Explaining decoupling in high income countries: A structural decomposition analysis of the change in energy footprint from 1970 to 2009

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Abstract

The decoupling of energy use from economic growth is an essential element in the transition to a sustainable future. However, little is known about the long-term drivers of decoupling, especially considering the possibility that it is at least partially due to increased trade. This study uses structural decomposition analysis to examine the main factors that contribute to changes in the energy footprint of Denmark, the United Kingdom, France and the United States of America back to 1970. The results show that the changes in energy footprint have been driven mainly by two countervailing forces: declines in energy intensity and increases in consumption per capita. Energy efficiency improvements that take place abroad play an increasingly important role. In recent years they accounted for a greater share of the reduction in energy footprint than domestic energy efficiency improvements. The trade sourcing effect was negligible in the beginning of the study period but has grown in importance since 1995 and accelerated the growth of the energy footprint by roughly 0.5% per year. Whilst the electricity sector has clearly played the dominant role, the contribution of factor changes in services and manufacturing should not be overlooked.

Keywords: Structural Decomposition Analysis, International Trade, Energy Footprint, Input-Output analysis

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Introduction

The rate of growth of global primary energy use has been remarkably stable since 1850 (2.4%/year ± 0.08%) (Sorrell, 2015). However, since primary energy use has grown more slowly than gross domestic product (GDP), there has been a steady decline in global energy intensity (energy use/GDP). Declining energy intensity is a sign of decoupling, which comes in two forms: relative and absolute.

Relative decoupling occurs when energy use increases at a slower rate than output. It has been evident in England since the late nineteenth century (Warde, 2007) in the US from 1920 (Schurr and Netschert, 1960), and at an aggregate European level and globally since around 1970 (Kander et al., 2013; Smil, 2016).

Absolute decoupling on the other hand, refers to a situation in which energy use declines in absolute terms whilst output continues to grow. It is a much more recent phenomenon evident only in a few countries (see Figure 1). For example, in the UK and the USA, GDP per capita increased at about 2% per year at the same time energy use per capita declined at about 0.5% per year. Gardoki et al. (2018) presents evidence of absolute decoupling between energy and human development index for the period 2000-2014. Quéré et al. (2019) reports similar findings for absolute decoupling between CO_2 and GDP for 18 developed economies.

There are a number of factors that affect the relationship between economic growth and energy use. On the demand side changes in lifestyle and household incomes trigger shifts in consumption patterns. According to Engel's Law, as income rises, demand diversifies away from necessities (e.g. food) towards other goods and services. Shifts in consumption patterns and shifts in the composition of the economy are inter-dependent. On the supply side firms of various industries aim to accommodate changes in final demand. Driven by competition and profit, firms innovate, enabling continuous increases in productivity and declining prices. This in turn stimulates further demand and allows firms/industries to grow in both relative (structural change) and absolute terms.

To date most of the energy-growth literature has focused on investigating energy use from the production-based (PB) perspective. The PB perspective takes into account energy used within the borders of the country including energy used for the production of goods and services that are exported to other countries (EEA, 2013). However, this approach does not take into account energy use associated with imported goods. An alternative consumption-based (CB) approach, also known as a footprint, represents energy use associated with the consumption of goods and services, and takes into account energy use needed to produce imported goods and services. The difference between the two accounting approaches centers on how they account for trade. Both methods have their own strengths and weaknesses, and which one is better depends on the question at hand (see Afionis et al., 2017, for a detailed comparison of PB vs CB approaches).

Since 1980, developments in information and communication technologies (ICT) and declining coordination costs have led to what Baldwin (2006) calls "globalization's second unbundling". The ICT revolution and lower transaction costs made it feasible to geographically separate some stages of production and explore advantages of the vast international wage differences. Inevitably these developments affected international trade which has grown by an average of 7.5% per year between 1980 and 2011 (WTO, 2013). Furthermore, during this period world trade grew much faster than world output (roughly 3%) indicating an increasing fragmentation of production through global supply chains.

Parallel to this increase in trade there has been a growing interest on understanding the interactions between trade and the environment. Many studies have quantified the content of various environmental indicators embodied in trade (see e.g. Wiedmann and Lenzen, 2018). Recent results demonstrate that in 2011, 29% of the global energy use, 26% of global land use, 32% of materials, 26% of global water use and over 24% of global greenhouse gas (GHG) emissions are embodied in trade (Wood et al., 2018). Most indicators display relative decoupling at global scale with land use being the only indicator showing small absolute decoupling from both PB and CB perspectives.

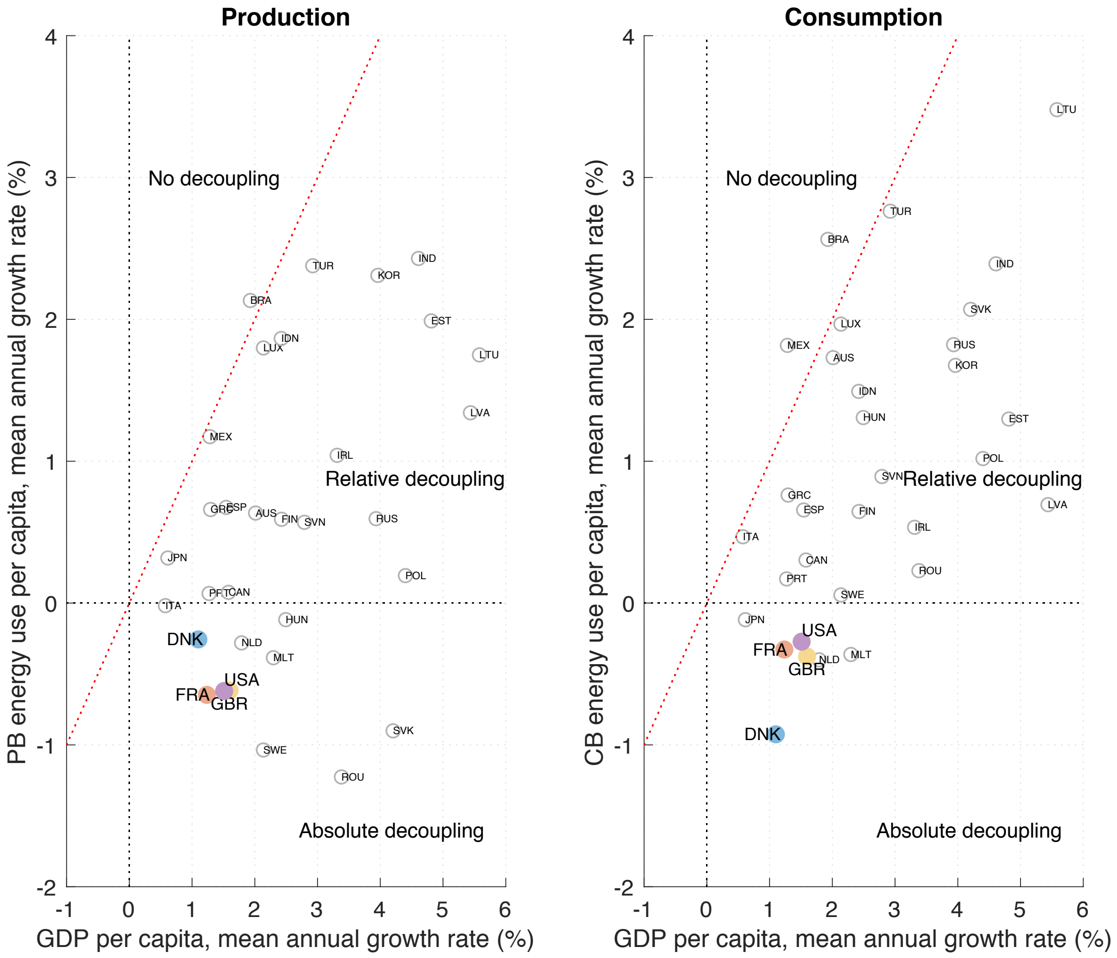
Decoupling – and in particular absolute decoupling – is a highly desirable sustainability goal as it indicates a weakening relationship between energy use and economic growth. Since energy use accounts for two-thirds of GHG emissions (IEA, 2015), it also implies that economic growth can be achieved without an increase in emissions. Understanding the drivers behind national and sectoral dynamics of energy has important policy implications. Knowing how these drivers have changed over time can help us understand how they are likely to evolve in the future. Linking the results with future projections on energy use (Schandl et al., 2016) can shed light on the potential areas where the reduction of energy use can be achieved with minimal impacts on living standards.

Tracing how the connection between changes in energy footprint and changes in the economy has evolved requires identifying specific factors of change. In this study we employ structural decomposition analysis (SDA) to examine the main factors that contribute to decoupling of energy footprint and economic growth in four high income countries (Denmark, Great Britain, France and the United States of America). We chose these countries, as they have demonstrated strong decoupling in CB and PB accounting and have high quality structural (input-output), trade and energy data going back to before the 1970s energy crisis. Furthermore, the four countries are high income countries, and as such, are likely to have some aspects of their development replicated in the development of less well-developed countries.

