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

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ABSTRACT

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

## 1. Introduction

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

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

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

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

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

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

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

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

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

## 2. Methodology

### 2.1. The extended Kaya decomposition identity

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

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

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

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

where:

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

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

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

[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.