A. (2010), *Statistics on World Population, GDP and per capita GDP, 1-2008 AD*, www.ggdc.net/maddison.

Malanima, P. (2006), *Energy consumption in Italy in the 19th and 20th Centuries. A statistical outline*. Naples: Consiglio Nazionale delle Ricerche.

Madureira, N.L. (1997), *Mercado e privilégios: A Indústria Portuguesa entre 1750 e 1834*, Lisboa: Editorial Estampa.

MIC - Ministry of Internal Affairs and Communications, Statistics Bureau, Director-General for Policy Planning (Statistic Standards) & Statistical Research and Training Institute (2008), *Historical Statistics of Japan*, http://www.stat.go.jp/english/data/chouki/index.htm.

Nadal, J. (2003), Atlas de la Industrialización de España, Bilbao: Fundación BBVA.

Malanima, P. (2011), The Long Decline of a Leading Economy, GDP in Central and Northern Italy 1300-1913, *European Review of Economic History*, 15(02), 169-219.

Mitchell, B.R. (2007a), *International Historical Statistics: Africa, Asia and Oceania, 1750-2005,* Cambridge: University Press.

Mitchell, B.R. (2007b), *International Historical Statistics: Europe 1750-2005*, Cambridge: University Press.

Mitchell, B.R. (2007c), *International Historical Statistics: the Americas: 1750-2005*, Cambridge: University Press.

Mitchell, B.R. (1962), *Abstract of British Historical Statistics*, Cambridge: University Press.

Minami, R. (1982), Water Wheels in the Pre-industrial Economy of Japan, *Hitotsubashi Journal of Economics*, 22 (2), 1-15.

Minami, R. (1977), Mechanical Power in the Industrialization of Japan, *Journal of Economic History*, 37 (4), 935-958.

Mosk, C. (1978), Fecundity, Infanticide and Food consumption in Japan, *Explorations in Economic History*, 15(3), 269-289.

Odyssee (2011), European Energy Efficiency Indicators Database, www.odyssee-indicators.org/database/database.php, September 2011.

Pfister, U. (2011), *Economic growth in Germany, 1500–1850*, Paper presented at the Conference on Quantifying Long Run Economic Development, Venice, 22-24 March, 2011.

Reis, J, C.A. Martins and L.F.Costa (2011), *New Estimates of Portugal´s GDP per capita 1500-1850*, prepared for the Quantifying long run economic conference, University of Warwick in Venice 22-24 March 2011.

Rubio, M.d.M. (2005), Economía, Energía y CO_2: España 1850-2000, *Cuadernos Económicos de ICE 70*, vol. 2, 55-71.

Schurr, S.H. and C. Netschert (1960), *Energy in the American economy 1850-1975: an economic study of its history and prospects*, Baltimore: The Johns Hopkins Press.

Schumpeter, E.B. (1960), *English Overseas Trade Statistics 1697-1808*, Oxford: Clarendon Press.

Statistics Canada (2014), Canada Yearbook Historical Collection, www.statcan.ga.ca, last accessed February 2014.

Statistics Denmark (2014), StatBankDenmark: Population Figures from the Census (1769-2014), www.statbank.dk, last accessed February 2014.

SOS - Sveriges Officiella Statistik (1915), Industri, 1913 and 1917, Stockholm: ISAAC.

Steward, F.R. (1978), Energy consumption in Canada since confederation, *Energy Policy*, 6 (3), pp. 239-245.

Sutch, R. (2006). National Income and Product in S. B. Carter, A.L. Olmstead, R., Sutch, G. Wright, S.S. Gartner and M. R. Hains (2006), The Historical Statistics of the United States, vol.4, Part D: Economic Sectors, Millennial Edition, New York: Cambridge University Press.

Sugiyama, S. (2012), *Japan's industrialization in the World Economy 1859-1899: Export, trade and overseas competition*, London, New York: Bloomsbury

Taylor, R. (1848), *Statistics of Coal*, Philadelphia: J. W. Moore.

Totman, C. (2014), *Japan: an environmental history*, I.B. Tauris.

Urquhart, M.C. and K.A.H. Buckley (1965), *Historical statistics of Canada*, Cambridge University Press.

Warde, P. (2007), *Energy consumption in England & Wales 1560-2000*, Naples: Consiglio Nazionale delle Richerche.