To understand what structural changes have resulted in strong decoupling, we examine the changes in energy footprints due to changes in energy efficiency (energy use per unit of output), production technology, mix and level of final demand, affluence, population and international trade. We look at how these factors change over time, and assess whether the main reasons for decoupling have been energy efficiency measures, changes in the structure of the economy (e.g. a move towards a service based economy), or offshoring of production activities. Whilst other cross-country energy SDA studies (see e.g. Kaltenegger et al., 2017; Lan et al., 2016) have been performed, this study is unique in its coverage of time: from the impact of the oil crisis in the 1970s, to the rapid growth in global trade in the 2000s. By focusing on countries with good data quality, we can use tables in constant prices (or chained previous-year prices) that include product level deflation for both output and imports. Furthermore, we look specifically at the contribution of the substitution effect of trade – capturing the impact of different energy productivities in different regions of the world.

In the remainder of the paper, we first go further into the background of energy decomposition work before presenting the method and data used in this study. The results section follows, with results broken down into the 1970-1990 and 1995-2009 time spans as well as product level results. A discussion of results and conclusions that can be drawn concludes.

Figure 1 PB and CB energy use per capita vs. GDP per capita, average yearly change 1995–2011



Notes: Data extracted from Wood et al (2018) supplementary material. Only countries covered by WIOD 2013 release are displayed. Filled circles represent the countries considered in this study. Dotted red line separates decoupling and non-decoupling areas. Countries bellow the horizontal show evidence of absolute decoupling i.e. increasing output with declining energy requirements in absolute terms. Full country names are given in Table B1 in the SI.

Background

Extensive research has been carried out to explain the link between energy and GDP (output) at the sectoral, national or international level. The interest in energy studies emerged with the first oil crisis in 1973/74 and the subsequent energy price rise which triggered concerns about the availability and use of primary resources. Early studies focused on understanding the mechanism that explain changes in energy use, in particular how structural shifts in industrial production affects energy demand (Ang and Zhang, 2000). Since 1990 with the growing awareness of climate change an increasing number of studies have attempted to quantify changes in energy related greenhouse gas emissions (Ang, 2004).

The latest survey by Wang et al. (2017) lists a total of 67 journal papers on economy-wide SDA applied to energy and emissions between 2000 and 2015, of which trade-related analysis is becoming increasingly common. Wang et al (2017) notes that most SDA studies can be classified into three broad categories. The first group examines energy/emissions content embodied in trade using single-region input-output model and focusing on a single country (see e.g. OTA, 1990; Proops, 1984; Rose and Chen, 1991; Wood, 2009). The second type of studies examine energy/emission content embodied in trade between two or more countries (see e.g. Kagawa and Inamura, 2004). The third type is based on a multi-region input-output model which traces all energy/emissions associated with final products back to the country where the impacts occurred (see e.g. Kaltenegger et al., 2017; Lan et al., 2016).

The three methods differ in their assumptions about technology of imported goods as well as the treatment of imported intermediate goods. For instance, the single-region input-output (SRIO) model assumes that imported goods are produced with the technology of the importing country, hence this assumption is known as the domestic technology assumption (DTA). Andrew et al. (2009) show that using the DTA assumption might lead to overestimation of emissions embodied in trade and suggest that this assumption can be alleviated by using world average or a representative country technology. The multi-region input-output (MRIO) model overcomes the issues associated with the SRIO method and DTA assumption by distinguishing imports that are directed towards final consumption and those that are directed towards intermediate consumption.

Although a detailed comparison of the empirical outcomes of these studies is difficult because of the variation in the selection of countries, periods, environmental issues and decomposition methods, it is possible to draw some general conclusions. For most developed economies, the final demand level is the most important long-term determinant of increased energy use (Lenzen, 2016). Changes in technology through energy intensity (energy per unit of production) has generally been found to be the most important force for decline in aggregate energy use. Technological changes through input-output coefficients (A and L matrices) and the final demand mix effect (i.e. structural change) has been found to have a modest effect on reductions in energy use.

Evidence from recent energy footprint studies reinforce these findings and shows that affluence and population growth are driving energy footprints worldwide whilst energy intensity partially counteracts these effects (Kaltenegger et al., 2017; Lan et al., 2016). For the United Kingdom, Hardt et al. (2018) provide a decomposition that in addition to the above results captures a strong offshoring effect for the UK. Rather than using a structural decomposition approach to the analysis, they calculate an index showing the percentage of foreign output to global output required for the UK demand. Here we extend this analysis by applying structural decomposition methods to look specifically at substitution both in the supply-chain (intermediate production), and by final consumers. Furthermore, we lengthen the period of analysis, and broaden it to include four countries that have shown absolute decoupling.

Model and Data

Input-output analysis

This study uses input-output analysis (IO) developed by (Leontief, 1970, 1936). Within the input-output framework, two methods are commonly used to calculate energy embodied in international trade. The single-region input-output (SRIO) model and the multi-region input-output (MRIO) model (Miller and Blair, 2009). The standard Leontief IO model can be expressed as:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} = \mathbf{L}\mathbf{y} \tag{1}$$

where $\mathbf{x}$ is the vector of output, $\mathbf{A}$ is the matrix of technical coefficients, $\mathbf{y}$ represents final demands, $(\mathbf{I} - \mathbf{A})^{-1} = \mathbf{L}$ is the total requirement matrix (often known as the Leontief inverse) representing interdependencies between industries and $\mathbf{I}$ is the identity matrix.

In this study, we make use of both SRIO and MRIO models. In practice, the MRIO model consists of many countries, but it can be illustrated as consisting of two countries: the focal country and the rest of the world (ROW) region (see e.g. Hambÿe et al., 2018;

Serrano and Dietzenbacher, 2010). The model in equation (1) can be expressed for two regions as:

$$\begin{bmatrix}\mathbf{x}^1\\ \mathbf{x}^2\end{bmatrix}=\left[\begin{bmatrix}\mathbf{I} & \mathbf{0}\\ \mathbf{0} & \mathbf{I}\end{bmatrix}-\begin{bmatrix}\mathbf{A}^{11} & \mathbf{A}^{12}\\ \mathbf{A}^{21} & \mathbf{A}^{22}\end{bmatrix}\right]^{-1}\begin{bmatrix}\mathbf{y}^{11}+ & \mathbf{y}^{12}\\ \mathbf{y}^{21}+ & \mathbf{y}^{22}\end{bmatrix}=\begin{bmatrix}\mathbf{L}^{11} & \mathbf{L}^{12}\\ \mathbf{L}^{21} & \mathbf{L}^{22}\end{bmatrix}\begin{bmatrix}\mathbf{y}^{11}+ & \mathbf{y}^{12}\\ \mathbf{y}^{21}+ & \mathbf{y}^{22}\end{bmatrix} \qquad (2)$$

where $\mathbf{A}^{11}$ and $\mathbf{A}^{22}$ are domestic input coefficient matrices, $\mathbf{A}^{21}$ and $\mathbf{A}^{12}$ are foreign input coefficient matrices, $\mathbf{y}^{11}$ and $\mathbf{y}^{22}$ gives the final domestic demands and $\mathbf{y}^{12}$ represent exports of final products from country 1 to country 2, and $\mathbf{y}^{21}$ captures exports of final products from country 2 to country 1.

Energy use can be incorporated into equation (2) as:

$$\begin{aligned}\begin{bmatrix}\mathbf{e}^{11} & \mathbf{e}^{12}\\ \mathbf{e}^{21} & \mathbf{e}^{22}\end{bmatrix}&=\begin{bmatrix}\hat{\mathbf{q}}^1 & \mathbf{0}\\ \mathbf{0} & \hat{\mathbf{q}}^2\end{bmatrix}\begin{bmatrix}\mathbf{L}^{11} & \mathbf{L}^{12}\\ \mathbf{L}^{21} & \mathbf{L}^{22}\end{bmatrix}\begin{bmatrix}\mathbf{y}^{11} & \mathbf{y}^{12}\\ \mathbf{y}^{21} & \mathbf{y}^{22}\end{bmatrix}\\ &=\begin{bmatrix}\hat{\mathbf{q}}^1\mathbf{L}^{11}\mathbf{y}^{11}+\hat{\mathbf{q}}^1\mathbf{L}^{12}\mathbf{y}^{21} & \hat{\mathbf{q}}^1\mathbf{L}^{11}\mathbf{y}^{12}+\hat{\mathbf{q}}^1\mathbf{L}^{12}\mathbf{y}^{22}\\ \hat{\mathbf{q}}^2\mathbf{L}^{21}\mathbf{y}^{11}+\hat{\mathbf{q}}^2\mathbf{L}^{22}\mathbf{y}^{21} & \hat{\mathbf{q}}^2\mathbf{L}^{21}\mathbf{y}^{12}+\hat{\mathbf{q}}^2\mathbf{L}^{22}\mathbf{y}^{22}\end{bmatrix} \qquad (3)\end{aligned}$$

where $\mathbf{q}^1$ and $\mathbf{q}^2$ represent direct energy use per unit of output (i.e. energy intensity). $\mathbf{e}^{11}$ and $\mathbf{e}^{22}$ capture domestic energy use, $\mathbf{e}^{12}$ gives energy required to produce exports from country 1 to country 2, and $\mathbf{e}^{21}$ represents energy needed to produce imports to country 1 from country 2. The production-based (PB) energy use in country 1 is given by $\mathbf{e}^{PB}=\mathbf{e}^{11}+\mathbf{e}^{12}$. The consumption-based (CB) energy use is given by $\mathbf{e}^{CB}=\mathbf{e}^{11}+\mathbf{e}^{21}$. The consumption-based energy use also known as energy footprint is the primary focus of this study, from here onwards we refer to it by $\mathbf{e}$ (without the superscript CB).

To calculate energy footprint for the period from c1970–1990 we use the SRIO model. The SRIO model consists of a single country, but with several assumptions, it can be expressed as a composition of two countries/regions (see e.g. Andrew et al., 2009; Proops et al., 1992; Serrano and Dietzenbacher, 2010) as:

$$\begin{bmatrix}\mathbf{e}^{11} & \mathbf{e}^{12}\\ \mathbf{e}^{21} & \mathbf{e}^{22}\end{bmatrix}=\begin{bmatrix}\hat{\mathbf{q}}^1 & \mathbf{0}\\ \mathbf{0} & \hat{\mathbf{q}}^2\end{bmatrix}\left[\begin{bmatrix}\mathbf{I} & \mathbf{0}\\ \mathbf{0} & \mathbf{I}\end{bmatrix}-\begin{bmatrix}\mathbf{A}^{11} & \mathbf{0}\\ \mathbf{A}^{21} & \mathbf{A}^{11}+\mathbf{A}^{21}\end{bmatrix}\right]^{-1}\begin{bmatrix}\mathbf{y}^{11} & \mathbf{y}^{12}\\ \mathbf{y}^{21} & \mathbf{0}\end{bmatrix} \qquad (4)$$

In this setting an artificial ROW region has no final consumption of domestic production i.e. $\mathbf{y}^{22}=0$ and exports of the intermediate production from region 1 are not linked to imports to ROW i.e. $\mathbf{A}^{22} = 0$. This assumption (i.e. $\mathbf{A}^{22} = 0$) is known as the *small country* assumption (see e.g. Proops et al., 1992; Serrano and Dietzenbacher, 2010) it reflects the fact country 1 exports of intermediate goods are negligible compared with total output by the ROW. Another common assumption in the SRIO framework is the *domestic technology* assumption. It implies that imports from the ROW to country 1 are produced with the domestic technology of country 1 i.e. $\mathbf{A}^{11} + \mathbf{A}^{21} = \mathbf{A}^{12} + \mathbf{A}^{22}$, as a result in equation (4) $\mathbf{A}^{12} + \mathbf{A}^{22}$ is given by $\mathbf{A}^{11} + \mathbf{A}^{21}$. It is also assumed that energy intensities are the same in both regions i.e. $\mathbf{q}^{1} = \mathbf{q}^{2}$. To partially relax this assumption we use a weighted four country average energy intensity such $\mathbf{q}^{2} = \sum_{k}^{4} \mathbf{u}_{k} \,/\, \sum_{k}^{4} \mathbf{x}_{k}$, where $\mathbf{u}$ represents energy use by sector in country k.

The final model to compute energy footprint can be expressed in a compact form as:

$$\mathbf{e} = \mathbf{q}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{Y} = \mathbf{qLY} + \mathbf{h} \tag{5}$$

Note that in this case $\mathbf{q}$ is a row vector (not a diagonal as was the case in equations 3 and 4) and $\mathbf{h}$ is the direct energy use by households (e.g. for heating).

Structural decomposition analysis (SDA)

The central idea of Structural decomposition analysis (SDA) is that changes in energy footprint $\mathbf{e}$ within a certain period can be decomposed into various driving forces of change: energy intensity, level and structure of final demand, population, etc. (Hoekstra and van der Bergh, 2003). In this study we are specifically interested in the effects that capture changes in the trade structure. To isolate these effects equation (5) can be split into several additional factors as:

$$\mathbf{e} = \mathbf{q}\,\underbrace{(\mathbf{I} - \mathbf{T} \otimes \mathbf{H})^{-1}}_{\mathbf{L}}\,\underbrace{(\mathbf{B} \otimes \mathbf{G})\hat{\mathbf{d}}\hat{\mathbf{p}}}_{\mathbf{Y}} + \underbrace{\hat{\mathbf{d}}^{h}\mathbf{p}^{h}}_{\mathbf{h}} \tag{6}$$

Where $\mathbf{A} = \mathbf{T} \otimes \mathbf{H}$ ($\otimes$ represents the Hadamard product or element by element multiplications) is split into the trade structure of intermediate inputs $(\mathbf{T})$ and the overall production structure $(\mathbf{H})$ effects. The final demand $\mathbf{Y} = (\mathbf{B} \otimes \mathbf{G})\hat{\mathbf{d}}\hat{\mathbf{p}}$ is broken down into the final demand trade $(\mathbf{B})$, the final demand mix $(\mathbf{G})$, the per capita level of final demand $(\mathbf{d})$ and the population $(\mathbf{p})$ effects. The direct energy use by households is split into the direct energy use per capita ($\hat{\mathbf{d}}^h$) and the population ($\mathbf{p}^h$) effects. For a full appraisal of the approach, the reader is referred to (Arto and Dietzenbacher, 2014; Hoekstra et al., 2016) and Appendix A in the SI.

Given the total energy footprint at time 0 as $\mathbf{e}^0$ and at time 1 as $\mathbf{e}^1$, then the change $\Delta\mathbf{e} = \mathbf{e}^1 - \mathbf{e}^0$ can be decomposed into an exhaustive sum of the following factors:

$$\Delta\mathbf{e} = \Delta\mathbf{q} + \Delta\mathbf{T} + \Delta\mathbf{H} + \Delta\mathbf{B} + \Delta\mathbf{G} + \Delta\mathbf{d} + \Delta\mathbf{p} \tag{7}$$

where

$\Delta\mathbf{q}$: the energy intensity (efficiency) effect measures how falling or rising sectoral energy intensity affects energy footprint (PJ/\$).

$\Delta\mathbf{T}$: the trade structure of intermediate inputs effect, measures how change in intermediate input shares affect energy footprint. It has positive effect if intermediate inputs structure shifts towards more energy-intensive countries.

$\Delta\mathbf{H}$: the overall production technology effect, measures changes in the technology of the economy irrespective of the source country.

$\Delta\mathbf{B}$: the final demand trade structure effect, measures the change in energy footprint due to changes in the composition of imports for final demand.

$\Delta\mathbf{G}$: the final demand structure (mix) effect, measures the change in energy footprint due to changes in the composition of final demand.

$\Delta\mathbf{d}$: the final demand level per capita effect ($\Delta\mathbf{d} = \Delta\mathbf{d} + \Delta\mathbf{d}^h$), measures the change in energy footprint due to increasing or decreasing levels of final demand per capita and changes in the direct energy use per capita $\hat{\mathbf{d}}^h$.

$\Delta\mathbf{p}$: the population effect ($\Delta\mathbf{p} = \Delta\mathbf{p} + \Delta\mathbf{p}^h$), measures the change in energy footprint due to changes in population.

As shown by (Dietzenbacher and Los, 1998) there is no unique way to decompose a change in one variable into the changes in its determinants. In the case of k components, the number of equivalent decompositions amounts to $k!$. We use an average of the two so-called polar decomposition forms proposed by (Dietzenbacher and Los, 1998) to solve the non-uniqueness problem.

Data

The World Input-Output Database (WIOD) is the main source of data for the period 1995–2009. The WIOD consist of series of multi-region input-output tables and environmental/energy sub-databases covering 35 industries and 41 countries/regions, including 27 EU and 13 other major advanced and emerging economies, plus a region called "Rest of the World" (Timmer et al., 2015) see Table B1 and B2 in the SI for more detailed data coverage. We eliminate price effects by using deflated IO tables (in previous year's prices) and chaining the pairwise results.

For the period from c.1970 to 1990, the data were extracted from two sources: IO tables in 1980 (1982 for the USA) constant prices from the OECD IO (OECD, 2016) database and energy balances from IEA (IEA, 2016). The OECD SRIO tables distinguish between 36 industrial sectors. The data are available for a limited number of years and specific countries (see Table B3 in the SI for data coverage, the final year of data availability from this dataset is 1990). Given limited data availability, this study focuses on four countries Denmark, France, the United States (USA) and the United Kingdom (UK). These four economies by no means constitute a complete picture of high income countries, but they do provide a flavor across several important dimensions (see Table B7 in the SI): all four countries show strong decoupling and are similar in terms of their income per capita but differ in terms of the total GDP, which ranges from small (Denmark) to medium (the UK and France) and large (the US); engagement in trade with Denmark being the most engaged, France and the UK somewhat in the middle and the US the least engaged in trade; energy requirements per capita and per unit of GDP, in this respect the US has much higher energy requirements than the three European countries.

The WIOD database offers "ready to use" harmonised MRIO tables and energy accounts with the same sectoral classification. The OECD IO tables and the IEA energy balances, however use different industrial classifications. Typically, the IEA sectors are more aggregated than the OECD IO sectors. The connection of the physical IEA energy balances with the monetary OECD IO tables follows the "minimum information method" as in the WIOD 2013 release (Genty et al., 2012). Two types of energy accounts are available in the WIOD database: emissions relevant energy use and gross energy use. For this analysis we utilise emissions relevant energy use.

Results

The results are presented in two parts: (i) for the period 1970–90 (SRIO model) and (ii) for the period 1995–2009 (MRIO model).

Period I c.1970-1990

Decomposition results for the period c.1970–1990 are presented in Table 1 and visualised in Figure 2. The results are presented as annualised percentage rates of change from the base year figure and total for the entire period. Individual country results show that changes in energy efficiency of industrial production ($\mathbf{q}$) and changes in production structure ($\mathbf{H}$) have a negative impact on energy footprint. The effect of industrial structure ($\mathbf{H}$) was negative for all countries except the UK. Changes in the final demand structure ($\mathbf{G}$), resulted in a decline in energy footprint in most years (with few exceptions) but played a relatively minor role. Improvement in energy efficiency was the strongest negative factor accounting for -7.4% to -52.8% decrease in energy footprint. If all other components had remained constant (i.e. $\Delta\mathbf{T} = 0$, $\Delta\mathbf{H} = 0$, $\Delta\mathbf{B} = 0$, $\Delta\mathbf{G} = 0$, $\Delta\mathbf{d} = 0$, $\Delta\mathbf{p} = 0$), this would represent how the energy footprint would have changed over time due to improvement in energy efficiency ($\mathbf{q}$).

In contrast, changes in consumption per capita ($\mathbf{d}$) and population ($\mathbf{p}$) had positive effects on energy footprint. The final demand level per capita was the strongest component in this group accounting for between 7.8% and 55% of the change in energy footprint. This reflects an increasing level of spending (people demanding more things), which, everything else being equal, leads to an increase in energy requirements. The population effect was the strongest in the US (18.7%), while for France (6.4%) and the UK (4.6%) it had a minor contribution to the changes in energy footprint.

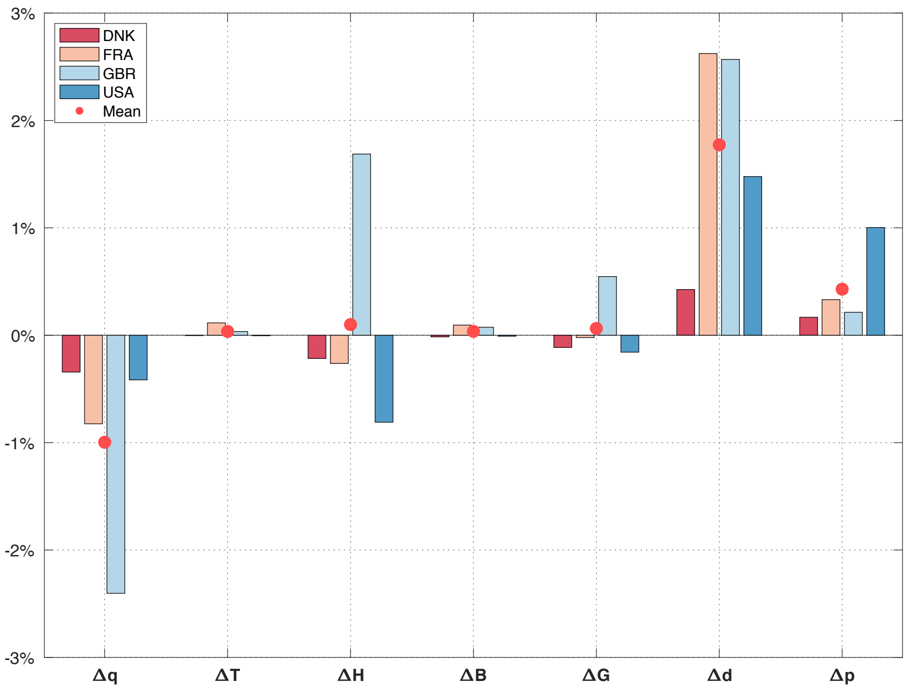
Table 1 SDA c1970 – 1990 (percentage change)

	q	T	H	B	G	d	p	e
DNK 72-77	0.5	0.1	-0.8	0.1	-0.1	1.1	0.4	1.3
DNK 77-80	-0.7	0.0	0.5	0.0	-0.9	-0.8	0.2	-1.7
DNK 80-85	-3.1	0.0	-0.6	0.0	0.2	1.4	0.0	-2.3
DNK 85-90	1.6	-0.1	0.3	-0.1	0.0	-0.4	0.1	1.4
DNK 72-90	-0.4	0.0	-0.2	0.0	-0.1	0.4	0.2	-0.2
DNK 72-90 (total)	**-7.4**	**0.0**	**-4.0**	**-0.2**	**-2.2**	**7.8**	**3.0**	**-3.0**
FRA 72-77	-1.7	0.0	-0.2	0.1	0.3	2.4	0.6	1.5
FRA 77-80	0.2	0.8	-0.8	0.2	-0.4	2.7	0.5	3.2
FRA 80-85	-4.4	0.0	-0.6	0.0	-0.1	2.3	0.6	-2.2
FRA 85-90	2.6	0.0	0.3	0.1	-0.1	3.7	-0.1	6.4
FRA 72-90	-1.0	0.1	-0.3	0.1	0.0	2.8	0.4	2.1
FRA 72-90 (total)	**-17.3**	**2.2**	**-5.2**	**1.8**	**-0.5**	**50.5**	**6.4**	**37.9**
GBR 68-79	-3.2	0.1	0.9	0.1	0.3	2.9	0.2	1.2
GBR 79-84	-1.2	-0.1	-1.0	0.1	-2.0	0.2	0.1	-3.9
GBR 84-90	-1.9	0.1	5.0	0.0	2.7	3.7	0.4	10.0
GBR 68-90	-2.4	0.0	1.6	0.1	0.4	2.5	0.2	2.4
GBR 68-90 (total)	**-52.8**	**0.6**	**34.5**	**1.7**	**9.8**	**55.1**	**4.6**	**53.6**
USA 72-77	-0.2	0.0	0.0	0.0	-0.1	1.1	1.0	1.8
USA 77-82	-2.0	0.0	-0.1	0.0	-0.5	-0.1	0.7	-2.0
USA 82-85	0.0	0.0	-1.2	0.0	-0.2	2.6	1.6	2.6
USA 85-90	0.6	0.0	-2.3	0.0	0.1	3.0	1.1	2.5
USA 72-90	-0.5	0.0	-0.9	0.0	-0.2	1.5	1.0	1.1
USA 72-90 (total)	**-8.1**	**-0.1**	**-15.3**	**-0.2**	**-3.0**	**27.5**	**18.7**	**19.5**

Notes: Text in **bold** provides cumulative change in energy footprint for the entire period, all other results are presented as annual percentage change. **q** – energy intensity effect, **T** – intermediate demand trade structure effect, **H** – production technology effect, **B** – final demand trade structure effect, **G** – consumption mix effect, **d** – affluence effect, **p** – population effect, **e** – total change in energy footprint.

To a large extent the effect of spending is offset by improvements in energy efficiency and to some extent by the production recipe. Broadly this can be treated as technological change. The Leontief effect is interpretable as a technological effect of changes in the intermediate input structure, and the intensity effect assesses the effect of change in the sector level use of the indicator per unit output (Hoekstra and van der Bergh, 2003). These two effects show that the methods and processes used to produce a set level and mix of output had changed so they required less energy. The trade effect – i.e. the sum of trade in intermediated products **T** and final **B** – had a positive forcing effect on energy use. This effect would be equal to zero if imports of intermediate and final goods were produced with identical technologies in all countries. Thus, even if a country imports more goods and services over time the effect might be zero if these imports come from countries with the same technologies.

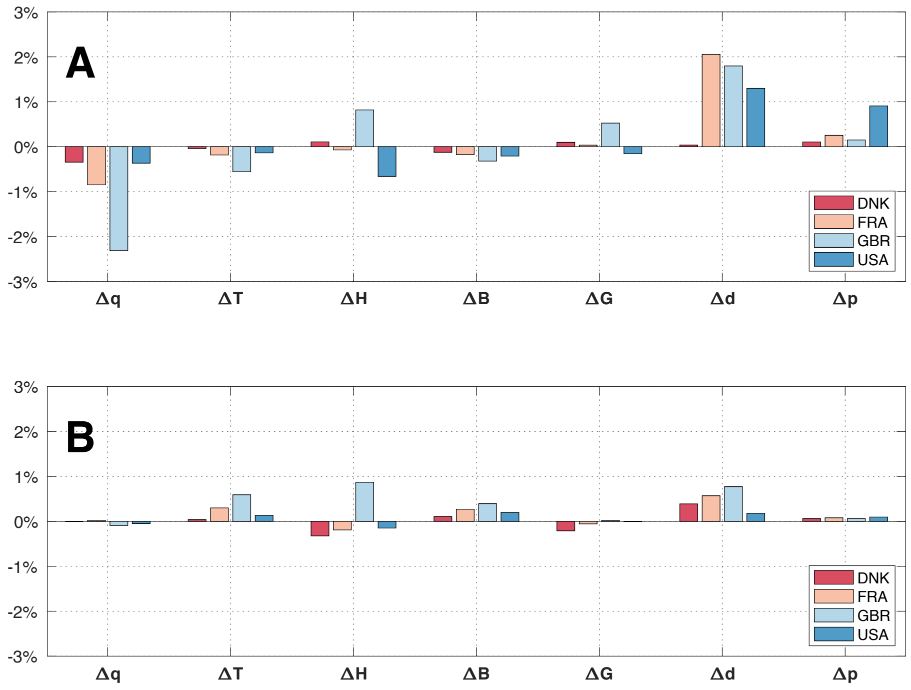
Figure 2 SDA by country, average yearly change for the period c.1970–1990.



Notes: **q** – energy intensity effect, **T** – intermediate demand trade structure effect, **H** – production technology effect, **B** – final demand trade structure effect, **G** – consumption mix effect, **d** – affluence effect, **p** – population effect. The four country mean is denoted by red dot.

As shown in equation (3), energy footprint for a given country depends on changes at home (i.e. $\mathbf{e}^{11}$) and abroad (i.e. $\mathbf{e}^{21}$). To gain additional insights about the importance of trade and the source of changes, we split each of the driving factors (e.g. $\mathbf{q}$) into changes that occur at home and abroad. The results for this exercise are presented in Figure 3 (for the period 1970–1990) and Figure 5 (for period the 1995-2009) and more detailed results can be found in the SI Table B5 and Table B6. For the earlier period we find that in all four countries most of the changes in $\mathbf{q}$ occur at home. For instance, $\Delta\mathbf{q}$ accounts for -2.4% reduction in the USA energy footprint per year (see Table 1), most of this (-2.2%, Figure 3 panel A) is due to changes at home and only (-0.2%, Figure 3 Panel B) is attributable to the changes abroad.

Figure 3 SDA by country split into changes at home (panel A) and abroad (panel B). Average yearly change for the period c.1970–1990.



Notes: Panel A represent changes that occur at home, i.e. energy use in country *r* to deliver final demand in country *r*. Panel B contains changes that occur abroad to meet final demand requirements in the focal country i.e. energy use in country *s* to deliver final demand in country *r*. **q** – energy intensity effect, **T** – intermediate demand trade structure effect, **H** – production technology effect, **B** – final demand trade structure effect, **G** – consumption mix effect, **d** – affluence effect, **p** – population effect.

Splitting **T** and **B** effects into changes at home and abroad show how the reduction of domestic sourcing impacts energy use abroad. For Denmark and the USA, **T** and **B** are close to zero (see Table 1). The decline in domestically sourced goods leads to lower energy use at home, but it comes at the expense of increased use of foreign inputs, production of which require virtually the same energy use abroad. For France and the UK, production of foreign goods require more energy, and thus this leads to a positive **T** and **B** effects.

Interestingly, for Denmark (the most engaged country in trade in our sample) **T** and **B** factors have a negligible effect on energy footprint. This can be explained by the lack of changes in its trade structure and production technology of similar energy efficiency as its trading partners. The results in Table B5 show that the change in energy footprint due to changes at home were -0.7% for **T** and -2.1% for **B**. This decline was compensated by an increase of inputs from abroad (0.7% for **T** and 1.9% for **B**). The net effect (for **T**

0.7+0.7=0 and for **B** -2.1+1.9=-0.2 as displayed in Table 1) was almost zero because the products imported for intermediate and final use were produced with virtually the same energy efficiency. In fact, imports for the final consumption were produced with higher efficiency. For Denmark, most of the changes related to production abroad were concentrated **d** effect (6.9%), which captures the change in the level of imports.

Furthermore, we also find that 53.1% (out of 53.6%) of the total change of the UK energy footprint can be attributed to changes abroad. To large extent this is due to increasing level of imports (**d**), worsening production structure (**H**) and lack of energy efficiency improvements abroad (**q**) see Figure 3 Panel B for more details. For other countries, changes abroad account for about half of the total change in energy footprint (see Table B5 in the SI).

Period II 1995–2009

Decomposition results for the period from 1995 to 2009 and its sub-periods are presented in Table 2, and Figure 4 shows the average contribution of **q**, **T**, **H**, **B**, **G**, **d** and **p** over the period for each country.

From the sub-period decomposition, we can see that the contribution of different factors varies from year to year in terms of size and sign. Changes in energy intensity (**q**) contributed the most to the negative change in energy footprint in all countries. Between 1995–2009 the cumulative effect for Denmark was -21.4%, France -1.1%, the UK -23.7% and the US -13.3%. Changes in the production structure (**H**) had negative but considerably smaller impact for all countries except the US (-12.6%). Most of the negative effect was outweighed by the changes in the final demand per capita (**d**). For Denmark this component accounted for 12.9%, for France 20.6% for the UK 28.2% and for the USA 25.9%. This counterbalancing between energy intensity and level of final demand resembles what has been observed in the earlier period (c.1970 –1990).

The changes in the trade structure of intermediate (**T**) and final (**B**) products had mainly positive albeit very low effects. The positive effect implies that imported intermediate and final goods (**T**) had shifted to countries where the production of the same goods and services required more energy.

Table 2 SDA 1995 – 2009 (percentage change)

	q	T	H	B	G	d	p	e
DNK 95-00	-2.3	-0.2	-0.4	0.2	-0.2	1.6	0.4	-0.8
DNK 00-05	-1.5	0.6	1.0	0.5	-0.3	1.5	0.3	2.1
DNK 05-09	-0.7	0.0	-0.9	0.3	-1.3	-0.7	0.5	-2.8
DNK 95-09	-1.5	0.1	-0.1	0.3	-0.6	0.8	0.4	-0.5
DNK 95-09 (total)	**-21.4**	**2.1**	**-0.8**	**4.8**	**-7.5**	**12.9**	**5.6**	**-4.3**
FRA 95-00	3.9	-0.1	-1.9	0.2	-3.0	2.6	0.5	2.2
FRA 00-05	-2.3	0.3	1.3	0.3	0.3	1.2	0.8	2.0
FRA 05-09	-2.3	-0.1	-0.2	-0.1	0.4	0.4	0.7	-1.2
FRA 95-09	-0.2	0.0	-0.2	0.2	-0.8	1.4	0.7	1.0
FRA 95-09 (total)	**-1.1**	**0.4**	**-3.3**	**2.3**	**-11.9**	**20.6**	**9.4**	**16.5**
GBR 95-00	-2.1	0.4	0.7	0.3	-0.3	3.8	0.3	3.1
GBR 00-05	-1.7	0.7	-0.2	0.8	-0.3	2.8	0.6	2.8
GBR 05-09	-1.2	0.2	-1.4	0.2	-0.7	-1.3	0.9	-3.2
GBR 95-09	-1.7	0.4	-0.3	0.4	-0.5	1.8	0.6	0.9
GBR 95-09 (total)	**-23.7**	**6.3**	**-3.1**	**6.5**	**-6.1**	**28.2**	**8.5**	**16.6**
USA 95-00	-2.6	0.2	0.9	0.1	-0.3	3.6	1.2	3.1
USA 00-05	0.5	0.3	-2.1	0.3	-0.7	2.3	1.1	1.6
USA 05-09	-0.6	0.2	-1.7	0.1	-0.3	-0.9	1.1	-2.0
USA 95-09	-0.9	0.2	-1.0	0.2	-0.5	1.7	1.2	0.9
USA 95-09 (total)	**-13.3**	**3.2**	**-12.6**	**2.4**	**-6.7**	**25.9**	**16.2**	**15.2**

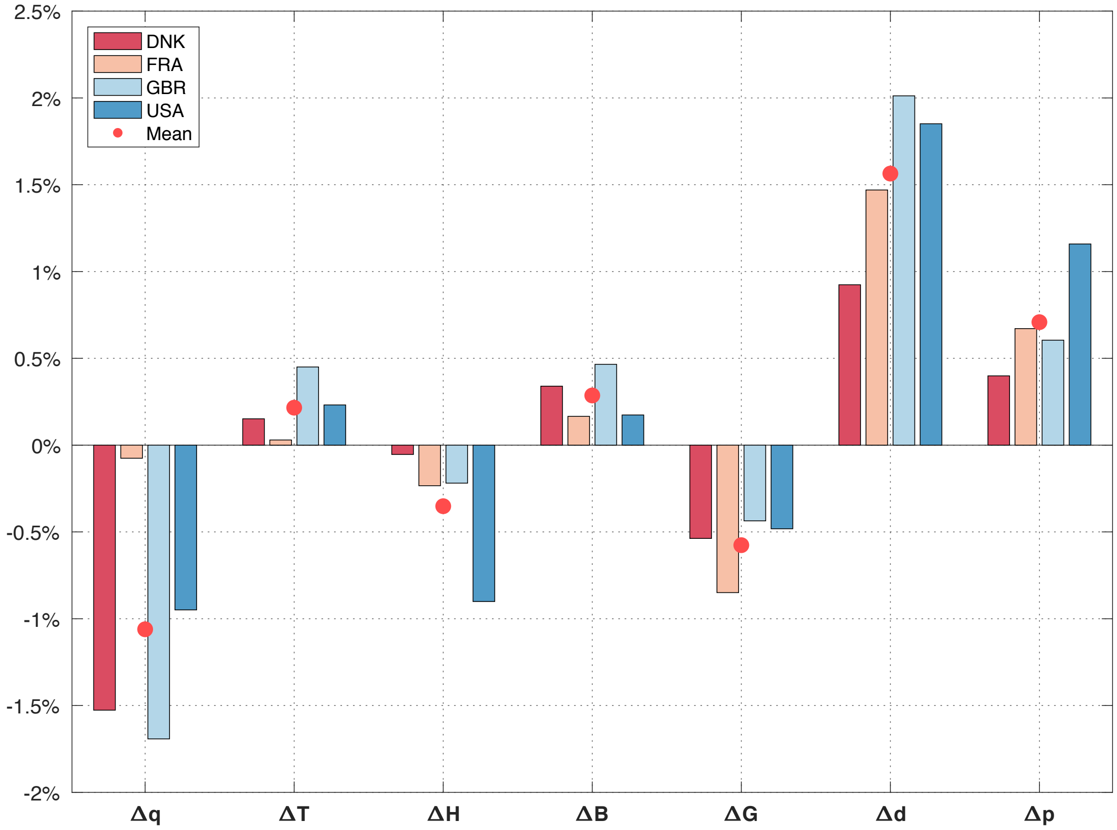
Notes: Text in **bold** provides cumulative change in energy footprint for the entire period, all other results are presented as annual percentage change. **q** – energy intensity effect, **T** – intermediate demand trade structure effect, **H** – production technology effect, **B** – final demand trade structure effect, **G** – consumption mix effect, **d** – affluence effect, **p** – population effect, **e** – total change in energy footprint.

As shown in Figure 2 and Figure 4 the average contribution of **q**, **d** and **p** to the changes in energy footprint was similar during both periods. In contrast, the effect of structural factors (i.e. **T**, **H**, **B** and **G**) was more pronounced during the second period from 1995 to 2009. To large extent this was due to two reasons. First, in the earlier period trade as a share of GDP was lower. For instance, in France trade (imports + exports) as a share of GDP was 31% in 1970, 44% in 1995, other countries follow a similar pattern (see Table B7 in the SI for more details). Second, high-income countries which tend to have similar energy intensities traded relatively more with each other, and as a result it mattered less (in terms of energy use) whether the goods where produced at home or abroad. This change is reflected in the domestic and foreign part of **T** and **B** factors (see Figure 5 and Table B6 in the SI). Decreasing energy at home due to changes in **T** and **B** factors is offset by more than proportional increase in energy use abroad. For instance, for the USA we find that -4.8% (-0.3% per year) change in energy use due to a lower share of domestically sourced products (sum of **T** and **B**) was offset by 10.6% (0.8% per year) increase in energy use abroad.

Other countries display similar results in the sense that -1% change of energy use at home is associated with about 2% increase of energy use abroad (see Figure 5 and Table B6 in the SI for more details). In contrast, during the period 1970-1990 the decline in energy due to lower share of domestically sourced products was offset by more or less equivalent increase in energy use abroad. These results indicate that replacing domestic products by imports from countries with more energy-intensive technologies comes at a higher cost in the second period.

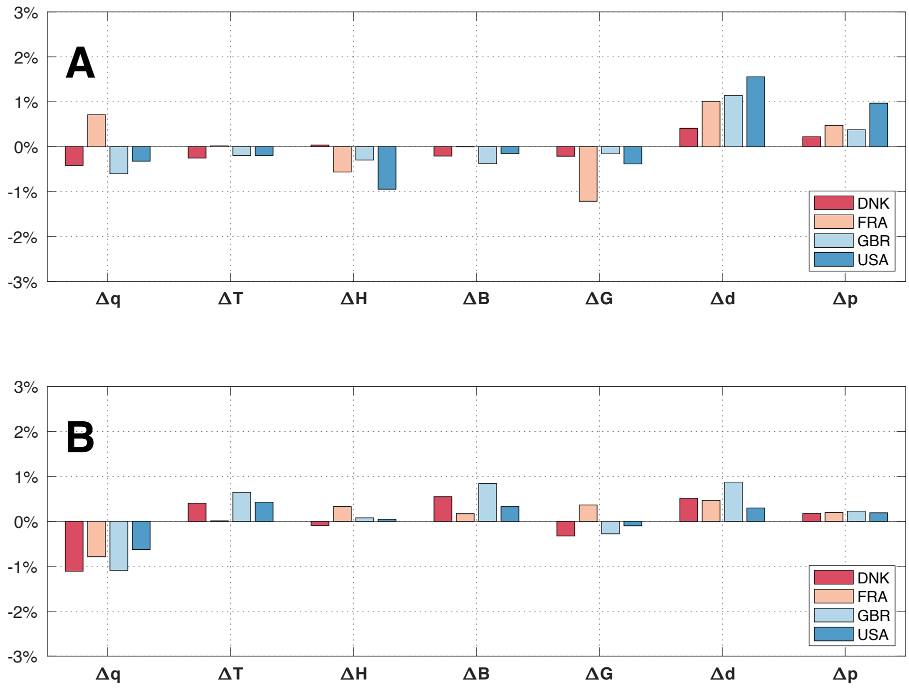
Furthermore, in the second period, more than half of the total change in **q** has occurred abroad. These technological changes that occur in foreign countries play an important role in reducing energy footprints for all countries in our sample.

Figure 4 SDA by country, average for period 1995–2009



Notes:. **q** – energy intensity effect, **T** – intermediate demand trade structure effect, **H** – production technology effect, **B** – final demand trade structure effect, **G** – consumption mix effect, **d** – affluence effect, **p** – population effect. The four country mean is denoted by red dot.

Figure 5 SDA by country split into changes at home (panel A) and abroad (panel B). Average for the period 1995–2009.



Notes: Panel A represent changes that occur at home, i.e. energy use in country *r* to deliver final demand in country *r*. Panel B contains changes that occur abroad to meet final demand requirements in the focal country i.e. energy use in country *s* to deliver final demand in country *r*. **q** – energy intensity effect, **T** – intermediate demand trade structure effect, **H** – production technology effect, **B** – final demand trade structure effect, **G** – consumption mix effect, **d** – affluence effect, **p** – population effect.

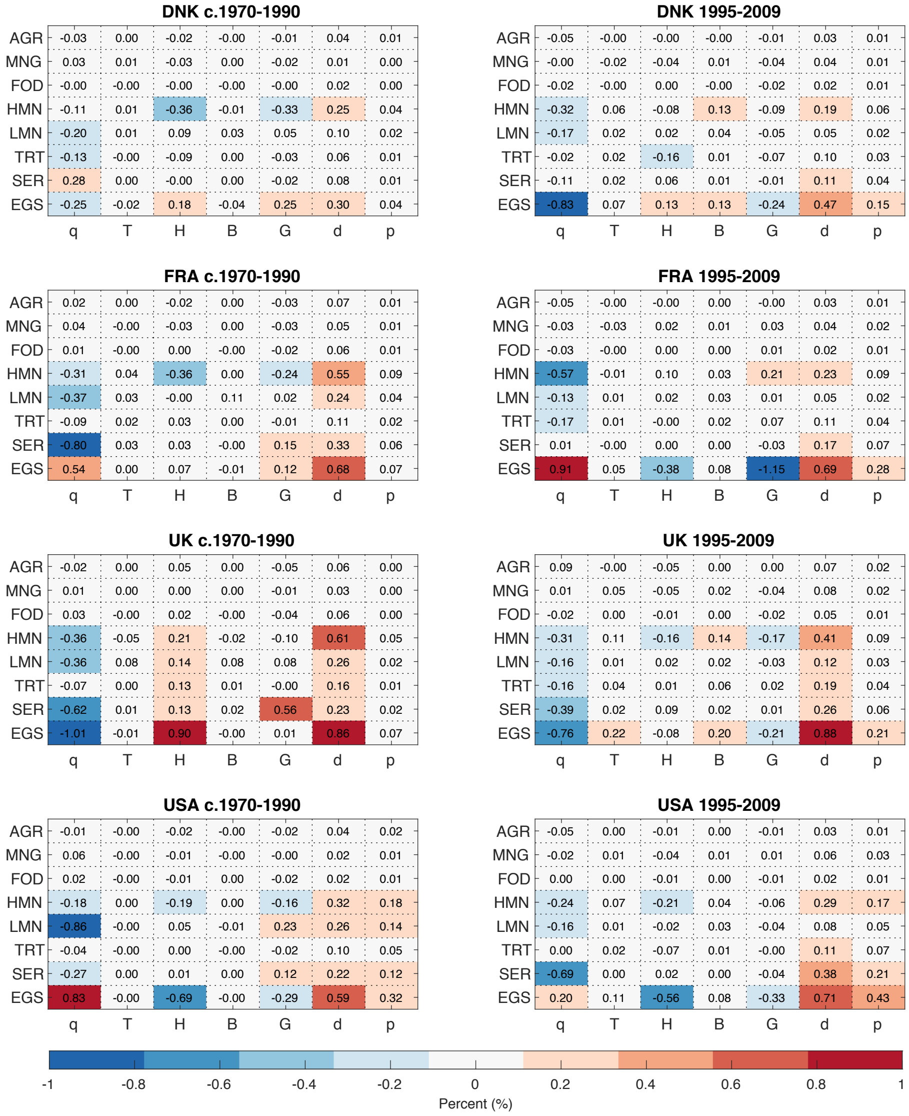
Product groups

To make the results more informative, we aggregated the sectoral decomposition into eight broad groups (the initial 36 industry classification was aggregated to 8 categories, see Table B2 and B4 in the SI for details). This exercise allows us to see which sectors contribute the most to the increase and decrease of energy footprint (note that the direct energy use by households is not included here).

Sectoral decomposition results for each factor, all countries and both time periods are presented in Figure 6. The results show that the effects are not uniform across sectors. That is, the effect of a certain factor is positive in some sectors but negative in others. For instance, the energy intensity effect in Denmark c1970–1990 is positive in energy-intensive manufacturing (HMN) and services (SER) but negative in all other sectors. This implies that energy demands to produce one unit of output in HMN and SER have increased over time.

Most of the changes in energy footprint are concentrated in energy-intensive manufacturing (HMN), non-energy intensive-manufacturing (LMN), services (SER), transport (TRT) and electricity and gas supply (EGS). Agriculture (AGR), mining (MNG) and food (FOD) are less important contributors to the changes in energy footprint. It is important to note that the low effect in some industries might occur simply due to the lack of change over time which does not necessarily imply a lack of energy use. For example, as shown in Voigt et al. (2014) mining (MNG) accounted on average for 2.3% of global energy use (6th highest share out of 35 sector) during 1995–2007, but its average energy intensity has changed very little over the same time span.

Figure 6 SDA by sector and factor for the periods c.1970–1990 and 1995–2009, (annual percentage change)



DNK c.1970-1990

	q	T	H	B	G	d	p
AGR	-0.03	0.00	-0.02	-0.00	-0.01	0.04	0.01
MNG	0.03	0.01	-0.03	0.00	-0.02	0.01	0.00
FOD	-0.00	-0.00	-0.00	-0.00	-0.00	0.02	0.00
HMN	-0.11	0.01	-0.36	-0.01	-0.33	0.25	0.04
LMN	-0.20	0.01	0.09	0.03	0.05	0.10	0.02
TRT	-0.13	-0.00	-0.09	0.00	-0.03	0.06	0.01
SER	0.28	0.00	-0.00	0.00	-0.02	0.08	0.01
EGS	-0.25	-0.02	0.18	-0.04	0.25	0.30	0.04

DNK 1995-2009

	q	T	H	B	G	d	p
AGR	-0.05	-0.00	-0.00	-0.00	-0.01	0.03	0.01
MNG	-0.00	-0.02	-0.04	0.01	-0.04	0.04	0.01
FOD	-0.02	-0.00	0.00	-0.00	-0.02	0.02	0.01
HMN	-0.32	0.06	-0.08	0.13	-0.09	0.19	0.06
LMN	-0.17	0.02	0.02	0.04	-0.05	0.05	0.02
TRT	-0.02	0.02	-0.16	0.01	-0.07	0.10	0.03
SER	-0.11	0.02	0.06	0.01	-0.01	0.11	0.04
EGS	-0.83	0.07	0.13	0.13	-0.24	0.47	0.15

FRA c.1970-1990

	q	T	H	B	G	d	p
AGR	0.02	0.00	-0.02	0.00	-0.03	0.07	0.01
MNG	0.04	-0.00	-0.03	0.00	-0.03	0.05	0.01
FOD	0.01	-0.00	0.00	-0.00	-0.02	0.06	0.01
HMN	-0.31	0.04	-0.36	0.00	-0.24	0.55	0.09
LMN	-0.37	0.03	-0.00	0.11	0.02	0.24	0.04
TRT	-0.09	0.02	0.03	0.00	-0.01	0.11	0.02
SER	-0.80	0.03	0.03	-0.00	0.15	0.33	0.06
EGS	0.54	0.00	0.07	-0.01	0.12	0.68	0.07

FRA 1995-2009

	q	T	H	B	G	d	p
AGR	-0.05	-0.00	-0.00	0.00	-0.00	0.03	0.01
MNG	-0.03	-0.03	0.02	0.01	0.03	0.04	0.02
FOD	-0.03	-0.00	0.00	0.00	0.01	0.02	0.01
HMN	-0.57	-0.01	0.10	0.03	0.21	0.23	0.09
LMN	-0.13	0.01	0.02	0.03	0.01	0.05	0.02
TRT	-0.17	0.01	-0.00	0.02	0.07	0.11	0.04
SER	0.01	-0.00	0.00	0.00	-0.03	0.17	0.07
EGS	0.91	0.05	-0.38	0.08	-1.15	0.69	0.28

UK c.1970-1990

	q	T	H	B	G	d	p
AGR	-0.02	0.00	0.05	0.00	-0.05	0.06	0.00
MNG	0.01	0.00	0.00	0.00	-0.01	0.03	0.00
FOD	0.03	-0.00	0.02	-0.00	-0.04	0.06	0.00
HMN	-0.36	-0.05	0.21	-0.02	-0.10	0.61	0.05
LMN	-0.36	0.08	0.14	0.08	0.08	0.26	0.02
TRT	-0.07	0.00	0.13	0.01	-0.00	0.16	0.01
SER	-0.62	0.01	0.13	0.02	0.56	0.23	0.02
EGS	-1.01	-0.01	0.90	-0.00	0.01	0.86	0.07

UK 1995-2009

	q	T	H	B	G	d	p
AGR	0.09	-0.00	-0.05	0.00	0.00	0.07	0.02
MNG	0.01	0.05	-0.05	0.02	-0.04	0.08	0.02
FOD	-0.02	0.00	-0.01	0.00	-0.02	0.05	0.01
HMN	-0.31	0.11	-0.16	0.14	-0.17	0.41	0.09
LMN	-0.16	0.01	0.02	0.02	-0.03	0.12	0.03
TRT	-0.16	0.04	0.01	0.06	0.02	0.19	0.04
SER	-0.39	0.02	0.09	0.02	0.01	0.26	0.06
EGS	-0.76	0.22	-0.08	0.20	-0.21	0.88	0.21

USA c.1970-1990

	q	T	H	B	G	d	p
AGR	-0.01	-0.00	-0.02	-0.00	-0.02	0.04	0.02
MNG	0.06	-0.00	-0.01	-0.00	-0.00	0.02	0.01
FOD	0.02	-0.00	-0.01	0.00	-0.02	0.02	0.01
HMN	-0.18	0.00	-0.19	0.00	-0.16	0.32	0.18
LMN	-0.86	-0.00	0.05	-0.01	0.23	0.26	0.14
TRT	-0.04	-0.00	0.00	-0.00	-0.02	0.10	0.05
SER	-0.27	0.00	0.01	0.00	0.12	0.22	0.12
EGS	0.83	-0.00	-0.69	-0.00	-0.29	0.59	0.32

USA 1995-2009

	q	T	H	B	G	d	p
AGR	-0.05	0.00	-0.01	0.00	-0.01	0.03	0.01
MNG	-0.02	0.01	-0.04	0.01	0.01	0.06	0.03
FOD	0.00	0.00	-0.01	0.00	-0.01	0.02	0.01
HMN	-0.24	0.07	-0.21	0.04	-0.06	0.29	0.17
LMN	-0.16	0.01	-0.02	0.03	-0.04	0.08	0.05
TRT	0.00	0.02	-0.07	0.01	-0.00	0.11	0.07
SER	-0.69	0.00	0.02	0.00	-0.04	0.38	0.21
EGS	0.20	0.11	-0.56	0.08	-0.33	0.71	0.43

Note: AGR – Agriculture; MNG – Mining; FOD – Food; HMN – Energy-intensive manufacturing, LMN – Non-energy-intensive manufacturing; TRT – Transport services; SER – Services; EGS – Electricity and gas supply.. **q** – energy intensity effect, **T** – intermediate demand trade structure effect, **H** – production technology effect, **B** – final demand trade structure effect, **G** – consumption mix effect, **d** – affluence effect, **p** – population effect.

Total sectoral effects (row sum in Figure 6) are mostly positive with minor exception for Denmark and France which show some negative contributions. It is also evident that the sectoral changes were more significant during the earlier period c1970-1990 (more intense red and blue color). Furthermore most of the changes are concentrated in the EGS category. This is expected because in addition to the direct energy use (e.g., for home heating) a significant amount is used indirectly e.g. in transport services.

Discussion

Economic growth was associated with an increasing use of energy in industrialised economies until about the 1970s. Since then the level of energy use has remained virtually unchanged or increased at a very low rate in high income countries. The main aim of this study has been to examine what is behind the reduction in energy footprint of selected countries exhibiting strong energy decoupling.

We decomposed and compared the energy footprint for Denmark, France, the UK and the USA during the period from c.1970 to 2009. Our analysis shows that the countries bear many similarities, but only Denmark displayed absolute decline in energy footprint. In the other countries, energy footprint has increased by roughly 2% per year during the earlier sub-period (c1970–1990) and 1% during the second sub-period (1995–2009).

On the supply side, we looked at three factors: energy intensity, structure of production and trade in intermediate goods. Energy intensity had a decreasing effect on overall energy footprints during both sub-periods. The UK, and to a lesser extent France saw large improvements in energy intensity induced reduction in footprints in the 1970-1990 period, whilst Denmark, the UK and the US had similar reduction in the 1995-2009 period. The reasons for these reductions vary. Emission intensity improvements in the electricity sector are the main driver of overall footprint change for the UK for both periods (mainly due to the movement away from using coal-fired generation). Perhaps more surprising is the significant role service industries have had in lowering aggregate energy use by efficiency improvements. For all four countries and for both periods, a reduction in energy footprint due to improvements in energy intensity of the services sector was observed. The contributions of efficiencies in the service industry to lowering energy demand have often not been offset by increased demand to the same extent. It is perhaps this observation that is key to understanding future opportunities for decoupling as countries develop. The services sector becomes an increasingly large portion of the economy as a country moves up the income scale.

Moreover, energy efficiency improvements that take place abroad play an increasingly important role. In the second sub-period, they accounted for a greater share of the reduction in energy footprint than domestic energy efficiency improvements. To large extent this is due to differences in underlying energy infrastructures between countries.

Across the economy, however, the net decrease attributable to the improvements of energy use on the supply side was offset by growth in the overall level of demand. As the household and other final demand categories demand more goods and services, this triggers an increase in energy footprint. During the earlier period these factors increased overall energy footprints by roughly 2%, and from 1995 to 2009 by roughly 1.5% per year. This effect was accentuated further by changes in population. Increased aggregate demand has the largest impact on electricity and manufactured goods (Figure 6).

In the second sub-period, we especially see a stronger role of product-mix factors in reducing overall energy footprints in the domestic economy. Both the changing mixture of products in industrial structure (**H**) and the final demand structure effect (**G**, which represents changes in lifestyle and consumption patterns) generally show a negative effect on energy footprint. On the production side, the most consistent effect was attributable to reductions in the electricity sector, but this was not the case for Denmark (which has probably seen the strongest penetration of renewables). Other major changes were seen through manufacturing and transport. The effect on the demand side (G) accounted for roughly -0.5% a year in all countries (and was stronger during the second sub-period from 1995 to 2009). Hence whilst overall demand has grown, the lower elasticities of basic goods like electricity mean that a lower percentage of demand goes to these sectors. In comparison, the displacement to the service sector is also seen – especially in the early periods, we see the consumption mix of services in GBR, FRA and USA create a strong upward driver of energy use in final demand. As such, the evidence confirms that countries are in general shifting their final demand towards goods and services that are less energy-intensive on average. Changes in the trade of intermediate and final products accelerated the growth of the global energy footprint by roughly 0.5% per year. Such results imply that there has been a substitution of more energy efficient domestic production by foreign production of lower efficiency (or more efficient foreign production with less efficient one). Mostly, this type of substitution was evident during the second sub-period (1995-2009), while in the earlier sub-period, domestic production was replaced by foreign production, which was as efficient as the domestic. However, for the earlier sub-period the results should be taken with caution because we make an assumption that foreign products were produced with a weighted four country average technology. For a large country such as the United States this means that a four country average technology is likely to be very similar to its domestic technology. This might explain why the effect of **T** and **B** in the earlier sub-period is very small.

Despite several minor yearly differences, the general pattern of what is driving energy footprint up and what works in the opposite direction seems to be similar across countries.

Energy efficiency improvements have been a dominant source of energy savings for a long time, and this is likely to continue into the future, at least from what we observe in developing countries. In the past, it was electricity that freed factory design from restrictions associated with steam and water power. Information technologies have played an important role since the 1970s by allowing more precise and controlled production processes. Perhaps more of a concern is the overall limited increases in efficiency that has occurred in developed countries in more recent years (with results showing that most efficiency effects being due to improvements abroad). If such trends are replicated globally, then it is unlikely that future efficiency improvements will be able to offset the overall growth in demand side factors. One could speculate that adoption and diffusion of artificial intelligence will play a new role in driving efficiency. For instance, by allowing producers to manage energy output generated from multiple sources to match social, spatial, and temporal variations in demand in real-time (Wolfe, 2017). However, with the central role that the current energy system has in producing greenhouse gas emissions, it is clearly one of the main focuses for policies to achieve deep decarbonisation. Our results imply that either these supply side efficiencies must be radically increased, or much more needs to be done on the demand side to break the strong, consistent pull that increasing affluence has. With the majority of the global population looking to emulate the lifestyle choices that these developed countries have, the link between affluence and energy demand is likely to become more important, not less.

Conclusion

In this work, the reasons for why energy footprints in four high income countries have declined were investigated using structural decomposition analysis. A "footprint" based approach was undertaken in order to capture the changes in energy use to service final demand of a country, including energy use abroad.

Results showed that in general, improvements in energy efficiency have been offset by increases in aggregate demand. Energy efficiency improvements in the manufacturing and electricity sectors have been a dominant source of energy savings for a long time, but increasingly efficiency improvements in the service sector are becoming as important.

In addition, we found that changes in the production structure and consumption mix of the four high-income countries are beginning to become more important than the domestic changes in efficiency.

Trade when looked at as a substitute of foreign vs domestic production has had a minimal effect on energy footprints in the earlier sub-period but the effect has increased in the second-sub period. However, when we break down efficiency improvements into those occurring domestically versus those occurring abroad, we find that the later are growing strongly, and that improvements abroad were more important than domestic improvements for the second sub-period of 1995-2009.

At the sector level, despite electricity obtaining a smaller budget share of expenditure in these countries, the overall demand for electricity is still going up and having the largest positive driver for most of the high-income countries.

The question then is how developed countries will further manage their future energy footprints based on these results. It is perhaps most significant that the improvements in energy efficiency that have occurred domestically in these high-income countries are becoming less relevant in reducing overall energy use. Instead, as efficiency improvements are now mainly being seen in developing trade partners rather than in the domestic economy, it would be expected that this productivity source will decline as developing countries pick low-hanging energy efficiency measures. Likewise, the further impact that trade substitution will have will highly depend on the global convergence or divergence of technology – if developing countries catch-up, future impacts embodied in trade will likely reduce, but if energy efficiency is ramped up as a means of climate mitigation in developed countries, the importance of energy embodied in trade will still likely increase.

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